1 2 9 0

UNIVERSIDADE Ð
COIMBRA

Andreina Michelle Zerega Marques

INFLUENCE OF URBAN STREAM HYDROMORPHOLOGY ON AQUATIC INVERTEBRATE COMMUNITIES

Dissertation in the Integrated Master's in Environmental Engineering, in the Specialization in Territory and Environmental Management, supervised by Professor Nuno Eduardo Simões and by Professor Maria João Feio and presented to the Civil Engineering Department of the Faculty of Sciences and Technology of University of Coimbra.

October 2020

Faculty of Science and Technology of the University of Coimbra
Department of Civil Engineering

Andreina Michelle Zerega Marques

INFLUENCE OF URBAN STREAM HYDROMORPHOLOGY ON AQUATIC INVERTEBRATE COMMUNITIES

INFLUÊNCIA DA HIDROMORFOLOGIA DOS RIBEIROS URBANOS NAS COMUNIDADES DE INVERTEBRADOS AQUÁTICOS

Dissertation in the Integrated Master's in Environmental Engineering, in the Specialization in Territory and Environmental Management,
supervised by Professor Nuno Eduardo Simões and by Professor Maria João Feio

October of 2020

1 2 9 0

UNIVERSIDADE Ð
COIMBRA

ACKNOWLEGMENTS

I wish to thank my supervisors, Prof. Nuno Eduardo Simões and Prof. Maria João Feio, without whom I would never have been able to finish this dissertation. Thank you for guiding me through my first dwelling into the world of academic research, for constantly keeping me on track, and for patiently bearing with my lack of motivation. I must admit that this last hurdle in my academic formation was much more challenging than I ever expected. The sudden strike of a global pandemic shook the ground beneath our feet, completely altering our plans for this project and every expectation I had ever built. I could not have done it without your guidance. My sincerest thank you.

I would also like to acknowledge my colleague and friend, Daniela Ferreira, for sticking with me through this last challenge and bearing with my exasperation for almost an entire year. Thank you for all the encouragement, and congratulations on your own dissertation.

Lastly, to my family, João, and my friends, thank you for your unconditional love and support throughout this challenging chapter of my life.

RESUMO

Atualmente, mais de metade da população global vive em zonas urbanas, prevendo-se que este número continue a crescer. A urbanização traz vários desafios ambientais, sendo a gestão da água uma delas, particularmente a gestão da drenagem urbana. A alteração da hidrologia urbana (como o aumento do volume de escoamento superficial e diminuição do tempo de resposta) afeta os ecossistemas urbanos de água doce, particularmente os ribeiros urbanos. Esta dissertação sublinha a importância dos ribeiros urbanos para alcançar a sustentabilidade da gestão de água urbana, uma vez que se trata de soluções azul-verdes, baseadas na natureza, que fornecem vários serviços de ecossistema importantes à população urbana. Estes serviços incluem, entre outros, a redução do risco de cheias, a regulação da temperatura do ar, e a melhoria do bem-estar dos residentes urbanos. Estes benefícios contribuirão para alcançar a sustentabilidade urbana e melhorar a resiliência das cidades face ao crescimento urbano e às alterações climáticas.

Tendo em conta que a ecologia dos ribeiros urbanos está comprometida devido à urbanização, a restauração destes sistemas é imperativa. Apresenta-se um artigo de revisão abordando a restauração de ribeiros urbanos, nomeadamente a razão pela qual alguns projetos de restauração falham, e como garantir o sucesso de tais esforços. As comunidades de macroinvertebrados bentónicos revelam o estado ecológico de um ecossistema fluvial, e portanto, medidas que melhorem a diversidade destes conjuntos irão, inerentemente, melhorar o ecossistema global e, consequentemente, a sua função e serviços de ecossistema. Essencialmente, para garantir o sucesso dos projetos de restauração de ribeiros urbanos, todo o contexto ecológico do sistema de ribeiros deve ser avaliado, incluindo interações biológicas, a morfologia, hidrologia, estado da bacia urbana, qualidade da água, fontes de poluição, e utilização do território. Considerando o enquadramento do projeto, as medidas de restauração devem ser priorizadas de acordo com as necessidades dos ecossistemas.

Palavras-chave: urbanização, ribeiros urbanos, gestão de água urbana, drenagem pluvial urbana, comunidades de invertebrados aquáticos

ABSTRACT

Currently, over half of the global population lives on urban areas, and this number is expected to continue growing. Urbanisation brings several environmental issues, water management being one of them, particularly stormwater management. The alteration of urban hydrology such as the increase of flashiness and runoff volume affects urban freshwater ecosystems, particularly urban streams. This dissertation highlights the importance of urban streams for achieving sustainable urban water management, since they are blue-green nature-based-solutions that provide several important ecosystem services to the urban population. Such services include, amongst others, the diminishing of flood risk, temperature regulation, and human wellbeing improvement. These benefits will contribute to achieving urban sustainability and improve the resilience of cities in face of urban growth and climate change.

Considering how the ecology of urban streams is compromised due to urbanisation, the restoration of such systems is imperative. A review paper is introduced regarding urban stream restoration, namely why some restoration projects fail and how to successfully carry out such efforts. The communities of benthic macroinvertebrates expose the ecological state of a stream ecosystem, and thus implementing measures that improve the diversity of such assemblages will inherently improve the overall ecosystem and consequently, its function and ecosystem services. Essentially, to guarantee the success of urban stream restoration projects, the whole ecological context of the urban stream system needs to be assessed, including biologic interactions, morphology, hydrology, state of the watershed, water quality, sources of pollution, and land use. Once the context of the project is thoroughly understood, actions need to be prioritised according to the needs of the ecosystems.

Keywords: urbanisation, urban streams, urban stormwater management, urban drainage, aquatic invertebrate communities

INDEX

1 GENERAL INTRODUCTION

The urban era is upon us (Anderson et al., 2013; Ljungkvist et al., 2010; Montgomery, 2008; Seto et al., 2010). Currently, more than half of the global population lives in urban areas, and this trend is only expected to persist. In 1950, thirty per cent of the world’s population was urban. By 2050, it is projected to reach sixty-eight per cent (United Nations, 2018).

Following the same trend as urban development, the current world population of 7.7 billion is anticipated to reach almost 10 billion by 2050 (United Nations, 2019). Populational growth calls for cultural and economic development, which in turn, translates into urban growth and ultimately, urbanisation (Dey et al., 2010; Tandon & Jyotsna, 2016). Metropolitan growth brings about several environmental problems, at several different scales, including atmospheric pollution, degradation of water quality, disturbance of hydrologic patterns, contribution to climate change, the heat island effect, loss of biodiversity, and overall disruption of local to global biogeochemical cycles (Grimm et al., 2008). Such environmental issues impose a threat not only to the environment, but also to human health, thus making urban sustainability a challenge to be tackled through environmentally sound territorial planning (United Nations, 2017).

This dissertation focuses on urban streams as ecosystems that provide services, as blue-green nature-based solutions, for the current challenge of urban sustainability. Urban streams are running-water ecosystems highly influenced by urban land-use, whether it be urban, suburban, or exurban development. Urban land use affects them through the occupation of ecosystem areas, causing profound alterations to their morphology, hydrology, and water quality due to the runoff from impervious areas such as roads, buildings, and parking lots (Booth et al., 2016; Ferreira et al., 2016).

However, restoring urban stream ecosystems can positively promote the sustainability of cities. In the context of the 2030 Agenda for Sustainable Development of the United Nations, urban streams contribute to the 11th goal of sustainable urbanisation, protecting the world’s cultural and natural heritage, mitigating the effects and adapting cities to climate change, increasing their resilience to natural disasters (such as floods), and providing access to green public spaces (United Nations, 2015). Urban streams also contribute to several other goals with the preservation of aquatic and terrestrial biodiversity, climate action, sustainable management of water and sanitation, and with human health and well-being.

With the European Water Framework Directive (WFD), the European Parliament and the Council of the European Union adopted in 2000 a regulatory framework for measures in the field of water policy, making the WFD the key management imperative in watersheds across Europe. Achieving a good ecological and chemical status for all European surface waters by 2015 was one of the goals of the WFD, which has now been postponed to 2027. This status is defined by a near-natural biological assemblage of aquatic flora, benthic invertebrate and fish fauna as well as specific pollutants, hydromorphological, chemical and physico-chemical components as expected in conditions of minimal anthropogenic changes and disturbances (Booth et al., 2016; Brettschneider et al., 2019; European Commission, 2000; Reyjol et al., 2014). This mission required the restoration of all aquatic habitats to good ecological quality, including urban streams (Moss, 2018).

1.1 Aims & Objectives

Ecohydrology is an integrated strategy for watershed management that implements the combined approach of hydrology and ecology, concepts that would traditionally be viewed as individual and exclusive from one another. This emerging paradigm suggests that, in order to conserve water resources, natural processes such as water and nutrient circulation, and energy flow, at the basin scale, must be preserved through the interplay between biota and hydrology. That is, taking advantage of how to regulate the biological processes of the basin using hydrology, and vice-versa, how to use ecosystem properties as water management tools (Ashley et al., 2013; Fletcher et al., 2015; Wassen & Grootjans, 1996; Wolanski et al., 2004; Zalewski, 2006).

In spite of the many publications regarding streams restoration, many of these projects still fail to successfully recover biological components of the ecosystem and its functionality, due to the inadequacy of measures towards existing problems (Beechie et al., 2008; Palmer et al., 2005, 2014). In view of this, the present thesis reviewed the existing literature with the following main objectives: 1) determine the effects of hydromorphological alterations in biological communities; 2) establish the most important restoration measures to recover urban stream ecosystems. Achieving these objectives will contribute to sustainable urban development by providing urban water management with an integrated ecohydrology perspective on urban streams.

1.2 Structure

The structure of this dissertation is composed of a contextualisation chapter (chapter 2), which will address the fundamental concepts of urban water management and the components of a freshwater aquatic ecosystem, which are crucial for the understanding of ecohydrology and stream restoration. The following chapter (chapter 3) is a review paper focused on urban stream restoration, particularly hydromorphological measures, and its effects on benthic macroinvertebrate assemblages, since aquatic invertebrates are a key component of freshwater ecosystems and a bioindicator used worldwide in the ecological assessment of rivers (Kenney et al., 2009). Finally, chapter 4 contains the general conclusions and main insights relevant for urban stream management extracted from this thesis, followed by aspects deemed for future research.

2 CONTEXTUALISATION ON URBAN WATER MANAGEMENT AND AQUATIC ECOSYSTEMS

2.1 Urban Water Management

Urban water management encompasses the planning, design and operation processes that secure the supply of potable water, sanitation, drainage of stormwater runoff, recreational parks, and the maintenance of urban ecosystems. Urban drainage currently faces two demanding challenges: urban growth, and climate change (Oral et al., 2020).

A brief analysis on the background of urban drainage management shows that early stormwater paradigms mainly focused on keeping water out of the way and preventing flooding by digging ditches and culverts. This, eventually, shifted to combined sewer pipes, and later on, separate stormwater pipes. Thus, the modern urban drainage infrastructure was born: a drainage system which purpose was to collect stormwater and lead it, through pipes, to the nearest receiving body of water (Debo, 2003; Oral et al., 2020). Thus, stormwater is efficiently and quickly removed from urban areas (Ashley et al., 2013). Despite this paradigm being efficient in its function, it becomes unsustainable in light of urban growth and climate change.

Urban growth, as previously stated, alters the natural land cover of the earth, replacing natural surfaces with impervious materials. These impervious areas prevent stormwater from infiltrating or being retained, thus increasing superficial runoff volume and peak flows, as shown in Figure 2.1 (Chadwick et al., 2006; Ferreira et al., 2016; Konrad & Booth, 2002, 2005; Paul & Meyer, 2001; Walsh et al., 2004). The focus on urban flooding has redoubled due to the increase in frequency and magnitude of pluvial events resulting of climate change (Haghighatafshar et al., 2019). Volatile rainfall patterns and an increasing number of extreme events can lead to the overload of drainage systems and consequent flooding. In light of such extreme events, conventional drainage systems become utterly unsustainable. When these flood events are followed by long drying periods, it forces cities into resorting to additional demand for irrigation water for urban green areas, due to the lack of stored rainwater (Oral et al., 2020).

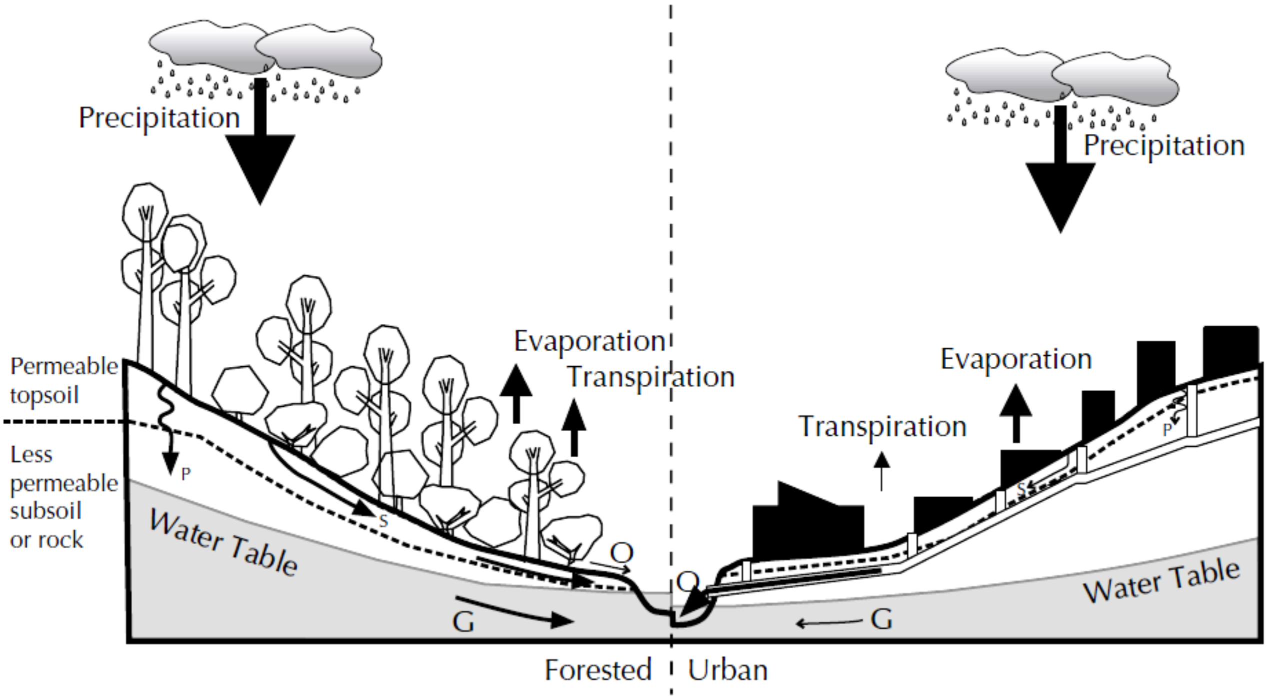

Figure 2.1- Illustration of the water cycle in a natural forested setting versus an urbanised watershed with conventional stormwater drainage. The size of the arrows indicates qualitative water volumes in relation to each other. O- overland flow (or superficial runoff that is drained through pipes); S- subsurface flow through permeable topsoil; P- percolation; G- groundwater flow. Source: Walsh et al. (2004).

In light of the mentioned challenges, it is imperative to enhance the resilience of cities towards climate change, whilst maintaining functionality of the existing infrastructure (Haghighatafshar et al., 2019; Oral et al., 2020). Blue-green infrastructure is a valuable tool for achieving this, since not only does it enhance resilience, but also provides several other benefits. Urban blue-green infrastructure is a network of natured-based features located in the midst of the urban landscape. The concept of “blue-green infrastructure” can be considered as a “nature based solution” (Baravikova, 2020), and therefore both terms are used interchangeably in this text. These features are based on either vegetation, water, or both. Examples of blue-green infrastructure are green roofs and walls, grassed areas, trees, parks, rain gardens, swales, rivers and ponds (K. Brown & Mijic, 2020). The implementation of this strategy has also been driven by other pressing challenges that cities face, such as water quality standards, water security, and ecosystem degradation (Liao et al., 2017). Nature based solutions allow imitating natural hydrologic patterns by infiltrating stormwater, detaining runoff close to its source, and evapotranspiration performed by the vegetation (Oral et al., 2020). Unlike the single-functioned grey infrastructure that makes up conventional drainage systems, blue-green infrastructure yields several benefits other than efficient stormwater management (Ashley et al., 2013; Liao et al., 2017).

The current paradigm concerning urban water management has evolved, just as priorities have too (Figure 2.2). New philosophies in water management recognise the value of blue-green infrastructure, acknowledging it crucial for meeting the challenges that come with urban growth and climate change (Ashley et al., 2013). The following concepts are examples of new, more integrated, approaches to overall water management and, more specifically, stormwater drainage. These are fairly similar and emerged roughly at the same time in different parts of the world (Fletcher et al., 2015):

- Water Sensitive Urban Drainage (WSUD)- originated in Australia, WSUD is a philosophy that aims to minimise the hydrologic impacts of urbanisation. It targets the protection and enhancement of natural water bodies by filtering stormwater with multiple-use corridors, maximising visual and recreational amenities (Figure 2.3). It also pursues the reduction of runoff volume and peak flows by incorporating local detention measures and minimising impervious areas.
- Low Impact Development (LID)- most commonly used in North America and New Zealand, this approach aims to minimise the cost of stormwater management by designing drainage systems with natural components. It aims to achieve natural hydrologic patterns by employing small-scale stormwater treatment devices, such as bioretention systems, green roofs, and swales.
- Sustainable Urban Drainage Systems (SUDS)- practised in the United Kingdom, SUDS are an approach to stormwater management based on the concept of replicating (as much as possible) natural, pre-development drainage (Figure 2.4). SUDS are characterised by a multi-element train approach, which consists of a sequence of stormwater practices and technologies (SCMs- stormwater control measures). Taken together, the several small-scale SCMs that make up the SUDS management train can attain the goal of replicating natural drainage, reducing ultimate runoff volume (Haghighatafshar et al., 2019).

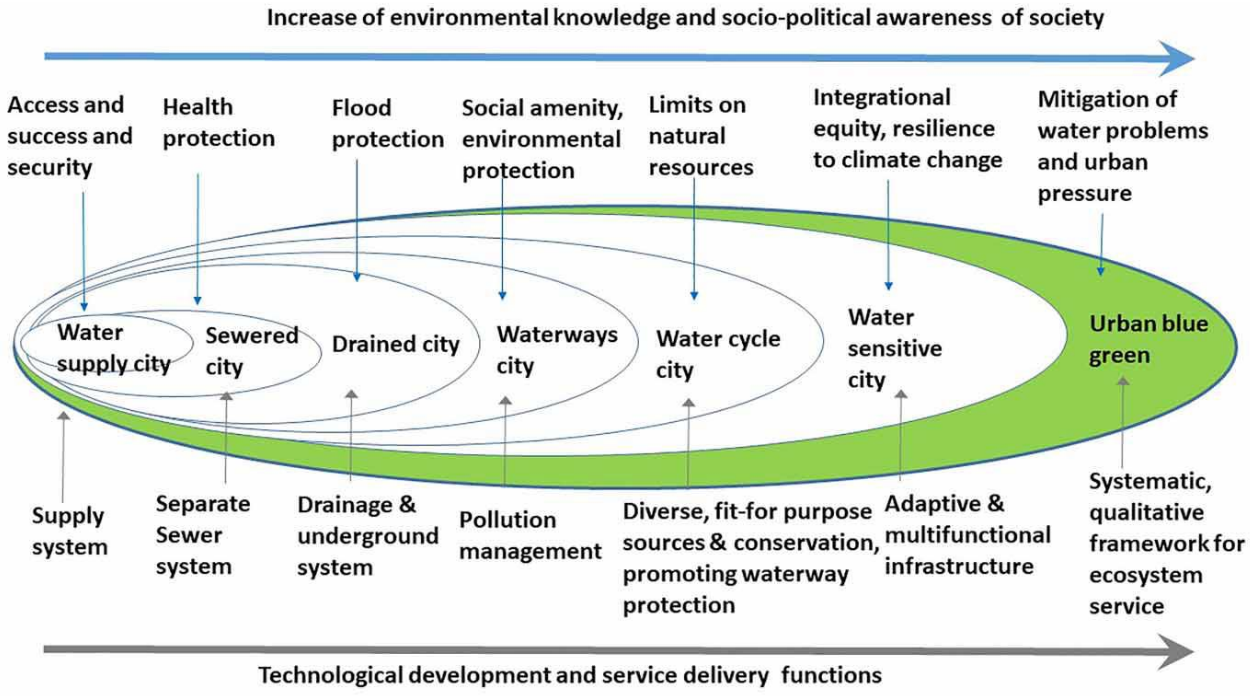

Figure 2.2- Development of urban water management priorities throughout history. Source: Oral et al. (2020).

Figure 2.3- Examples of stormwater control measures. (A) bioretention swales- comprised of a filter medium and vegetation, they convey, filter, detain, and even remove nitrogen and other fine particulate contaminants through biological uptake. Source: NACTO (2017). (B) vegetated swales- similar to bioretention swales, with the difference of lacking a filtering medium, and thus not as efficient (Melbourne Water, 2013). Source: Lucke et al. (2014).

Figure 2.4- Illustration demonstrating the implementation of SUDS, replicating natural pre-development drainage as much as possible. Source: Thames21@ (2020).

All these new approaches ultimately share the same broad principles: (i) mitigating the alteration of hydrologic patterns, due to urbanisation, and aiming to replicate the natural, pre-development, flow regime as much as possible; and (ii) improving the quality of the water that is finally discharged onto the receiving wastewater treatment system (Fletcher et al., 2015). These emerging paradigms concerning stormwater management are all tools for integrated urban water management (IUWM). This concept encompasses all the environmental, economic, social, technical, and political aspects of urban water management. IUWM provides a framework for planning, designing, and managing all urban water systems (supply, drainage, and wastewater treatment). It undertakes the optimisation of water resources management, considering alternative opportunities, and the protection of urban ecosystems. Integrated urban water management is a crucial step towards attaining the ultimate goal of sustainable urban development (Fletcher et al., 2015; Furlong et al., 2017; Oral et al., 2020).

Nature-based solutions, such as blue-green infrastructure, not only are efficient tools for IUWM but also provide additional amenities and ecosystem services. Urban streams prove to be a valuable NBS because of the numerous benefits they provide to the urban population, as well as their contribution towards sustainability.

According to the Millennium Ecosystem Assessment, ecosystem services are defined as the benefits people obtain from ecosystems. This definition comprises both the “goods” and “services” that ecosystems yield, that is, tangible (such as food, fuels, raw materials) and intangible (for instance, waste assimilation and air purification) benefits (Millennium Ecosystem Assessment, 2003). The different benefits people can obtain from ecosystems are categorised in four groups: regulating, supporting, cultural, and provisioning services.

Urban streams provide the following ecosystem services (summarized in Table 2.1):

1. Regulating services
    1.1. **Reduce pluvial flood risk**- vegetation can intercept, retain, and release water through evapotranspiration while its underlying soil acts as a sponge by infiltrating and storing water until it percolates. Floodplains and riparian zones manage to slow water flow from land to freshwater body, reducing flood frequency and magnitude (Alves et al., 2019; Bolund & Hunhammar, 1999; De Vleeschauwer et al., 2014; Gómez-Baggethun et al., 2013; Palmer & Richardson, 2009; Sörensen & Emilsson, 2019; Voskamp & Van de Ven, 2015).
    1.2. **Urban temperature regulation**- the urban heat island phenomenon is caused due to urban landscape: dark, impervious materials and canyon effect of buildings and pavement that retain heat. Bodies of water will regulate temperature deviations both during summer and winter (Bolund & Hunhammar, 1999; Palmer & Richardson, 2009). Riparian vegetation, besides shading, can lower urban temperature through evapotranspiration. These services improve thermal comfort, reduce heatwaves and energy usage in buildings. An additional benefit of this service is the reduction of the inversion phenomena, which leads to better air quality (Antoszewski et al., 2020; Maksimović et al., 2015).
    1.3. **Improved air quality**- riparian vegetation filters pollutants such as particulate matter, nitrogenous compounds and sulphur oxides originated by transport in urban zones, therefore improving public health (Maksimović et al., 2015; Oral et al., 2020; World Health Organization, 2017).
    1.4. **Noise reduction-** soil and vegetation can attenuate noise pollution through absorption, deviation, reflection, and refraction (Gómez-Baggethun et al., 2013; Oral et al., 2020)
    1.5. **Water purification-** streams can retain, store, and remove excess nutrients and decompose organic matter. Riparian plants and microorganisms can also biologically process excess sediments, heavy metals, and other contaminants in the water (Alves et al., 2019; Iojă et al., 2018; Palmer & Richardson, 2009).
    1.6. **Global climate regulation-** riparian vegetation and aquatic plants and algae have the ability to sequester and store carbon from atmospheric carbon dioxide, reducing the concentration of this greenhouse gas and thus contributing to the global climate regulation (Gómez-Baggethun et al., 2013; Iojă et al., 2018; Palmer & Richardson, 2009; Voskamp & Van de Ven, 2015).
2. Supporting services
    2.1. **Habitat for biodiversity-** urban streams provide habitat for numerous aquatic and terrestrial species from a wide variety of biological groups, including aquatic and terrestrial invertebrates, fish, algae, plants, amphibians, reptiles, and birds (Dodds & Whiles, 2010; Feio & Ferreira, 2019; Wetzel, 2001).

Urban biodiversity can be defined as the number of organisms (animals and plants) that live within an urbanised area; the evenness of their distribution; their functional traits and the interactions with each other and their surroundings (Hooper et al., 2005; Nilon, 2011). The term ecosystem functionality refers to the properties and processes that occur within an ecosystem that depend on its biodiversity (Hooper et al., 2005; Jax, 2005).

Biodiversity, in an urban context, is important due to both instrumental and non-instrumental values. Instrumental values are the anthropogenic benefits that humans yield from biodiversity, such as economic benefits from resource conservation; supporting life on earth and human welfare; spiritual and/or aesthetic satisfaction. Non-instrumental values, opposingly, are independent from human benefit, regarding biodiversity as important by its own sake (Gaia & John Jones, 2017)

3. Cultural services
    3.1. **Aesthetic and health benefits-** the mere existence of urban blue-green spaces is believed to reduce stress and improve physical and mental health, leading to higher quality of life and therefore increased productivity (Bolund & Hunhammar, 1999; Goldenberg et al., 2018; Gómez-Baggethun et al., 2013; Nutsford et al., 2016).
    3.2. **Cognitive development and education-** contact with nature helps youngsters develop environmental awareness, a sense of responsibility towards it, and recognition of ecosystem services (Gómez-Baggethun et al., 2013; Nilon, 2011).
    3.3. **Social cohesion-** neighbourhood blue-green spaces are considered valuable and attractive. If surroundings are pleasant, more people will choose to stroll outside, meet, and socialise, developing stronger social cohesion and reduced criminality (Maksimović et al., 2015).
4. Provisioning services
    4.1. **Water supply-** urban streams can provide water for residential, commercial and urban use, as well as irrigation supply for agriculture (Palmer & Richardson, 2009).
    4.2. **Food supply-** streams and rivers can supply freshwater fish, crayfish, and molluscs, as well as herbs for medicinal or culinary practices (Harrison et al., 2010).

Table 2.1- Summary of the ecosystem services that urban streams yield.

Urban Streams Ecosystem Services	
Regulating Services	Urban temperature regulation Reduced flood risk Improved air quality Noise reduction Water purification Global climate regulation
Supporting Services	Habitat for biodiversity
Cultural Services	Aesthetic and health benefits Cognitive development and education Social cohesion
Providing Services	Water supply

2.2 Streams as Freshwater Aquatic Ecosystems

From an ecology point of view, streams are ecosystems composed of morphological and hydrological characteristics that interplay with a variety of biological elements, which together perform the ecosystem functionality that sustains its habitat and biological communities (Hooper et al., 2005; Jax, 2005). A river or stream is constituted by its watershed (which is the geographical area that drains water from rainfall into the streamflow), the riparian zone, the channel, streambank, and in-stream structures (organic, like woody debris, or inorganic, such as sediments and rocks; Moss, 2018).

The riparian zone is an ecotone composed of dense vegetation with high affinity to water, between aquatic and terrestrial systems, located on both sides of the channel (Figure 2.5). The riparian vegetation includes trees, shrubs, ferns, and bryophytes (liverworts, hornworts, and mosses). This area can be inhabited by terrestrial invertebrates, birds, amphibious, reptiles, and semi-aquatic mammals. Many invertebrates are insects that only remain aquatic whilst juveniles, shifting to the riparian zone or a more distant terrestrial habitat once adults (Moss, 2018).

The riparian vegetation is the main source of energy to stream ecosystems, due to the input of allochthonous organic matter. This matter includes leaf litter, branches, twigs, and even large tree trunks. These components are considered allochthonous production since they are produced externally to the stream. They are primarily consumed by decomposers such as bacteria, fungi, and benthic invertebrates (Moss, 2018). Woody debris, apart from being a source of fine detritus, is also responsible for creating habitat for aquatic organisms, and retaining materials that would otherwise be washed downstream, like leaves for instance (Melillo et al., 1983).

The riparian corridor also provides canopy cover, which controls shading and therefore, primary production through photosynthesis and consequential algal growth (da Silva Gonçalves et al., 2018; Moss, 2018). The riparian zone also ensures connectivity of the aquatic ecosystem with adjacent areas (Tabacchi et al., 1998). Additionally, the riparian forest provides stability to the streambank and protection against erosion. It also proves to be an important biological buffer against pollutants and nutrients resulting of nonpoint-source pollution (Aguiar et. al., 2019).

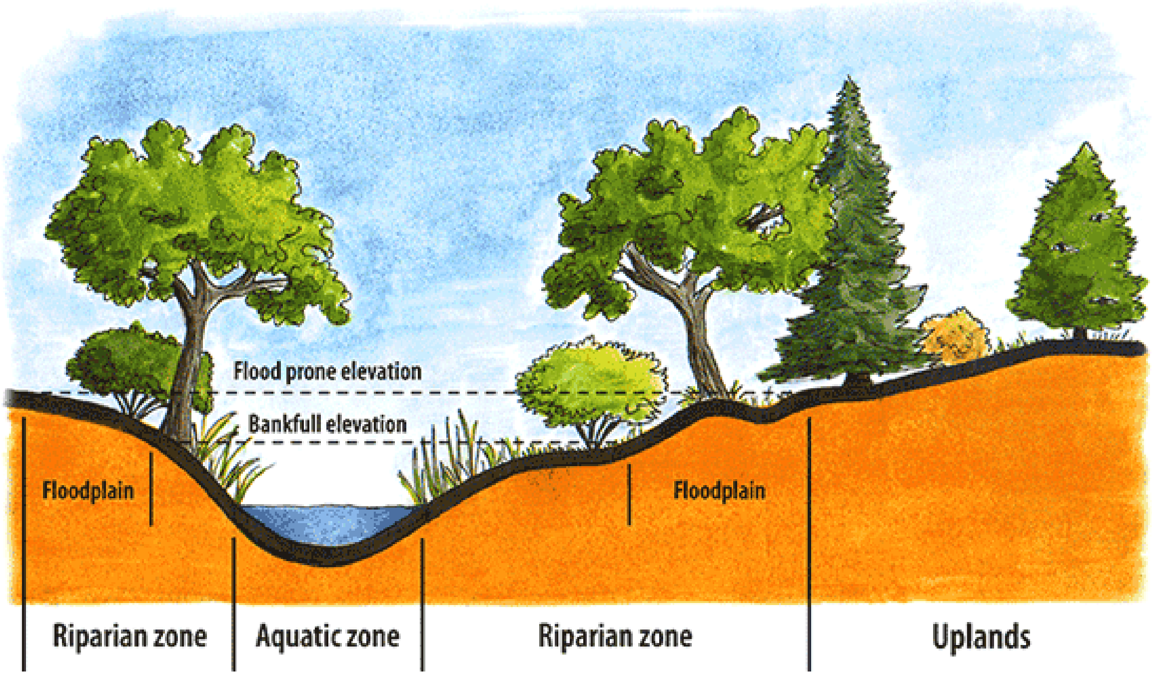

Figure 2.5- Illustration of the riparian zone and other components that compose a stream ecosystem. Source: SLCo@ (2020).

The flora associated to freshwater ecosystems can be structured in specific communities according to the characteristics of the aquatic environment. Strictly aquatic vegetation includes macrophytes, which can be emergent (rooted to the streambed but leaves extend out of the water), submergent (live completely underwater and can be rooted or not), floating (leaves float on the water surface and may be rooted to the substrate or not) and algae (Wetzel, 2001).

Algae are the base of trophic webs and biogeochemical cycles in aquatic ecosystems. The majority of algae are strictly aquatic, thriving along the water column and colonising all types of substrate (such as rocks, boulders, and sediments). The most common algae in running waters are Chlorophyta (green algae) and Bacillariophyceae (diatoms), as well as Cyanobacteria (blue algae), and, generally less abundant, Rhodophyta (red algae). These are primary producers, constituting an important source of food for primary consumers. By performing photosynthesis, they intake inorganic nutrients from the water, transforming them into organic compounds by accumulating them in their biomass and thus regulating the presence of such nutrients in the aquatic environment. Algae depend on light and nutrient availability, as well as the velocity of the current (S. F. P. Almeida et. al., 2019; Wetzel, 2001).

Another important aquatic biological element are fish, their communities depend on water quality, the hydromorphology of the stream, and the constitution of the riparian forest (P. R. Almeida et. al., 2019).

Amphibians and reptiles also use freshwater ecosystems. Amphibians are generally dependant on aquatic environments in order to reproduce but live most of their lives on the land, whilst reptiles reproduce on the land and can live almost exclusively in the water. Both amphibians and reptiles generally live in lentic areas, since they suffer predation from bigger fish. Also, high streamflow velocities can easily drag eggs downstream. All these organisms are generally sensitive towards environmental disturbance, and thus their presence generally indicate a good ecological state of the site (Rebelo et. al., 2019).

Bird communities depend on the quality of habitat of the channel, the riparian forest, and the streambank. Vegetation provides nesting sites, shelter, and food source for migrating birds. A higher number of individuals and different species occur in undisturbed sites with highly diverse riparian forests. Birds usually occupy the highest trophic levels of freshwater ecosystems as predators, and therefore the state of their communities reflect the ecological state of the aquatic environment as well as the riparian forest (Ramos et. al., 2019).

There are also mammals associated to freshwaters. Some mammals are exclusively aquatic (e.g., the otter), whilst others are simply semi-aquatic, resorting to aquatic environments for food source, while they procure land for shelter and reproduction (Santos-Reis et. al., 2019).

Finally, the aquatic invertebrates are the main primary consumers in freshwater ecosystems, linking inferior trophic levels to superior ones in the food chain. They feed on algae, microorganisms, and allochthonous organic detritus, and then serve as food source to predators such as other invertebrates, fish, birds, and amphibians (Serra et al., 2019b).

The invertebrates of streams can be organised into functional feeding groups based on how food is gathered. Grazers and scrapers consume resources- algae and benthic biofilm- from substrate surfaces; shredders feed on leaves enriched with microbes; predators on other animals; gatherers/collectors consume small organic particles accumulated at the bottom of the stream; filterers capture particles directly from the water column (Allan & Castillo, 2007). As a whole, macroinvertebrate communities perform crucial functions that are imperative to the ecosystem functionality of the stream. Even rare species can perform critical roles. Some of the functional feeding roles that macroinvertebrates perform in streams are summarised in Table 2.2.

Table 2.2 – Functional feeding roles of macroinvertebrates in stream ecosystems (Wallace & Webster, 1996).

Grazers	Regulate algal biomass, affecting hydraulic retention and nutrient assimilation. Increase downstream export of fine particulate organic matter from grazed surfaces.
Shredders	Transform coarse particulate organic matter into fine and dissolved organic matter, which facilitates its downstream transport.
Gatherers	Decompose deposited fine particles. The most abundant stream macroinvertebrates, playing an important role as prey in wood webs.
Filterers	Remove particles from suspension. Supply larger organic matter particles through their feces for deposit-feeding detritivores.
Predators	Affect prey, not only with mortality, but also with feeding activities, growth rates, fecundity, and overall behaviour.

After the conditioning of leaves by fungi and bacteria, invertebrate shredders feed on the leaves and, by doing so, produce fine particles. These particles, plus shredder feces and other allochthonous fine particles, result in suspended organic matter, which fungi and bacteria will recolonise in order to continue conditioning leaves. Some fine particles become food for invertebrate filter-feeders, others settle in quieter areas of the stream, where invertebrate deposit-feeders will burrow into and ingest the organic matter. In this manner, coarse leaf material is gradually converted into animal tissue and carbon dioxide. High diversity of the different invertebrate feeding guilds facilitates the processing of organic matter. Macroinvertebrates also feed on biofilms and bryophytes. Where there is sufficient light, a biofilm will develop over rocks and stones that are relatively stable. These are made up of algae, bacteria, fungi, and protozoa (which feed on the latter microorganisms; Moss, 2018). Aquatic invertebrates will serve as food source to predators such as other invertebrates, fish, birds, and amphibians (da Silva Gonçalves et al., 2018; Serra et al., 2019b).

Benthic macroinvertebrates are living organisms found at the bottom (”benthos”) of streams (Dodds & Whiles, 2010). They lack a backbone (hence, “invertebrate”) and are visible to the naked eye (thus, “macro”). They are frequently found attached to rocks and vegetation or burrowed into the bottom substrate of the streambed (EPA@, 2016). The communities of these beings are the focus of this study, since they are some of the most frequently used bioindicator in order to assess the ecological state of a stream (Kenney et al., 2009). They are suited to assess the impacts of urbanisation on streams because of their sensitivity towards land cover change, hydromorphological degradation and organic pollution (Hering et al., 2004). They are rather sedentary and their communities heterogeneous, usually representing several phyla, which means that the probability of containing groups that will be sensitive to the impact of stressors is high, making them good bioindicators, and amongst the compulsory quality elements to assess rivers ecological quality, according to the European Water Framework Directive (Berkman et al., 1986; European Commission, 2000; Kenney et al., 2009). Figures 2.6, 2.7, and 2.8 show examples of sensitive invertebrates, part of the EPT (Ephemeroptera-Plecoptera-Trichoptera) group, that allow to assess invertebrate communities (Serra et al., 2019a).

Figure 2.6- Male mayfly (Ephemeroptera). One of the most well-known stream invertebrates, they occur in places with good water quality. Source: Goodernham & Tsyrlin (2002).

Figure 2.7- Adult stonefly (Plecoptera). Widely used to assess the ecological state of a stream, since they are very sensitive towards water quality. Source: (Goodernham & Tsyrlin, 2002).

Figure 2.8- Adult caddisfly (Trichoptera). Many caddisfly larvae are sensitive to water quality. Source: Goodernham & Tsyrlin (2002).

Overall, a healthy ecosystem is one that is sustainable, as in, one that shows resilience and can uphold its structure and function when confronted with disturbance and external stress (Costanza & Mageau, 1999).

3 URBAN STREAMS RESTORATION- HYDROMORPHOLOGICAL MEASURES AND THEIR EFFECTS ON INVERTEBRATE COMMUNITIES: A REVIEW

ABSTRACT

Increasing efforts have been put into the restoration of urban streams due to their important contribution towards urban sustainability. Despite these efforts, many restoration projects continue to fail in achieving desired outcomes. The present paper reviewed recent literature regarding stream restoration, particularly hydromorphological measures, in order to understand why some projects fail, and how to guarantee success. Urbanisation affects the natural hydromorphology of streams due to the implementation of impervious surfaces and other means of land cover change that ultimately increase the volume of runoff, flashiness, and overall alter hydrological patterns. These alterations profoundly affect freshwater ecosystems. Such impacts can be assessed by benthic macroinvertebrate communities. These communities are sensitive, most of all, towards hydrological alterations and poor water quality. Many restoration projects implement measures that aim to enhance the habitat heterogeneity of streams by introducing physical structures. These restoration measures alone, however, do not improve invertebrate assemblages. The present article found that the most important measures to employ, when restoring urban streams, are the attainment of pre-development hydrological patterns and good water quality. Hydromorphological restoration, although fruitful (if not for the improvement of invertebrate communities, then for the enhancement of the stream’s function and resilience), is not enough to achieve satisfactory results. Nevertheless, when executing physical restoration actions, refugia must be provided to guarantee successful recolonisation. Bryophytes, superficial sediments, and the hyporheic zone provide valuable refugia. Overall, an integrated ecohydrology approach that considers the entire watershed and its interactions between ecosystems and anthropological activities will be the most feasible solution towards the management and restoration of urban streams.

Keywords: urban streams, stream restoration, hydromorphological restoration, benthic macroinvertebrate communities

INTRODUCTION

Urban streams are the most degraded aquatic and semi-aquatic ecosystems in the world (Francis & Hoggart, 2008; Tsakaldimi & Tsitsoni, 2016; Vörösmarty et al., 2010). These streams are highly impacted by the accumulation of anthropogenic actions in their catchments, such as direct alterations to their channels, banks, and riparian zones by construction, or runoff from impervious areas like roads, buildings, and parking lots that ultimately affect stream condition (Konrad & Booth, 2005). The “urban stream syndrome” is a term used to describe such ecologically degraded streams located in urban basins. Symptoms are diverse and include flashier hydrographs, high concentrations of nutrients and pollutants in the water, altered channel morphology, and reduced biotic richness (with increased dominance of tolerant species; Walsh et al., 2005).

Consequently, the restoration of urban streams is urgent, since these ecosystems have the potential of offering numerous important services to the populations of cities (Bolund & Hunhammar, 1999; Maksimović et al., 2015; Millennium Ecosystem Assessment, 2003). The restoration of streams enhances urban biodiversity, which in turn yields ecosystem services that are essential for human wellbeing and sustainable urban management, supporting the achievement of several goals in the 2030 Agenda for Sustainable Development of the United Nations (Opoku, 2019; United Nations, 2015). Indeed, the ecological integrity of freshwater ecosystems has become an imperative matter and is supported by many international, national, and regional plans and legislation (Findlay & Taylor, 2006). Legislative measures, such as the Clean Water Act in the United States, the Water Framework Directive and the Habitats Directive in Europe, continue to be major drivers for the increasing implementation of stream restoration (Bennett et al., 2011; Council of the European Union, 1992; European Commission, 2000; *Clean Water Act*, 1972).

Stream restoration involves several strategies and measures that target the mitigation of prior disturbance, with the ultimate goal of reaching the most natural scenario possible (Violin et al., 2011; Walsh et al., 2005). An integrated ecohydrology approach deems stream restoration as improving hydrologic, geomorphic, and ecological processes in impaired watershed systems, resulting in its improved capacity to provide clean water, consumable fish, wildlife habitat, and healthier coastal waters (Bennett et al., 2011; Palmer & Bernhardt, 2006). Despite restoration projects being increasingly employed, many continue to fail in achieving desired outcomes. Palmer et al. (2005) propose five criteria for measuring successful river restoration: 1) the specified image of a more dynamic, healthy river that could exist at the site should serve as the guiding base of the project’s design; 2) the ecological condition of the stream must be measurably improved; 3) the river system should be more self-sustainable and resilient to the point that minimal follow-up maintenance will be necessary; 3) during the construction stage of the project, no lasting perturbations should remain on the ecosystem; 4) both pre- and post-assessment must be carried out, as well as data must be made publicly available.

In the particular case of urban streams, the restoration of the ecosystem, although highly desired, can be exceptionally challenging, as the alterations may have started a long time ago and already caused dramatic changes in the structure and function of the stream (Booth, 2005; Feio et al., 2015; Shoredits & Clayton, 2013). Therefore, the recovery of the ecosystem to its pre-development state may be impossible to achieve and thus restoration projects become a mere rehabilitation. Rehabilitation, as opposed to restoration, is not the full recovery of an ecosystem, but the reclamation of as many of its natural, pre-development, components and functions as possible (Cortes et al., 2019; Findlay & Taylor, 2006; Rutherfurd et al., 2000). There is a series of plausible causes for project failure, such as the misunderstanding of habitat response to geomorphological alteration, non-native invasions, and undetected water quality impairments. Additionally, many projects fail due to the attempt of managing individual species or habitat characteristics rather than the ecosystem as a whole (Beechie et al., 2008).

Therefore, it is essential to analyse the main factors influencing the integrity of an urban stream ecosystem and their main constraints, in order to plan effective and realistic restoration measures (Palmer et al., 2005). Among other factors that influence aquatic communities, the hydrology of a stream has profound effects on its ecosystem (Konrad & Booth, 2005). Lotic systems present high variability in the quantity, timing, and temporal patterns of streamflow. However, the amount of water should always be enough to fulfil its ecological needs in order to sustain the biological community- the environmental discharge (Allan & Castillo, 2007). Stream geomorphology is another key factor in the ecosystem functioning. It is based on the interplay between streamflow and landscape. Channel features like sinuosity (or meandering), riffles, pools, runs and the actual floodplain depend on cycles of erosion and deposition that, in turn, are determined by supplies of both water and sediments. This dynamic mosaic of geomorphologic traits provides a wide variety of habitats to biological communities, including benthic invertebrates, fish, and aquatic plants (Allan & Castillo, 2007; Dodds & Whiles, 2010; Feio & Ferreira, 2019; Wetzel, 2001).

Considering the importance of urban streams for achieving the ultimate goal of urban sustainability, we reviewed recent literature on stream restoration measures to retrieve insights and recommendations for achieving successful urban stream restoration. In particular, we focus on hydromorphological measures, and their subsequent effects on the stream's benthic macroinvertebrate community, as key bioindicators of the ecological condition of streams (Kenney et al., 2009). Using a step-by-step approach, we investigated which are: 1) the impacts of urbanisation and climate change on urban stream hydrology; 2) the responses of invertebrate assemblages to alterations in the hydrology and morphology of streams; 3) the hydromorphological restoration measures usually applied to streams and their effect on invertebrate communities.

3.1 Impacts of urbanisation and climate change on urban stream hydrology

Land cover change, particularly urbanisation, has several effects on the hydrology of natural streams. These range from the alteration of streamflow patterns and runoff processes to the ultimate impairment of stream ecosystems. Small streams are particularly sensitive towards land cover change, due to their small catchment areas (altered land use will cover greater proportions of a small stream’s catchment than if it were a large river). Hydrologic processes are altered as a result of removal of vegetation from hillslopes, stream channelization, surface levelling, and construction of impervious surfaces such as roads and buildings. These actions reduce interception, infiltration, subsurface flow, aquifer recharge, evapotranspiration, stormwater storage on hillslopes, and overall time for stormwater to reach a stream. As impervious cover increases, the percentage of water that flows as surface runoff increases (Figure 3.1). This translates into more frequent stormflow events with high peak discharge and rapid stormflow recession (flashiness). Urbanisation brings about the redistribution of water from periods of base flow to periods of storm flow, as well as increased daily variation in streamflow (Chadwick et al., 2006; Ferreira et al., 2016; Konrad & Booth, 2002, 2005; Palmer & Richardson, 2009; Paul & Meyer, 2001; Serpa et al., 2015; Walsh et al., 2004). Impervious surfaces in immediate riparian zones increase the risk of stream impairment (due to the decrease in buffer capacity for filtering impaired surface and ground water; Hall & Azad Hossain, 2020).

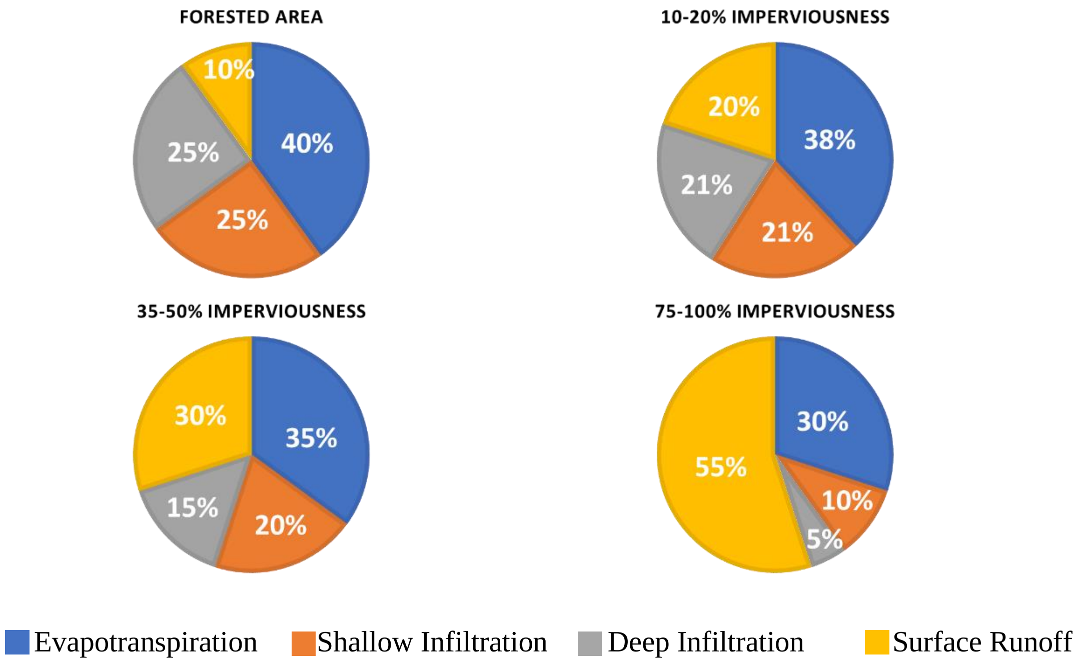

Figure 3.1- Alteration in the hydrologic flow distribution of stormwater with increasing impervious cover in urbanised catchments. Adapted from Paul & Meyer (2001).

The “urban stream syndrome” identifies streams that suffer from a set of symptoms that include flashier hydrographs, high concentrations of nutrients and pollutants, altered channel morphology, and reduced biotic richness with increased dominance of tolerant species (Walsh et al., 2005). Recurrent commonalities on the urban stream syndrome include (Booth et al., 2016; L. R. Brown et al., 2009): i) increase of frequency and magnitude of high flow events and flashiness; ii) increase in channel cross-section due to higher discharge and therefore, increased bed and bank erosion, leading to the enlargement of streams; iii) increase in conductance and overall decrease of water quality thanks to the drainage of pollutants (such as PAHs that result of combustion and petroleum products, and insecticides used for pest control) into streams; iv) declines in fish and benthic macroinvertebrate communities due to the degradation of ecosystems.

However, streams around the world respond differently to urbanisation. Feasible reasons for divergence in response are (Booth et al., 2016): i) climate- as in rainfall and frequency of high flow events. In consistent climate conditions, urbanisation radically affects the frequency-magnitude-duration balance in streamflow, which leads to major ecological modifications; ii) sediment delivery- urbanisation usually decreases delivery of sediments due to streambank armouring and stabilization of hillslopes. So, in regions that would naturally yield high loadings of sediments, this shortage of sediment delivery can affect channel morphology as much as increased discharge; iii) urban infrastructure- as in age, timing of development and history of land cover.

Such regional and local divergences reinforce the complexity of urbanisation and its influence on natural streams. In order to set realistic and feasible management goals, it is crucial to understand how and why urban streams differ from one another, and how they will respond differently to the same restoration actions. This requires an understanding of the relationship between watershed and urban traits, the regional ecological composition, and the social and economic practicability of management approaches. For this reason, it is difficult to state a list of restoration measures that will rehabilitate urban streams worldwide. Yet, commonalities in urban stream management can be pointed out (Booth et al., 2016; Ferreira et al., 2016): i) disconnecting impervious areas from streams by improving infiltration and retention/harvesting. These actions will show varying efficiency according to regional storm characteristics; ii) address main water quality issues first, such as sewage disposal and other sources of pollution.

Among the hydrologic shortcomings of conventional stormwater management approaches, load-reduction strategies attempt to reduce pollutant loads and peak flow rates. These alone, however, are not sufficient. The most common measure in this approach are end-of-catchment stormwater wetlands. These prove to be efficient at reducing pollutant loads and peak flows, but their retention capacity and ability to reduce volumes through infiltration and evapotranspiration are limited, which often results in outflow rates that exceed channel erosion thresholds, degrading geomorphic and ecological conditions. Additionally, constructed wetlands can reduce baseflow, altering hydrologic patterns even further; they are unable to protect upstream waters from pollutants since they are located at the end of the catchment; and finally, they replace lengths of the stream with a dissimilar ecosystem, disrupting the stream’s longitudinal connectivity. Other load-reduction approaches, such as dispersed biofiltration systems, have the ability of protecting upstream water quality. However, these systems exhibit low hydrologic retention capacities and are connected to the stormwater drainage system, minimizing potential for volume reduction through evapotranspiration and exfiltration to surrounding soils. Flow-regime management is crucial to achieve successful stream restoration and such tools need to become a standard (Burns et al., 2012). The true restoration of urban streams can only be achieved once hydrologic processes and the spatial distribution of water-storage is re-established throughout the urban basin (Konrad & Booth, 2005).

In order to protect and successfully restore urban streams, five principles for urban stormwater management are (Walsh et al., 2016): 1) ecosystems to protect must be identified and objectives for their ecological state must be set; 2) the resulting interplay between evapotranspiration, infiltration and streamflow should resemble predevelopment conditions. This usually entails keeping significant runoff volumes from reaching the stream; 3)

Stormwater control measures (SCMs) should yield flow regimes that resemble the predevelopment regime in both quality and quantity; 4) SCMs should be able to store water from high flow events so that the frequency of disturbance to biota does not increase in comparison to predevelopment conditions; and 5) SCMs should be implemented to all impervious surfaces in the catchment of the target stream.

Examples of SCMs are rainwater tanks, vegetated infiltration systems that receive overflow from tanks and impervious surfaces, and biofiltration systems. These tools can be applied at several scales, such as residential, public, and commercial buildings, streetscapes, blocks, etc. Such tools, however, are only effective when employed at a large enough scale to re-establish hydrologic patterns (Burns et al., 2012; Maksimović et al., 2015).

Urbanisation, apart from hydrology, also affects channel geomorphology, which in turn, can degrade the overall ecological state of a stream. Urbanisation can impact channel geomorphology and streambed sedimentological characteristics through the reduction in riffle habitant frequency, increased streambed substrate embeddedness, frequency of fine substrate, and streambed siltation (Zeiger & Hubbart, 2019). Restoration projects should thus also aim to restore geomorphology to a new equilibrium that enhances the health and ecological state of the stream (Findlay & Taylor, 2006).

Climate change affects urban areas by altering air temperature and precipitation patterns, exacerbating both magnitude and duration of climate extremes such as droughts and floods (Maksimović et al., 2015). Flow regime modification due to such events is expected to occur, for instance, transition of perennial rivers to intermittent due to extreme drying periods. Increased water temperatures lead to altered species distribution, survival rates, and phenology. It is estimated that approximately 50% of global freshwater species are threatened by climate change (Reid et al., 2019). The combined effects of both land cover modification and climate change will be even greater on smaller streams. In summary, climate change will have a stronger effect on runoff increase, but land use change will exacerbate it, which translates into higher flood peaks, more frequent flood events, and increased runoff volumes (Hung et al., 2020).

3.2 Response of aquatic invertebrate assemblages to alterations in the hydrology and morphology of streams

The anthropogenic actions that embody urbanisation alter many aspects of the stream ecosystem. This consequently modifies their associated biodiversity, communities composition and ecosystem functioning (Figure 3.2; Karr & Yoder, 2004; Konrad & Booth, 2005). Among other elements of the aquatic communities, benthic invertebrates are one of the most diversified and abundant assemblages and their taxa respond differently to the different stressors affecting freshwater ecosystems. They respond to land cover change, hydromorphological degradation and organic pollution (Hering et al., 2004). Therefore, the composition and structure of these assemblages will also be affected by urbanisation, not only through hydrologic alteration, but also through water quality and habitat degradation.

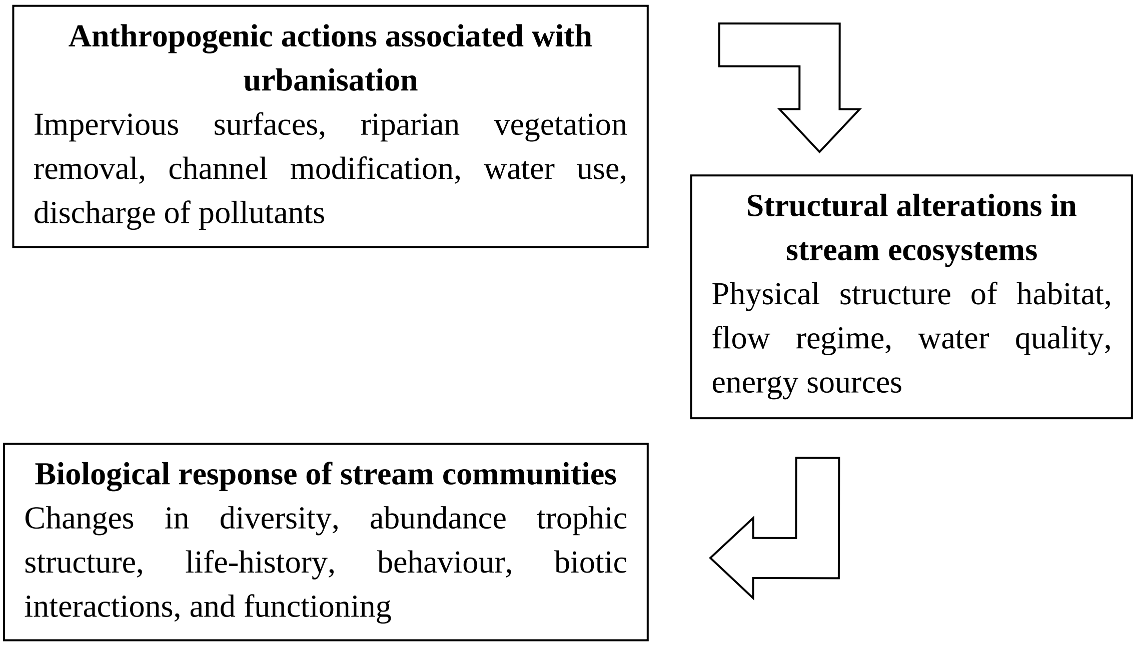

Figure 3.2- Resulting biological response of stream communities towards urbanisation actions. Modified from Konrad & Booth (2005).

Poor water quality, with high concentrations of pollutants, low rates of dissolved oxygen, and low pH levels alter the proportion of functional feeding groups, impoverishing invertebrate communities to the point of being reduced to tolerant species only (Xu et al., 2014). The ecological assessment of a South African wetland showed that macroinvertebrate communities were impaired due to agricultural activity that diminished pH and macrophyte cover, as well as increased concentrations of phosphate and ammonium (Dalu & Chauke, 2020). Concordantly, when comparing the communities of urban streams of a township in Cameroon to their comparable forest sites, higher taxa richness and abundance of sensitive species appeared to be correlated to higher dissolved oxygen, canopy cover, and overall better water quality (as in, absence of heavy metals and organic pollution; Tchakonté et al., 2015). Through the assessment of a Mediterranean urban stream, (Serra et al., 2019) found also that the months of the study period with worst water quality corresponded to the ones with higher peaks of discharge, with high conductivity and hardness due to the dissolution of alkaline substrates (such as calcareous rocks). These periods revealed the ecologically worst macroinvertebrate assemblages, with higher abundance of generalist taxa and biological traits that indicate adverse conditions. The authors suggest that the effects of peak discharge could be abated through flow management, by keeping the water level constantly higher. Mor et al. (2019) found that streams respond differently to wastewater effluent discharge, depending on their hydromorphology. Streams with low discharge present reduced dilution capacity, which could point to a “threshold” of water level that should be maintained, particularly during dry periods, in order to mitigate the effects of inevitable point-source pollution.

It is well known that macroinvertebrate assemblages are conditioned by streamflow characteristics. Complementary taxonomic groups respond in opposite directions, depending on their biological traits, such as body form, fixation ability, capacity to escape into sediments, type of locomotion (e.g., active or passive swimming), among others. Streamflow metrics seem to limit the maximum richness/abundance of sensitive taxa, while for tolerant taxa they act as the minimum for their relative richness/abundance (Konrad et al., 2008). Table 3.1 displays streamflow characteristics found to be ecologically significant, and thus should be considered to restore the biological communities of a stream.

Table 3.1- Streamflow metrics that influence benthic macroinvertebrate communities (Konrad et al., 2008).

Magnitude	Median annual mean streamflow
	Median annual minimum daily streamflow
Duration	Median annual duration of the longest high flow event
Frequency	Median annual number of continuous periods of high flow events when daily streamflow exceeds Q_{10}
Timing	Month of maximum monthly streamflow
Variation	Coefficient of variation of annual minimum streamflow
	Per cent daily change in streamflow
	Baseflow recession rate
	Coefficient of variation of monthly mean streamflow
	Median annual maximum daily streamflow as a fraction of mean streamflow (Q_{max}/Q_{mean})

	Median annual streamflow exceeded 10% of the year as a fraction of median streamflow (Q_{10}/Q_{50})
	Mean streamflow 100 days prior to invertebrate sampling divided by median streamflow (100-day Q_{mean}/Q_{50})
	Minimum streamflow 100 days prior to invertebrate sampling divided by median streamflow (100-day Q_{min}/Q_{50})

Benthic macroinvertebrate assemblages are directly affected by altered hydrology through the removal of organisms by high flows that drag them downstream or that even kill them. Altered flows also change the distribution and input of allochthonous resources. Flow reduction reduces benthic habitats available feeding resources and dilution capacity, increasing the concentration of nutrients and other pollutants in the water. High flows can also reduce habitat, by increasing the rate of bed scour, turbidity, and disturbing streambed sediments (Konrad & Booth, 2005; Serra et al., 2019). Benthic macroinvertebrates are heavily influenced by the heterogeneity of inorganic substratum (Caro-Borrero & Carmona-Jiménez, 2018) and, therefore, disturbing the stream's sedimentological characteristics will degrade invertebrate communities.

Another recurrent hydrologic characteristic that influences macroinvertebrates is flow permanence. Parker et al. (2019) found that calibrating hydrologic models according to flashiness and flow permanence provide models better suited to describe biotic condition variability, even if they do not accurately represent flow regimes. The study of Stubbington et al. (2017) explains how invertebrate communities inhabit intermittent rivers and ephemeral streams. They observe that the main threats to these habitats are altered hydrology, including changes to flow permanence (for instance, artificially shifting to a perennial regime), deterioration of water quality (these habitats are especially sensitive due to a low dilution capacity); changes to channel morphology as a result of sediment extraction, loss or alteration of riparian vegetation; and emergence of invasive taxa. Komínková et al. (2005) conclude that combined sewage disposal reduces water and sediment quality, causing both chemical and hydraulic stress. Overflows alter the hydrological pattern of the stream, affecting the benthic community, especially during summer storm events. These discharges increase the stream's natural flow and carry heavy metals. On the other hand, Schriever et al. (2015) find that the increase in flow permanence increases functional richness, evenness, and taxonomic richness. They realise that flow permanence influences the invertebrate community more than any other environmental variable. In agreement, Bogan et al. (2013) conclude that flow permanence overwhelms other hydrologic factors, such as connectivity to upstream reaches. Arscott et al.

(2010) found that taxonomic richness and density are significantly higher in the perennial sections of an alluvial river, rather than the ephemeral and intermittent sections.

In conclusion, benthic macroinvertebrate communities are, indeed, affected by hydrology and thus, by hydrologic changes result of urbanisation. Any alteration to the natural hydrology of a stream will modify the taxonomic composition of its macroinvertebrate community and therefore, its functionality. Flow permanence appears to be one of the most important hydrologic traits. However, whereas, by rule of thumb, perennial streams show more diverse communities, naturally intermittent streams should not be artificially shifted to a permanent flow regime.

3.3 Hydromorphological restoration measures applied to streams and their effect on invertebrate communities

The structure of water bodies has been degraded for decades now, in favour of urban development, agriculture, and navigation. This has been done through channelization, obstruction of streambeds, dredging of banks, construction of weirs, disconnection of streams from the floodplain, etc (Brettschneider et al., 2019). As such, restoration efforts often take the hydromorphologic route, implementing actions that aim to restore the natural hydrology and geomorphologic structure of a stream. For example, from 178 stream restoration projects in Florida, USA, 73% involved hydromorphologic measures, such as stream reclamation, flow modification, bank stabilization, channel reconfiguration, floodplain reconnection, and in-stream habitat heterogeneity improvement (Castillo et al., 2016).

However, such measures do not always have a positive effect on macroinvertebrate assemblages. Restoration efforts in urban streams may be successful at stabilizing stream banks, preventing bank sloughing, and further incision but in biological terms these measures may not be sufficient (Selvakumar et al., 2010). For instance, Turunen et al. (2017) found that the addition of wooden structures enhances hydraulic retention and, in turn, re-establishes a more natural flood regime. The implementation of boulders proves to be effective at improving habitat heterogeneity. These measures combined were thought to have improved the benthic macroinvertebrate communities of forestry impaired streams, but instead, they did not respond at all. In accordance, Ernst et al. (2012) found that natural channel design restoration has little change on the macroinvertebrate community, even though it can benefit the stream habitat and its fish assemblages.

Some studies explored the possibility of enhancing benthic macroinvertebrate assemblages as a result of structural restoration projects that targeted other species, such as salmonids, or that simply did not target invertebrate communities per se. Results show, however, that they do not respond to this type of restoration measures (Louhi et al., 2011; Smith et al., 2020). Such outcomes demonstrate that structural restoration does not show any evidence of enhancing invertebrate communities. Probably because new habitats are not being created at scales that are relevant to the assemblages. Or perhaps due to regional/watershed scale factors that override any structural restoration efforts. Nevertheless, physical restoration measures prove to enhance ecosystem function by enhancing leaf retentiveness (Muotka & Syrjänen, 2007). This is facilitated by low discharge and high hydrologic retention, which can be achieved by the addition of any physical structure in-stream (Koljonen et al., 2012).

In light of the most common approaches regarding stream restoration and the frequent failures concerning the improvement of benthic invertebrate communities, Palmer et al. (2010) critically reviewed the paradigm of habitat heterogeneity. This paradigm considers that increasing the structural diversity of habitat, by adding structures such as boulders, artificial riffles, and addition of meanders, will restore biodiversity by enhancing structural heterogeneity. The evaluation of 78 independent restoration projects lead to the finding that habitat heterogeneity had indeed improved, but only two showed a significant increase in biodiversity. Palmer et al. concluded that there is no evidence that habitat heterogeneity alone increases invertebrate diversity. And therefore, suggest that projects should prioritise first the mitigation of stressors such as source pollution and hydrologic alteration, and only then move to measures such as increasing physical complexity.

On the other hand, Szita et al. (2019) found that in Hungarian streams, water quality and biological state remained good, despite urban development. These facts were attributed to the preservation of near-natural hydromorphologic and riparian conditions that significantly reduced urbanisation effects and preserved water status. Then again, not all projects fail to recover aquatic assemblages, and other studies show that these efforts are worthwhile. Bain et al. (2014) obtain evidence of a healthier, more diverse benthic macroinvertebrate assemblage after a major urban stream restoration project in the USA. Despite this progress, positive changes are threatened by the persistence of extreme flow events from the urbanised watershed. Similarly, Purcell et al. (2002) obtained both improved biological diversity and habitat quality when comparing a small restored stream to unrestored sites. However, it still hadn’t reached the conditions of a comparable stream that had undergone restoration 12 years prior.

Other important shortcomings occur besides the efficiency of restoration measures, one of them being the motivation to restore. In fact, often failure happens in media/politically driven restoration projects as restoration actions that enhance the aesthetics of the site do not necessarily address pressing ecological issues. Moreover, the lack of communication between experts and practitioners often prevents the success of restoration in urban areas (Cockerill & Anderson, 2014).

Another issue that seems to be recurrent with restoration projects is not addressing or prioritising watershed-scale issues, such as source pollution and land use management practices. Hydromorphological restoration actions as a stand-alone measure are insufficient to improve the ecological status of a stream as long as water and sediment quality remain impaired (Brettschneider et al., 2019; Palmer et al., 2010). Reach-scale restoration actions are not enough to promote improvement in the invertebrate community if watershed-scale problems such as land use and hydrological regime disturbance persist (Ernst et al., 2012; Tullos et al., 2009).

Verdonschot & Nijboer (2002), with the intention of kick-starting a decision support system for stream restoration in the Netherlands, analyse three examples of restoration projects and their shortcomings. First was the case of re-meandering the Vloedgraaf stream: a channelized, impaired stream due to the discharge of sewage and effluent of a purification plant. Restoration measures included the digging of meanders; construction of a transversal profile in order to create wetland-like inundation areas; digging of pools and oxbow lakes; as well as the plantation of trees at some stretches. Five years after these actions were implemented, the status of water quality and macroinvertebrate assemblages remained the same. Probably because of persistent water pollution.

The second case was water retention in the stream Gasterense diep: a middle course, lowland stream which water quality was good. Firstly, sewage discharge was eliminated. Secondly, the wet riparian areas parallel to the stream were restored, improving conditions for groundwater dependent vegetation. The project also involved constructing submersed weirs into the stream channel, with the purpose of withholding sand transported by the stream. Five years after removing sewage disposal, target species of macroinvertebrates increased, but seemed to react negatively to installed weirs. The weirs decreased the diversity of substrate due to a drop in current velocity.

Finally, the third case considered was the wetland construction along the stream Midden Regge: a channelized lowland stream that received discharges from purification plants and sewer systems. These discharges caused fluctuations in the streamflow during storm events. The status of the water quality was moderate, whilst the bottom of the stream was polluted. Restoration actions consisted of the construction of a gradient between land and water in order to allow erosion and deposition in a riparian zone; removal of the 20 cm contaminated topsoil layer in the riparian zone; and the increase of the stream’s bottom width and depth. Six years after the intervention, riparian vegetation diversity increased, but shortly after, decreased again due to the eutrophication of the soil as a result of sand and silt deposition in the riparian zone. The increase in profile width and depth lead to a decrease in flow velocity and increase in algal development, culminating in oxygen depletion. This is another example of not targeting crucial matters first, in the case of the Midden Regge, sediment deposition.

In conclusion, hydromorphological actions are effective at improving the quality of stream habitats, but these actions alone may not be sufficient to restore biological communities. An integrated ecological approach to stream restoration is required, in which ecological concepts, threats, and former experience are combined (Verdonschot & Nijboer, 2002). As seen in the literature, macroinvertebrate communities and therefore, stream ecosystems, will not improve unless more important stressors are taken care of first. Sometimes, habitat heterogeneity may not even be a limiting factor to begin with (Louhi et al., 2011). Stressors such as point-source pollution, sediment deposition, and modified hydrologic patterns need to be prioritised.

Scale is also a challenge for restoration projects, as reach-scale actions are often inefficient if the rest of the watershed is impaired (Miller et al., 2019; Tasca et al., 2020).

Finally, time is also an important variable in the evaluation of the effect of restoration measures. In fact, benthic biodiversity generally drops right after restoration actions are employed (Muotka & Syrjänen, 2007). This can be attributed to the fact that restoration represents a disturbance to the invertebrate community, since it unnaturally modifies stream habitat. Resilience of the biota to such disturbances can be facilitated by use of refugia. Refugia are locations that aren't as affected by disturbance as its surrounding area. Organisms that manage to seek refuge have a higher probability of surviving the period of disturbance and later recolonising the restored habitat. Bryophytes can act as refugia for benthic invertebrates after the first impact of restoration. Since restoration actions leave the streambed unstable for a long period of time, invertebrates take refuge in stable stones that are covered in bryophytes. These increase the structural complexity of the substratum, decrease water velocities, and accumulate detritus and epiphytic algae, providing food and shelter for invertebrates. Restoration projects should thus leave patches of stream bottom intact in order to facilitate recolonisation after conditions settle (Korsu, 2004).

Another important refuge for benthic invertebrates is the hyporheic zone (Hancock, 2002). This area constitutes a transition between the surface stream and groundwater (Boulton et al., 1998; Chamorro et al., 2015). Hydrologically, the hyporheic zone can also be defined as the interstitial spaces adjacent to the stream bank and below the streambed, spaces which are saturated and contain some of the channel water (Merill & Tonjes, 2014). Both the hyporheic zone and superficial sediments of the streambed show capacity of acting as a refuge for invertebrates whilst conditions are unstable right after restoration (Stubbington et al., 2009). Sediments with interstices large enough may be a morphologic trait to preserver/restore on streams that suffer from drying periods, considering that the climate change challenge will exacerbate these types of events.

The hyporheic zone also contributes to maintaining water quality through biological filtration, and porous sediments adjacent to the stream act as buffers to rising water levels, reducing, delaying, or even preventing flooding. A few management measures can restore the hyporheic zone, such as the periodic release of environmental flows to flush silt and reoxygenate sediments, planting and maintenance of riparian buffers, effective land use practices, and suitable groundwater and surface water extraction policies. In terms of sediments, the careful introduction of gravel, the loosening of existing gravel by mechanical methods, and the reintroduction of bends, large boulders, and logs to induce down-welling and sediment deposition (Hancock, 2002).

Recolonisation of restored sites also depends on taxon pool occurrence rate and proximity to this pool. Barriers do not seem to impose a significant challenge, since only a few species appear to be susceptible to them. This being the case, an assessment of the pool's taxonomic composition and dispersal modes may be interesting to perform beforehand, assisting with the spatial prioritisation of restoration (Tonkin et al., 2014). Considering that restoration projects disturb communities at first, recolonisation happens from macroinvertebrates that take refuge whilst conditions are not stable, as well as from new species that migrate from other habitats. Thus, the ease with which this happens depends on the dispersal capacity of the community, distance, and connectivity from its source of colonisers (Spänhoff & Arle, 2007).

In order to facilitate recolonisation, it seems imperative that refuge is provided for the existing macroinvertebrate assemblage, so as to endure unstable conditions caused by restoration. This may be done by leaving a patch of streambed intact and close to a taxon pool with adequate dispersal capacity to recolonise the newly restored habitat

INSIGHTS AND RECOMMENDATIONS

The urban stream syndrome is comprised of a few commonalities, such as flashier hydrographs, high concentrations of nutrients and pollutants, altered channel morphology, and reduced biotic richness with increased dominance of tolerant species. Nevertheless, all urban streams are different and unique to their region, hence, it is impossible to prescribe a "recipe" for restoring all kinds of urban streams. Nonetheless, a few common recommendations on the management of such streams could be extracted from the previous analyses.

First, an urban stream is a freshwater aquatic ecosystem, and therefore must be regarded as so. Practitioners should familiarise themselves with the habitat components that a natural stream would present at the region in question and aim to rehabilitate them, such as riparian vegetation, streambed composition, and natural discharge. A stream's flow rate must be enough to satisfy the ecological discharge of the ecosystem and therefore sustain its biological communities and functionality. Since invertebrate communities show development limits towards hydrologic characteristics (such as magnitude, duration, frequency, timing, and variation), the assessment of such limits could be done beforehand, allowing practitioners to predictively model and procure optimal solutions to the implementations of measures that will regulate superficial runoff. No stream will ever be ecologically acceptable if its water remains polluted. Therefore, another universal approach towards urban streams management is to prioritise water quality. The most important steps when restoring urban streams will therefore be re-establishing, as much as possible, a pre-development hydrological pattern, and sorting any water quality issues as to ensure that it is satisfactory enough to sustain a healthy ecosystem.

In addition, restoration projects need to consider the whole catchment and not be limited to reach-scale. End-of-pipe treatments do not improve water quality upstream and therefore are not enough to improve the ecological state of a watershed-scale stream system. Another important aspect to consider is the disturbance caused by the physical restoration actions.

Refugia must be provided in order to facilitate recolonisation after conditions have settled. The hyporheic zone can prove to be valuable refugia in some streams, it also plays an important role in the regulation of water quality and buffering floods. In order to restore and/or maintain the hyporheic zone, environmental flows can be periodically discharged to flush silt and reoxygenate sediments; riparian buffers must be planted and/or maintained; effective policies for land use practices, groundwater and surface water extraction must be implemented. Superficial sediments can provide refuge for invertebrates that cannot survive in the hyporheic zone. To restore this aspect of the streambed, gravel can be loosened and further added, as well as the re-introduction of meanders, boulders, and logs to induce down-welling and sediment deposition. Bryophytes also prove to be a critical source of refuge, and therefore patches of the stream bottom must remain intact to facilitate recolonisation after restoration. Also, recolonisation depends on the composition and proximity to a taxon pool, as well as their dispersal traits. An analysis of such traits could be interesting to perform before planning restoration.

Finally, for an efficient restoration, it is imperative to ensure a good communication between scientists and managers. Moreover, the assessment of the urban population’s interests may bring to light new important aspects to consider whilst simultaneously raising the awareness of the local community to the importance of urban streams. Thus, sensibilization and education actions are also essential measures.

This review pointed out some aspects that need to be further investigated to support effective restoration projects in urban streams. One of them is the potential definition of reference values for streamflow metrics as limits for the maximum richness/abundance of sensitive taxa. This requires a great deal of experimental work covering different situations and the construction of large databases but would be very useful for managers, as well as testing the usefulness of such approach with real-case scenarios. Another concept to explore is if a threshold for water level exists in order to provide enough dilution capacity to sustain macroinvertebrate diversity when water pollution is unavoidable or difficult to solve.

REFERENCES

Allan, J. D., & Castillo, M. M. (2007). *Stream Ecology: Structure and Function of Running Waters* (2nd ed.). Springer.

Arscott, D. B., Larned, S., Scarsbrook, M. R., & Lambert, P. (2010). Aquatic invertebrate community structure along an intermittence gradient: Selwyn River, New Zealand. *Journal of the North American Benthological Society*, *29*(2), 530–545. https://doi.org/10.1899/08-124.1

Bain, D. J., Copeland, E. M., Divers, M. T., Hecht, M., Hopkins, K. G., Hynicka, J., Koryak, M., Kostalos, M., Brown, L., Elliott, E. M., Fedor, J., Gregorich, M., Porter, B., Smith, B., Tracey, C., & Zak, M. (2014). Characterizing a Major Urban Stream Restoration Project: Nine Mile Run (Pittsburgh, Pennsylvania, USA). *Journal of the American Water Resources Association*, *50*(6), 1608–1621. https://doi.org/10.1111/jawr.12225

Beechie, T., Pess, G., Roni, P., & Giannico, G. (2008). Setting River Restoration Priorities: A Review of Approaches and a General Protocol for Identifying and Prioritizing Actions. *North American Journal of Fisheries Management*, *28*(3), 891–905. https://doi.org/10.1577/m06-174.1

Bennett, S. J., Simon, A., Castro, J. M., Atkinson, J. F., Bronner, C. E., Blersch, S. S., & Rabideau, A. J. (2011). The evolving science of stream restoration. *Geophysical Monograph Series*, *194*, 1–8. https://doi.org/10.1029/2011GM001099

Bogan, M. T., Boersma, K. S., & Lytle, D. A. (2013). Flow intermittency alters longitudinal patterns of invertebrate diversity and assemblage composition in an arid-land stream network. *Freshwater Biology*, *58*(5), 1016–1028. https://doi.org/10.1111/fwb.12105

Bolund, P., & Hunhammar, S. (1999). Ecosystem services in urban areas. *Ecological Economics*, *29*(2), 293–301. https://doi.org/10.1016/S0921-8009(99)00013-0

Booth, D. B. (2005). Challenges and prospects for restoring urban streams: A perspective from the Pacific Northwest of North America. *Journal of the North American Benthological Society*, *24*(3), 724–737. https://doi.org/10.18990887-3593(2005)024\2.0.CO;2

Booth, D. B., Roy, A. H., Smith, B., & Capps, K. A. (2016). Global perspectives on the urban stream syndrome. *Freshwater Science*, *35*(1), 412–420. https://doi.org/10.1086/684940

Boulton, A. J., Findlay, S., Marmonier, P., Stanley, E. H., & Maurice Valett, H. (1998). The functional significance of the hyporheic zone in streams and rivers. *Annual Review of Ecology and Systematics*, *29*, 59–81. https://doi.org/10.1146/annurev.ecolsys.29.1.59

Brettschneider, D. J., Misovic, A., Schulte-Oehlmann, U., Oetken, M., & Oehlmann, J. (2019). Poison in paradise: increase of toxic effects in restored sections of two rivers jeopardizes the success of hydromorphological restoration measures. *Environmental Sciences Europe*, *31*(1). https://doi.org/10.1186/s12302-019-0218-9

Brown, L. R., Cuffney, T. F., Coles, J. F., Fitzpatrick, F., McMahon, G., Steuer, J., Bell, A. H., & May, J. T. (2009). Urban streams across the USA: Lessons learned from studies in 9 metropolitan areas. *Journal of the North American Benthological Society*, *28*(4), 1051–1069. https://doi.org/10.1899/08-153.1

Burns, M. J., Fletcher, T. D., Walsh, C. J., Ladson, A. R., & Hatt, B. E. (2012). Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. *Landscape and Urban Planning*, *105*(3), 230–240. https://doi.org/10.1016/j.landurbplan.2011.12.012

Caro-Borrero, A., & Carmona-Jiménez, J. (2018). Habitat preferences in freshwater benthic macroinvertebrates: Algae as substratum and food resource in high mountain rivers from Mexico. *Limnologica*, *69*(November 2017), 10–17. https://doi.org/10.1016/j.limno.2017.10.002

Castillo, D., Kaplan, D., & Mossa, J. (2016). A Synthesis of Stream Restoration Efforts in Florida (USA). *River Research and Applications*, *32*(7), 1555–1565. https://doi.org/10.1002/rra.3014

Chadwick, M. A., Dobberfuhl, D. R., Benke, A. C., Huryn, A. D., Suberkropp, K., & Thiele, J. E. (2006). Urbanization affects stream ecosystem function by altering hydrology, chemistry, and biotic richness. *Ecological Applications*, *16*(5), 1796–1807. https://doi.org/10.1890/1051-0761(2006)016[1796:UASEFB]2.0.CO;2

Chamorro, A., Giardino, J. R., Granados-Aguilar, R., & Price, A. E. (2015). *Chapter 7 - A Terrestrial Landscape Ecology Approach to the Critical Zone* (J. R. Giardino & C. B. T.-D. in E. S. P. Houser (eds.); Vol. 19, pp. 203–238). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-444-63369-9.00007-0

Clean Water Act, 33 USC § 1251 et seq. (1972)

Cockerill, K., & Anderson, W. P. (2014). Creating false images: Stream restoration in an urban setting. *Journal of the American Water Resources Association*, *50*(2), 468–482. https://doi.org/10.1111/jawr.12131

Cortes, R., Ferreira, T., & Hughes, S. J. (2019). Conservação e restauro fluvial. In Rios de Portugal: comunidades, processos e alterações (pp. 359–379). Imprensa da Universidade de Coimbra. https://doi.org/10.14195/978-989-26-1624-7_15

Council of the European Union. (1992). *Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora*.

Dalu, T., & Chauke, R. (2020). Assessing macroinvertebrate communities in relation to environmental variables: the case of Sambandou wetlands, Vhembe Biosphere Reserve. *Applied Water Science*, *10*(1), 1–11. https://doi.org/10.1007/s13201-019-1103-9

Dodds, W. K., & Whiles, M. R. (2010). Freshwater Ecology. In *Freshwater Ecology: Concepts and Environmental Applications of Limnology* (2nd ed.). Elsevier. https://doi.org/10.1016/C2016-0-03667-7

Ernst, A. G., Warren, D. R., & Baldigo, B. P. (2012). Natural-Channel-Design Restorations That Changed Geomorphology Have Little Effect On Macroinvertebrate Communities In Headwater Streams. *Restoration Ecology*, *20*(4), 532–540. https://doi.org/10.1111/j.1526-100X.2011.00790.x

European Commission. (2000). *Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy*.

Feio, M. J., & Ferreira, V. (2019). *Rios de Portugal: comunidades, processos e alterações*. Imprensa da Universidade de Coimbra. https://doi.org/10.14195/978-989-26-1624-7

Feio, M. J., Ferreira, W. R., Macedo, D. R., Eller, A. P., Alves, C. B. M., França, J. S., & Callisto, M. (2015). Defining and Testing Targets for the Recovery of Tropical Streams Based on Macroinvertebrate Communities and Abiotic Conditions. *River Research and Applications*, *31*(1), 70–84. https://doi.org/10.1002/rra.2716

Ferreira, C. S. S., Walsh, R. P. D., Nunes, J. P. C., Steenhuis, T. S., Nunes, M., de Lima, J. L.

M. P., Coelho, C. O. A., & Ferreira, A. J. D. (2016). Impact of urban development on streamflow regime of a Portuguese peri-urban Mediterranean catchment. *Journal of Soils and Sediments*, *16*(11), 2580–2593. https://doi.org/10.1007/s11368-016-1386-5

Findlay, S. J., & Taylor, M. P. (2006). Why rehabilitate urban river systems? *Area*, *38*(3), 312–325. https://doi.org/10.1111/j.1475-4762.2006.00696.x

Francis, R. A., & Hoggart, S. P. G. (2008). Waste not, want not: The need to utilize existing artificial structures for habitat improvement along urban rivers. *Restoration Ecology*, *16*(3), 373–381. https://doi.org/10.1111/j.1526-100X.2008.00434.x

Hall, J., & Azad Hossain, A. K. M. (2020). Mapping urbanization and evaluating its possible impacts on streamwater quality in Chattanooga, Tennessee, using GIS and remote sensing. *Sustainability (Switzerland)*, *12*(5). https://doi.org/10.3390/su12051980

Hancock, P. J. (2002). *Human Impacts on the Stream – Groundwater Exchange Zone*. *29*(6), 763–781. https://doi.org/10.1007/s00267-001-0064-5

Hering, D., Meier, C., Rawer-Jost, C., Feld, C. K., Biss, R., Zenker, A., Sundermann, A., Lohse, S., & Böhmer, J. (2004). Assessing streams in Germany with benthic invertebrates: Selection of candidate metrics. *Limnologica*, *34*(4), 398–415. https://doi.org/10.1016/S0075-9511(04)80009-4

Hung, C. L. J., James, L. A., Carbone, G. J., & Williams, J. M. (2020). Impacts of combined land-use and climate change on streamflow in two nested catchments in the Southeastern United States. *Ecological Engineering*, *143*(November 2019), 105665. https://doi.org/10.1016/j.ecoleng.2019.105665

Karr, J. R., & Yoder, C. O. (2004). Biological assessment and criteria improve total maximum daily load decision making. *Journal of Environmental Engineering*, *130*(6), 594–604. https://doi.org/10.1061/(ASCE)0733-9372(2004)130:6(594)

Kenney, M. A., Sutton-grier, A. E., Smith, R. F., & Gresens, S. E. (2009). *Benthic macroinvertebrates as indicators of water quality : The intersection of science and policy Benthic macroinvertebrates as indicators of water quality : April 2018*. https://doi.org/10.1163/187498209X12525675906077

Koljonen, S., Louhi, P., Mäki-Petäys, A., Huusko, A., & Muotka, T. (2012). Quantifying the effects of in-stream habitat structure and discharge on leaf retention: Implications for stream restoration. *Freshwater Science*, *31*(4), 1121–1130. https://doi.org/10.1899/11-173.1

Komínková, D., Stránský, D., Šťastná, G., Caletková, J., Nabělková, J., & Handová, Z. (2005). Identification of ecological status of stream impacted by urban drainage. *Water Science and Technology*, *51*(2), 249–256. https://doi.org/10.2166/wst.2005.0054

Konrad, C. P., & Booth, D. B. (2002). Hydrologic trends associated with urban development for selected streams in the Puget Sound Basin, Western Washington. *Water-Resources Investigations Report ;02-4040, vi, 40 p.*, vi, 40 p. https://doi.org/10.1007/s10661-010-1363-1

Konrad, C. P., & Booth, D. B. (2005). Hydrologic changes in urban streams and their ecological significance. *American Fisheries Society Symposium*, *2005*(47), 157–177.

Konrad, C. P., Brasher, A. M. D., & May, J. T. (2008). Assessing streamflow characteristics as limiting factors on benthic invertebrate assemblages in streams across the western United States. *Freshwater Biology*, *53*(10), 1983–1998. https://doi.org/10.1111/j.1365-2427.2008.02024.x

Korsu, K. (2004). Response of benthic invertebrates to disturbance from stream restoration: The importance of bryophytes. *Hydrobiologia*, *523*(1–3), 37–45. https://doi.org/10.1023/B:HYDR.0000033086.09499.86

Louhi, P., Mykrä, H., Paavola, R., Huusko, A., Vehanen, T., Mäki-Petäys, A., & Muotka, T. (2011). Twenty years of stream restoration in Finland: Little response by benthic macroinvertebrate communities. *Ecological Applications*, *21*(6), 1950–1961. https://doi.org/10.1890/10-0591.1

Maksimović, Č., Kurian, M., & Ardakanian, R. (2015). *Rethinking Infrastructure Design for Multi-Use Water Services*. Springer International Publishing. https://doi.org/10.1007/978-3-319-06275-4

Merill, L., & Tonjes, D. J. (2014). A review of the hyporheic zone, stream restoration, and means to enhance denitrification. *Critical Reviews in Environmental Science and Technology*, *44*(21), 2337–2379. https://doi.org/10.1080/10643389.2013.829769

Millennium Ecosystem Assessment. (2003). *Ecosystems and Human Well-being, A Framework for Assessment.*

Miller, J. W., Paul, M. J., & Obenour, D. R. (2019). Assessing potential anthropogenic drivers of ecological health in piedmont streams through hierarchical modeling. *Freshwater Science*, *38*(4), 771–789. https://doi.org/10.1086/705963

Mor, J. R., Dolédec, S., Acuña, V., Sabater, S., & Muñoz, I. (2019). Invertebrate community responses to urban wastewater effluent pollution under different hydro-morphological conditions. *Environmental Pollution*, *252*, 483–492. https://doi.org/10.1016/j.envpol.2019.05.114

Muotka, T., & Syrjänen, J. (2007). Changes in habitat structure, benthic invertebrate diversity, trout populations and ecosystem processes in restored forest streams: A boreal perspective. *Freshwater Biology*, *52*(4), 724–737. https://doi.org/10.1111/j.1365-2427.2007.01727.x

Opoku, A. (2019). Biodiversity and the built environment: Implications for the Sustainable Development Goals (SDGs). *Resources, Conservation and Recycling*, *141*(October 2018), 1–7. https://doi.org/10.1016/j.resconrec.2018.10.011

Palmer, M. A., & Bernhardt, E. S. (2006). Hydroecology and river restoration: Ripe for research and synthesis. *Water Resources Research*, *42*(3). https://doi.org/10.1029/2005WR004354

Palmer, M. A., & Richardson, D. C. (2009). Provisioning services: A focus on fresh water. In *The Princeton Guide to Ecology* (pp. 625–633). Princeton University Press.

Palmer, M. A., Bernhardt, E. S., Allan, J. D., Lake, P. S., Alexander, G., Brooks, S., Carr, J., Clayton, S., Dahm, C. N., Follstad Shah, J., Galat, D. L., Loss, S. G., Goodwin, P., Hart, D. D., Hassett, B., Jenkinson, R., Kondolf, G. M., Lave, R., Meyer, J. L., … Sudduth, E. (2005). Standards for ecologically successful river restoration. *Journal of Applied Ecology*, *42*(2), 208–217. https://doi.org/10.1111/j.1365-2664.2005.01004.x

Palmer, M. A., Menninger, H. L., & Bernhardt, E. (2010). River restoration, habitat heterogeneity and biodiversity: A failure of theory or practice? *Freshwater Biology*, *55*(SUPPL. 1), 205–222. https://doi.org/10.1111/j.1365-2427.2009.02372.x

Parker, S. R., Adams, S. K., Lammers, R. W., Stein, E. D., & Bledsoe, B. P. (2019). Targeted hydrologic model calibration to improve prediction of ecologically-relevant flow metrics. *Journal of Hydrology*, *573*(March), 546–556.

https://doi.org/10.1016/j.jhydrol.2019.03.081

Paul, M. J., & Meyer, J. L. (2001). Streams in the Urban Landscape. In *Urban Ecology* (pp. 207–231). Springer US. https://doi.org/10.1007/978-0-387-73412-5_12

Purcell, A. H., Friedrich, C., & Resh, V. H. (2002). An assessment of a small urban stream restoration project in Northern California. *Restoration Ecology*, *10*(4), 685–694. https://doi.org/10.1046/j.1526-100X.2002.01049.x

Reid, A. J., Carlson, A. K., Creed, I. F., Eliason, E. J., Gell, P. A., Johnson, P. T. J., Kidd, K. A., MacCormack, T. J., Olden, J. D., Ormerod, S. J., Smol, J. P., Taylor, W. W., Tockner, K., Vermaire, J. C., Dudgeon, D., & Cooke, S. J. (2019). Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biological Reviews*, *94*(3), 849–873. https://doi.org/10.1111/brv.12480

Rutherfurd, I., Jerie, K., & Marsh, N. (2000). *A Rehabilitation Manual for Australian Streams*. *1*.

Schriever, T. A., Bogan, M. T., Boersma, K. S., Cañedo-Argüelles, M., Jaeger, K. L., Olden, J. D., & Lytle, D. A. (2015). Hydrology shapes taxonomic and functional structure of desert stream invertebrate communities. *Freshwater Science*, *34*(2), 399–409. https://doi.org/10.1086/680518

Selvakumar, A., O'Connor, T. P., & Struck, S. D. (2010). Role of stream restoration on improving benthic macroinvertebrates and In-stream water quality in an urban watershed: Case study. *Journal of Environmental Engineering*, *136*(1), 127–139. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000116

Serpa, D., Nunes, J. P., Santos, J., Sampaio, E., Jacinto, R., Veiga, S., Lima, J. C., Moreira, M., Corte-Real, J., Keizer, J. J., & Abrantes, N. (2015). Impacts of climate and land use changes on the hydrological and erosion processes of two contrasting Mediterranean catchments. *Science of the Total Environment*, *538*, 64–77. https://doi.org/10.1016/j.scitotenv.2015.08.033

Serra, S. R. Q., Calapez, A. R., Simões, N. E., Sá Marques, J. A. A., Laranjo, M., & Feio, M. J. (2019). Effects of variations in water quantity and quality in the structure and functions of invertebrates' community of a Mediterranean urban stream. *Urban Ecosystems*, *22*(6), 1173–1186. https://doi.org/10.1007/s11252-019-00892-4

Shoredits, A. S., & Clayton, J. A. (2013). Assessing the Practice and Challenges of Stream Restoration in Urbanized Environments of the USA. *Geography Compass*, *7*(5), 358–372. https://doi.org/10.1111/gec3.12039

Smith, R. F., Neideigh, E. C., Rittle, A. M., & Wallace, J. R. (2020). *Assessing macroinvertebrate community response to restoration of Big Spring Run : Expanded analysis of before - after - control - impact sampling designs*. *September 2018*, 79–90. https://doi.org/10.1002/rra.3556

Spänhoff, B., & Arle, J. (2007). Setting attainable goals of stream habitat restoration from a macroinvertebrate view. *Restoration Ecology*, *15*(2), 317. https://doi.org/10.1111/j.1526-100X.2007.00216.x

Stubbington, R., Bogan, Greenwood, A. M., Wood, P. J., Armitage, P. D., Gunn, J., & Robertson, A. L. (2009). The response of perennial and temporary headwater stream invertebrate communities to hydrological extremes. *Hydrobiologia*, *630*(1), 299–312. https://doi.org/10.1007/s10750-009-9823-8

Stubbington, R., Bogan, M. T., Bonada, N., Boulton, A. J., Datry, T., Leigh, C., & Vander

Vorste, R. (2017). The Biota of Intermittent Rivers and Ephemeral Streams: Aquatic Invertebrates. In *Intermittent Rivers and Ephemeral Streams: Ecology and Management*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-803835-2.00007-3

Szita, R., Horváth, A., Winkler, D., Kalicz, P., Gribovszki, Z., & Csáki, P. (2019). A complex urban ecological investigation in a mid-sized Hungarian city – SITE assessment and monitoring of a liveable urban area, PART 1: Water quality measurement. *Journal of Environmental Management*, *247*(June), 78–87. https://doi.org/10.1016/j.jenvman.2019.06.063

Tasca, F. A., Goerl, R. F., Michel, G. P., Leite, N. K., Sérgio, D. Z., Belizário, S., Caprario, J., & Finotti, A. R. (2020). Application of Systems Thinking to the assessment of an institutional development project of river restoration at a campus university in Southern Brazil. *Environmental Science and Pollution Research*, *27*(13), 14299–14317. https://doi.org/10.1007/s11356-019-06693-8

Tchakonté, S., Ajeagah, G. A., Camara, A. I., Diomandé, D., Nyamsi Tchatcho, N. L., & Ngassam, P. (2015). Impact of urbanization on aquatic insect assemblages in the coastal zone of Cameroon: the use of biotraits and indicator taxa to assess environmental pollution. *Hydrobiologia*, *755*(1), 123–144. https://doi.org/10.1007/s10750-015-2221-5

Tonkin, J. D., Stoll, S., Sundermann, A., & Haase, P. (2014). Dispersal distance and the pool of taxa, but not barriers, determine the colonisation of restored river reaches by benthic invertebrates. *Freshwater Biology*, *59*(9), 1843–1855. https://doi.org/10.1111/fwb.12387

Tsakaldimi, M., & Tsitsoni, T. (2016). *The importance of streams protection in urban areas from the perspective of ecology and environmental awareness*. *September 2015*.

Tullos, D. D., Penrose, D. L., Jennings, G. D., & Cope, W. G. (2009). Analysis of functional traits in reconfigured channels: Implications for the bioassessment and disturbance of river restoration. *Journal of the North American Benthological Society*, *28*(1), 80–92. https://doi.org/10.1899/07-122.1

Turunen, J., Aroviita, J., Marttila, H., Louhi, P., Laamanen, T., Tolkkinen, M., Luhta, P. L., Kløve, B., & Muotka, T. (2017). Differential responses by stream and riparian biodiversity to in-stream restoration of forestry-impacted streams. *Journal of Applied Ecology*, *54*(5), 1505–1514. https://doi.org/10.1111/1365-2664.12897

United Nations. (2015). *Transforming our world : the 2030 Agenda for Sustainable Development*.

Verdonschot, P. F. M., & Nijboer, R. C. (2002). Towards a decision support system for stream restoration in the Netherlands: An overview of restoration projects and future needs. *Hydrobiologia*, *478*(1986), 131–148. https://doi.org/10.1023/A:1021026630384

Violin, C. R., Cada, P., Sudduth, E. B., Hassett, B. A., Penrose, D. L., & Bernhardt, E. S. (2011). Effects of urbanization and urban stream restoration on the physical and biological structure of stream ecosystems. *Ecological Applications*, *21*(6), 1932–1949. https://doi.org/10.1890/10-1551.1

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R., & Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature*, *468*(7321), 334–334. https://doi.org/10.1038/nature09549

Walsh, C. J., Booth, D. B., Burns, M. J., Fletcher, T. D., Hale, R. L., Hoang, L. N., Livingston, G., Rippy, M. A., Roy, A. H., Scoggins, M., & Wallace, A. (2016).

Principles for urban stormwater management to protect stream ecosystems. *Freshwater Science*, *35*(1), 398–411. https://doi.org/10.1086/685284

Walsh, C. J., Leonard, A. W., Ladson, A. R., & Fletcher, T. D. (2004). *Urban Stormwater and the Ecology of Streams*. *January*, 44. http://www.urbanstreams.unimelb.edu.au/Docs/urban_stormwater_streamecology.pdf

Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M., & Morgan, R. P. (2005). The urban stream syndrome: Current knowledge and the search for a cure. *Journal of the North American Benthological Society*, *24*(3), 706–723. https://doi.org/10.1899/04-028.1

Wetzel, R. G. (2001). *Limnology*. Elsevier. https://doi.org/10.1016/C2009-0-02112-6

Xu, M., Wang, Z., Duan, X., & Pan, B. (2014). Effects of pollution on macroinvertebrates and water quality bio-assessment. *Hydrobiologia*, *729*(1), 247–259. https://doi.org/10.1007/s10750-013-1504-y

Zeiger, S. J., & Hubbart, J. A. (2019). Characterizing land use impacts on channel geomorphology and streambed sedimentological characteristics. *Water (Switzerland)*, *11*(5). https://doi.org/10.3390/w11051088

4 GENERAL CONCLUSIONS AND FUTURE RESEARCH

4.1 General Conclusions

Considering the value of urban streams for sustainable urban management, the purpose of this dissertation was to retrieve insights and recommendations from the review of recent literature addressing stream restoration, particularly hydromorphologic actions, and their subsequent effects on the stream's benthic macroinvertebrate community. The goal was to contribute to sustainable urban development by providing urban water management an integrated ecohydrology perspective on urban streams. In view of this, the present thesis reviewed the existing literature with the following specific main objectives: 1) determine the effects of hydromorphological alterations in biological communities; 2) establish the most important restoration measures to recover urban stream ecosystems.

Urban streams are an important blue-green nature-based solution that yields many ecosystem services, including regulation of urban temperature and global climate, improved biodiversity, and decrease of stormwater runoff, which leads to reduced urban flood risk. Therefore, urban stream ecosystems must be preserved and restored.

Urbanisation entails the implementation of impervious cover (amongst other land cover change), which alters the hydrological pattern of the urban basin by reducing crucial processes such as interception, infiltration, and evapotranspiration. These changes lead to overall higher flashiness and variation in the flow of streams due to the increase in surface runoff and, consequentially, in discharge too. Morphological and chemical alterations are also the result of urbanisation. Climate change will only exacerbate these issues by altering temperature and precipitation patterns, enhancing the magnitude and duration of climate extremes such as floods and droughts.

Benthic macroinvertebrate assemblages are highly sensitive towards water quality, and therefore, their communities become impoverished and reduced to tolerant taxa in the presence of pollutants resulting of urban drainage, losing ecosystem functionality. Likewise, hydrology affects invertebrate communities. High flows drag organisms downstream and destroy benthic habitat, whereas low flows reduce habitat and enhance the concentration of pollutants in the water. Flow permanence appears to be the most important hydrologic characteristic. Whilst, by rule-of-thumb, permanent flows show more diverse communities, artificially shifting naturally intermittent streams to a permanent flow regime degrades these ecosystems.

The scale of restoration is also a key issue. Stream restoration projects fail when the watershed’s state is not considered. When the whole watershed is impaired, whether it is due to water pollution or the alteration of natural hydrologic patterns, restoration actions that enhance the habitat heterogeneity of streams will not improve the diversity of macroinvertebrate communities. Due to region-specific settings unique to each urban stream, it is impossible to prescribe a global recipe for the urban stream syndrome. Nonetheless, a few common points on the management of such streams can be considered: aim to reduce the ultimate runoff volume by employing practises based on the infiltration, harvesting, and use of stormwater, and by doing so disconnecting impervious areas from streams. Stream restoration should prioritise issues such as water quality and altered hydrologic patterns at a watershed scale, and only after resolving these matters move on to enhancing habitat heterogeneity, if necessary, and restoring components of the pre-development habitat. Since physical restoration actions disturb the existing condition of the stream’s habitat, refugia must be provided in order to facilitate recolonisation after conditions have settled.

Before embarking on a new restoration project, an understanding of the interplay between the watershed and its urban traits must be cemented, aiming to re-establish the natural distribution of stormwater and hydrologic processes. This demands a recognising of the relationship between watershed and urban traits, the regional ecological composition, and the social and economic practicability of management approaches. Finally, an efficient restoration requires good communication between experts and practitioners, as well as the interest of the urban population. Thus, sensibilization and education actions are also essential.

Practitioners must work in integrated, multidisciplinary, teams that can approach urban stream management from an ecohydrology point of view.

4.2 Future Research

The few suggestions given throughout this thesis need further research. One of them being streamflow metrics as limits for the maximum richness/abundance of sensitive taxa. Field work could explore this hypothesis and find out if it could be indeed an added paradigm to consider in restoration projects.

Another concept to explore is if streams indeed possess a given “threshold” for water level to possess enough dilution capacity in order to sustain macroinvertebrate diversity when water pollution is unavoidable or difficult to solve.

The importance of re-establishing pre-development hydrological patterns has been thoroughly stressed throughout this research. However, it is widely known that rivers and streams are ever-evolving systems, so who is to say that their current hydrologic pattern would, indeed, correspond to pre-development conditions? Another aspect to consider is the fact that urbanisation completely alters the catchment and so, perhaps different circumstances to the expected natural ones would yield even better ecological conditions and ecosystem services. Modelling systems could be developed to predict the outcomes of restoration projects according to different approaches before settling on one.

Overall, the more data available about restoration projects, the planning involved, objectives and after monitorisation and results, the better. Such projects should involve experts in the field of aquatic ecology to assess the taxon pool beforehand and the traits that macroinvertebrate communities possess, as well as for the determination of ecological quality, to see if these would actually be helpful when planning a restoration project.

5 REFERENCES

Aguiar, F. C., Espírito-Santo, M. D., & Ferreira, M. T. (2019). Plantas aquáticas e florestas ribeirinhas. In Rios de Portugal: comunidades, processos e alterações (pp. 123–146). Imprensa da Universidade de Coimbra. https://doi.org/10.14195/978-989-26-1624-7_6

Allan, J. D., & Castillo, M. M. (2007). Stream Ecology: Structure and Function of Running Waters (2nd ed.). Springer.

Almeida, P. R., Ferreira, M. T., Ribeiro, F., Quintella, B. R., Mateus, C. S., & Alexandre, C. M. (2019). Peixes. In Rios de Portugal: comunidades, processos e alterações (pp. 171–201). Imprensa da Universidade de Coimbra. https://doi.org/10.14195/978-989-26-1624-7_8

Almeida, S. F. P., Luís, A. T., Elias, C. L., Novais, M. H., Santos, L. M. A., Vasconcelos, V., Craveiro, S. C., & Calado, A. J. (2019). Algas. In Rios de Portugal: comunidades, processos e alterações (pp. 75–96). Imprensa da Universidade de Coimbra. https://doi.org/10.14195/978-989-26-1624-7_4

Alves, A., Gersonius, B., Kapelan, Z., Vojinovic, Z., & Sanchez, A. (2019). Assessing the Co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management. Journal of Environmental Management, 239(March), 244–254. https://doi.org/10.1016/j.jenvman.2019.03.036

Anderson, P. M. L., Okereke, C., Rudd, A., & Parnell, S. (2013). Regional assessment of Africa. In Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Global Assessment. https://doi.org/10.1007/978-94-007-7088-1_23

Antoszewski, P., Krzyżaniak, M., & Świerk, D. (2020). Statistical Review of Quality Parameters of Blue-Green Infrastructure Elements Important in Mitigating the Effect of the Urban Heat Island in the Temperate Climate (C) Zone. International Journal of Environmental Research and Public Health, 2020. https://doi.org/10.3390/ijerph17197093

Ashley, R., Lundy, L., Ward, S., Shaffer, P., Walker, L., Morgan, C., Saul, A., Wong, T., & Moore, S. (2013). Water-sensitive urban design: Opportunities for the UK. Proceedings of the Institution of Civil Engineers: Municipal Engineer, 166(2), 65–76. https://doi.org/10.1680/muen.12.00046

Baravikova, A. (2020). The uptake of new concepts in urban greening: Insights from Poland. Urban Forestry and Urban Greening, 56, 126798. https://doi.org/10.1016/j.ufug.2020.126798

Beechie, T., Pess, G., Roni, P., & Giannico, G. (2008). Setting River Restoration Priorities: A Review of Approaches and a General Protocol for Identifying and Prioritizing Actions. North American Journal of Fisheries Management, 28(3), 891–905. https://doi.org/10.1577/m06-174.1

Berkman, H. E., Rabeni, C. F., & Boyle, T. P. (1986). Biomonitors of stream quality in agricultural areas: Fish versus invertebrates. Environmental Management, 10(3), 413–419. https://doi.org/10.1007/BF01867267

Bolund, P., & Hunhammar, S. (1999). Ecosystem services in urban areas. Ecological Economics, 29(2), 293–301. https://doi.org/10.1016/S0921-8009(99)00013-0

Booth, D. B., Roy, A. H., Smith, B., & Capps, K. A. (2016). Global perspectives on the urban stream syndrome. Freshwater Science, 35(1), 412–420. https://doi.org/10.1086/684940

Brettschneider, D. J., Misovic, A., Schulte-Oehlmann, U., Oetken, M., & Oehlmann, J. (2019). Poison in paradise: increase of toxic effects in restored sections of two rivers jeopardizes the success of hydromorphological restoration measures. Environmental Sciences Europe, 31(1). https://doi.org/10.1186/s12302-019-0218-9

Brown, K., & Mijic, A. (2020). *Integrating green and blue spaces into our cities: Making it happen: Grantham Institute Briefing paper No 30. 30*. https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/briefing-papers/Integrating-green-and-blue-spaces-into-our-cities---Making-it-happen-.pdf

Chadwick, M. A., Dobberfuhl, D. R., Benke, A. C., Huryn, A. D., Suberkropp, K., & Thiele, J. E. (2006). Urbanization affects stream ecosystem function by altering hydrology, chemistry, and biotic richness. Ecological Applications, 16(5), 1796–1807. https://doi.org/10.1890/1051-0761(2006)016[1796:UASEFB]2.0.CO;2

Costanza, R., & Mageau, M. (1999). What is a healthy ecosystem? Aquatic Ecology, 33(1), 105–115. https://doi.org/10.1023/A:1009930313242

da Silva Gonçalves, C., de Souza Braga, F. M., & Casatti, L. (2018). Trophic structure of coastal freshwater stream fishes from an Atlantic rainforest: evidence of the importance of protected and forest-covered areas to fish diet. Environmental Biology of Fishes, 101(6), 933–948. https://doi.org/10.1007/s10641-018-0749-8

De Vleeschauwer, K., Weustenraad, J., Nolf, C., Wolfs, V., De Meulder, B., Shannon, K., & Willems, P. (2014). Green-blue water in the city: Quantification of impact of source control versus end-of-pipe solutions on sewer and river floods. Water Science and Technology, 70(11), 1825–1837. https://doi.org/10.2166/wst.2014.306

Debo, T. N. (Thomas N. (2003). Municipal stormwater management. In Municipal stormwater management (Second edi). Lewis Publishers.

Dey, S., Pramanik, C., & Dey, C. (2010). Mathematical modelling of the effects of urbanization and population growth on agricultural economics. Intellectual Economics, 2(8), 7–20–20.

Dodds, W. K., & Whiles, M. R. (2010). Freshwater Ecology. In Freshwater Ecology: Concepts and Environmental Applications of Limnology (2nd ed.). Elsevier. https://doi.org/10.1016/C2016-0-03667-7

EPA@ (2016). https://www.epa.gov/national-aquatic-resource-surveys/indicators-benthic-macroinvertebrates#:~:text=Benthic%20macroinvertebrates%20are%20commonly%20used,in%20their%20tolerance%20to%20pollution . United States Environmental Protection Agency. Accessed 03 August 2020.

European Commission. (2000). Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy.

Feio, M. J., & Ferreira, V. (2019). Rios de Portugal: comunidades, processos e alterações. Imprensa da Universidade de Coimbra. https://doi.org/10.14195/978-989-26-1624-7

Ferreira, C. S. S., Walsh, R. P. D., Nunes, J. P. C., Steenhuis, T. S., Nunes, M., de Lima, J. L.

M. P., Coelho, C. O. A., & Ferreira, A. J. D. (2016). Impact of urban development on streamflow regime of a Portuguese peri-urban Mediterranean catchment. Journal of Soils and Sediments, 16(11), 2580–2593. https://doi.org/10.1007/s11368-016-1386-5

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J. L., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D., & Viklander, M. (2015). SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. Urban Water Journal, 12(7), 525–542. https://doi.org/10.1080/1573062X.2014.916314

Furlong, C., Brotchie, R., Considine, R., Finlayson, G., & Guthrie, L. (2017). Key concepts for Integrated Urban Water Management infrastructure planning: Lessons from Melbourne. Utilities Policy, 45, 84–96. https://doi.org/10.1016/j.jup.2017.02.004

Gaia, S., & John Jones, M. (2017). UK local councils reporting of biodiversity values: a stakeholder perspective. Accounting, Auditing & Accountability Journal, 30(7), 1614–1638. https://doi.org/10.1108/AAAJ-12-2015-2367

Goldenberg, R., Kalantari, Z., & Destouni, G. (2018). Increased access to nearby green-blue areas associated with greater metropolitan population well-being. Land Degradation & Development, 29(10), 3607–3616. https://doi.org/10.1002/ldr.3083

Gómez-Baggethun, E., Gren, Å., Barton, D. N., Langemeyer, J., McPhearson, T., O'Farrell, P., Andersson, E., Hamstead, Z., & Kremer, P. (2013). Urban Ecosystem Services. In Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities (pp. 175–251). Springer Netherlands. https://doi.org/10.1007/978-94-007-7088-1_11

Goodernham, J., & Tsyrlin, E. (2002). *The waterbug book: A guide to the freshwater macroinvertebrates of temperate Australia*. CSIRO PUBLISHING.

Grimm, N. B., Faeth, S. H., Golubiewski, N. E., Redman, C. L., Wu, J., Bai, X., & Briggs, J. M. (2008). Global change and the ecology of cities. Science, 319(5864), 756–760. https://doi.org/10.1126/science.1150195

Haghighatafshar, S., Yamanee-Nolin, M., Klinting, A., Roldin, M., Gustafsson, L. G., Aspegren, H., & Jönsson, K. (2019). Hydroeconomic optimization of mesoscale blue-green stormwater systems at the city level. Journal of Hydrology, 578(August), 124125. https://doi.org/10.1016/j.jhydrol.2019.124125

Harrison, P. A., Vandewalle, M., Sykes, M. T., Berry, P. M., Bugter, R., de Bello, F., Feld, C. K., Grandin, U., Harrington, R., Haslett, J. R., Jongman, R. H. G., Luck, G. W., da Silva, P. M., Moora, M., Settele, J., Sousa, J. P., & Zobel, M. (2010). Identifying and prioritising services in European terrestrial and freshwater ecosystems. Biodiversity and Conservation, 19(10), 2791–2821. https://doi.org/10.1007/s10531-010-9789-x

Hering, D., Meier, C., Rawer-Jost, C., Feld, C. K., Biss, R., Zenker, A., Sundermann, A., Lohse, S., & Böhmer, J. (2004). Assessing streams in Germany with benthic invertebrates: Selection of candidate metrics. Limnologica, 34(4), 398–415. https://doi.org/10.1016/S0075-9511(04)80009-4

Hooper, D. U., Chapin, F. S., Ewel, J. J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J. H., Lodge, D. M., Loreau, M., Naeem, S., Schmid, B., Setälä, H., Symstad, A. J., Vandermeer, J., & Wardle, D. A. (2005). Effects of biodiversity on ecosystem functioning: A consensus of current knowledge. Ecological Monographs, 75(1), 3–35. https://doi.org/10.1890/04-0922

Iojă, I. C., Osaci-Costache, G., Breuste, J., Hossu, C. A., Grădinaru, S. R., Onose, D. A., Niță, M. R., & Skokanová, H. (2018). Integrating urban blue and green areas based on historical evidence. Urban Forestry and Urban Greening, 34(July), 217–225. https://doi.org/10.1016/j.ufug.2018.07.001

Jax, K. (2005). Function and “functioning” in ecology: What does it mean? In Oikos (Vol. 111, Issue 3, pp. 641–648). https://doi.org/10.1111/j.1600-0706.2005.13851.x

Kenney, M. A., Sutton-grier, A. E., Smith, R. F., & Gresens, S. E. (2009). Benthic macroinvertebrates as indicators of water quality : The intersection of science and policy Benthic macroinvertebrates as indicators of water quality : April 2018. https://doi.org/10.1163/187498209X12525675906077

Konrad, C. P., & Booth, D. B. (2002). Hydrologic trends associated with urban development for selected streams in the Puget Sound Basin, Western Washington. Water-Resources Investigations Report ;02-4040, vi, 40 p., vi, 40 p. https://doi.org/10.1007/s10661-010-1363-1

Konrad, C. P., & Booth, D. B. (2005). Hydrologic changes in urban streams and their ecological significance. American Fisheries Society Symposium, 2005(47), 157–177.

Liao, K.-H., Deng, S., & Tan, P. Y. (2017). Blue-Green Infrastructure: New Frontier for Sustainable Urban Stormwater Management. 203–226. https://doi.org/10.1007/978-981-10-4113-6_10

Ljungkvist, J., Barthel, S., Finnveden, G., & Sörlin, S. (2010). The Urban Anthropocene: Lessons for Sustainability from the Environmental History of Constantinople. In Studies in Global Archaeology (Vol. 15, pp. 367–390).

Lucke, T., Mohamed, M., & Tindale, N. (2014). Pollutant Removal and Hydraulic Reduction Performance of Field Grassed Swales during Runoff Simulation Experiments. *Water*, *6*(7), 1887–1904. https://doi.org/10.3390/w6071887

Maksimović, Č., Kurian, M., & Ardakanian, R. (2015). Rethinking Infrastructure Design for Multi-Use Water Services. Springer International Publishing. https://doi.org/10.1007/978-3-319-06275-4

Melbourne Water. (2013). Water Sensitive Urban Design Guidelines South Eastern Councils.

Melillo, J. M., Naiman, R. J., Abet, J. D., & Eshleman, K. N. (1983). Oecologia on wood decomposition dynamics *. Civil Engineering, 281–285.

Millennium Ecosystem Assessment. (2003). Ecosystems and Human Well-being, A Framework for Assessment.

Montgomery, M. R. (2008). The Urban Transformation of the Developing World. Science, 319(5864), 761–764. https://doi.org/10.1126/science.1153012

Moss, B. R. (2018). Ecology of Freshwaters: Earth’s Bloodstream. Wiley. https://books.google.pt/books?id=41BWDwAAQBAJ

NACTO (2017) Stormwater Elements. In: Urban Street Stormwater Guide. Island Press, Washington, DC. https://doi.org/10.5822/978-1-61091-814-5_4

Nilon, C. H. (2011). Urban biodiversity and the importance of management and conservation. Landscape and Ecological Engineering, 7(1), 45–52. https://doi.org/10.1007/s11355-010-0146-8

Nutsford, D., Pearson, A. L., Kingham, S., & Reitsma, F. (2016). Residential exposure to visible blue space (but not green space) associated with lower psychological distress in a capital city. Health & Place, 39, 70–78. https://doi.org/10.1016/j.healthplace.2016.03.002

Oral, H. V., Carvalho, P., Gajewska, M., Ursino, N., Masi, F., Hullebusch, E. D. van, Kazak, J. K., Exposito, A., Cipolletta, G., Andersen, T. R., Finger, D. C., Simperler, L., Regelsberger, M., Rous, V., Radinja, M., Buttiglieri, G., Krzeminski, P., Rizzo, A., Dehghanian, K., … Zimmermann, M. (2020). A review of nature-based solutions for urban water management in European circular cities: a critical assessment based on case studies and literature. Blue-Green Systems, 2(1), 112–136. https://doi.org/10.2166/bgs.2020.932

Palmer, M. A., & Richardson, D. C. (2009). Provisioning services: A focus on fresh water. In The Princeton Guide to Ecology (pp. 625–633). Princeton University Press.

Palmer, M. A., Bernhardt, E. S., Allan, J. D., Lake, P. S., Alexander, G., Brooks, S., Carr, J., Clayton, S., Dahm, C. N., Follstad Shah, J., Galat, D. L., Loss, S. G., Goodwin, P., Hart, D. D., Hassett, B., Jenkinson, R., Kondolf, G. M., Lave, R., Meyer, J. L., … Sudduth, E. (2005). Standards for ecologically successful river restoration. Journal of Applied Ecology, 42(2), 208–217. https://doi.org/10.1111/j.1365-2664.2005.01004.x

Palmer, M. A., Hondula, K. L., & Koch, B. J. (2014). Ecological restoration of streams and rivers: Shifting strategies and shifting goals. Annual Review of Ecology, Evolution, and Systematics, 45, 247–269. https://doi.org/10.1146/annurev-ecolsys-120213-091935

Paul, M. J., & Meyer, J. L. (2001). Streams in the Urban Landscape. In Urban Ecology (pp. 207–231). Springer US. https://doi.org/10.1007/978-0-387-73412-5_12

Ramos, J. A., Godinho, C., & Encarnação, V. (2019). Aves. In Rios de Portugal: comunidades, processos e alterações (pp. 233–249). Imprensa da Universidade de Coimbra. https://doi.org/10.14195/978-989-26-1624-7_10

Rebelo, R., Carretero, M., Gonçalves, H., Segurado, P., Sequeira, F., & Lopes, I. (2019). Anfíbios e répteis. In Rios de Portugal: comunidades, processos e alterações (pp. 203–231). Imprensa da Universidade de Coimbra. https://doi.org/10.14195/978-989-26-1624-7_9

Reyjol, Y., Argillier, C., Bonne, W., Borja, A., Buijse, A. D., Cardoso, A. C., Daufresne, M., Kernan, M., Ferreira, M. T., Poikane, S., Prat, N., Solheim, A. L., Stroffek, S., Usseglio-Polatera, P., Villeneuve, B., & van de Bund, W. (2014). Assessing the ecological status in the context of the European Water Framework Directive: Where do we go now? Science of the Total Environment, 497–498, 332–344. https://doi.org/10.1016/j.scitotenv.2014.07.119

Santos-Reis, M., Petrucci-Fonseca, F., & Pedroso, N. M. (2019). Mamíferos. In Rios de Portugal: comunidades, processos e alterações (pp. 251–279). Imprensa da Universidade de Coimbra. https://doi.org/10.14195/978-989-26-1624-7_11

Serra, S. R. Q., Calapez, A. R., Simões, N. E., Sá Marques, J. A. A., Laranjo, M., & Feio, M. J. (2019a). Effects of variations in water quantity and quality in the structure and functions of invertebrates' community of a Mediterranean urban stream. Urban Ecosystems, 22(6), 1173–1186. https://doi.org/10.1007/s11252-019-00892-4

Serra, S. R. Q., Espírito-Santo, M. D., & Ferreira, M. T. (2019b). Invertebrados. In Rios de Portugal: comunidades, processos e alterações (pp. 147–169). Imprensa da Universidade de Coimbra. https://doi.org/10.14195/978-989-26-1624-7_7

Seto, K. C., Sánchez-Rodríguez, R., & Fragkias, M. (2010). The new geography of contemporary urbanization and the environment. Annual Review of Environment and Resources, 35, 167–194. https://doi.org/10.1146/annurev-environ-100809-125336

SLCo@ (2020). https://slco.org/watershed/streams-101/the-riparian-zone/ . Salt Lake County, Salt Lake City. Acessed 16 October 2020.

Sörensen, J., & Emilsson, T. (2019). Evaluating flood risk reduction by urban blue-green infrastructure using insurance data. Journal of Water Resources Planning and Management, 145(2), 1–11. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001037

Tabacchi, E., Correll, D. L., Hauer, R., Pinay, G., Planty-Tabacchi, A. M., & Wissmar, R. C. (1998). Development, maintenance and role of riparian vegetation in the river landscape. Freshwater Biology, 40(3), 497–516. https://doi.org/10.1046/j.1365-2427.1998.00381.x

Tandon, A., & Jyotsna, K. (2016). Modeling the effects of environmental pollution intensified by urbanization on human population. International Journal of Modeling, Simulation, and Scientific Computing, 7(3), 1–13. https://doi.org/10.1142/S1793962316500136

Thames21@ (2020). https://www.thames21.org.uk/sustainable-drainage-systems/ . Thames21, London. Acessed 14 October 2020.

United Nations. (2015). Transforming our world : the 2030 Agenda for Sustainable Development.

United Nations (Habitat III). (2017). New Urban Agenda. www.habitat3.org

United Nations. (2018). World Urbanization Prospects. In Demographic Research (Vol. 12). https://doi.org/10.4054/demres.2005.12.9

United Nations. (2019). World Population Prospects 2019: Highlights. United Nations Publication, 141, 1. https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/files/documents/2020/Jan/wpp2019_highlights.pdf

Voskamp, I. M., & Van de Ven, F. H. M. (2015). Planning support system for climate adaptation: Composing effective sets of blue-green measures to reduce urban vulnerability to extreme weather events. Building and Environment, 83, 159–167. https://doi.org/10.1016/j.buildenv.2014.07.018

Wallace, J. B., Webster, J. R., & Webster, W. (1996). THE ROLE OF MACROINVERTEBRATES IN STREAM ECOSYSTEM FUNCTION. 131.

Walsh, C. J., Leonard, A. W., Ladson, A. R., & Fletcher, T. D. (2004). Urban Stormwater and the Ecology of Streams. January, 44. http://www.urbanstreams.unimelb.edu.au/Docs/urban_stormwater_streamecology.pdf

Wassen, M., & Grootjans, A. P. (1996). Ecohydrology: An interdisciplinary approach for wetland management and restoration. Vegetatio, 126. https://doi.org/10.1007/BF00047757

Wetzel, R. G. (2001). Limnology. Elsevier. https://doi.org/10.1016/C2009-0-02112-6

Wolanski, E., Boorman, L. A., Chícharo, L., Langlois-Saliou, E., Lara, R., Plater, A. J., Uncles, R. J., & Zalewski, M. (2004). Ecohydrology as a new tool for sustainable management of estuaries and coastal waters. Wetlands Ecology and Management, 12(4), 235–276. https://doi.org/10.1007/s11273-005-4752-4

World Health Organization. (2017). Urban green spaces: a brief for action. In Regional Office For Europe. https://doi.org/10.1590/S1516-89132004000200018

Zalewski, M. (2006). Ecohydrology - an interdisciplinary tool for integrated protection and management of water bodies. River Systems, 16(4), 613–622. https://doi.org/10.1127/lr/16/2006/613