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HOW VEGETATION CAN AID IN COPING WITH RIVER MANAGEMENT CHALLENGES: A BRIEF REVIEW

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Abstract

Key Words: aquatic vegetation, riparian vegetation, river management, compound channels, pollution reduction, flood control

New sustainable, cost-effective solutions are urgently needed for river management since conventional practices have posed serious ecological threats on streams, rivers and the surrounding riparian areas. Besides addressing the societal needs e.g. for flood management, river management should increasingly address the ecosystem requirements for improved water quality and biodiversity. We argue that it is not feasible to solve existing and future river management challenges with intensive restoration projects. Instead, we believe that less resource-intensive solutions using natural channel processes and features, including vegetation, should be investigated. Besides directly supporting biota, aquatic and riparian vegetation traps, takes up and helps to process nutrients and harmful substances, and thus this paper emphasizes vegetation as a tool for nature-based solutions (NBS) in river management. In this paper, emphasis is placed on the usage of vegetation as a NBS in river management. We synthesize findings from key literature, showing that the fate of substances in channel systems is largely controlled by abiotic and biotic processes facilitated and modified by vegetation, including flow hydrodynamics, channel morphology, and sediment transport. Subsequently, we demonstrate how vegetation can be incorporated into channel designs, focusing on a two-stage (compound) design to improve resilience to flooding, control the transport of substances, and enhance the ecological status. As a conclusion, clever use and maintenance of vegetation present unused potential to obtain large-scale positive environmental impacts in rivers and streams experiencing anthropogenic pressures.

1 Introduction

Mimicking nature often leads to methodologies that allow for the development of efficient solutions to numerous scientific and real-life problems. Such approaches are successfully used even in seemingly remote scientific disciplines including mathematical optimization techniques. For example, natural processes have become a source of inspiration for plenty of novel heuristic optimization algorithms. Most of these have been motivated by biological features of living creatures, like the process of evolution, immune systems, the behaviour of swarms of animals, or other types of animal activities (e.g., de Castro, 2007; Piotrowski et al., 2014). It is therefore hardly surprising that the development of nature-based solutions is in the focus of domains where nature is directly present, i.e., where we attempt to mitigate the adverse anthropogenic effects on the environment.

Exploring nature based solutions (NBS) in river valleys is an obvious choice, and relevant examples will be shown in this paper. The concept of NBS is understood in different ways. The European Commission defines NBS as living solutions which are inspired and continuously supported by nature and which are designed to address various societal challenges in a resource-efficient and adaptable manner providing simultaneously economic, social, and environmental benefits (Maes and Jacobs 2017). The International Union for Conservation of Nature (IUCN) describes NBS as actions to protect, sustainably manage and restore natural or modified ecosystems in order to address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (Cohen-Shacham et al., 2016). Thus, NBS constitute an alternative to technological strategies and consist in managing systems in a comprehensive approach to sustain and potentially increase the delivery of ecosystem services to humans (Eggermont et al., 2015). A comprehensive discussion of the present understanding of NBS for water management is provided in WWAP (2018).

Eggermont et al. (2015) distinguish three types of nature-based solutions, and the present paper focuses on their Type 2 described as management approaches that develop sustainable and multifunctional ecosystems and landscapes to improve the delivery of selected ecosystem services compared to conventional practices. For instance, NBS are associated with the innovative planning of agricultural landscapes but are equally important in urban areas. To achieve “water smart cities” (Hattum et al., 2016) and thus EU policy objectives, water management in cities should be increasingly based on the concept of urban green infrastructure (e.g., Xin et al., 2017). Examples are low impact development (LID), best management practices (BMPs), sustainable urban drainage systems (SUDS), or water sensitive urban design (WSUD) that support the infiltration, evapotranspiration or use of stormwater in order to protect water quality and aquatic habitats in receiving water bodies (see e.g., Fletcher et al. 2015; Barbosa et al. 2012 .

The need for sustainable, cost-effective solutions for river management is pressing: rivers, streams, and floodplains are hydro-environments which are most severely affected by human alterations (e.g., Brinson and Malvárez 2002; Tockner and Stanford 2002; Blann et al. 2009). Most notably, geomorphic alterations changing the shape of rivers as well as hydrologic alterations modifying their water balance have dramatically increased sediment and nutrient transport rates (e.g., Owens et al. 2005) and have resulted in losses in habitat, biodiversity and ecosystem services (see Section 2). Climate change will impose additional challenges on the management of rivers and streams by modifying e.g. the hydrographs, vegetation, and loading from the catchment areas and consequently by altering riparian habitats (Perry et al. 2015).

Due to the inherent conflict between ecological aspects and human requirements on the river systems we argue that typically it is not feasible to solve these river management challenges with restoration projects on a large scale (Fig. 1). The cost of such undertakings will simply be too high: a pan-European assessment revealed that the median cost of river restoration is ~80 000 €/ha of the restored channel-floodplain system (Szałkiewicz et al. 2018). An example of large-scale restoration with the costs of ~60 000 €/ha distributed over the entire catchment is the medium-sized Emscher River in Germany where the total cost for the 865 km^2 catchment is 5.3 billion €. In fact, such immense costs pay off in very densely populated urban areas when the ecosystem, societal and social benefits are considered (e.g. Gerner et al. 2018), but would not be feasible in large parts of the world where the population density is sparser.

Another obstacle to complete river restoration is that the majority of water systems in densely populated landscapes (e.g., most of Europe, much of North America and Southeast

Asia) are used for numerous human needs such as recreation, landscape development, irrigation, drainage, and flood management. In recognition of this, recent ecological research is proposing that ecosystems should be managed for adaptive and functional integrity rather than attempting to restore them to an idealized conception of the natural state (e.g. Barnosky et al. 2017). Hilderbrand and Utz (2015) go even further and claim that the perceived ability to restore a system back to its predisturbance state is usually naïve because of the high multidimensionality of most ecological relationships. It is even claimed that there is little evidence of successfully restoring stream ecosystems back to an undisturbed state in spite of the vast amount of money spent on restoration projects (Bernhardt and Palmer, 2011; Palmer et al. 2014).

In riverine environments, vegetation provides an important tool for nature-based solutions as it is an integral part of both permanently submerged aquatic ecosystems and occasionally submerged riparian ecosystems. Vegetation growing on the channel bed, river banks, floodplains, and on other surfaces or floating on the water surface not only provides habitat, reproduction and rearing sites, shelter and nourishment for biological communities but also modifies the biological, chemical and physical environment (e.g., Tabacchi et al. 1998) and can thus mitigate harmful environmental impacts on water bodies. Consequently restoration of vegetation is actively promoted in a wide range of projects for different purposes (Gonzalez et al., 2015). For example, vegetation traps sediment as well as particle-bound nutrients and heavy metals, takes up dissolved nutrients while, at the same time, releasing dissolved organic carbon, thus serving as a natural filter (e.g., Clarke 2002). Regarding water quality, NBS employing vegetation have in many cases been shown to perform equal or even better than the grey infrastructure alternative for water purification and flood protection at similar costs, with wildlife support and recreation as additional benefits (e.g., Liquete et al., 2016 and references therein).

Figure 1. River management challenges include combining the ecosystem requirements, including improved water quality and riverine biodiversity, and the human uses of rivers, including drainage, flood management and reclamation of floodplains. The case from the Ritobäcken Brook (Finland, left, see e.g., Västilä et al. 2016) is an example for the application of nature-based solutions for holistic river management in agricultural areas; the Kinzig River (Germany, right) shows an example for a river profile optimized for drainage with managed floodplains.

The aim of this paper is to investigate how vegetation can be used as a nature-based solution for tackling river management problems such as resilience to flooding, transport of substances and improvement of ecological status, with emphasis placed on the role of vegetation in solving hydraulic deficiencies. As many river systems have been heavily modified (Section 2), we cannot count on expensive local solutions or restoration projects but need low-cost system-wide interventions through the utilization of the ecosystem services provided by plants (Sections 3-4). In fact, we argue that there is unused potential to gain positive large-scale environmental effects by reintroducing and maintaining riparian and aquatic vegetation in rivers and streams experiencing high anthropogenic pressures. The view on vegetation is manifold, as, for instance, it may be regarded as a control to local hydrological conditions including groundwater level (e.g. Tabacchi et al. 2000), a nuisance reducing hydraulic conveyance capacity (Wu and Ze, 2009) or spawning gravel area (Merz et al., 2008). On top of that, some investigators indicate that encroachment of riparian vegetation in formerly open floodplain areas may have negative impact on the biodiversity (Miller et al., 2013) not to mention invasive species which cause serious problems in many regions (e.g., Hultine and Bush 2011; Nilsson et al., 2010; Schneider et al., 2013). The practical applicability of the findings is highlighted for cases in agricultural water management (Section 5).

2 Challenges of conventional river management practices: view on agriculture

Starting from ancient times, humans have applied water management strategies to enhance the prospects of living. Depending on the geographical, climatic and geological conditions, management goals have included supplying water to fields through irrigation, preventing excess flooding, and creating arable areas on riverine floodplains though artificially decreasing the groundwater levels by drainage. Across the world, humans have markedly modified the natural flow paths and storage zones of water by channelizing natural rivers and streams to enhance flow conveyance. Channelization has included dredging the streams, removing vegetation and other elements that slow down the flow, and straightening the course of the streams. Additionally, networks of sub-surface or surface drainage conduits have been established to remove excess water from areas that used to be wetlands, e.g. frequently inundated floodplains. Such man-made drainage systems have markedly modified the catchment-scale hydrological regimes throughout large parts of the Northern America and North-Western Europe (e.g., Blann et al. 2009). These conventional practices have caused large-scale environmental impacts, such as losses of morphological heterogeneity and habitats, and disruption of the natural channel dynamics (e.g., Grizzetti et al. 2017).

Securing agricultural production has always been a major objective for water and river management. Developing sustainable agricultural water management practices is crucial for achieving positive, system-wide changes in the ecological status of the hydro-environment (e.g., Pierce et al. 2012) since a staggering 40% of the total ice-free land area on the Earth has been directly modified by humans for agricultural purposes (Hooke et al. 2012). As a consequence, a large part of the pollutant, nutrient and fine sediment loading to water bodies originates from agriculturally used areas (e.g., Moss, 2008). This loading results in severe eutrophicating effects in the downstream water bodies as the conventional ditches and channelized rivers lack the features for efficiently processing nutrients and other substances originating from the catchment areas (e.g., Bukaveckas 2007). Generally, agricultural loading is tackled by field-scale to landscape-scale measures, including reduced tillage practices, buffer strips and constructed wetlands. Despite the large-scale use of these measures, the ecological and morphological status of rivers, streams, and coastal waters is typically bad or moderate in intensively cultivated parts of the world (e.g., Grizzetti et al. 2017).

The above reviewed challenges of conventional river management practices are strongly related to research questions pertaining to the hydrodynamic complexity associated with vegetation, temporal and spatial variation of momentum and mass transport in vegetated channels and particularly on the prediction of hydraulic resistance in highly variable vegetated channels (see next Sections for a short overview). Given the potentially conflicting effects, such as ecological benefits but reduced water flow capacity, the real challenge in river management is how to best use and manage vegetation to achieve desirable effects.

3 New paradigm in assessing hydrodynamic implications of riverine vegetation

Riverine vegetation strongly influences, and is influenced by, the entire abiotic and biotic river–catchment system (Figure 2). In addition, anthropogenic pressures and modifications related to e.g. land use and climate change have a cross-cutting effect on all natural features and functions of this system. In the published literature, vegetation is often considered from one discipline or viewpoint, most importantly through its interconnections to water flow, transport and mixing processes, river morphodynamics, water quality or stream ecology (see references in Figure 2). In the management of heavily modified urban and rural channels, the main focus has traditionally been and typically still is on the technical implications of vegetation.

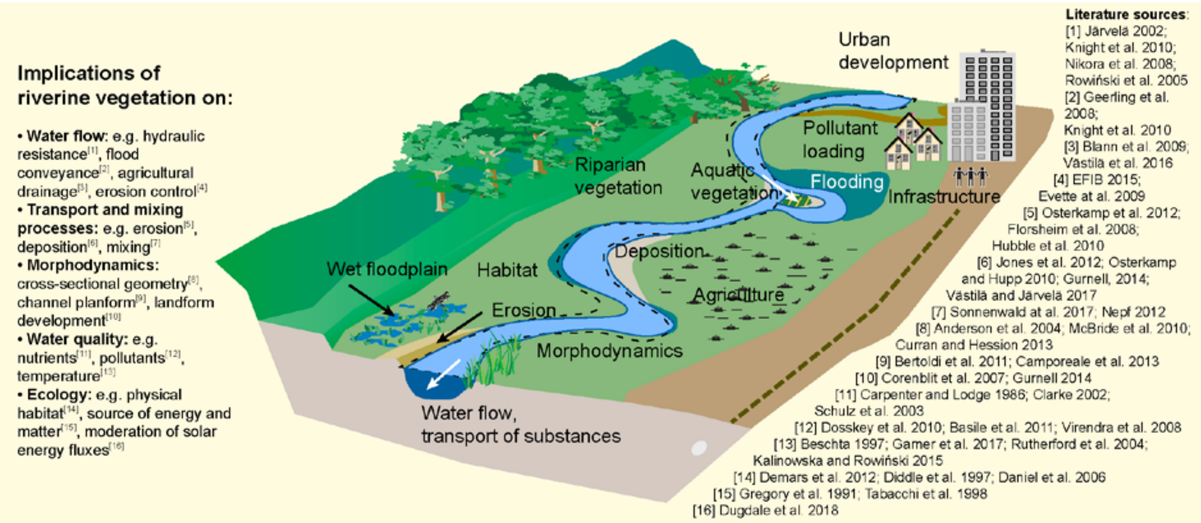

Figure 2. A schematic representation of the influence of riverine vegetation on water flow, river morphodynamics, transport and mixing processes, water quality and stream ecology. Anthropogenic modifications, including river management and climate change, need to be considered as further driving forces in the system.

Influence of vegetation on hydraulic resistance and conveyance was acknowledged in the hydraulics publications in the first half of the 20th century (e.g., Palmer 1945), but the way of its parametrization was overly simplified in comparison to the present process-based understanding (e.g., Vargas-Luna et al. 2015, Västilä and Järvelä 2017, Rubol et al. 2018). In the 1950s, agricultural engineers began to conduct investigations on the hydraulic properties of riverine vegetation to determine roughness coefficients and develop design methods for flood conveyance, drainage, irrigation, and erosion protection. However, little of the work was directed towards gaining a better understanding of the physical processes and thus the early approaches are not suited for analyzing many of the present problems. Since the 1970's, more physically-based scientific approach to investigate vegetation started to receive attention (e.g., Kouwen and Unny 1973, Li and Shen 1973, Pasche and Rouvé 1985, Petryk and Bosmajian 1975), but far-reaching simplifications have remained in use in practical channel hydraulics for decades. In fact, flow through natural vegetation has been a subject of rigorous, systematic research mainly over the last two decades (e.g., Fathi-Maghadam and Kouwen 1997; Järvelä 2002). The recent studies have provided new insights into the turbulent flow structure alterations (e.g., Sukhodolov 2015), multi-scale flow-plant interactions (e.g., Nepf 2012), and the flexibility-induced reconfiguration of complex aquatic and riparian plants and their consequences for flow resistance and transport processes (e.g., Aberle and Järvelä 2015).

To mitigate the adverse anthropogenic effects on the hydro-environment, the grand challenges for our society include understanding flow-biota interactions in rivers. For instance, ASCE Task Committee (Shields et al. 2017) states that engineers will increasingly design and manipulate floodplain vegetation as the restoration and conservation of ecosystems grows in importance. They expect that vegetation along stream corridors may direct overbank flows, improve flood storage, reduce scour and erosion, facilitate sediment transport, and alleviate other flood risk factors, while also providing critical habitat. Nikora (2010) points towards emerged ecologically-oriented research areas including eco-geomorphology, bio-geomorphology, eco-hydrology, eco-hydraulics, environmental hydraulics, biofluidmechanics and ecobiomechanics. Marion et al. (2014) emphasize the role of hydrodynamic interfaces characterized by strong gradients in flow velocity, concentration, temperature and other quantities. Interfacial heterogeneities include individual submerged and emergent plants at the mesoscale and vegetation patches at larger scales. Based on literature studies on the geomorphological influence of vegetation within fluvial systems, Gurnell (2014) states that during the late 20th century research was largely pursued through field observations, but during the early years of the 21st century, complementary field, flume and theoretical/modelling investigations have contributed to major advances in understanding the influence of plants on fluvial systems. She also argues that progress in this field is important not only for improving our understanding of how fluvial systems function but also for informing the assessment, sustainable management and restoration of rivers and riparian systems.

4 Potential of vegetation for reducing pollution concentrations in watercourses

In channel and river systems, the fate of pollutants is largely controlled by transport processes governed by water flow, channel shape, sediment transport and – what is the focus of this paper – vegetation (see e.g. Figure 2). For instance, harmful substances retained on agricultural floodplains can be released during flood events or end up in agricultural products such as meat through grazing (Krüger and Gröngröft 2003). On annual and longer time scales, areas growing aquatic or riparian plants can act as a source or sink of different compounds (e.g., Naiman and Décamps 1997). The seasonal rates of retention, processing and release depend e.g. on the seasonal phenology of the plant species, the processes in the underlying sediment, and the water level (e.g., Carpenter and Lodge 1986). Within shorter time scales the key role of riparian vegetation zones is the reduction of the impact of pollution on the water environment by providing a barrier to and breaking down pollutants before they reach the watercourse (e.g., the use of riparian strips acting as buffer zones along streams) and trapping and processing the compounds that are already in the watercourse.

The influence of vegetation on mass transport processes may be judged based on tracer tests performed over relatively short (e.g., Czernuszenko et al. 1998) or long distances (e.g., Rowiński et al. 2003; 2008). The response to the slug injection of a soluble tracer is assumed to imitate the transport characteristics of a soluble pollutant so understanding how tracers mix and disperse in a stream is essential to understanding the processes of pollution transport. If vegetated areas appear along the river reach the conceptual model used for the analyses might be one-dimensional transient storage model (Czernuszenko et al. 1998; Nordin and Troutman 1980) allowing for the reconstruction of the abrupt leading edges and the long upper tails in the temporal distributions of solute concentrations. The long tails constitute a mathematical manifestation of the filtering ability of the transient storage zones which among others may be created by vegetated zones along the river channels (see Fig. 3). Ensign and Doyle (2005) used similar methodology to examine the effect of in-channel flow obstructions such as vegetation on transient storage and nutrient uptake. In their experiments in highly vegetated rivers, submerged aquatic vegetation accounted for most of the cumulative effect of transient storage on reach-scale retention whereas in less vegetated rivers wooden debris and leaf litter played that role. Transient storage models as the simplest approach but also 2D and 3D mass transport models verified against relevant flume or river data are common (although rarely used in practice) tools allowing to study and understand mixing of pollutants within vegetation in open channels (see Nepf, 1999; Sonnenwald et al., 2017; Tanino and Nepf, 2008).

It seems that the above-mentioned approaches may be used to determine where to apply soil and water bioengineering methods (e.g. EFIB 2015), also known as soft or green engineering techniques, such as establishing vegetated areas along river banks or in side pockets, although further investigations are required to verify the practical applicability. Potential applications include pre-planted vegetation rolls placed at the toe of the bank and living brush mattresses on slopes (see e.g., Studer and Zeh 2014; Eubanks and Meadows 2002). Often vegetated buffer strips are recommended as they are not only beneficial for the wildlife but also for pollution prevention. Other possible applications are related e.g., to two-stage channels consisting of a vegetated floodplain and main channel (reviewed in next section). For estimating the net influence of introduced vegetation, the channel system needs to be studied in a holistic way. Obviously the problem is complex as the planted trees or shrubs filter pollutants, capture and recycle mineral nutrients and increase biodiversity but on the other hand cause shade which may depress and eliminate aquatic plant growth, influence the amount of incoming solar radiation and stream temperature and thus affect stream metabolism (see references in Figure 2).

Figure 3. Narew River (Poland) with the main channel widths of ~ 15-25 m and the natural vegetated zones along the river channels. Photo by A. Bielonko.

5 Two-stage channels as a means of solving management problems in lowland rivers

In riverine environments, both restoration projects and nature-based management commonly attempt to reconnect rivers to their floodplains in order to benefit from the purifying and regulating ecosystem services provided by the riparian zones (see e.g. Figure 2). Such undertakings have been numerous worldwide, traditionally focusing on ecosystem conservation or flood control purposes (Knight et al. 2010). Recently, a channel design based on constructing a confined floodplain on one or both sides of an existing river, stream or ditch has been proposed as an environmentally preferable alternative to the conventional regular re-dredging of the channels for maintaining the conveyance (e.g., Powell et al. 2007; Blann et al. 2009; Västilä and Järvelä 2011). Such two-stage (compound) channels imitate natural lowland streams in that the main channel conveys low flows while floodplains become inundated at higher discharges, providing flood capacity and protection against erosion (Fig. 4). In comparison to an over-wide trapezoidal channel, the narrower main channel has a higher flow velocity during low to medium flows, which decreases the excessive deposition and growth of aquatic vegetation on the channel bed (e.g., Powell et al. 2007). The narrower main channel also results in higher water tables during dry season, improving both the ecological and agricultural resilience to drought. For instance, the flow conditions in the main channel remain suitable for fish while the vegetated floodplain is expected to contribute to enhanced biodiversity and to function as a small-scale ecological corridor. The two-stage channel design allows optimizing the functioning of channels from low to medium and high flows, and can thus enhance the resilience of agricultural areas against challenges related to climate change, climate variability and extreme events.

The two-stage design offers a nature-based solution that uses natural channel processes on a large scale to retain and process suspended sediment and nutrients on the vegetated floodplains (Fig. 4). These processes include deposition of sediment and sediment-bound particles and assimilation of nutrients into plant tissues (e.g., Kiedrzyńska et al. 2008; Västilä et al. 2015). In addition, the wetted surface area of two-stage channels is larger than that of trapezoidal channels, which can lead to enhanced biochemical nutrient processing, including denitrification and phosphorus sorption (e.g., Davis et al. 2015; Mahl et al. 2015). Compared to re-dredging an over-wide trapezoidal channel, construction of a two-stage cross-section prevents underwater excavation, minimizing the disturbance of the channel bed and the associated release of pollutants (e.g., Västilä and Järvelä 2011).

The two-stage approach has been used for single-thread channels with a relatively straight planform that abound in both urban and rural settings because of the past channelization projects (see references in e.g., Västilä and Järvelä 2017). In gently meandering reaches, floodplains can be constructed alternately on the inner bends to create a favourable passage of the flood water. Under temperate climate and predominantly fine sediment, two-stage channels with bed slopes of ~0.001-0.004 have been found relatively stable (e.g., D'Ambrosio et al. 2015; Västilä and Järvelä 2017). Floodplains can grow grasses with scattered shrubs depending on the requirements of the surrounding land use and the ecosystem.

The likely value-added environmental benefits or external costs associated with a given channel design should be taken into account when comparing the design alternatives. Two-stage channels need more space than trapezoidal channels, but the loss of economically productive land is minimized if the floodplain and its bank are counted as part of a buffer strip in the agri-environmental schemes (e.g., Powell et al. 2007). For the three most thoroughly investigated sites in Finland, the construction costs of two-stage channels per excavated soil volume ranged from similar to over 50% lower compared to re-dredging (personal communications, H. Aulaskari, Uusimaa Centre for Economic Development, Transport and the Environment, 19 April 2018; M. Ortamala, Drainage Center of Southern Finland, ProAgria Southern Finland, 23 April 2018; A. Sallmén, Southwest Finland Centre for Economic Development, Transport and the Environment, 22 May 2018). The construction costs per linear channel meter varied from ~10% higher to up to five times higher mainly depending on the designed cross-sectional area to be excavated, which ranged from ~5% larger to up to ~10 times larger compared to the re-dredged reference reaches. Mainly because of the larger volume of excavation, 2-4 times higher construction and total costs per linear channel meter have been reported for US two-stage channels compared to conventional re-dredging when ~100-year floods have been used as design flows (e.g., Powell et al. 2007; Paradis and Biron 2016).

However, the difference in costs markedly decreases if the up to three times longer expected life cycle of two-stage channels is taken into account (Paradis and Biron 2016). To maintain the conveyance capacity, two-stage channels are expected to require lowering of the floodplains less frequently than trapezoidal channels need re-dredging.

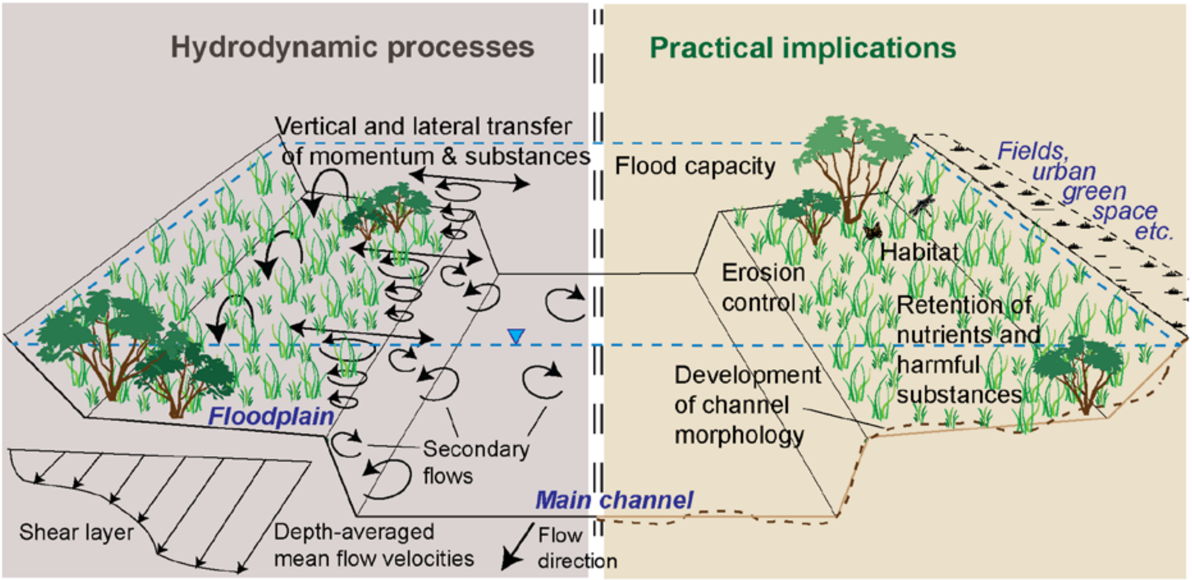

Figure 4. Two-stage channel design offers flood capacity while floodplain vegetation controls sediment deposition and nutrient retention. The associated hydrodynamic processes such as interaction of the main channel and floodplain flows, and the transport and fate of substances, pose research challenges in human –modified urban and rural channels. Note that drawing is not to scale.

Pilot studies have found two-stage channels to decrease the flooding of surrounding agricultural areas, improve water quality, and decrease channel erosion (e.g., Mahl et al. 2015; Västilä et al. 2016). Although the performance of two-stage channels is sensitive to the frequency of floodplain inundation, high retain rates have been observed for the particulate substances (e.g., Västilä et al. 2015; Västilä and Järvelä 2017), resulting in ~10-20% lower concentrations and loads for soluble reactive phosphorus and total phosphorus compared to trapezoidal reaches (Davis et al. 2015; Faust et al. 2017). By contrast, the concentrations of ammonium have been found slightly higher and those of nitrate equal as in reference reaches, but critical gaps in knowledge include the retention and processing at overbank flow events.

The optimal design and management of two-stage channels require improved understanding on how the channel geometry (e.g. the level and width of the floodplain) and complex floodplain vegetation control the transport and fate of suspended sediment and nutrients. Compared to unmaintained vegetated areas that can act as a source of certain nutrient fractions during the wilting period (e.g., Ledford and Lautz, 2015), there is potential that floodplain vegetation in two-stage channels may be maintained to optimize the water quality benefits (see e.g., Västilä and Järvelä, 2017). As an example, by mowing herbaceous vegetation from the floodplain and banks annually at the end of the growing season and collecting the residues, a net decrease in the amount of nutrients in the channel network can be expected through the permanent removal of the nutrients assimilated into these plant tissues (e.g., Kiedrzyńska et al., 2008; Västilä et al., 2015).

6 Concluding remarks

The power of nature-based solutions (NBS) to water management is that, as proven by observations from field sites, the proposed solutions work, although the processes under investigation are often not yet holistically understood. The present paper has introduced selected examples to highlight the use of vegetation in riverine environments to aid us in coping with a variety of water management challenges. At the same time, we realize that there are numerous research gaps that still do not allow us to fully understand critical controls and interconnections even within the given examples. Whether naturally established or introduced, vegetation is a feature of channels affecting both the flow hydrodynamics and transport processes across various spatial scales ranging from the leaf to the reach scale.

A combination of field, laboratory, computational and theoretical research has resulted in great advances in the understanding of the role of vegetation in river systems during the last two decades but still a lot of questions await further investigations. In most cases we have more qualitative than quantitative information. For example, the dynamics of mass transfer between the unobstructed part of the stream cross-section and the transient storage zones created by vegetation patches or floodplains are still poorly understood. Modelling of flow hydrodynamics in vegetated channels requires further development to incorporate a physically solid description of the vegetation at relevant scales. Considering the geometrical complexity of compound channels, our ability to predict the fate of pollutants for such conditions is still inadequate. Using the full potential of vegetation for holistic river management requires truly transdisciplinary research combining hydraulic, hydrological, biochemical, geomorphological and ecological expertise.

As an example of NBS in channel design, two-stage channels consisting of a main channel and a vegetated floodplain offer new potential for ecologically and economically advantageous water management. The available information indicates they increase the resilience of agriculture against floods and droughts while reducing the pollution of water bodies. Cost-efficiency is optimized through the large-scale adoption of natural features and functions and management of the associated natural processes. Taking into account that climate change is expected to increase the loads of nutrients, fine sediment and sediment-bound substances as well as the occurrence of extreme events, the need for efficient nature-based solutions to tackle those problems seems to be even higher. If there is no guarantee of success, we are left to judge whether the prospective benefits to be gained and the costs of not trying to implement nature-based solutions are worthwhile. In our opinion, learning from nature is a means to achieve sustainable uses of the natural environments, including river valleys.

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