Advancing on the promises of techno-ecological nature-based solutions: A framework for green technology in water supply & treatment

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ABSTRACT

Nature-based solutions (NBS) are increasingly proposed for effectively and adaptively addressing societal challenges such as water security and natural disasters. However, NBS that are exclusively reliant on natural processes are not fit-for-purpose for the provision of safe drinking water – some range of built technology is required. There is a wide spectrum of techno-ecological NBS – 'green technologies' – that are fit-for-purpose in the treatment and distribution of safe drinking water. A framework was developed to enable an accurate and transparent description of the 'green' attributes of technology – including green infrastructure – in the water industry. The framework differentiates technology 'greenness' by relatively examining key attributes that may cause environmental impacts across the technology's life cycle through the lens of the environmental setting in which it is applied. In the water industry, green technology can be described by four main attributes: natural-resource basis, energy consumption, waste production, and footprint. These attributes are closely linked and must be considered relative to the biophysical and human environments in which they are applied and the other technologies to which they are being compared. The use of the framework can facilitate techno-ecological decision-making that strives to address diverse stakeholder priorities – including the influence of sociocultural factors on the green technology preferences of individuals, groups, or communities.

KEYWORDS

biofiltration, drinking water, green infrastructure, greenness, natural capital, source water protection

GRAPHICAL ABSTRCT

[Figure 2]

INTRODUCTION

Nature-based solutions (NBS) are increasingly proposed for effectively and adaptively addressing societal challenges such as water security and natural disasters – they have been defined as ‘actions to protect, sustainably manage and restore natural or modified ecosystems … while simultaneously providing human well-being and biodiversity benefits’ (Cohen-Shacham et al. 2016). NBS are growing in popularity globally; however, they are not a panacea to water security, climate change, or any other of society’s grand challenges. The practical implementation of NBS can be challenging because of differences in what should be prioritized and the relative importance associated with those priorities. These challenges were recently highlighted by O’Sullivan et al. (2020) who cautioned that NBS have sometimes been framed too idealistically, leading to undervaluation of biodiversity and unrealistic expectations of the capacity of natural processes to provide the ‘solutions’ that are needed. Recognition that the value and limits of NBS must be understood, so that they are robust and resilient is also growing (Seddon et al. 2021). While rigid differentiation between nature- and technology-based approaches for managing some challenges has been suggested (Mustafa et al. 2019), efforts to describe the synergies between technological and ecological systems are growing (Bakshi et al. 2015) and discussions of NBS that are enhanced by or integrated with technology – ‘techno-ecological NBS’ – are emerging.

In the drinking water industry, the emergence of techno-ecological NBS is evident in industry-wide prioritization of source water protection (SWP) (AWWA 2020) and increasing the promotion of ‘green’ approaches, such as the use of forest management-based strategies and other NBS for source water quality management and climate change adaptation (Ernst et al. 2004; Emelko et al. 2011; McLain et al. 2012; Robinne et al. 2019; Oral et al. 2020). Water managers are increasingly asked to integrate ‘green’ approaches into water supply and treatment practices. Both ‘green infrastructure’ and ‘green technology’ terminologies are used in the water industry. They are also frequently integrated to yield techno-ecological concepts of natural resource-based treatment processes that reflect the technological aspects of natural landscape processes, such as low-cost cascade aeration systems that enhance the air–water transfer of atmospheric gases (e.g., oxygen and nitrogen) and volatile organic compounds (Figure 1).

The use of 'green infrastructure' in the water industry is consistent with its common broader use, which reflects the practical application, preservation, and enhancement of natural capital using a management approach that 'emphasizes the importance of environmental systems and networks for the direct provision of ecosystem services to human populations' (Chenoweth et al. 2018). Here, the term 'natural capital' is also consistent with its broader use and refers to environmental assets that provide people with free goods and services that are often referred to as ecosystem services (Chenoweth et al. 2018). Thus, in the water industry, 'green infrastructure' not only reflects natural capital, but also often encompasses natural resource-based management approaches to achieve engineering (i.e., treatment) targets – this inter-relationship between green infrastructure and natural capital directly aligns with the recognition that there is a spectrum of degrees of 'naturalness' that ranges from environments with minimal human influence to those that have been built (Chenoweth et al. 2018).

In contrast, the use of 'green technology' in the water industry tends to reflect approaches that may be linked to, but not necessarily reliant upon natural capital. Notably, while the 'green' descriptor is frequently used interchangeably with 'sustainable' (Ngo et al. 2016), sustainability analysis typically considers broad impacts on the environment, the economy, and society (Purvis et al. 2019). While life cycle analysis is regularly included in technology evaluation and selection in the water industry, all of the pillars of sustainability are not typically reflected in decision-making – even when they are discussed, trade-offs are of course required because of economic limitations.

The implementation of 'green technologies' in the water industry tends to focus on the treatment processes themselves (Wu et al. 2015; Neoh et al. 2016) and reflects various engineering priorities such as energy efficiency and low waste production, which can be described as ‘green’. These technologies are generally understood to complement and sometimes replace more traditional ‘grey technologies’, which are human-engineered without reliance on the practical application, or prioritization of the preservation or enhancement, of natural capital. This is because ‘green technologies’ are believed to offer environmentally conscientious, energy-efficient, and/ or increasingly economically viable solutions to address challenges such as the need to concurrently protect human health, adapt to climate change-exacerbated threats to water security, and reduce the environmental impacts of water treatment and distribution (Gill et al. 2007; Emelko et al. 2011; Ngo et al. 2016).

Despite the widespread use of the term ‘green’ across the broader water sector and within the drinking water industry specifically, there is no consistently applied definition or framework for what constitutes ‘green technology’ or which aspects of ‘greenness’ are valued. A framework for describing the ‘green’ attributes of the broad range of technologies – including natural capital – relevant to the water industry is needed, as these attributes dictate how technologies are prioritized relative to others, and whether they are considered ‘green’ at all. Such a framework will also enable stakeholders to better communicate the technical and engineering aspects of technology approaches that best align with community and individual sociocultural values, beliefs, and attitudes. In addition to the challenges associated with the lack of a framework to describe the ‘green’ attributes of technologies or infrastructure options for meeting broader water industry objectives, it is important to recognize that ‘green technology’ has not had much uptake in the drinking water industry, as compared to other segments of the water sector.

[Figure 1]

The drinking water industry is necessarily conservative and somewhat averse to real or perceived risks to public health that may be attributed to innovative technologies that are unproven, or require operational shifts for control, relative to conventional technologies. These challenges have been underscored for decades in the lack of widespread uptake of biological treatment processes because of concerns regarding health risks that might be attributable to microbially mediated treatment, difficulties in operation, and unlikely regulatory approvals (Brown et al. 2015). While such concerns are misplaced (Brown et al. 2015), well-known events such as the 1993 Milwaukee cryptosporidiosis outbreak, in which more than 50 people died and more than 400,000 people became ill (EPA 1998), serve as stark reminders of the importance of public health protection through the provision of safe drinking water as the industry's paramount objective. Thus, any shifts in the fundamental way in which drinking water is treated and distributed must be approached with clarity in purpose and confidence that public health protection is not compromised.

Consistent with that recognition, it has been recently emphasized that the good science that is needed for meaningful advancement of sustainability goals such as the development of NBS requires clearly defined terminology rather than reliance on vague metaphors (Vos et al. 2007; Aronson 2011). Fortunately, the promises of green technology can be advanced in the water supply and treatment sector with sound initial foundations in scientific and engineering principles. These begin with the foremost recognition that all drinking water treatment technologies must be effective for the protection of public health – these targets must be achievable in regular practice, not only at idealized conditions. Thus, any green technologies that would be considered for use within the drinking water industry must be 'fit-for-purpose' for the protection of public health, meaning that they meet or exceed the drinking water treatment performance expectations and regulatory criteria that they are intended to address. For this reason, NBS that are exclusively reliant on natural processes are not fit-for-purpose for the provision of safe drinking water – some range of built technology is required. For example, recent work has demonstrated that viruses can be present in high-quality groundwater supplies and require substantial treatment even in situations where it has been historically believed that no treatment is required (Borchardt et al. 2012; Emelko et al. 2019). Additional built technologies would be required to indicate water safety and ensure its safe distribution. In contrast, it will be demonstrated herein that there is a wide spectrum of techno-ecological NBS – 'green technologies' – that are fit-for-purpose in the treatment and distribution of safe drinking water.

Using the imperative fit-for-purpose criterion as a starting point, a framework is developed herein to enable an accurate and transparent description of the 'green' attributes of technology – including green infrastructure – used in the water industry. It differentiates technology 'greenness' by relatively examining key attributes that may cause environmental impacts across the technology's life cycle through the lens of the environmental setting in which it is applied. It is proposed that the framework developed herein can contribute to the development of more comprehensive techno-ecological NBS by providing clear and accurate description of the 'green' attributes of technology options for the water industry, as well as a framework for their relative comparison, thereby facilitating techno-ecological decision-making that strives to address diverse stakeholder priorities. While a cost–benefit analysis would be essential for the ultimate selection of a treatment technology, the associated analysis is beyond the scope of the present work, which is focused on framework development. Microbiologically mediated biofiltration technologies are presented as obvious and effective examples of underutilized green technology opportunities in the drinking water industry. They are used to demonstrate that there is a wide spectrum of techno-ecological NBS – 'green technologies' – that are fit-for-purpose in the treatment and distribution of safe drinking water. Finally, two case studies are briefly presented to highlight the benefits of green technologies in drinking water treatment, the use and limitations of the developed framework, and the influence of sociocultural factors on green technology preferences of individuals, groups, or communities.

A framework for evaluating technology greenness. The most widely recognized 'green' technologies in the broader water industry are likely found in stormwater management and include low-impact development practices such as vegetated rooftops, roadside plantings, absorbent gardens, and other measures. They are designed to mimic natural hydrological processes and landscape features to reduce stormwater flows and improve stormwater quality by filtration, adsorption, or other means before discharging to surface and groundwater supplies (Gill et al. 2007). In contrast, reductions in energy consumption and waste production are common green foci of wastewater treatment (Wu et al. 2015; Neoh et al. 2016). Here, many of the ‘green’ technologies include biological treatment processes that remove or neutralize pollutants or other target compounds, often to yield less toxic or non-toxic materials at a lower cost than technologies that are not biologically mediated (Delgadillo-Mirquez et al. 2016). Membrane bioreactors are one such example; they combine biological, secondary, and tertiary wastewater treatment in one unit, thereby reducing carbon footprint relative to more conventional processes (Smith et al. 2012; Neoh et al. 2016). Groundwater treatment at contaminated sites increasingly involves the implementation of green in situ bioremediation technologies to reduce energy costs and largely eliminate excavation and incineration costs common to ex situ ‘pump and treat’ approaches (Haritash & Kaushik 2009; Wang & Chen 2009).

While the use of the term ‘green technology’ is less common in the drinking water industry, its broader emergence is inevitable. For example, nature-based coagulants produced from renewable resources (Teixeira et al. 2017) are regularly referred to as ‘green’ technologies. Reductions in energy consumption and waste production are already common goals in the industry, and biological filtration processes that ‘work for free’ are referred to as either ‘natural’ or ‘green’ treatment technologies – their use in drinking water treatment plants (DWTPs) is increasingly described as ‘by design’ rather than de facto (Basu et al. 2015; Brown et al. 2015; Petrescu-Mag et al. 2016; Kirisits et al. 2019). At the regional landscape scale, sophisticated watershed management techniques focused on maintaining high-quality source water are often relied upon to avoid the construction of costly filtration plants and are being increasingly implemented for the mitigation of climate change-exacerbated landscape disturbances such as severe wildfires (Emelko et al. 2011; Cristan et al. 2016; NAS 2018; Robinne et al. 2019). Indeed, interest in the promise of 'green tech' is growing across the water industry and to the general public who increasingly value it, and contribute to promoting it, as evident from public acceptance and willingness-to-pay for green tech implementation for water resource management and treatment (Newburn & Alberini 2016; Brent et al. 2017; The Water Institute 2017).

As highlighted by the examples above, green technologies in the field of drinking water supply and treatment have been most frequently described as 'green' based on three key attributes or factors that are broadly associated with reducing environmental impacts: (1) nature- or natural resource-based origin (Spatari et al. 2011; Keeley et al. 2013; Liu et al. 2017), (2) relatively low-energy consumption (Wu et al. 2015; Ngo et al. 2016), and (3) relatively low waste production (Neoh et al. 2016; Ngo et al. 2016). Physical footprint is further proposed as a fourth key factor that contributes to technology greenness in the water supply and treatment field. The physical footprint of watershed management activities such as forest harvesting, DWTP construction, and associated residuals management infrastructure has the potential to adversely impact human health and ecosystems through fossil fuel emissions, destruction of sensitive habitat, habitat fragmentation, and biodiversity decline, to name a few. The impacts of physical footprint are generally understood to be linked to environmental impacts because they initiate a chain reaction of environmental impacts that can be broadly characterized as human health and ecosystem damage footprints. Thus, physical infrastructure footprints must be included in any evaluation of greenness to reflect these cumulative environmental impacts. Accordingly, a framework for characterizing water industry technology greenness based on four main key technology attributes is proposed. As illustrated in Figure 2, they are (1) natural-resource basis, (2) energy consumption, (3) waste production, and (4) footprint. Various fit-for-purpose drinking water treatment technology examples considered for application in the same environmental setting are presented in Figure 2 to demonstrate how the framework developed herein might be used. A more detailed description of the technology attributes that contribute to greenness follows, and opportunities to link the framework to more comprehensive evaluations of trade-offs between technological NBS in the water sector are briefly discussed.

[Figure 2]

Natural resource-based technology incorporates renewable or non-depletable materials that are either sourced from the surrounding environment or utilize natural processes to achieve treatment. Several of these technologies, such as biofiltration and solar disinfection, are intrinsically passive and do not require additional chemical inputs (McGuigan et al. 2012; Basu et al. 2015), which in turn contributes to their low-energy consumption and waste production. Some natural coagulants, such as moringa seeds, have been described as ‘green’ (Teixeira et al. 2017); however, despite being natural resource-based, coagulants that are not sourced from the surrounding environment must still be transported to treatment facilities for use. As such, proximity of the material source and site of use should be considered, and those materials whose haulage has significant environmental costs should not be considered green in this context. Beyond drinking water treatment, natural resource-based technologies also include approaches such as forested watershed management practices that are applied for managing drinking water source quality (i.e., SWP technologies) (Cristan et al. 2016; NAS 2018).

Energy consumption is often cited as an important and highly valued aspect of technology greenness (Bolla et al. 2011; Ngo et al. 2016; Barcelos et al. 2018). Energy-efficient technologies often offer a co-benefit of reduced long-term operational costs; this is mainly attributed to their passive nature and dependence on non-energy-intensive processes (e.g., naturally occurring biological activity) to achieve treatment goals (Wu et al. 2015; Neoh et al. 2016). Processes that require high energy inputs to operate, such as ozonation and UV disinfection, are relatively less green. High energy expenditures can also result from water conveyance through pumping. Therefore, the elevation of a DWTP site is an important design consideration and can impact overall energy consumption (Randtke & Horsley 2012). For example, the need for pumping may be reduced if plant configuration follows natural topography. Even less major design choices, such as the selection of flocculator type, can also result in energy consumption changes. Although they offer substantively more operational control, mechanical flocculators require higher energy inputs compared to hydraulic mixers and are therefore less green in this respect (Crittenden et al. 2012). These types of decisions underscore the trade-offs that must be clearly articulated and considered in the selection and design of water treatment technologies.

Waste produced during water treatment has the potential to cause adverse environmental impacts as a result of its quantity and/or toxicity; thus, it is an important contributor to technology greenness. Treatment processes that produce large amounts of waste products, such as coagulation (i.e., sludge) and membrane technologies (i.e., brine, backwash, and residuals), can be generally considered as less green. However, some chemical additions may reduce waste production, such as the addition of polymers to alum or ferric chloride coagulants (Randtke & Horsley 2012). Membrane technologies produce wastes in the form of backwash and cleaning-in-place residuals. Cleaning-in-place can increase both waste quantity and toxicity because it involves chemicals such as hypochlorite, citric acid, and caustic soda (Randtke & Horsley 2012). Additionally, waste in the form of emissions implies that air stripping processes may be relatively less green due to exhaust fume emissions (Randtke & Horsley 2012).

The physical footprint of infrastructure contributes to water treatment technology greenness because it can also readily result in adverse environmental impacts. Processes that require a large footprint, such as horizontal flow basins and slow sand filters, will tend to be less green in this respect. Additional infrastructures – such as residuals management plants, chemical storage, and pumping infrastructure – also increase footprint. This highlights the interplay between green attributes; for example, high waste-producing processes typically require the construction of a residuals management plant, which increases the footprint and contributes to the reduction in greenness of the process. Additionally, chemically-assisted processes require chemical storage infrastructure on-site, which increases footprint and can also increase energy consumption through the need for heating, ventilation, and air conditioning (HVAC) systems and hydraulic lifting (Randtke & Horsley 2012). While this discussion generally suggests that larger environmental footprints are more disruptive, infrastructure footprints cannot be considered in a vacuum as they are intrinsically tied to the environmental setting in which they are to be applied. Thus, the inclusion of physical footprint in an evaluation of technology greenness necessarily requires consideration of the impacts to both the biophysical and human environments within that setting. For example, the optimal location and extent of DWTP footprint is dependent on several factors including distance from source water, elevation, and available space. Other environmental factors such as the presence of important fish habitat in a natural waterway receiving discharge from the waste stream of the DWTP also require consideration, however; as a result, limiting waste production may be ultimately prioritized in this setting to limit adverse impacts to biodiversity in the natural waterway.

The four attributes of water industry technology that impact greenness (natural-resource basis, energy consumption, waste production, and footprint) are closely linked and must be considered relative to both the specific environmental settings in which they are applied and the other technologies to which they are being compared. Thus, life cycles and supply chains should also be considered. Life cycle analysis (LCA) involves the evaluation of the environmental impacts of a product, process, or service over all of its stages of the life cycle; thus, it includes the environmental impacts of all relevant life cycle aspects, which may include raw material extraction or processing, manufacturing, distribution, use, regeneration, recycling, and final disposal (Ayres 1995). For example, processes using activated carbon materials are generally less green since they require high energy inputs during the production and regeneration stages. Rigorous LCA will thus reflect several aspects of supply chain analysis including how risks can be reduced by bypassing certain suppliers and/or processes and reduce unnecessary inventories. Shipment of materials over long distances is a simple example of the importance of supply chains in evaluating technology greenness because of associated indirect increases in energy consumption and waste production via increased emissions. Co-benefits associated with certain technologies should also be considered. For example, some of the waste products from water treatment processes may be reused for various purposes such as land application, composting, cement manufacturing, and road subgrade (Randtke & Horsley 2012; Márquez et al. 2019). While it could be argued that an absolute, quantitative index could be developed to measure the 'greenness' of a given technology, this is not proposed herein because such a metric would require assumptions regarding both the relative value of the 'greenness' attributes and the impacts of the technology on the biophysical and human environments relevant to the setting where it is to be applied.

It is at this point of greenness evaluation that the inter-connectedness of the choice between technology options and their relative greenness becomes iterative and complicated. The evaluation becomes iterative because of the chain reaction of environmental impacts that is initiated by these decisions, as demonstrated above. Approaches for characterizing these impacts are available, however. For example, they can be broadly characterized as human health and ecosystem damage footprints. Comprehensive damage assessments and LCAs have recently been applied to harmonized resource-based footprints (i.e., energy, material, land, and water) to demonstrate that resource footprints provide good proxies for environmental (i.e., human health and ecosystem) damage (Steinmann et al. 2017). Evaluations of technology greenness and ultimate implementation are also complicated, however, because of trade-offs between techno-ecological services. For example, the fail-safe provision of safe water may conflict with other techno-ecological services such as waste minimization. Conflicts may result from divergent sociocultural preferences among individuals, communities, or other stakeholders that are differently impacted by the techno-ecological services that can be provided by the technology that is ultimately implemented (King et al. 2015). Frameworks to characterize trade-offs in ecosystem services that reflect biophysical constraints and divergent values have been developed (Cavender-Bares et al. 2015; King et al. 2015) and offer further opportunities to advance on the promises of techno-ecological NBS in the water sector. While the explicit recognition of differences among stakeholder values and preferences is integral to ensuring that techno-ecological NBS achieve intended impacts, strategies for navigating such conflicts and evaluating the implications of trade-offs impacting biophysical and human environments are beyond the scope of the present work.

To illustrate the utility of the greenness framework shown in Figure 2 for identifying, naming, and describing the ‘green’ attributes of treatment technology that may be valued in certain situations, the relatively simple selection of fit-for-purpose surface water treatment systems can be explored in two distinct environmental settings: remote and urban. Notably, technology typologies are excluded from the discussion; only key green attributes are discussed. A remote community may be challenged by accessibility and unreliable supply chains, unreliable power supplies, and institutional memory and staff retention (Hall 2018; Chattha 2020) – these challenges may not be as significant in an urban environment. In contrast, while available space and footprint may not be an issue in a rural or remote area, an urban community may be constrained by the available space. Despite these differences, both communities are likely challenged by competing demands between finances and treatment capacity, resilience, and redundancy, as well as operational burden. The remote community may, therefore, value technologies that are natural resource-based and easy to maintain, and reduce energy consumption and waste production as compared to those that reduce physical footprint. Natural resource-based technologies would address accessibility challenges as fewer components and chemicals would need to be sourced externally for operation, maintenance, and repairs, thereby reducing often high transportation costs. Additionally, natural resource-based technologies tend to be passive and therefore typically have lower energy demands and are associated with lower operational burdens and capacities than non-passive technologies. Thus, natural resource-based technologies may help to mitigate the challenges presented by power supply reliability, institutional memory and staff retention, finances, and operational burden and capacity. Technologies that generate relatively less waste might be prioritized, as the management of waste and hazardous substances add to both the operational burden and technical capacity requirements. Conversely, footprint may not be prioritized, as the small population and remote location imply lower water demand and more available space, respectively.

In contrast, an urban centre may value footprint, energy conservation, and low waste production as important green factors, with less importance placed on the passive quality of natural resource-based technologies. Technologies designed to reduce the footprint may minimize the environmental impact caused by the extent of infrastructure required to meet high production demands. Competition for financial resources may encourage a focus on reducing energy consumption, as this often represents a large fraction of a water utility’s operational costs (Crittenden et al. 2012). Additionally, limiting waste production reduces the need for additional waste management infrastructure, further reducing footprint and energy demands.

It should be underscored that the framework illustrated in Figure 2 constitutes a simple organizational structure to identify, name, and describe the ‘green’ attributes of the broad range of technologies – including natural capital – relevant to the water industry to enable stakeholders to clearly and accurately communicate the technical and engineering aspects of technology approaches that best align with their individual or community sociocultural values, beliefs, and attitudes. The framework necessarily requires consideration of the environmental setting in which the technology is to be applied and assessment of the technology’s life cycle within that setting to provide structured discussion regarding techno-ecological trade-offs as a first step in facilitating techno-ecological decision-making that strives to address diverse stakeholder priorities.

Biofiltration as a key example of green technology for drinking water treatment. While minimizing waste production and energy consumption are somewhat obvious strategies for increasing the greenness of drinking water treatment and distribution approaches, the incorporation of natural resource-based green technologies as techno-ecological NBS is at the precipice of a revolution in the water industry. Biofiltration processes are arguably the most obvious and effective examples of underutilized green technology opportunities in the drinking water industry. They have not yet experienced as much uptake as conventional treatment technologies in some regions due to concerns regarding the health risk attributable to microbially mediated treatment, difficulties in operation, and unlikely regulatory approvals (Brown et al. 2015). However, such concerns are misplaced (Brown et al. 2015; Kirisits et al. 2019). Biofiltration technologies differ from conventional filtration in that biological activity is promoted and maintained within and on filter media – in-built vessels or naturally in the subsurface – to remove suspended particles (including pathogens) and dissolved organics from the water phase (Basu et al. 2015; Kirisits et al. 2019). Biofiltration technologies harness natural microbial processes, do not generally require additional energy inputs, and do not typically produce significant waste relative to other treatment processes designed to achieve the same objectives (Fowler & Smets 2017). However, when biofilters are operated passively at low flow rates, they often require large footprints to ensure targeted yields of drinking water. Notably, there are many types of biofiltration technologies; although they can also be considered green, they fall along a spectrum of greenness. Some common types of biofiltration used in drinking water treatment include:

- Classical biofiltration: biofiltration in an otherwise conventional DWTP (preceded by coagulation/flocculation/sedimentation);
- Classical direct biofiltration: biofiltration preceded by coagulation/flocculation;
- Biofiltration with pre-ozonation: biofiltration, either classical or classical direct, preceded by ozonation;

- Slow sand filtration (SSF): passively operated filtration through sand media; and
- Riverbank filtration (RBF): induced surface water infiltration to bankside abstraction wells.

[Figure 3]

The greener biofiltration technologies in this spectrum are generally operated passively and take advantage of natural processes in the surrounding environment to achieve treatment goals; such technologies include SSF and RBF. Combinations of biofiltration processes – such as roughing filters, managed aquifer recharge and storage, and reservoir storage – may provide additional treatment and can increase operational control, but increase footprint and energy requirements. As well, processes such as classical biofiltration indirectly contribute to waste production due to pre-treatment by coagulation and clarification processes prior to filtration; it is also more energy-intensive because it is not passively operated and requires backwashing to remove accumulated solids. Biofiltration technologies preceded by ozonation are especially effective in removing organics, but less green because of the energy-intensive nature of ozonation.

While not reflected in Figure 3, filter media are also an important factor contributing to biofiltration technology greenness. Biofiltration technologies employing a form of granular-activated carbon are intrinsically less green because of the high energy required to manufacture adsorptive media. The physical and chemical manufacturing processes involve carbonization, or conversion of the raw material to a char, and activation or oxidation to develop the internal pore structure – temperatures of 800–900°C are needed for the activation process (Edzwald 2011). Readily available filtration media, such as anthracite coal and sand, are more green options, especially when they can be locally sourced.

Greenness assessment of drinking water treatment systems. In addition to the relative greenness ranking of biofiltration technologies, common drinking water treatment systems may also be relatively ranked according to their greenness. Figure 4 presents a relative ranking of common drinking water treatment system configurations; however, actual evaluation of technology greenness is case-specific, as discussed previously. Generally, treatment systems using biofiltration, such as classical biofiltration, SSF, or RBF (all followed by chlorine-based disinfection), are among the greenest treatment approaches relative to conventional (i.e., coagulation, flocculation, sedimentation, non-biological filtration, and chlorine-based disinfection) treatment because they are natural resource-based, require relatively lower energy inputs, and produce relatively less waste. It is important to note, however, that some key trade-offs exist between less energy-intensive technologies and operational control. Although energy-efficient technologies are generally more green, they often do not offer as much operational control as more conventional treatment systems because of factors such as the lack of design and operational (i.e., typically mechanical) controls over system components such as flow rates or microbially mediated degradation of contaminants. As such, some green technologies are less able to respond to sudden changes in source water quality, which can potentially compromise public health protection – this issue requires further investigation to ensure resilient treatment, especially in environments vulnerable to climate change-exacerbated landscape disturbances such as wildfires (Emelko et al. 2011; Stone et al. 2011).

[Figure 4]

Applying the green technology framework to case studies. Two DWTP design case studies presented below highlight benefits of green technologies in drinking water treatment, use and limitations of the developed framework, and influence of sociocultural factors on the green technology preferences of individuals, groups, or communities.

CASE 1) Biofiltration to treat high ammonia groundwater for a small system (EPA 2014)

The implementation of an innovative biofiltration system for a small drinking water system in Iowa highlights the promise of green tech to achieve a technologically fit-for-purpose treatment design. The

EPA conducted pilot-scale and full-scale studies for implementation of a novel biofiltration treatment technology in Palo, Iowa, which did not have centralized water treatment prior to 2008. Palo is a small town of just over 1,000 people, with limited technical capacity as the utility relies solely on one treatment plant operator who is also responsible for other municipal operations such as snow plowing and landscaping. Source water for the DWTP is groundwater characterized by high ammonia and iron concentrations and is low in dissolved oxygen.

Breakpoint chlorination is a common treatment option to address high ammonia concentrations (Edzwald 2011). However, the chlorine dose required to adequately oxidize ammonia and nitrogen species would be excessive for a small system. As an innovative alternative to breakpoint chlorination to treat ammonia-rich groundwater, the EPA designed a novel biofiltration treatment system. The treatment system, patented by the EPA, consists of aeration contactors, blowers, and dual media filters, with added chemical feeds of phosphate, chlorine, and sodium hydroxide. An aeration contactor was needed to ensure sufficient oxygen required for nitrification, as the groundwater source was low in dissolved oxygen. The main goal of the treatment plant is to remove ammonia and iron, which was consistently achieved in both the pilot- and full-scale systems.

An evaluation of all four green attributes discussed herein was not reported, as this is often not possible due to limited time or resources. Nonetheless, the biofiltration system may be described as green because it is natural resource-based and requires substantially less chemical input compared to breakpoint chlorination, the alternative treatment option. Because of these green aspects, the biofiltration system is operationally less demanding and thus also matches the operational (i.e., operator training and treatment processes supervision) capacity of a smaller system. Most importantly, the treatment system produces drinking water that consistently meets the regulatory targets set for contaminants of concern, thereby ensuring a fit-for-purpose treatment design for the protection of public health.

CASE 2) RBF for pre-treatment of municipally and industrially impacted surface water in Louisville, Kentucky (Ball 2012)

Louisville Water Company in Louisville, Kentucky, implemented an RBF system as pre-treatment to address concerns of microbial contamination possibly not addressed by the city's conventional treatment system. The city is reliant upon the municipally and industrially impacted Ohio River for drinking water. The Ohio River is consistently ranked as the most polluted in the United States, with an estimated 30 million pounds of toxic chemicals illegally dumped into its waters each year (Kuhlman 2019). Louisville is a relatively large, established city and thus has limited available space. The Louisville Water Company served a population of 764,769 in 2019 (EWG 2019) and has a high level of technical capacity.

To address microbial contaminant concerns, the city launched a project to investigate the implementation of an RBF system on the Ohio River. The RBF system would also address challenges with water main breaks in the distribution system due to large variations in water temperature. As part of the project, the city investigated drilling options for the tunnel and wells. Ultimately, the city decided on a completely underground RBF system that includes a tunnel and collector wells. Although an above-ground system would have been much easier and less expensive to construct, the public did not want any above-ground structures to impact the aesthetic value of the Ohio River. Additionally, while vertical wells would be much easier to maintain than collector wells, collector wells were chosen due to the possibility for construction complications with vertical wells. Additionally, the city's high technical capacity was able to address the increased maintenance requirements associated with collector wells.

Similar to the previous case study in Palo, information detailing the green attributes of the treatment process was not reported. Nonetheless, it is clear that Louisville's RBF system is relatively natural resource-based, as it utilizes the natural subsurface to eliminate taste and odour compounds, provides an additional barrier for waterborne pathogen removal, and creates a stable water temperature that results in fewer main breaks in the distribution system. Despite this, the physical footprint of the RBF system is relatively large due to the footprint needed during the construction of an underground system.

This case study highlights the importance of discussing stakeholder priorities accurately and transparently to achieve fit-for-purpose and socioculturally appropriate treatment design. Louisville Water Company considered stakeholder priorities after ensuring treatment design met regulatory requirements to uphold the protection of public health. While the public held sociocultural values that aligned with preserving the aesthetic quality of the Ohio River, the Louisville Water Company sought to minimize risk of construction complications. These needs were ultimately met by the selection of an underground RBF system equipped with collector wells.

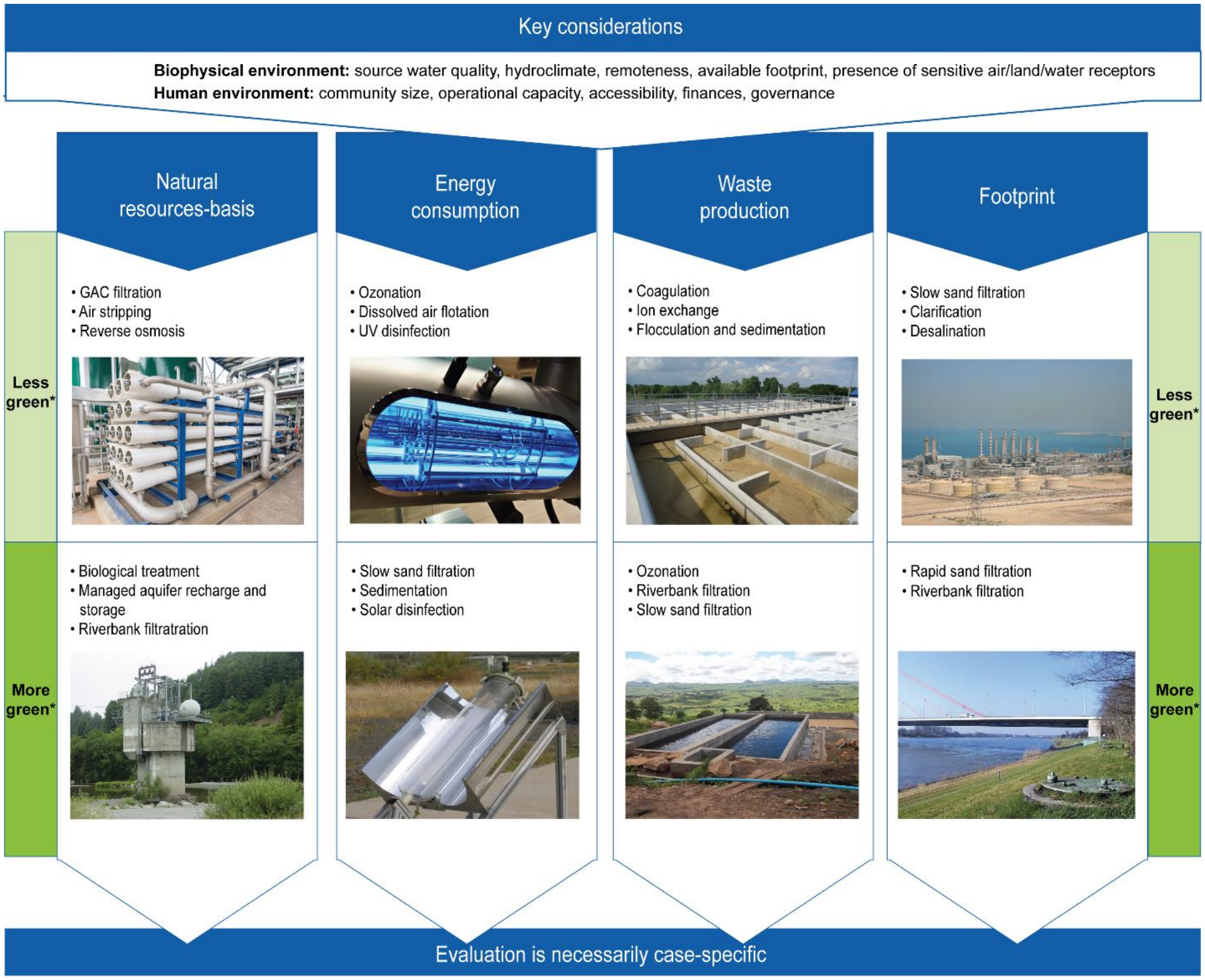
CONCLUSIONS

The main conclusions of the analysis presented herein are briefly summarized below. They are:

1. While the concept of green technology is widely recognized, its meaning varies considerably. In the water industry, green technology can be described by four main attributes: natural resource-basis, energy consumption, waste production, and footprint.
2. The greenness of a technology can be evaluated with respect to each of the above-mentioned attributes and is therefore relative to both the environmental setting and the other technologies to which it is being compared.
3. The paramount objective of treatment is public health protection and thus technologies must be fit-for-purpose with respect to their use and meet regulated performance targets regardless of their greenness.
4. Operational control is often reduced as the greenness of a technology is increased.

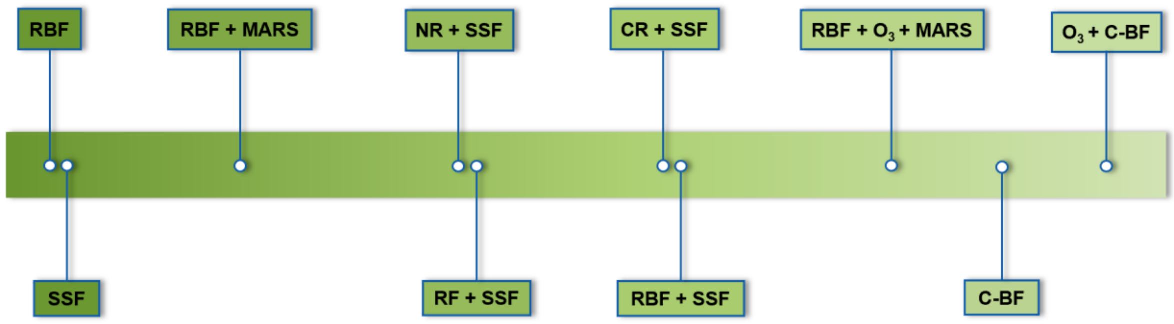
5. In the water sector, environmental setting (i.e., location-specific factors including hydroclimate, sensitive habitat(s), water quality, temperature, etc.) is a critical consideration that can limit the practical application of some technologies.
6. Biofiltration processes are arguably the most obvious and effective examples of underutilized green technology opportunities in the drinking water industry. These technologies can be differentiated along a spectrum of greenness.
7. Prioritization of the factors contributing to technology greenness varies based on sociocultural considerations of individuals, groups, and communities, as identified based on their collective knowledge, values, attitudes, beliefs, feelings, and behaviours.
8. The framework developed herein enables an accurate and transparent description of the 'green' attributes of technology – including green infrastructure – used in the water industry. It differentiates technology 'greenness' by relatively examining key attributes that may cause environmental impacts across the technology's life cycle through the lens of the environmental setting in which it is applied. It can contribute to the development of more comprehensive techno-ecological NBS by providing a clear and accurate description of the 'green' attributes of technology options for the water industry, as well as a framework for their relative comparison, thereby facilitating techno-ecological decision-making that strives to address diverse stakeholder priorities.

Figure 1: Low-cost cascade aeration system that enhances the air-water transfer of atmospheric gases (e.g. oxygen, nitrogen) and volatile organic compounds. The term ‘green technology’ commonly invokes images of such technologies; however, green technologies span a broad spectrum of treatment typologies.



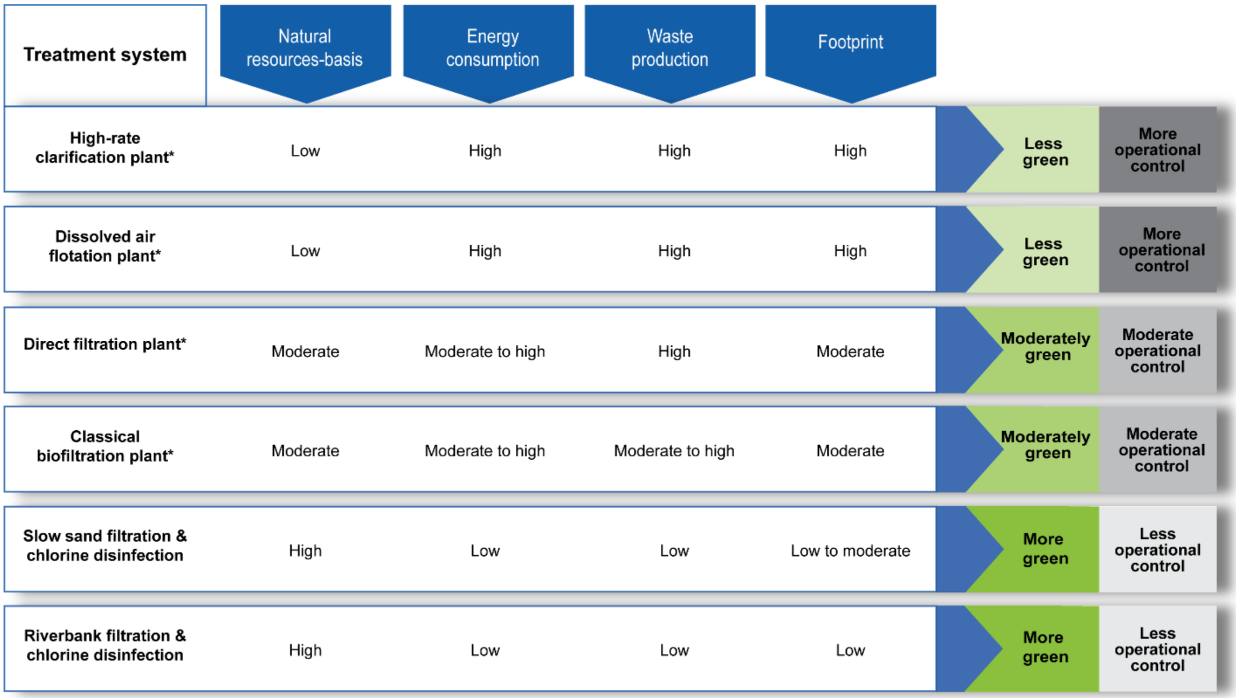
*Technologies are assumed to be fit-for-purpose. Whether or not technologies are green is not absolute; they are more or less green relative to one another.

Figure 2: Framework for the evaluation of green attributes of water supply, treatment, and distribution technologies. (Photo credits bottom row from left to right: Humboldt Bay Municipal Water District; Reprinted from Nalwanga et al. (2014), with permission from Elsevier; Mount Carmel Ltd; DVGW, Water Technology Center, Karlsruhe).



RBF	Riverbank filtration
SSF	Slow sand filtration
MARS	Managed aquifer recharge and storage
NR	Natural reservoir
CR	Constructed reservoir
RF	Roughing filtration
O_3	Ozonation
C-BF	Classical biofiltration

Figure 3: Greenness spectrum of biofiltration technologies for drinking water treatment.



Treatment system	Natural resources-basis	Energy consumption	Waste production	Footprint		
High-rate clarification plant*	Low	High	High	High	**Less green**	**More operational control**
Dissolved air flotation plant*	Low	High	High	High	**Less green**	**More operational control**
Direct filtration plant*	Moderate	Moderate to high	High	Moderate	**Moderately green**	**Moderate operational control**
Classical biofiltration plant*	Moderate	Moderate to high	Moderate to high	Moderate	**Moderately green**	**Moderate operational control**
Slow sand filtration & chlorine disinfection	High	Low	Low	Low to moderate	**More green**	**Less operational control**
Riverbank filtration & chlorine disinfection	High	Low	Low	Low	**More green**	**Less operational control**

* plant refers to an otherwise conventional treatment setting

Figure 4: General greenness assessment of common drinking water treatment typologies.

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