Integrated Environmental Assessment and Management — Volume 00, Number 00—pp. 1–9
Received: 28 November 2020 | Returned for Revision: 7 January 2021 | Accepted: 16 May 2021

Special Series

From landfills to landscapes—Nature-based solutions for water management taking into account legacy contamination

Sarah E. Hale,[1] Marja S. Folde,[2] Unni H. Melby,[3] Elisabeth U. Sjødahl,[4] Andreas B. Smebye,[1] and Amy M. P. Oen[1]

[1]*Norwegian Geotechnical Institute, Oslo, Norway*
[2]*ALT. arkitektur as, Oslo, Norway*
[3]*Skien kommune, Skein, Norway*
[4]*The Oslo School of Architecture and Design, Oslo, Norway*

EDITOR'S NOTE:

This article is part of the special series "Incorporating Nature-based Solutions to the Built Environment." The series documents the way in which the United Nations Sustainable Development Goal (SDG) targets can be addressed when nature-based solutions (NBS) are incorporated into the built environment. This series presents cutting-edge environmental research and policy solutions that promote sustainability from the perspective of how the science community contributes to SDG implementation through new technologies, assessment and monitoring methods, management best practices, and scientific research.

Abstract

Nature-based solutions (NBS) can be used in combination with the reopening of piped rivers to support area development. In certain cases, piped rivers can run through disused landfills. This presents a complicating factor because landfills provide the possibility for river water to be contaminated by waste. In Skien municipality, close to Oslo, Norway, NBS are being considered as part of a potential reopening of the Kjørbekk stream. A 4-km stretch of the stream is contained in an aging pipe infrastructure that is buried under two disused landfills. The pipe infrastructure does not have the physical capacity to cope with an increase in precipitation brought about by current climate change, and in certain areas, the pipe has started to leak. This means that surface water runoff that cannot be accommodated by the pipe, as well as water that leaks from the pipe, can become contaminated by the waste in the disused landfill. Furthermore, the water can be transported with the stream course to the final recipient, taking the contamination with it. Reopening the stream and providing new water pathways can alleviate these problems, but it must be carried out so that contamination is not allowed to spread. This case study reveals how certain NBS that focus on reducing the amount of water in contact with pollutants, reducing the amount of particle spreading, remediating contaminated water, and remediating contaminated soil could be implemented at the site and function as a catalyst for an incremental city development. *Integr Environ Assess Manag* 2021;00:1–9. © 2021 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals LLC on behalf of Society of Environmental Toxicology & Chemistry (SETAC).

KEYWORDS: Daylighting, Landfill, Nature-based solutions, Pollution, Water quality

INTRODUCTION

Societal challenges in river landscapes are often water related, both in terms of water quantity (flooding and drought) and water quality (pollution). Climate change can additionally exacerbate these challenges. Suitable urban water management systems are needed in order to adapt to climate change and achieve resilient cities and urban infrastructure. The United Nations Sustainable Development Goal 11 calls on planners to "Make cities inclusive, safe, resilient, and sustainable" (https://sdgs.un.org/goals). Target 11.7 further reminds us to provide by 2030, "universal access to safe, inclusive and accessible, green and public spaces…." The incorporation of nature-based solutions (NBS) into the built environment can help to address this goal and target (United Nations, https://sdgs.un.org/goals).

Correspondence Sarah E. Hale, Norwegian Geotechnical Institute, Sognsveien 72, 0855, Oslo, Norway.
Email: sah@ngi.no

Published 21 May 2021 on wileyonlinelibrary.com/journal/ieam.

The term NBS has been extensively defined (Escobedo et al., 2019; Pagano et al., 2019; T. C. Wild et al., 2017), discussed (Albert et al., 2019; Gómez Martín et al., 2020; Reynaud et al., 2017) and conceptualized (Albert et al., 2020; Raymond et al., 2017), and many parallels have been drawn with the earlier terms "green-blue infrastructure" (Dorst et al., 2019) and ecosystem-based adaptation (Dorst et al., 2019). To this end, the term NBS can be viewed as all-encompassing, effectively collecting the others and widening the applicability domain of this discipline. The European Commission defined NBS in 2015, as "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social, and economic benefits and help build resilience" (European Commission, 2015) and highlighted the commonality of many of the definitions of NBS, that is, they provide the primary sought-after benefits as well as secondary co-benefits. The co-benefit aspect has also been reiterated by the recent addition of biodiversity requirements to the NBS definition from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In this definition, NBS are expected to benefit biodiversity and support delivery of a range of ecosystem services (European Commission, 2019).

According to the Intergovernmental Panel on Climate Change (IPCC), the frequency and intensity of heavy precipitation events have increased and will continue to increase in North America and Europe (Intergovernmental Panel on Climate Change, 2019). These effects of climate change stretch urban water management systems to their full capacity, because such systems generally rely on conventional and often outdated infrastructure based on underground pipe networks. Many rivers flow through these pipe networks, and recently, the resilience of these systems has been questioned as they struggle to accommodate the increased volume of surface water runoff and infiltration caused by extreme rainfall events.

Reopening a river course, referred to as "daylighting" (T. C. Wild et al., 2017), is a climate change adaptation strategy that creates more water pathways, thus helping alleviate flood event peaks. At the same time, daylighting provides social and economic benefits by reducing the climatic risk to communities and infrastructure. During periods of increased rainfall, pollutants contained in soil or waste can be mobilized and transported longer distances by water. In cases where piped networks are buried under contaminated soil or waste, and especially if these networks are aging and leaky, an increase in water volume can have a pronounced negative effect on water quality by increasing the likelihood that water will come into contact with contamination. Disused landfills provide a case in point, because older landfill construction standards are often insufficient to protect against mobilization of pollutants under today's climate conditions.

Despite the recent attention given to defining NBS, their application and subsequent monitoring to address water-quality issues has been little explored (European Commission, 2020). In recent years, certain methods and techniques, such as the use of constructed wetlands (CW), phytoremediation, and bioremediation have been touted as NBS that can improve water quality to varying levels (O'Connor et al., 2019; Song et al., 2019). Prior to the introduction of NBS thinking, these methods had been well researched; however their framing as NBS to improve water quality and consideration of co-benefits has been limited. Most studies have focused on surface water runoff, river water, and wastewater in combination with nutrients (Oral et al., 2020), dissolved organic carbon (Liquete et al., 2016), nitrogen compounds (Meyer et al., 2013), and occasionally emerging contaminants of concern (Gorito et al., 2017). More traditional legacy contaminants, defined here as those that are known to have negative effects on human health and the environment and that are stringently regulated (such as polycyclic aromatic hydrocarbons; Bamforth & Singleton, 2005; and polychlorinated biphenyls; Bush et al., 1986) have scarcely been explored (European Commission, 2020).

For example, the use of CW, phytoremediation, and bioremediation have been touted as NBS that can improve water quality to varying levels (O'Connor et al., 2019; Song et al., 2019). Constructed wetlands can incorporate both zones of dense vegetation and deep-open water and as such can improve water quality biologically and chemically by supporting plant–microbial systems and physically by providing mechanisms for the retention and removal of pollutants from water. Such systems can be suitable at brownfield sites to treat groundwater and surface water runoff (including sewer overflows) contaminated by low concentrations of easily biodegradable contaminants (Gorito et al., 2017; Masi et al., 2017; Meyer et al., 2013). Phytoremediation exploits the ability of native or imported plant species to take up pollutants contained in soil or soil pore water, rendering them immobile (Conte et al., 2020; O'Connor et al., 2019). In addition, covering bare soil with plants can reduce the migration of soil pollutants via wind erosion and water transport. Bioremediation utilizes microbial activity to remove pollutants from soil and groundwater. The process can be enhanced by providing capable microorganism strains as well as substrata that are able to stimulate the degradation process.

Moreover, although these methods have been used to address pollutants in water, it is only recently that they have been defined as nature-based interventions and, as a result, their co-benefits have not been reported. It has also been recognized that a long period may be required before these (co)benefits are felt and that monitoring or assessing the success of the NBS is difficult and often not carried out. For example, in the Gorla Maggiore water park, Lombardy, Italy, the ability of gray (human engineered solutions) and green (natural solutions) infrastructure to remove pollutants (dissolved organic carbon and nitrogen) and manage flood risk were compared. An ecosystem-services approach was taken to evaluate multiple benefits and co-benefits such as water purification, flood regulation, natural habitat, and recreation that arise from the use of the NBS. The results demonstrated that the green infrastructure encompassing the NBS was the best option because it provided more than one benefit and was especially effective at improving water quality (Reynaud et al., 2017).

There are several successful examples of the use of NBS in Europe and America with the aim of either repurposing landfill sites or broadening their utility to include co-benefits. At Staten Island, New York, USA, a parkland is currently being constructed on the previous Fresh Kills landfill site with the aim of providing recreational, cultural, and ecological amenities (Klenosky et al., 2017). In the Czech Republic, a closed landfill site was restored using natural vegetation, which contributed to and indicated the health of the landfill site (Vaverková et al., 2018). Mathematical models were used to predict optimal vegetation performance measured in growth. At the Grønmo Landfill, Oslo, Norway, landscaping was used to divert water courses and reduce potential contact of water with polluted waste (Sjödahl, 2019). Furthermore, the Urban Nature Atlas (https://naturvation.eu/atlas) contains information about 1000 NBS interventions, making it the most comprehensive basis for the analysis of socioeconomic and innovation patterns associated with urban NBS in Europe.

Several smaller scale implementations that have been used to address water-quality issues caused by excess levels of nutrients and dissolved organic carbon have taken place across Europe. For example, CW were created in the Tolka Valley in Dublin, Ireland. Storm water retention basins have been used in Marseille, France, to relieve pressure on sewage networks. In Cardiff, UK, planters, swales, bioretention ponds, permeable paving, and curb drainage will be used to catch, clean, and divert water. Phytoremediation was used to remove metals from the site of a former installation for the dehydration of sewage sludge located in Leipzig, Germany. The CW used in Dublin led to an increase in biodiversity as well as a reduction in pollutant levels and soil erosion. In Cardiff, the NBS have created more green space and, through the number of trees planted, have improved air quality, created habitat, and increased biodiversity, as well as improved the urban environment. The phytoremediation used at Leipzig has not only reduced the concentrations of pollutants, but has also increased natural habitats and biodiversity. These and other examples illustrate the multiple co-benefits of implementing NBS.

This paper presents a unique case study from the Kjørbekk stream in Skien municipality in Oslo, Norway, where the predicted increased rainfall volume caused by climate change renders the current surface water network unable to meet this demand (Norwegian Environmental Agency, 2019). The stream runs in an aging pipe infrastructure that has started to leak and, in addition, does not have the capacity to handle the increased volume. The pipe is buried under two old, disused landfill sites that were constructed without bottom membranes. To accommodate the increased water volume, one option being evaluated is to reopen the stream through a daylighting process and create new water pathways using nature-based interventions. However, owing to the presence of pollutants in the waste in the disused landfills, it is imperative that these pathways do not lead to a mobilization and transport of pollutants by the water. This work presents a conceptual study to illustrate possible NBS that could be employed at the site and highlights their co-benefits, drawing on similar existing examples.

THE CASE STUDY SITE

Kjørbekk stream

Kjørbekk stream is located in Skien municipality, Norway, and is 4 km long (GPS coordinates 59.2096056°N, 9.6090139°E). Kjørbekk stream is in the Skien watershed (10 780 km^2), which is the third largest watershed in Norway, and it discharges into the Skien River. Kjørbekk stream runs between Lake Hvitsteintjern and the Skien River. The water in Kjørbekk stream is led into a pipe and then travels via the pipe system, constructed in the 1960s, approximately 4 km to the Skien River. The piped system is buried up to 15 m deep and, in certain places, is buried under two disused landfills. The first landfill (Landfill 1) was used between 1962 and 1976. It is approximately 85 000 ha and 5–7 m deep and does not have a bottom cover. The second landfill (Landfill 2), used between 1975 and 1993, is 120 ha and 13 m deep. It is unknown if this landfill has a bottom cover. Both landfills contain household waste, waste oil, and a mixture of special waste, with top covers of unknown material type and quality, varying from 0.3 to 1.5 m (Norwegian Environmental Agency, 2019).

Kjørbekk stream can be roughly divided into six different areas according to the type of terrain (Figure 1). Section A is dominated by forest, has a steep slope, a thin top soil layer on top of the bedrock, and a high rate of runoff. In Section B, the landscape is dominated by farmland and contains one of the disused landfills (Landfill 2) as well as an industrial area. In Section C, the topography is much flatter and is dominated by industrial buildings with impermeable surfaces, which leads to rapid runoff. Section D, which contains the other disused landfill (Landfill 1), is subject to flooding. In Sections E and F, the stream runs toward the Skien River, and runoff from the disused landfill spreads out into the Skien River.

Physical and geographical content

Skien municipality is located in southern Norway, approximately 130 km southwest of Oslo. The municipality covers a total area of 778 km^2, with approximately 479 km^2 forest, 46 km^2 agriculture, and 57 km^2 freshwater. The remaining 197 km^2 are inhabited and are dominated by cities and towns, residential areas, and industrial areas. The Skien River begins in Skien and runs through the city of Porsgrunn to the mouth of the river at the fjord Frierfjord with subsequent access to the sea. The waterfront is an important part of the Skien townscape, and access to the sea has been important to the development of the area. Skien was recognized as Norway's most important commercial and cultural center between the 1500 and 1800s. The periurban landscape between Porsgrunn and Skien provides the

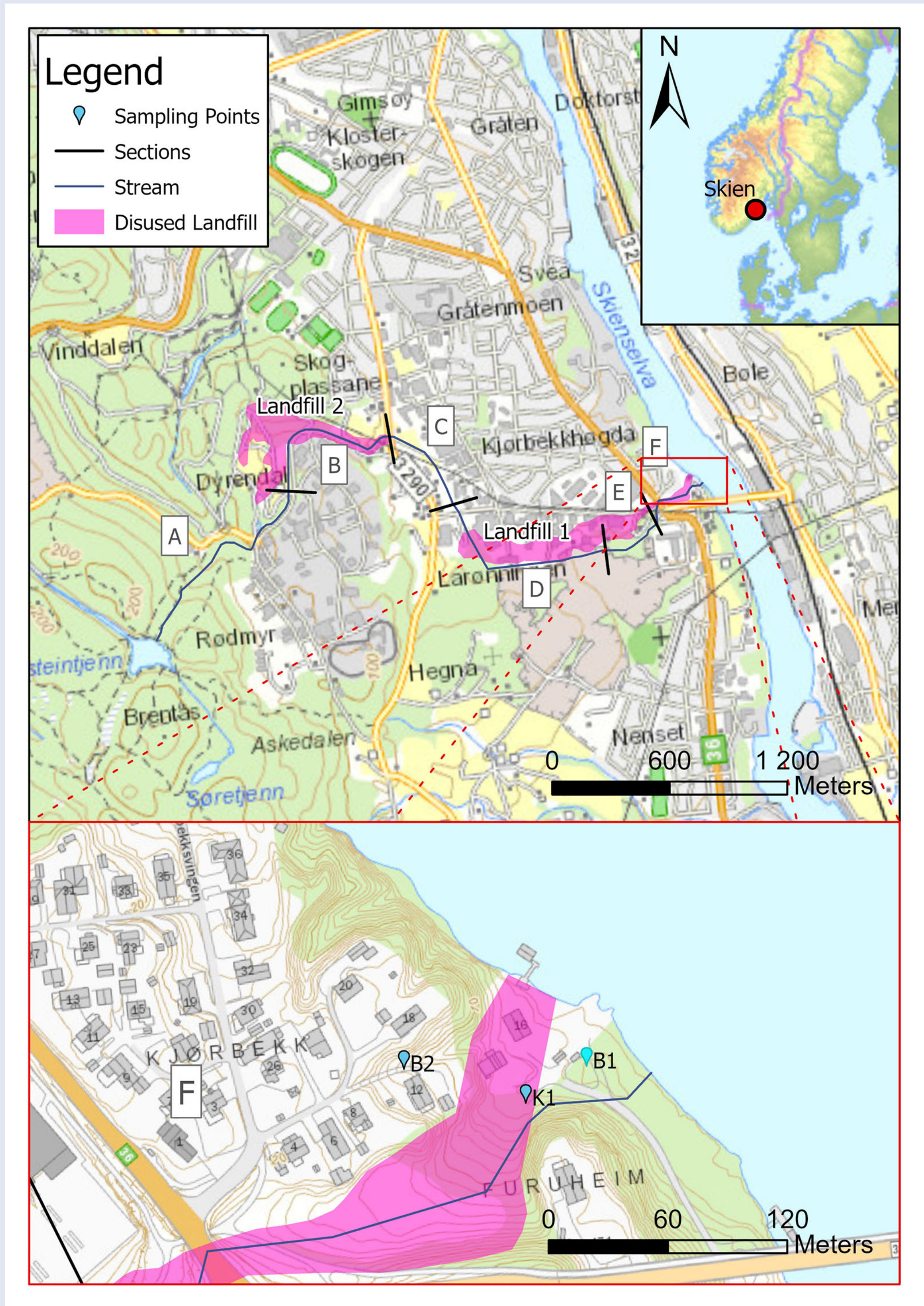

FIGURE 1 Map of the area showing: sampling locations of water samples taken in 2020; Sections A–F of the Kjørbekk stream, indicating where the stream is divided, based on site characteristics; the areas of disused landfills (Landfills 1 and 2); and the Kjørbekk stream itself

opportunity to improve connections between the river and the hills and agricultural landscape along the urban belt. These connections have been lost, and new green infrastructure designed to manage surface water, as well as additional social infrastructures, is proposed to regain these connections. Skien has a varied geology, and the area is a very productive agricultural area. The main soil types include a thin layer of moraine between bare mountain, thick layers of marine clay, and glacial fluvial deposits dominated by gravel and sand. Seasonal average daily temperatures in Skien vary from −2 °C in winter, between 1 and 10 °C in spring, 16 °C in summer, and 8–12 °C in autumn. These temperatures are expected to increase by 4.5 °C by 2100 under RCP8.5, outlined by the IPCC

(Norwegian Climate data; no.climate-data.org; Hanssen-Bauer et al., 2015). Precipitation in Skien varies between 370 and 880 mm/month; this amount is expected to increase by 30% in winter, 25% in spring, and 10% in autumn, by 2100 (Hanssen-Bauer et al., 2015). The amount of precipitation falling at the site has been increasing since 1971; the yearly amount has increased from 600 mm in 1971 to 1200 mm in 2020 (Norges vassdrags- og energidirektorat, www.nve.no).

Site contamination

It is not uncommon that leachate water originating in landfill sites reaches and then negatively affects a local water recipient. In fact, in Norway, it has been estimated that half of the leachate released enters water bodies without preliminary treatment (Norwegian Ministry of Climate and Environment, 2010). To investigate if excess surface water resulting from increases in precipitation caused by climate change, or stream water leaking from the aging pipe infrastructure, was contaminated by flowing through the disused landfills, two monitoring campaigns were carried out. In 2004, water was sampled from two wells at a depth of 4 m, corresponding to the level of leachate water (B1 and B2, Figure 1) and at the point at which water comes out of the pipe, just before it discharges into the Skien River (K1, Figure 1). In addition, two top soil samples were taken at the two landfill locations. All samples were analyzed for metals, total hydrocarbons, chlorinated solvents, polychlorinated biphenols (PBCs), polycyclic aromatic hydrocarbons (PAHs), phenol, benzene, toluene, ethylene, and xylene; for water, additional analysis was carried out for conductivity, pH, biological and chemical oxygen demand, total N, and ammonium. Concentrations of arsenic and chromium in the soil samples were above the acceptable thresholds set by the Norwegian Environment Agency. Concentrations of total hydrocarbons, PAHs, and zinc were all above detection limits but were below acceptable thresholds. In the water samples, concentrations of ammonium and benzene were above acceptable threshold values in all locations. In addition, results revealed elevated concentrations of nitrogen, phosphorous, ammonium, and chemical oxygen demand in the water just prior to discharge into the Skein River (Interconsult, 2004a, 2004b).

The monitoring round, carried out in August 2020, consisted of water sampling from the same locations as in 2004, and samples were analyzed for the same contaminants. August is one of the months with most precipitation (86 mm fell in August 2020), and the results revealed generally low concentrations with the exception of elevated levels of ammonium and zinc, which classify the water as having bad chemical status. To document the effects of variable precipitation on particle and contaminant transport, site investigations are being planned for different seasons.

REOPENING KJØRBEKK STREAM

The three challenges facing the site are (i) the pipe infrastructure does not have the capacity to handle the predicted future increases in rainfall volumes, (ii) there are concerns that the pipe infrastructure leaks, and (iii) the pipe is buried under the disused landfills. These three challenges increase the likelihood that surface runoff water may come in to contact with pollutants, thus impairing its quality, and that these pollutants will be mobilized and carried over large distances with the water. Solutions to increase the capacity of the pipe infrastructure, while avoiding contamination of a wider area caused by the pollution in the landfills, are needed (Sjödahl, 2019).

Daylighting

Reopening a river is a climate adaptation strategy that can create additional flood pathways and increase infiltration and attenuation of surface water, thus combating effects of climate change, such as increased rainfall and extreme events. This process is commonly referred to as deculverting, or daylighting, and in its broadest sense, can be defined as “opening up buried watercourses and restoring them to more natural conditions” (T. C. Wild et al., 2019). The process covers the opening of both piped and buried rivers and is viewed as a solution that delivers a wide range of social, economic, and environmental benefits. Deculverting can improve livelihoods by providing new recreational areas for the local community, can reduce flooding risk and associated economic and environmental problems, and enhance community resilience. Thus, it inherently provides an NBS.

Research related to daylighting, its monitoring, and evaluation of success is limited in the peer-reviewed literature, although many European countries have significant lengths of rivers that are buried. For example, Denmark and Sweden are reported to have between 15% and 20% of their river lengths lost to pipes (T. C. Wild et al., 2019). In 2008, the University of Sheffield, UK, began developing a web-based database using mapping applications to investigate deculverting and have published results of database findings. The main objectives of setting up the database were to generate information on a wider range of deculverting experiences and to better understand such practices. The link between deculverting and NBS was clearly highlighted in the work as participants cited challenges such as climate, water flow, erosion regulation, and disaster risk reduction as themes that can be addressed by NBS that are possible within deculverting projects. The database recorded 180 cases, mostly in Europe and North America, where deculverting was commonly driven by habitat restoration, other ecological factors, and flood mitigation (European Commission, 2020).

The reopening of Kjørbekk stream presents an interesting case study that can be added to this body of data. The complicating factors of pollutants spreading with water and the current lack of safe, open flood pathways leading to the catchment mean that opening Kjørbekk stream is a process that needs much consideration. A solution is needed in which the landscape is transformed to isolate and prevent the spread of pollutants. Nature-based interventions provide one tool that can be applied at Kjørbekk stream. The most likely nature-based interventions to be used to address

 DOI: 10.1002/ieam.4467

four main issues include: reducing the amount of water in contact with pollutants, reducing the amount of particle spreading, remediating contaminated water, and remediating contaminated soil. These are discussed below. The Skien case is currently in the planning phase and different solutions are being considered in the overall site development plan.

NBS FOR KJØRBEKK STREAM

Reducing the amount of water in contact with pollutants

Reducing flood peaks is paramount to avoid disturbing polluted soil and waste. Altering the landscape using nature-based interventions plays a decisive role in reducing the amount of water that comes in contact with potentially polluted soil and waste. Water can be led away from the disused landfills and the amount of water flowing through the area reduced through landscape modeling. By leading the water away from the landfill areas, infiltration is minimized and, subsequently, so is the amount of contaminated leachate water. Concave topography, terraced ditches, ditches to collect surface water, and dams that can pool water could all be used. The selection of the most appropriate landscaping depends on the local topography, including determining exactly where the piped stream flows and where the most heavily affected areas are. In addition to these changes in the landscape, the density of natural vegetation in the area could be increased to reduce the amount and the speed of infiltration water. Therefore, it is important to consider which species are planted where and how they will be managed. For example, a species with a deep rooting system would not be appropriate for an area where a membrane may have been used, because the rooting system may perforate and damage the membrane. In cases where the natural vegetation is able to accumulate pollutants (see below for more details), the vegetation must be handled appropriately to avoid further environmental pollution, which may mean landfilling or incinerating. Such follow-up management must be considered when NBS are selected.

Reducing the amount of particle spreading

The polluted soil at the site can, in addition to the water, spread the pollution to a wider area, because soil particles themselves (containing the bound pollutants) can be transported by air and water. This can be reduced using physical methods that limit the spread of airborne and waterborne particles. To reduce soil erosion, and thus the spread of both airborne and waterborne particles, a layer of natural vegetation or clean soil can be placed on top of the contaminated surface material (Song et al., 2019). This is a physical method, because a layer of clean material effectively traps the contaminated soil.

Remediating contaminated water

Constructed wetlands are one of the most commonly used NBS to control water pollution in cities. They are used to treat rainwater, combined sewer overflow, and outflow from existing wastewater treatment plants (WWTP; Carranza-Diaz et al., 2014; Gorito et al., 2017; Liquete et al., 2016; Masi et al., 2017; Meyer et al., 2013; O'Sullivan et al., 2015). They are constructed filtration systems with a defined filter material and are planted with wetland vegetation resulting in a conducive local microbial and plant ecosystem. In these systems, polluted water flows through the filter material, and the treatment is done by chemical, physical, and biological processes including volatilization, sorption and sedimentation, photodegradation, plant uptake, and microbial degradation. Constructed wetlands are recognized as being eco-friendly, simple in their construction and implementation, and inexpensive (Garfí et al., 2017). A previous quantitative comparison of the environmental impacts of CW and conventional WWTP revealed that CW had a two to five times lower impact than conventional WWTP, owing to lower electricity demands and chemical consumption (Garfí et al., 2017). Based on a life-cycle assessment of a traditional activated sludge wastewater treatment plant and two types of NBS—CW and a high-rate algal pond system—it was demonstrated that 45 kg CO_2eq p e^{-1} $year^{-1}$ could be saved by implementing NBS instead of conventional wastewater treatment plants. Both NBS were two to three times less expensive than the conventional WWTP.

Constructed wetlands are able to efficiently reduce concentrations of total suspended solids (TSS), organic matter, nutrients metals, and a range of organic pollutants, such as pesticides, pharmaceuticals, and contaminants of emerging concern (Gorito et al., 2017; Matamoros & Bayona, 2006), over periods of up to 20 years. In a recent review of the effectiveness of CW to remove priority substances defined in the Water Framework Directive (WFD; European Commission, 2000), extremely variable results were reported. Peer-reviewed literature was found for 24 of the 41 defined priority organic substances in the WFD. Benzene, atrazine, and chlorpyrifos were the most studied compounds, and removal rates for these and the other reported compounds varied greatly, between 0% and 100% (Gorito et al., 2017). The extremely large variation, both for the same compound and for different compounds compared with each other, makes general conclusions about removal efficiency difficult to draw. However, this emphasizes the need for detailed knowledge of the pollution type and concentration at a particular site prior to the consideration and selection of CW as the NBS of choice.

Remediating contaminated soil

NBS can be used to remediate contaminated soil, including aeration, natural degradation, and monitored natural attenuation. These methods are often less expensive than methods such as electrochemical treatment, ozonation, and hydrolysis; further, they reduce the use of chemicals that may affect human health and reduce potential environmental damage caused by employing harsher methods. In certain cases, simply allowing air access to polluted soil is enough to volatilize certain chemicals (e.g., volatile organic compounds such as benzene). Certain organic pollutants including benzene, toluene, ethylbenzene and xylene (Weelink et al., 2010), short-chain chlorinated compounds, and oil components can be degraded by native bacteria (da Silva et al. 2020). This process is most often limited by access to electron acceptors (O_2, NO_3^-, SO_4^{2-}, and CH_4) or electron donors (organic carbon) and can thus be stimulated by supplying oxygen or another oxidizer. Monitored natural attenuation relies on natural attenuation processes to achieve site-specific remediation objectives within a reasonable time frame. Five main processes that occur without human intervention, including biodegradation, sorption, chemical reactions, dilution, and evaporation, are all part of natural attenuation. The processes rely on optimal site conditions and in theory can reduce the concentration of pollutants in a given soil. Long-term monitoring is needed to ensure that treatment efficacy is maintained and that results are sufficient when compared with more active remediation approaches.

A further method that can be used to remediate contaminated soil is sorbent amendment where a small amount of a strongly sorbing material such as metal oxides, activated carbon, or biochar is added to the contaminated soil to lock the pollutants up (Palansooriya et al., 2020). Biochar has been added to soils contaminated with both inorganic and organic pollutants and has demonstrated very large reductions in leaching potential (Beesley et al., 2011). Biochar is produced from the pyrolysis of organic waste materials (Lehmann & Joseph, 2012) and is recognized as a sustainable alternative when compared with more traditional sorbent materials such as activated carbon (Sparrevik et al., 2011); its use for this purpose has been touted as a NBS (Song et al., 2019).

Co-benefits provided by the NBS for Kjørbekk stream

The nature-based interventions described above that can reduce the amount of water in contact with pollutants, reduce the amount of particle spreading, remediate contaminated water, and remediate contaminated soil also offer co-benefits. Altering the landscape to reduce the amount of water in contact with potentially contaminated soil provides the primary benefit of an increase in water quality while providing the co-benefit of the creation of alternative water ways. These alternative water ways will increase infiltration rates and the attenuation of surface water, thus combating effects of climate change such as increased rainfall and extreme events, ultimately reducing the risk of flooding. Reducing particle spreading by adding a layer of natural vegetation or clean soil also supports increased water quality and concurrently provides the potential co-benefit of improved ecological status and biodiversity in the area. Remediating contaminated water through the use of CW will remove pollutants from water in the Kjørbekk stream and can also provide additional social, economic, and environmental co-benefits (Garfí et al., 2017). Social co-benefits are felt through improved aesthetics in the area, economic co-benefits are felt through enhanced flood protection, and environmental co-benefits are achieved through an improvement in the state of the native ecosystem. The NBS that can be used to remediate contaminated soil (aeration, natural degradation, and monitored natural attenuation) are all less invasive than using harsh chemical and physical remediation methods. In this sense, economic, social, and environmental co-benefits can be achieved beyond a reduction in the severity of the pollution. The methods are often less expensive, use fewer chemicals that may affect human health, and reduce potential environmental damage caused by employing harsher methods. Sorbent amendment locks pollutants up for long periods and thus provides the main benefit of a reduction in pollutant concentrations. In addition, sorbent amendment reduces the quantity of waste and can improve aesthetics, thus providing social and economic co-benefits (Song et al., 2019).

THE WAY FORWARD FOR KJØRBEKK STREAM

The Kjørbekk stream is facing these challenges: (i) The pipe infrastructure does not have the capacity to handle the predicted increases in future rainfall volumes, (ii) there are concerns that the pipe infrastructure leaks, and (iii) the pipe is buried under the disused landfills. In this paper, the importance and potential applicability of using NBS to improve the quality of water in streams flowing through landfill environments have been discussed. The advantages and co-benefits that can be achieved when they are carefully planned has also been highlighted. All of the NBS described above could be used as part of a reopening strategy for Kjørbekk stream because they are able to create new waterways, thus alleviate flooding and divert water away from the contaminated disused landfills, reduce the risk of pollutants spreading, and remediate contaminated water and soil. In combination, these methods will ensure that water quality is maintained.

Skien municipality will proceed at the site by selecting the most fitting NBS in the overall site development plan that provides the intentional primary benefits, as well as secondary co-benefits. This decision will not only consider the environmental targets to achieve but also take into account the additional social (aesthetic and health benefits) and economic (flood control) effects of the intervention. In addition, the NBS selected must be appropriate for the landscape and topography of the area. For example, a layer of natural vegetation or clean soil placed on top of the contaminated surface soil to reduce the amount of particle spreading is likely to be more effective in areas with steeper slopes, which are more prone to erosion. Using a CW to remediate contaminated water would be most effective in the downstream area before discharge into the Skien River, because it is at this point that the pollution could impair water quality in a larger water body.

After the selection and implementation of NBS for the Kjørbekk stream, subsequent monitoring will play an important role in determining the success of the applied interventions. Environmental monitoring focusing on water quality will show if the NBS have been successful in alleviating water-quality problems. However, because the co-benefits of the NBS are often long lasting, tools are needed that allow a temporal factor to be considered. A life cycle impact assessment or the use of relevant sustainability indicators (for example, considering carbon sequestered via an intervention) can also be suitable methods for monitoring the performance of the NBS.

ACKNOWLEDGMENT

Gudny Okkenhaug and Erlend Sørmo of the Norwegian Geotechnical Institute are thanked for their input to the initial work related to the case study site. Funding was provided by Norwegian Research Council Project 300560, part of the JPI project "Nature-based solutions for water management in the periurban; linking ecological, social, and economic dimensions."

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DISCLAIMER

The peer-review process for this article was managed by the Editorial Board without the involvement of AMP Oen.

DATA AVAILABILITY STATEMENT

Additional associated data are available through the Supporting Information attached to this article.

ORCID

Sarah E. Hale https://orcid.org/0000-0002-7743-9199
Amy M. P. Oen https://orcid.org/0000-0002-3061-7488

REFERENCES

Albert, C., Brillinger, M., Guerrero, P., Gottwald, S., Henze, J., Schmidt, S., Ott, E., & Schröter, B. (2020). Planning nature-based solutions: Principles, steps, and insights. *Ambio*, 1–16. https://doi.org/10.1007/s13280-020-01365-1

Albert, C., Schröter, B., Haase, D., Brillinger, M., Henze, J., Herrmann, S., Gottwald, S., Guerrero, P., Nicolas, C., & Matzdorf, B. (2019). Addressing societal challenges through nature-based solutions: How can landscape planning and governance research contribute? *Landscape and Urban Planning*, *182*, 12–21. https://doi.org/10.1016/j.landurbplan.2018.10.003

Bamforth, S. M., & Singleton, I. (2005). Bioremediation of polycyclic aromatic hydrocarbons: Current knowledge and future directions. *Journal of Chemical Technology and Biotechnology*, *80*(7), 723–736. https://doi.org/10.1002/jctb.1276

Beesley, L., Moreno-Jiménez, E., Gomez-Eyles, J. L., Harris, E., Robinson, B., & Sizmur, T. (2011). A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. *Environmental Pollution*, *159*(12), 3269–3282. https://doi.org/10.1016/j.envpol.2011.07.023

Bush, B., Shane, L. A., Wilson, L. R., Barnard, E. L., & Barnes, D. (1986). Uptake of polychlorobiphenyl congeners by purple loosestrife (*Lythrum salicaria*) on the banks of the Hudson River. *Archives of Environmental Contamination and Toxicology*, *15*(3), 285–290. https://doi.org/10.1007/BF01061105

Carranza-Diaz, O., Schultze-Nobre, L., Moeder, M., Nivala, J., Kuschk, P., & Koeser, H. (2014). Removal of selected organic micropollutants in planted and unplanted pilot-scale horizontal flow constructed wetlands under conditions of high organic load. *Ecological Engineering*, *71*, 234–245. https://doi.org/10.1016/j.ecoleng.2014.07.048

Conte, A., Brunetti, P., Allevato, E., Stazi, S. R., Antenozio, M. L., Passatore, L., & Cardarelli, M. (2020). Nature-based solutions on the river environment: An example of cross-disciplinary sustainable management, with local community active participation and visual art as science transfer tool. *Journal of Environmental Planning and Managagement*, 1–18. https://doi.org/10.1080/09640568.2020.1822306

da Silva, I. G. S., de Almeida, F. C. G., da Rocha e Silva, N. M. P., Casazza, A. A., Convert, A., & Sarubbo, L. A. (2020). Soil bioremediation: Overview of technologies and trends. *Energies*, *13*(18), 4664. https://doi.org/10.3390/en13184664

Dorst, H., van der Jagt, A., Raven, R., & Runhaar, H. (2019). Urban greening through nature-based solutions—Key characteristics of an emerging concept. *Sustainable Cities and Society*, *49*, 101620. https://doi.org/10.1016/j.scs.2019.101620

Escobedo, F. J., Giannico, V., Jim, C. Y., Sanesi, G., & Lafortezza, R. (2019). Urban forests, ecosystem services, green infrastructure and nature-based solutions: Nexus or evolving metaphors? *Urban For Urban Green*, *37*, 3–12. https://doi.org/10.1016/j.ufug.2018.02.011

European Commission. (2015). Towards an EU Research and Innovation policy agenda for nature-based solutions & re-naturing cities. https://op.europa.eu/en/publication-detail/-/publication/fb117980-d5aa-46df-8edc-af367cddc202

European Commission. (2019). Nature-based solutions. https://ec.europa.eu/info/research-and-innovation/research-area/environment/nature-based-solutions_en

European Commission. (2020). Nature-based solutions improving water quality & waterbody conditions analysis of EU-funded projects. https://op.europa.eu/en/publication-detail/-/publication/d6efaeeb-d530-11ea-adf7-01aa75ed71a1/language-en

European Commission. (2000). Water Framework Directive 2000/60/EC. https://eur-lex.europa.eu/resource.html?uri=cellar:5c835afb-2ec6-4577-bdf8-756d3d694eeb.0004.02/DOC_1&format=PDF

Garfí, M., Flores, L., & Ferrer, I. (2017). Life cycle assessment of wastewater treatment systems for small communities: Activated sludge, constructed wetlands and high rate algal ponds. *Journal of Cleaner Production*, *161*, 211–219. https://doi.org/10.1016/j.jclepro.2017.05.116

Gorito, A. M., Ribeiro, A. R., Almeida, C. M. R., & Silva, A. M. T. (2017). A review on the application of constructed wetlands for the removal of priority substances and contaminants of emerging concern listed in recently launched EU legislation. *Environmental Pollution*, *227*, 428–443. https://doi.org/10.1016/j.envpol.2017.04.060

Gómez Martín, E., Máñez Costa, M., & Schwerdtner Máñez, K. (2020). An operationalized classification of nature-based solutions for water-related hazards: From theory to practice. *Ecological Economics*, *167*, 106460. https://doi.org/10.1016/j.ecolecon.2019.106460

Hanssen-Bauer, I., Førland, E. J., Haddeland, I., Hisdal, H., Mayer, S., Nesje, A., Nilsen, J. E. Ø., Sandven, S., Sandø, A. B., Sorteberg, A., & Ådlandsvik, B. (2015). Klima i Norge 2100 Kunnskapsgrunnlag for klimatilpasning oppdatert i. www.miljodirektoratet.no/20804

Interconsult. (2004a). Undersøkelse av grunnforurensning fra det nedlagte deponiet Kjørbekk 1. Report dated 15th June 2004, In Norwegian.

Interconsult. (2004b). Undersøkelse av grunnforurensning fra det nedlagte deponiet Kjørbekk 2. Report dated 15th June 2004, In Norwegian.

Intergovernmental Panel on Climate Change. (2019). Climate change and land an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/srccl/

Klenosky, D. B., Snyder, S. A., Vogt, C. A., & Campbell, L. K. (2017). If we transform the landfill, will they come? Predicting visitation to Freshkills Park in New York City. *Landscape and Urban Planning*, *167*, 315–324. https://doi.org/10.1016/j.landurbplan.2017.07.011

Lehmann, J., & Joseph, S. (2012). *Biochar for environmental management: An introduction* (1st ed., pp. 1–12). Routledge. https://doi.org/10.4324/9781849770552

Liquete, C., Udias, A., Conte, G., Grizzetti, B., & Masi, F. (2016). Integrated valuation of a nature-based solution for water pollution control.

Highlighting hidden benefits. *Ecosystem Services*, *22*, 392–401. https://doi.org/10.1016/j.ecoser.2016.09.011

Masi, F., Rizzo, A., Bresciani, R., & Conte, G. (2017). Constructed wetlands for combined sewer overflow treatment: Ecosystem services at Gorla Maggiore, Italy. *Ecological Engineering*, *98*, 427–438. https://doi.org/10.1016/j.ecoleng.2016.03.043

Matamoros, V., & Bayona, J. M. (2006). Elimination of pharmaceuticals and personal care products in subsurface flow constructed wetlands. *Environmental Science and Technology*, *40*(18), 5811–5816. https://doi.org/10.1021/es0607741

Meyer, D., Molle, P., Esser, D., Troesch, S., Masi, F., & Dittmer, U. (2013). Constructed wetlands for combined sewer overflow treatment-comparison of German, French and Italian approaches. *Water (Switzerland)*, *5*(1), 1–12. https://doi.org/10.3390/w5010001

Norwegian Environmental Agency. (2019). Fra deponi til landskap i et klimaperspektiv vannhåndtering for å hindre spredning av. https://www.miljodirektoratet.no/publikasjoner/2020/mai-2020/fra-deponi-til-landskap-i-et-klimaperspektiv---vannhandtering-for-a-hindre-spredning-av-gamle-miljosynder/

Norwegian Ministry of Climate and Environment. (2010). Sammen for et giftfritt miljø–forutsetninger for en tryggere fremtid. https://www.regjeringen.no/no/dokumenter/Stmeld-nr-14-2006-2007-/id441267/

O'Connor, D., Zheng, X., Hou, D., Shen, Z., Li, G., Miao, G., O'Connell, S., & Guo, M. (2019). Phytoremediation: Climate change resilience and sustainability assessment at a coastal brownfield redevelopment. *Environment International*, *130*(April), 104945. https://doi.org/10.1016/j.envint.2019.104945

Oral, H. V., Carvalho, P., Gajewska, M., Ursino, N., Masi, F., Hullebusch, E. D., 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

O'Sullivan, A. D., Wicke, D., Hengen, T. J., Sieverding, H. L., & Stone, J. J. (2015). Life cycle assessment modelling of stormwater treatment systems. *Journal of Environmental Management*, *149*, 236–244. https://doi.org/10.1016/j.jenvman.2014.10.025

Pagano, A., Pluchinotta, I., Pengal, P., Cokan, B., & Giordano, R. (2019). Engaging stakeholders in the assessment of NBS effectiveness in flood risk reduction: A participatory system dynamics model for benefits and co-benefits evaluation. *Science of the Total Environment*, *690*, 543–555. https://doi.org/10.1016/j.scitotenv.2019.07.059

Palansooriya, K. N., Shaheen, S. M., Chen, S. S., Tsang, D. C. W., Hashimoto, Y., Hou, D., Bolan, N. S., Rinklebe, J., & Ok, Y. S. (2020). Soil amendments for immobilization of potentially toxic elements in contaminated soils: A critical review. *Environment International*, *134*, 105046. https://doi.org/10.1016/j.envint.2019.105046

Raymond, C. M., Frantzeskaki, N., Kabisch, N., Berry, P., Breil, M., Nita, M. R., Geneletti, D., & Calfapietra, C. (2017). A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environmental Science & Policy*, *77*(June), 15–24. https://doi.org/10.1016/j.envsci.2017.07.008

Reynaud, A., Lanzanova, D., Liquete, C., & Grizzetti, B. (2017). Going green? Ex-post valuation of a multipurpose water infrastructure in Northern Italy. *Ecosystem Services*, *27*, 70–81. https://doi.org/10.1016/j.ecoser.2017.07.015

Sjödahl, E. (2019). Landscape measures for improved management of stormwater and leachate at old closed landfills. *Kart og Plan*, *112*, 138–159.

Song, Y., Kirkwood, N., Maksimović, Č., Zhen, X., O'Connor, D., Jin, Y., & Hou, D. (2019). Nature-based solutions for contaminated land remediation and brownfield redevelopment in cities: A review. *Science of the Total Environment*, *663*, 568–579. https://doi.org/10.1016/j.scitotenv.2019.01.347

Sparrevik, M., Saloranta, T., Cornelissen, G., Eek, E., Fet, A. M., Breedveld, G. D., & Linkov, I. (2011). Use of life cycle assessments to evaluate the environmental footprint of contaminated sediment remediation. *Environmental Science and Technology*, *45*(10), 4235–4241. https://doi.org/10.1021/es103925u

Vaverková, M. D., Radziemska, M., Bartoň, S., Cerdà, A., & Koda, E. (2018). The use of vegetation as a natural strategy for landfill restoration. *Land Degradation and Development*, *29*(10), 3674–3680. https://doi.org/10.1002/ldr.3119

Weelink, S. A. B., van Eekert, M. H. A., & Stams, A. J. M. (2010). Degradation of BTEX by anaerobic bacteria: Physiology and application. *Reviews in Environmental Science and Biotechnology*, *9*(4), 359–385. https://doi.org/10.1007/s11157-010-9219-2

Wild, T. C., Dempsey, N., & Broadhead, A. T. (2019). Volunteered information on nature-based solutions—Dredging for data on deculverting. *Urban for Urban Green*, *40*, 254–263. https://doi.org/10.1016/j.ufug.2018.08.019

Wild, T. C., Henneberry, J., & Gill, L. (2017). Comprehending the multiple 'values' of green infrastructure—Valuing nature-based solutions for urban water management from multiple perspectives. *Environmental Research*, *158*, 179–187. https://doi.org/10.1016/j.envres.2017.05.043

 DOI: 10.1002/ieam.4467