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Detailed Geophysical Mapping and Hydrogeological Characterisation of the Subsurface for Optimal Placement of Infiltration-Based Sustainable Urban Drainage Systems

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Abstract: The continuous growth of cities in combination with future climate changes present urban planners with significant challenges, as traditional urban sewer systems are typically designed for the present climate. An easy and economically feasible way to mitigate this is to introduce a Sustainable Urban Drainage System (SUDS) in the urban area. However, the lack of knowledge about the geological and hydrogeological setting hampers the use of SUDS. In this study, 1315 ha of high-density electromagnetic (DUALEM-421S) data, detailed lithological soil descriptions of 614 boreholes, 153 infiltration tests and 250 in situ vane tests from 32 different sites in the Central Denmark Region were utilised to find quantitative and qualitative regional relationships between the resistivity and the lithology, the percolation rates and the undrained shear strength of cohesive soils at a depth of 1 meter below ground surface (m bgs). The qualitative tests enable a translation from resistivity to lithology as well as a translation from lithology to percolation rates with moderate to high certainty. The regional cut-off value separating sand-dominated deposits from clay-dominated deposits is found to be between 80 to 100 Ωm. The regional median percolation rates for sand and clay till is found to be 9.9×10^{-5} m/s and 2.6×10^{-5} m/s, respectively. The quantitative results derived from a simple linear regression analysis of resistivity and percolation rates and resistivity and undrained shear strength of cohesive soils are found to have a very weak relationship on a regional scale implying that in reality no meaningful relationships can be established. The regional qualitative results have been tested on a case study area. The case study illustrates that site-specific investigations are necessary when using geophysical mapping to directly estimate lithology, percolation rates and undrained shear strength of cohesive soils due to the differences in soil properties and the surrounding environment from site to site. This study further illustrates that geophysical mapping in combination with lithological descriptions, infiltration tests and groundwater levels yield the basis for the construction of detailed planning maps showing the most suitable locations for infiltration. These maps provide valuable information for city planners about which areas may preclude the establishment of infiltration-based SUDS.

Keywords: geophysical mapping; DUALEM-421S; SUDS; infiltration tests; planning map; hydrogeological characterisation

1. Introduction

The United Nations estimate that in 2050, 68% of the world's population of approximately 10 billion people will reside in urban areas [1]. The continuous growth of cities in combination with future climate changes present authorities with significant challenges. In Denmark, climate models estimate that future climate changes will cause an increase in the overall amount of precipitation along with a changing precipitation pattern where more frequent cloudbursts are expected to occur [2,3]. As traditional urban sewer systems are designed for the present climate, the new precipitation pattern will increase the frequency of flooding in urban areas, which will hamper and destroy infrastructure, buildings and the environment [4]. According to the European Environment Agency, an economic loss of approximately 453 billion euro can be assigned to weather and climate-related extremes in the period from 1980 to 2017 [5]. Therefore, one of the most significant challenges for urban planners is to ensure stable disposal of waste and surface water. Consequently, over the last 20 years, there has been an increasing focus on using SUDS in cities. Implementing SUDS in surface water management plans has many benefits. Studies show that the handling of surface water using SUDS is less expensive than traditional handling using sewers [6–10]. In addition, the SUDS enable urban planners to use surface water as a resource instead of a problem, e.g., surface water can be used to make cities green, counteract urban heat effect as well as restore the hydraulic water cycle in urban areas [11–13].

One of the approaches used in Denmark is infiltration-based SUDS, such as ponds, swales, rain gardens, soakaways and infiltration trenches. The primary reason for this is that infiltration-based SUDSs are cost-effective and easy to construct, compared to many other SUDS solutions. In order to find the most suitable SUDS solution for a specific area, the ground conditions, such as infiltration capacity and groundwater conditions must be known in detail, as a site may restrict or preclude a particular SUDS solution. This is especially the case in former glaciated areas, as many glacial deposits often are highly heterogeneous, and thus, their hydrological conditions can likewise be highly variable [14,15]. The heterogeneity is both present within the individual units, e.g., sand lenses embodied in clay till, the presence of fractures, root holes and earthworm burrows [15] as well as between the units. To map both the internal heterogeneity as well as the overall heterogeneity of the subsurface, very detailed studies are required, which are typically time consuming and therefore also very expensive.

Typically, the data available for urban planners when designing new urban developments is point information, such as drilling in combination with overall 2D geological maps showing, e.g., soil type, infiltration capacity, areal extent and the thickness of the individual units. This is useful for identifying overall suitable locations for infiltration but is unsuitable for describing the geological and hydrogeological conditions in sufficient detail for urban planners to be able to select the best SUDS solution [16]. The need for on-site data remains. Furthermore, drillings are invasive and costly, making them unsuitable to map large areas in detail. To compensate for the lack of dense data derived from boreholes, geophysical methods represent an efficient and non-invasive tool for mapping both urban and rural areas [17–24]. Multiple studies throughout the last decades have shown that an empirical correlation between resistivity and lithology exists [25–28]. This correlation depends on several factors, such as water saturation, clay content, clay type, soil compaction, pore water ion content and matrix resistivity [29]. Therefore, the same lithological unit can have a wide resistivity range [30,31], and thus, large-scale investigations have been conducted in Denmark in order to estimate the overall resistivity range for various lithologies. Barfod et al., [31] have made a national resistivity atlas of Denmark in grids spanning 10 × 10 km in which lithological information from boreholes has been integrated with resistivity from various transient electromagnetic methods, thus creating resistivity histograms for selected lithologies (clay, sand and gravel). The resistivity atlas of Denmark was created for two layers; 12.5 to 25 m and 25 to 55 m, respectively, and not for the near subsurface.

For near-surface investigations, electromagnetic induction (EMI) methods have proven to be very effective in successfully mapping the subsurface [32–35]. For instance, Frederiksen et al., [36] made a quantitative comparison of a 1000 ha coherent EMI data set and 125 boreholes showing that the EMI instrument DUALEM-421S is able to map the geology of the upper 6 m in a complex glacial environment.

To the author's knowledge, few Danish studies have tried to establish a quantitative and/or qualitative relationship between resistivity and infiltration capacity, lithology and geotechnical tests based on large-scale data sampling. Until now, only site-specific geophysical mapping has been used to investigate the best placement of SUDSs as well as their infiltration performance in Denmark [37,38].

Therefore, it would be advantageous if more generic similarities between geoelectric resistance, lithology, geotechnical in situ vane tests and infiltration capacity could be achieved covering larger areas. If such compilations can be established, it can help city planners make credible decisions based on as little data as possible and choose the right combination of data types in order to create reliable planning maps. With better knowledge, optimal SUDSs can be better chosen within each area and an over-or underestimation or at worst case—the completely wrong solution can be avoided.

The objective of this paper is to use high-density geophysical mapping in combination with borehole data, infiltration tests and geotechnical data to outline the benefits of geophysical mapping for improved fidelity of the geological and hydrogeological characterisation at 1 m below ground surface (bgs) which is typically the construction depth of vast infiltration-based SUDS solutions in Denmark, e.g., soakaways. Data from the Central Denmark Region has been collected from 2015 and onwards from 32 different locations, and it comprises 1315 ha of high-density electromagnetic (DUALEM-421S) data, detailed lithological soil descriptions of 614 boreholes, 153 infiltration tests and 250 in situ vane tests. The data will be quantitatively and qualitatively analysed, and possible relationships between resistivity and the main lithological description and infiltration capacity and geotechnical data will be evaluated. The results will be exemplified with one case study from Provstlund, Denmark, in order to demonstrate how detailed geophysical and hydrogeological information can yield maps of the infiltration potential of urban development areas.

2. Materials and Methods

2.1. Study Locations

In this study, 1315 ha of DUALEM-421S have been obtained from 32 different locations from the central part of Denmark (Figure 1 and Table 1). The vast majority of the sites are primarily agricultural, and the geophysical mapping has therefore been conducted outside the cropping season in either spring or autumn.

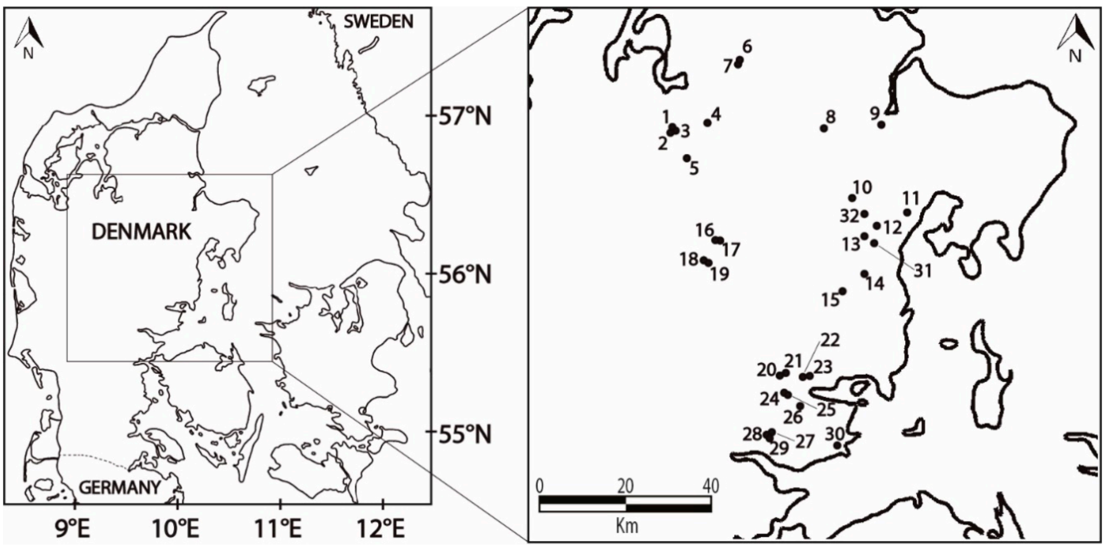

Figure 1. Overview map showing the location of the 32 sites. For names, specific locations and available data of each site, see Table 1.

Alongside the geophysical mapping, detailed lithological soil descriptions of a total of 614 boreholes, 153 infiltration tests and 250 in situ vane tests were obtained. As seen in Table 1, all the geophysical mapping sites held drillings, with the highest amount being at Provstlund and Østerhåb Vest. The highest number of infiltration tests was conducted at Nørrestrand Øst with 25, followed by Ørnstrup Møllevej and Hatting with 20.

Table 1. Information on all the Investigated Sites.

No.	Name	Location (UTM32E89)	Geophysical Mapping (Ha)	Drillings	Infiltration Tests	In Situ Vane Tests
1	Vestbyen	520650,6255950	219	24	7	
2	Viborg 4F3	520249,6254507	132	11	4	
3	Viborg 4F4P	521524, 6255114	11.6	4	2	
4	Taphede	529380, 6257010	221	21	4	
5	Almind	524262, 6248129	1.2	2	1	
6	Klejtrup E11	538680, 6272919	1.8	2	1	
7	Klejtrup E12	538131, 6271512	9.5	5		
8	Svenstrup	558371, 6255606	11	4		
9	Drastrup	572599, 6256509	23	8		
10	Hinnerup	565390, 6238320	150	4		
11	Gammel Kirkevej	579049, 6234795	3.8	7		7
12	Lisbjerg	571500, 6231350	24	20		12
13	Tilst	568650, 6228343	10	7		4
14	Lemmingvej	568390, 6219499	15	12		10
15	Hørning Syd	562950, 6215150	55	12		2
16	Astrid Lindgrensvej	531507, 6227910	40	8		6
17	Balle Bygade	532336, 6227859	4	4		
18	Funder Skole	528462, 6222890	5.5	7		
19	Funder	529602, 6222190	7	5	3	
20	Lund	547340, 6194190	36	19	16	8
21	Provstlund	548810, 6194830	27	161	18	46
22	Nørrestrand Vest	553170, 6193810	60	8	6	
23	Nørrestrand Øst	554850, 6194120	150	25	25	
24	Hatting	548500, 6189890	27	20	20	10
25	Østerhåb Vest	549380, 6189380	40	143	15	124
26	Ørnstrup Møllevej	552474,6186625	17	20	20	
27	Constantiaparken	545460, 6180130	8.5	3	4	
28	Rugmarken	544090, 6179390	2.5	6	4	3
29	Silkavej	544630, 6178850	2.5	4	3	
30	Vejlevej	561103,6175409	4.5	3		
31	Marienlystvej	570746,6227953	8	5		4
32	Aarhusvej	567723,6233531	40	30		14

All the study sites are located in the eastern part of Jutland which was covered by ice during the Weichselian glaciation [39]. The geology in all sites has the same overall lithological log. At the surface, approximately 0.5 to 1 m of topsoil/fillings is observed, followed by either glacial deposits, such as clay till or meltwater sand, or a 0.5 to 2 m thick section of postglacial sediments. The glacial sediments were deposited during the Late Weichselian glaciations spanning 23,000 to 17,000 years ago. The postglacial sediments were deposited in the Holocene period, beginning 11,700 years ago. As all the locations are inland, the postglacial sediments typically comprise clay, sand and peat and are present in lowlands and depressions. The groundwater level is monitored in the vast majority of the sites and is typically within the range of 1 to 5 m bgs.

2.2. Data

2.2.1. Dualem-421S

The geophysical mapping was conducted with the DUALEM-421S ground conductivity meter system (DUALEM Inc., Milton, ON, Canada) from 2015 to 2019. The individual investigations were conducted by various geophysical companies, all using the DUALEM-421S sensor and the same overall processing and inversion scheme. Therefore, the results are considered comparable. In total, approximately 1850 km of lines have been collected. For all investigations, the DUALEM-421S instrument was mounted on a nonmetallic sled and pulled at least 3 m behind a 4WD quad bike. The sled ensured smooth operation with minimum effects from pitch and roll. The sensor was located approximately 0.25 m above the ground surface. The DUALEM-421S sensor held six receiver coils arranged behind the transmitter coil in distances ranging from 1 to 4.1 m, three horizontal coplaner (HCP) coils at 1, 2 and 4 m and three perpendicular-planer (PRP) coils at 1.1, 2.1 and 4.1 m. The system operated at 9000 Hz with a maximum sampling rate of 10 Hz, which provided approximately two samples per 1 m when the equipment was operated at a speed of 15–20 km/h. The systems simultaneously measured the electrical conductivity (mS/m) and the susceptibility at the six coil-configurations. Through geophysical inversion, the depth of investigation (DOI) was calculated. The DOI depends on the electrical characteristics of the subsurface [40]. In clay-dominated soils, the DOI is typically around 5 m. In sand-dominated sediments, it can be up to 10 m. The horizontal and vertical resolutions are around 1 m and 0.5 m, respectively.

Data processing and inversion were carried out using the Aarhus Workbench software [41]. The measured conductivity of each of the six coil-configurations was imported and joined with the spatial position from the GPS. During the processing, the data sections were evaluated with overview maps including relevant information, e.g., the location of buried cables. Noisy and coupled data were removed in the processing. As the coupling effect was limited to 5–10 m from disturbing elements, usually only a minor portion, that is $< 5\%$ of the collected data was rejected from the dataset. Furthermore, the data was filtered using running mean filters in order to increase the signal to noise ratio.

The processed datasets were inverted using the spatially constrained inversion (SCI) scheme. SCI is a damped nonlinear least-squares inversion, where one-dimensional (1D) models are spatially constrained in a three-dimensional (3D) setup during inversion. This inversion approach enables the construction of a spatial inversion model that represents the optimal background for further use of the results [42]. Spatially constrained inversion (SCI) was applied for a smooth 14- or 15-layer model [42].

2.2.2. Drillings

In total, 614 drillings were compiled from the study areas. All the drillings were obtained from engineering companies and were characterised as high quality, as the drillings were made for geotechnical purposes. The drillings were made using a solid stem auger, providing the geologist with high-quality samples for soil description. The drillings were typically no more than 3–5 m deep. The vast majority of the drillings also includes groundwater head measurements, driller's logs, geological descriptions, in situ vane tests, drill depth and geographical coordinates.

2.2.3. Infiltration Tests

Two types of infiltration tests were conducted at the sites. The first type of infiltration test was based on the sieve analysis of sandy deposits. Hydraulic conductivity was found using the Danish standardisation DS 415 formula [43]

$$K = 0.01 \times d_{10}^2 \quad (1)$$

where K represents the hydraulic conductivity (m/s) and d_{10} is the 10% fractile from the effective grain size (mm). This formula is valid for d_{10} larger than 0.1 mm and smaller than 3.0 mm and with a uniformity coefficient U ($U = d_{60}/d_{10}$) less than 2.5.

The remaining infiltration tests were simple falling head tests (percolation tests) conducted according to the recommendations from the Danish Technological Institute [44]. The test consists of a preparation phase and an execution phase. In the preparation phase, a hole spanning 0.5×0.5 m is made with a depth under the top layer that is typically 0.5 m deep. Within this hole, the test hole spanning 0.25×0.25 m with a depth between 0.25 and 0.5 m is made. The bottom elevation of the test hole should correspond to the bottom elevation of the proposed basin (infiltration surface). The bottom of the test hole is then covered with 2 cm of gravel and then presoaked. The presoaking should last at least 30 min and until the infiltration rate is constant, after which the execution phase can begin. Here, 20 cm of water is added to the test hole, and the water level is measured during the test period.

The water head and the related time is measured for at least 15 min or until the test hole is empty. Based on the measured result, the percolation rate is calculated.

As the infiltration capacity derived from the sieve analysis represents the hydraulic conductivity for all three dimensions as well as the percolation rate from the falling head test, it was assumed that the two types of infiltration capacity tests could be collated. It should be noticed that the percolation rates derived from simple falling head tests are considered more inaccurate than, e.g., saturated hydraulic conductivity measured using a constant head test. Hence, comparing infiltration capacities from one investigation to another should only be done when the used infiltration test is known in detail.

2.2.4. In Situ Vane Tests

The vane shear test was used to find the undrained shear strength of cohesive soils. The test can be performed directly in the field and was conducted in accordance with the Danish Geotechnical Society-Field Committee (1999) guidelines [45]. In this study, the vane tests were conducted at the same depth as the infiltration tests or during the drillings at various drilling depths. The vane test was performed by gently lowering a four-blade stainless steel vane of approximately 10 cm into the ground. In order to find the peak of the undrained shear strength, the blade was slowly rotated (1 rotation per minute) until the maximum torque was reached, and the vane rotated due to the cylindrical surface fail of the soil by shear. To determine the remoulded undrained shear strength, the vane was rotated 10 times in the ground, and the torque was measured.

3. Results and Discussion

In the following section, the results of this study are presented and discussed. In order to perform a quantitative evaluation of the resistivities versus the infiltration capacity and the resistivities versus the undrained shear strength of cohesive soils, simple linear regression tests were conducted on the data. From the simple linear regression tests, we assessed whether a significant linear relationship between an independent variable X and a dependent variable Y exists. In our two tests, the dependent variable Y is either the percolation rate or the undrained shear strength of cohesive soils, and the independent variable *X* is, in both tests, the resistivity.

Assuming a linear relationship between an independent variable X and a dependent variable Y exists, their relationship can be expressed as follows:

$$Y_i = \alpha + \beta X_i \tag{2}$$

where α is a constant, β is the slope of the regression line, X_i is the independent variable, and Y_i is the dependent variable. In the simple linear regression test, we tested whether the slope of the regression line is significantly different from zero using the following hypothesis test:

$$\text{Null Hypothesis: } H_0\text{: } \beta = 0 \tag{3}$$

$$\text{Alternative Hypothesis: } H_a\text{: } \beta \neq 0 \tag{4}$$

In order to test the hypothesis, a linear regression t-test with $n - 2$ degrees of freedom was conducted using a significance level of 0.05. If the calculated p-value was less than the significance level, the null hypothesis was rejected. If the null hypothesis were rejected, we would be able to conclude that there is a significant relationship between the independent and dependent variables. Further information about the simple linear regression test is thoroughly described by, e.g., Blæsild and Granfeldt [46].

For qualitative evaluation of the lithologies versus resistivities and percolation rates, box plots were used.

3.1. Resistivities Versus Lithology

In Figure 2 we show the minimum, maximum and median values as well as the Q1 and Q3 quartiles for resistivities of various lithologies at 1 m bgs. for all the investigated sites. The lithologies derived from the drillings are only included if more than 75% of the soil within the depth interval, that is from 0.5 m to 1.5 m, had the same main lithology. The resistivity is obtained using the DUALEM-421S measurement nearest the drilling.

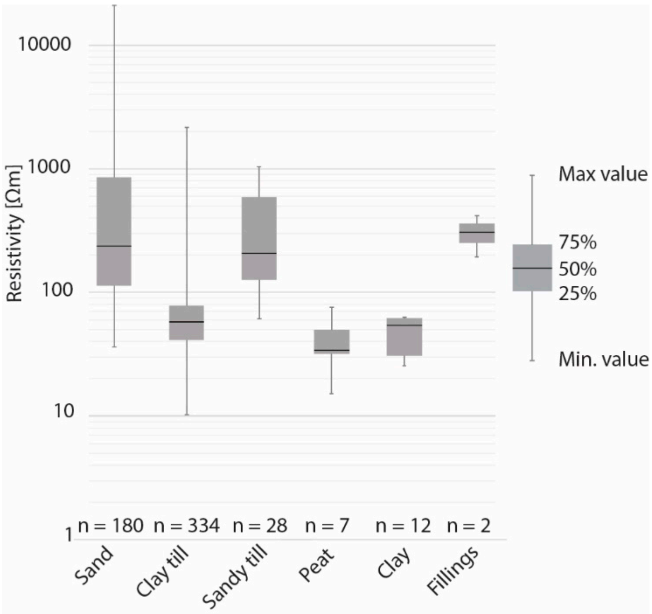

Figure 2. Box plot showing the resistivities of the different soil types observed within all the investigated areas. N represents the amount of measurements for each soil type.

As seen from the box plot, the units cannot, with high certainty, be distinguished from each other by their resistivities alone, as the maximum and minimum resistivity range in many situations are overlapping. However, the box plot shows that sand-dominated lithologies, such as sand, sandy till and fillings have higher resistivities relative to clay and organic-dominated lithologies, such as clay, clay till and peat/organic clay. The median resistivity for sand, sandy till and fillings are 229, 201 and 296 Ωm, compared to the median resistivity for clay till, peat and clay, which are 56, 33 and 30 Ωm. For the sand-dominated deposits, the Q1 quartile for sand is the lowest with 110 Ωm, and for the clay-dominated deposits, the Q3 quartile for clay till were the highest with 76 Ωm. Hence, a cut-off value ranging from 80 to 100 Ωm can be used on a regional scale to separate the sand-dominated deposits from the clay-dominated deposits. These findings are in accordance with other Danish investigations. In Barfod et al., [31] and in Frederiksen et al., [36], a cut-off value of 80 Ωm was selected in order to separate the sand-dominated deposits from the clay-dominated deposits. From Figure 2, it is also observed that it is impossible to separate sand from sandy till and fillings based on their resistivity alone, as their median resistivity values only show minor variances. Likewise, it is not possible to distinguish between clay till, peat and clay on a regional scale.

As described in the Introduction, multiple studies have described an empirical correlation between resistivity and lithology [25–28]. This correlation depends on several factors, such as water saturation, clay content, clay type, soil compaction, pore water ion content and matrix resistivity [29]. For water-saturated clay-free porous media, such as sand, Archie's law [25] is valid, showing an empirical relationship of electrical conductivity to fluid (pore water ion content) and water content:

$$\sigma_b = \frac{\sigma_w}{\mathrm{F}} \tag{5}$$

where σ_b is the bulk conductivity of the formation, σ_w is the fluid conductivity, and F is the formation factor. For clayey sediments, Archie's law is not valid, as the matrix itself is electrically conductive. Multiple models have been proposed in order to account for the conductive clay minerals [26,47,48]. In general, for both clay and clay-free sediments, the resistivity increases with decreasing water content [49,50]. As the present investigation focuses on the upper metres of the soil, the water saturation of the soil itself, as well as the groundwater level, has a strong influence on the measured resistivity. This is exemplified in the Provstlund case (described in Section 4) where the soil samples 1 m bgs in borehole B7, B11 and B13 all were described as clay till but had measured resistivities above 500 Ωm. All the soil samples were from the unsaturated zone located on the highest elevation of the site. The very high resistivities are assumed to result from a very low water saturation of the clay till.

The local and seasonal variations of water content are assumed to be the most important obstacle in interpreting the geophysical mapping and hence hamper a regional translation from resistivity into lithology, especially when operating in the upper 1–2 m bgs, where weather conditions have a huge impact on the water saturation of the soil and the presence of groundwater. The geophysical mapping, therefore, cannot stand alone and has to be correlated with soil descriptions from boreholes and infiltration tests covering the different units identified on the site.

3.2. Resistivities Versus Infiltration Tests

In Figure 3, resistivity is plotted against the percolation rates. A simple linear regression test has been conducted on the data. With a p-value below 0.05 (5.6×10^{-5}), we reject the null hypothesis representing uncorrelated parameters. Hence, a significant relationship between resistivity and the percolation rates on a regional scale exists. The linear regression line has an R^2 value of 0.11. Thus, the measured resistivity is only able to explain 11% of the observed variations in the percolation rates. The relationship between resistivity and percolation rates is therefore considered so weak on a regional scale that in reality no meaningful relationships can be establish. Notice, as the resistivity and percolation rates are plotted as a log-linear using a logarithmic scale on the x-axis, and a linear scale on the y-axis the linear regression line is curving.

3.3. Lithologies Versus Infiltration Tests

In Figure 3, a box plot showing the measured 147 percolation rates for various lithologies is presented. The lithologies were derived from boreholes located within 1 m from the infiltration test or from the soil sample itself. As observed from the box plot, it is possible to assign an infiltration capacity with moderate certainty based on the lithologies, as the Q1 quartiles for sand and sandy till do not overlap with the Q3 quartile for clay till. The sand-dominated units, such as sand and sandy till, have relatively higher percolation rates than the clay-dominated clay till and have median percolation rates of 9.9×10^{-5} m/s for sand and 6.5×10^{-5} m/s for sandy till, compared to 2.6×10^{-5} m/s for clay till.

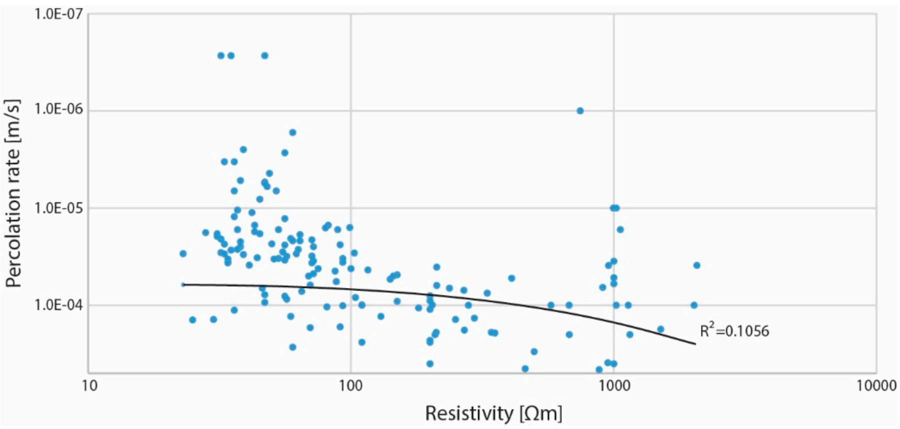

Figure 3. Plot showing the resistivity versus the percolation rate.

It is important to estimate the infiltration capacity of the different soils, as it will determine the most suitable location for the selected SUDS as well as the expected performance and size of the SUDS solution. As observed in Figure 4, the percolation rate of both sand and clay till varies significantly. For the sand-dominated deposits, a few infiltration test outliers and the presence of fine-grained sand account for the low percolation rates of around 1×10^{-6} m/s. The percolation rate of clay till varies from 2.7×10^{-7} m/s to 2×10^{-4} m/s. These results are in accordance with the results obtained by Bockhorn et al. [38]. The variation in percolation rates for the clay till is most likely due to soil structure, the CaCO3 boundary and earthworm burrows. Bockhorn et al. [15] investigated various factors controlling the infiltration capacity of SUDS in clay till and found that fractures, earthworm burrows and structural changes in the soil had a significant effect on the infiltration capacity.

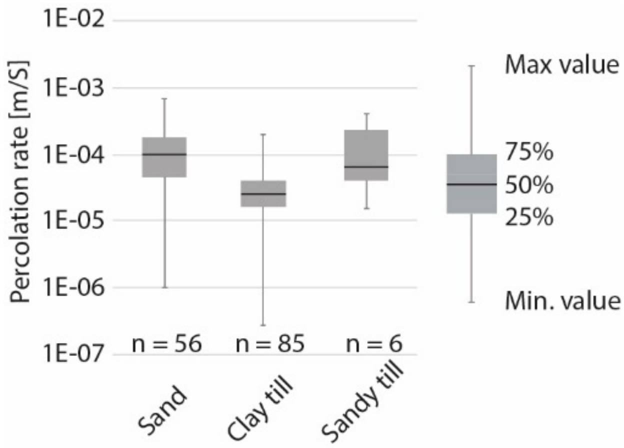

Figure 4. Box plot showing the percolation rates for sand, clay till and sandy till for all investigated areas. N represents the amount of measurements for each soil type.

3.4. Resistivities Versus in Situ Vane Tests

In Figure 5, resistivity is plotted against the undrained shear strength of cohesive soils obtained using the in situ vane tests. A simple linear regression test has been performed on the data. With a p-value below 0.05 (2.3×10^{-3}), we reject the null hypothesis that there is no relationship between the two variables being studied. Hence, there exists a significant linear regression relationship between resistivity and the undrained shear strength of cohesive soils. The linear regression line has an R^2 value of only 0.038. Thus, the measured resistivity is only able to explain 4% of the observed variations in the undrained shear strength of cohesive soils, implying that the relationship between the resistivity and undrained shear strength of cohesive soils must be very weak on a regional scale, and in reality no meaningful relationships can be establish. Notice, as the resistivity and the undrained shear strength of cohesive soils is plotted as a log-linear using a logarithmic scale on the x-axis, and a linear scale on the y-axis the linear regression line is curving. In the literature, other studies have tried to establish a relationship between electrical resistivity and geotechnical data, such as standard penetration test (SPT), dynamic cone penetration test (DCPT), Atterberg limit, triaxial compression, oedometer consolidation as well as the in situ vane test [51–56]. As in this study, they found that the relationships are area-specific, and the results cannot be transferred from one area to another.

As seen from the quantitative analysis, no reliable relationships could be established between resistivity and the percolation rate or the undrained shear strength of cohesive soils on a regional scale. The obtained DUALEM-421S data used in the quantitative analysis has not undergone any data transformation (e.g., been sorted or binned logarithmically) before being used in the statistical analysis which most likely would have improved the R^2values. However, as this study aims to investigate an immediate relationship between the measured DUALEM-421S data and the percolation rate or the undrained shear strength of cohesive soils without the use of a time-consuming and thereby more expensive data transformation process, this has not been conducted in this investigation.

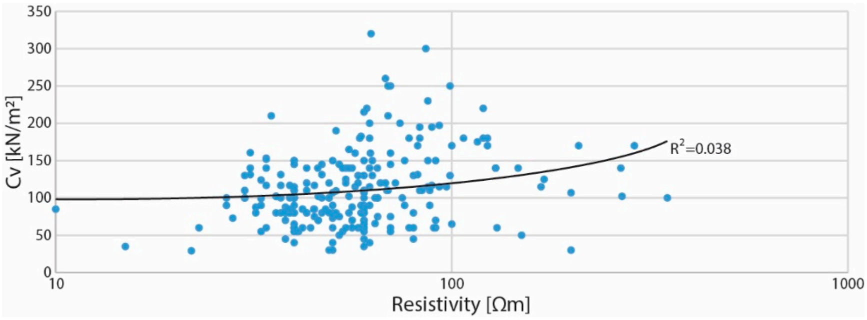

Figure 5. Resistivity plotted against the undrained shear strength of cohesive soils.

Based on the qualitative analysis, the comparison of the lithologies versus resistivities and percolation rates can be estimated with moderate to high certainty on a regional scale. If used with caution, the qualitative findings can be used in the initial investigation phase in order to translate the geophysical mapping into an overall lithology and assign a percolation rate as well as an undrained shear strength of cohesive soils. If more credible relationships are necessary for the urban planners to construct, e.g., potential infiltration planning maps, then site-specific local investigations are needed. This will be exemplified with one case study from Provstlund (no. 21, Figure 1 and Table 1).

4. Case Study: Provstlund

The Provstlund site is a 27 ha formerly agricultural area situated about 5 km northwest of Horsens, Figure 6. In 2017, the site was mapped with DUALEM-421S, resulting in a total of 60,301 measurements. Of that, 4.3% of the data was removed due to noise or couplings from buried conductors, leaving a total of 57,714 measurements for the inversion. The time span of the geophysical mapping was one day.

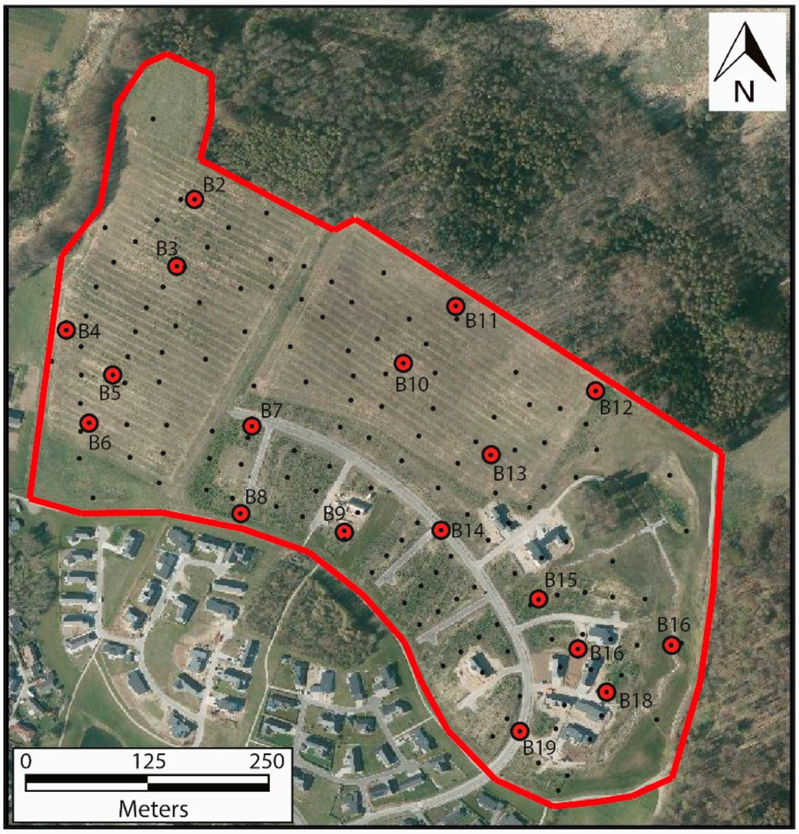

Figure 6. Overview map showing drillings (black dots) and infiltration test (red dots).

The mean interval resistivity plots from the DUALEM-421S are plotted in Figure 7. From 0 to 3 m bgs, the interval resistivity plots each represent the calculated mean resistivity within 50 cm of soil. From 3 to 6 m bgs, each interval resistivity plot represents 1 m. The calculated mean interval resistivity plots are blinded at the calculated penetration depth (DOI), so the number of data points decreases downwards. At the Provstlund site, the penetration depth varied from 5 to 7 m. The calculated mean resistivity is presented as points, and no kind of interpolation of the calculated values has been made. As observed in Figure 7, high resistances (> 100 Ωm) were generally seen in the upper 1.0 m in large parts of the area. Smaller areas with medium resistances (30–60 Ωm) were seen mainly in the north-western and south-eastern parts of the area. The extent of the medium resistivity areas was typically 150 to 200 m^2. From 1 to 2 m bgs, the medium resistivity areas expanded to more continuous and larger areas. The largest areas were observed towards the southeast, central and west. From 1.5 to 2 m bgs, 1/3 of the area comprised areas with medium resistivities, and 2/3 of the area comprised areas with high resistivities. Larger contiguous high-resistivity areas were seen in the central part of the region as well as in the north-eastern corner and in the north-western and south-western parts of the area. From 2.5 m bgs to 6 m bgs, similar resistivity patterns were observed, with half the area comprising of medium resistivity and the other half of high resistivity areas. The high resistivity areas were observed in the north-western, south-western and eastern parts of the area. The north-western and south-western high resistivity areas had the same overall size and shape, whereas the eastern high resistivity area shrank in size with depth.

Within a few days of the geophysical mapping, 18 drillings, each 4 m deep, 18 infiltration tests and 19 in situ vane tests were performed. The drillings were placed in uniform resistivity zones based on the geophysical mapping results. In the additional geotechnical investigation phase, around three months after the geophysical mapping, 143 drillings ranging in depth from 4 to 6 m and 141 in situ vane tests were conducted, as shown in Figure 6. Their placement was independent of the results from the geophysical mapping campaign.

In all the drillings, the groundwater level was observed to be situated below the terminus of the drillings, implying that it is located more than 4 m bgs. Out of the total set of drillings, 159 were described with respect to lithology and groundwater level and in 59 of the drillings the undrained shear strength was obtained. In Figure 8, the box plot showing the minimum, maximum and median values as well as the Q1 and Q3 quartiles for resistivities of various lithologies at 1 m bgs at Provstlund is plotted. The lithologies were derived from the drillings, and the resistivity was selected from the nearest DUALEM-421S measurement.

As observed from Figure 8, sand and clay till can be distinguished with moderate to high certainty based on their resistivities, as the upper Q3 (75%) and the lower Q1 (25%) quartiles do not overlap. On the other hand, it is not possible to clearly distinguish sandy till from either sand or clay till, as their upper Q3 (75%) and lower Q1 (25%) quartiles overlap. Thus, sandy till might be misinterpreted as sand or as clay till. The median resistivities were 445, 198 and 83 Ωm for sand, sandy till and clay till, respectively. At the Provstlund site, the differences in median resistivities for sand, sandy till and clay till were +216, -4 and +27 Ωm, respectively, compared to the regional median resistivity. The higher resistivities of sand and clay till at Provstlund were most likely due to low water saturation of the soils and low-lying groundwater level. Hence, the cut-off value between sand and clay till was set to 150 Ωm, compared to the regional scale cut-off value that is between 80 to 100 Ωm. The high difference in cut-off values between Provstlund and the regional value showed that local data sampling was necessary to create reliable translations between resistivities and lithologies.

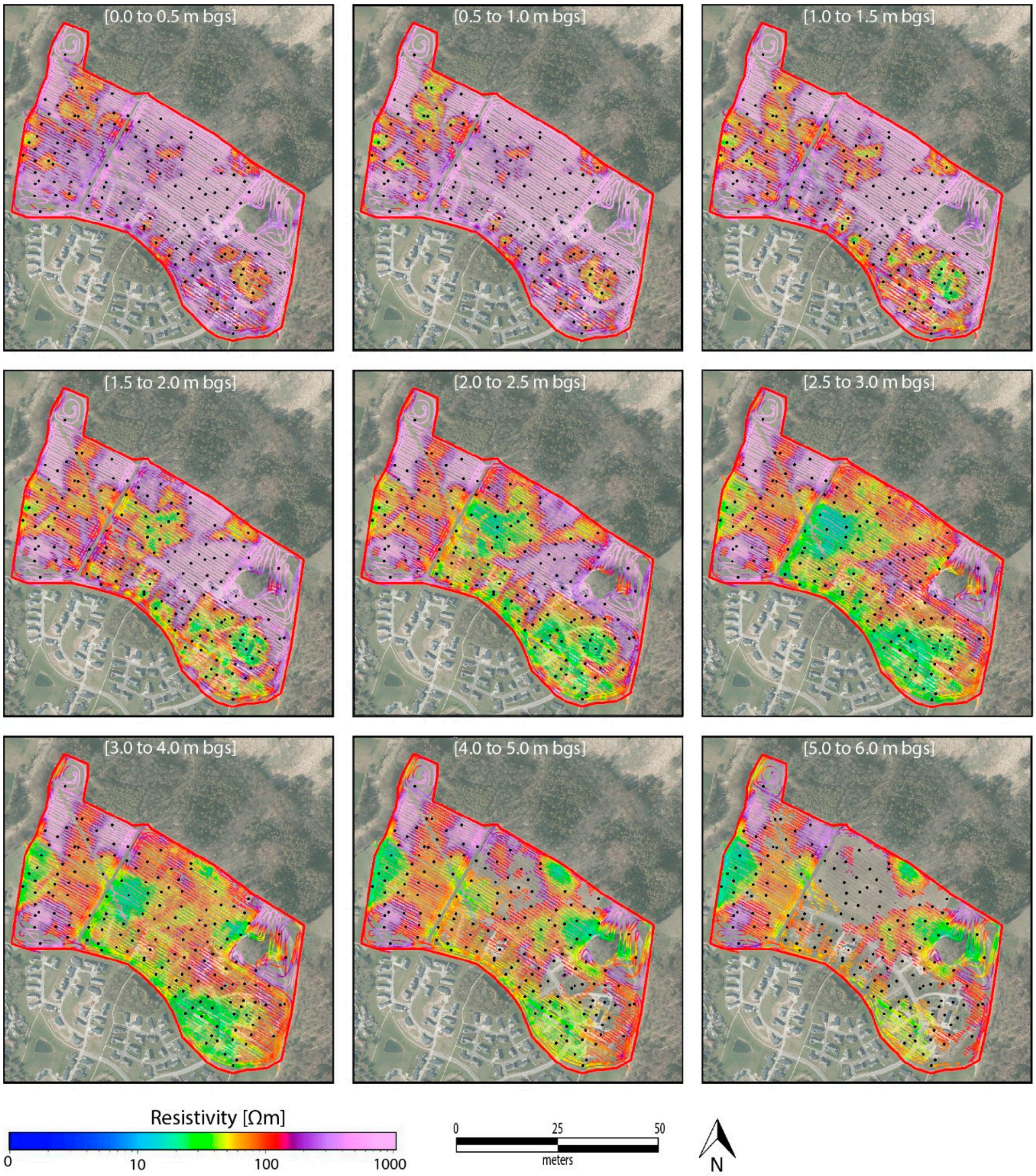

Figure 7. Interval resistivity maps from selected depths. The black dots represent drillings.

To obtain an overview of the hydraulic capacity of the soil layers in the area, 18 infiltration tests were performed (see Figure 6). The infiltration tests were performed next to the boreholes so that the results could be compared with the geological descriptions, as in Table 2. To obtain a representative measurement, the topsoil layer (approx. 0.5 to 1 m) was excavated before performing the infiltration tests, so that all tests were made on undisturbed soil. Table 2 shows the results of the infiltration tests and the geophysical mean resistivity values measured in the depth range 0.5 to 1 m, which represented the depth the infiltration tests were performed in. In general, a very good correlation was seen between areas with high resistance, a sandy lithology from the boreholes and high percolation rates spanning from 1×10^{-4} m/s to 4×10^{-5} m/s, Table 2. However, boreholes 11 and 13 should be mentioned; both showed high resistances but were described as moraine clays and had percolation rates of around 4 to 5×10^{-5} m/s, which was interpreted as dry moraine clays. The remaining boreholes were all described as having moraine clays in the upper 1 m, which correlated well with the low resistances (30–80 Ωm) and percolation rates spanning from 5×10^{-5} m/s to 5×10^{-6} m/s. All the percolation rates obtained at the Provstlund site are similar to the regional percolation rates (see Figure 4).

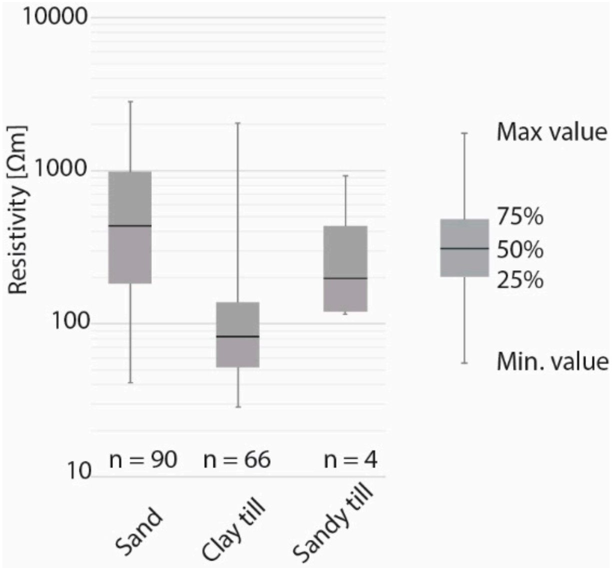

Figure 8. Box plot showing the resistivities within the Provstlund site. N represents the number of measurements for each soil type.

Table 2. Boreholes, Measured Percolation Rates, Nearest Resistivity and Lithology for the 18 Drillings at the Provstlund Site.

Borehole no	Percolation Rates (m/s)	Resistivity 1 m bgs (Ωm)	Lithology (1 m bgs)
B2	6.67×10^{-5}	40	Clay till, sandy
B3	7.78×10^{-5}	38	Clay till, sandy
B4	1.23×10^{-5}	36	Clay till
B5	4.39×10^{-6}	38	Clay till
B6	1.67×10^{-5}	886	Sand
B7	7×10^{-5}	541	Clay till
B8	3.33×10^{-5}	561	Sand
B9	2.96×10^{-5}	64	Clay till
B10	3.67×10^{-5}	73	Clay till
B11	6.55×10^{-5}	1750	Clay till, sandy
B12	2.33×10^{-5}	65	Clay till
B13	3.89×10^{-5}	2073	Clay till
B14	1.76×10^{-4}	2550	Sand
B15	3.33×10^{-5}	93	Clay till
B16	2.08×10^{-5}	53	Clay till
B17	3.52×10^{-5}	1601	Sand
B18	1.79×10^{-5}	50	Clay till, sandy
B19	1.50×10^{-5}	102	Clay till

A total of 46 in situ vane tests were conducted in Provstlund in order to achieve the undrained shear strength of cohesive soils. A simple linear regression test was conducted on the data. With a *p*-value above 0.05 (0.69), we cannot reject the null hypothesis that there is no relationship between the two variables being studied. Hence, at the Provstlund site, we cannot conclude whether or not there is a significant linear relationship between resistivity and the undrained shear strength of cohesive soils.

Thus, in order to achieve a reliable overview of the undrained shear strength, multiple in situ vane tests need to be conducted.

Based on the geophysical mapping, soil descriptions and infiltration tests, high-resistivity areas can be interpreted as sand-dominated areas having percolation rates spanning 2×10^{-5} m/s to 1×10^{-4} m/s, corresponding to medium to fine-grained sand. Similarly, low resistivity areas can be interpreted as clay-dominated areas with percolation rates between 5×10^{-5} m/s to 5×10^{-6} m/s, corresponding to clay tills. Based on the data, a planning map for the Provstlund site can be created showing areas suitable for the infiltration of surface water, as in Figure 9. The geophysical mapping, soil descriptions from boreholes and infiltration tests provide information on the volume, areal extent and hydraulic properties of various soils, and the groundwater head measurements provide information about the volume of the unsaturated zone. Combining the data enables city planners to construct planning maps with precise estimates of the most suitable areas for infiltration as well as the volume of free space in unsaturated soil for infiltrated water. As observed from Figure 9, the most suitable areas for infiltration are located throughout the Provstlund site, with the biggest continuous areas in the eastern and south-western parts of the site. Medium-sized areas are observed in the northern part of the site and the smallest area in the south. The areas are characterised as having high resistivity areas, boreholes showing sand-dominated soil descriptions, infiltration capacities of 2×10^{-5} m/s to 1×10^{-4} m/s and a thickness of more than 4 m in the unsaturated zone.

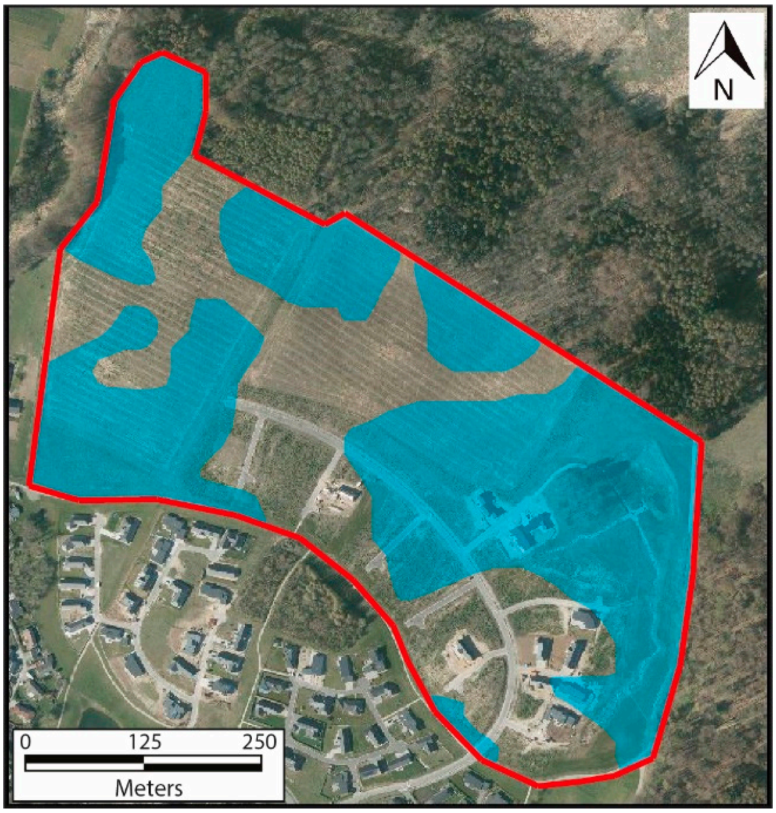

Figure 9. Areas marked with blue are found to be suitable areas for infiltration.

A planning map showing the most suitable areas for infiltration provides authorities with a powerful tool when planning the future urbanisation of the site. The map enables them to organise the areas based on holistic water cycle management, focusing on the best SUDS solution for the area, instead of having the individual citizens handling their own rainwater, creating multiple bad solutions. The best-suited locations for potential infiltration are defined, primarily based on the areal extents of the various soils, their percolation rates and the thickness of the unsaturated zone.

The DUALEM-421S method has proven to be very useful for producing a comprehensive overview of the horizontal and vertical resistivity distributions of the future urban site. The DUALEM-421S system, depending on site conditions, is able to cover up to 50 to 80 km in one field day, providing a high-density geophysical mapping of the upper 5 to 10 m of the subsurface. In this investigation, the DUALEM-421S was able to distinguish clay-dominated sediments, such as clay till and meltwater clay from sand-dominated sediments, such as sand, sandy till and fillings with moderate to a high degree of certainty. This investigation found the regional cut-off value between clay-dominated sediments and sand-dominated sediments to be around 80 to 100 Ωm, which is in accordance with the results from Frederiksen et al., [36] and Barfod et al., [31]. However, as the investigation focuses on the upper meters of the subsurface, the obtained resistivity results are highly dependent on the water saturation of the soil and the groundwater level. This is illustrated by the Provstlund site, where unsaturated sand and clay tills yielded a higher cut-off value of 150 Ωm. Thus, the DUALEM-421S method has to be supplemented with boreholes yielding soil descriptions and groundwater head measurements. Without dense geophysical mapping combined with infiltration tests, boreholes and groundwater head measurements, the planning maps would have been inaccurate, leading to incorrect decisions in the future.

The Provstlund case study illustrates that combining geophysical mapping with boreholes and infiltration tests facilitates the construction of accurate and reliable planning maps. The amount of data necessary for constructing the planning maps is highly dependent on the complexity of the geology and therefore changes from case to case. Typically, with a high-density geophysical mapping campaign with, e.g., DUALEM-421S, the number of boreholes and infiltration tests necessary for constructing the planning maps can be limited, compared to traditional Danish investigation strategies. In the Provstlund case, the strategy of placing 18 boreholes in various resistivity zones yielded sufficient information to construct the planning map with respect to water management. During the traditional geotechnical investigation, a total of 143 additional drillings were conducted, and they did not significantly improve the overall geological knowledge of the site. However, it should be noted that drillings are necessary, as the geophysical mapping cannot substitute the geotechnical data derived during the drilling campaign.

5. Conclusions

Based on 1315 ha of high-density electromagnetic (DUALEM-421S) data, detailed lithological soil descriptions of 614 boreholes, 153 infiltration tests and 250 in situ vane tests, regional relationships between resistivity and lithology and percolation rates and undrained shear strength of cohesive soils were tested at a depth of 1 m bgs.

This investigation revealed that the DUALEM-421S method is able to map the upper 5 to 10 m of the subsurface in very high detail, yielding a precise overview of the vertical and horizontal resistivity distribution.

Based on the qualitative tests a translation from resistivity to lithology as well as a translation from lithologies to percolation rates could be conducted with a moderate to high degree of certainty. We found a regional cut-off value separating sand-dominated deposits from clay-dominated deposits is between 80 to 100 Ωm and a regional median percolation rate for sand and clay till to be 9.9×10^{-5} m/s and 2.6×10^{-5} m/s, respectively.

The quantitative results showed a very weak relationship between the resistivity and percolation rates and the resistivity and the undrained shear strength of cohesive soils and in reality no meaningful relationships can be establish.

The regional qualitative results were tested on the Provstlund case-study area in order to illustrate how combining geophysical mapping with boreholes and infiltration tests can support the construction of accurate and reliable planning maps showing the most suitable locations for infiltration. The Provstlund case study finds that the overall regional results only should be applied in the initial screening phase in order to translate the geophysical results into lithology units and assign them with percolation rates. Hereafter site-specific investigations are necessary to directly estimate lithology, percolation rates and undrained shear strength of cohesive soils due to the differences in the physical properties of the soil from site to site. The largest uncertainties originate from the variation in soil saturation and groundwater level, causing resistivity ranges for each lithology to widen.

The presented findings reveal that geophysical mapping in combination with lithological descriptions, infiltration tests and measurements of groundwater levels yield the basis for the construction of detailed planning maps showing the most suitable locations for infiltration. These maps contain valuable information for city planners regarding future developments and reduce uncertainty. They provide unique information by which a SUDS in a specific area may be restricted or precluded, as well as information about the expected performance of the SUDS.

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A review of nature-based solutions for urban water management in European circular cities: a critical assessment based on case studies and literature

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Abstract

Nature-based solutions (NBS) can protect, manage and restore natural or modified ecosystems. They are a multidisciplinary, integrated approach to address societal challenges and some natural hazards effectively and adaptively, simultaneously providing human well-being and biodiversity benefits. NBS applications can be easily noticed in circular cities, establishing an urban system that is regenerative and accessible. This paper aims to offer a review on NBS for urban water management from the literature and some relevant projects running within the COST Action 'Implementing nature-based solutions for creating a resourceful circular city'. The method used in the study is based on a detailed tracking of specific keywords in the literature using Google Scholar, ResearchGate, Academia.edu, ScienceDirect and Scopus. Based on this review, three main applications were identified: (i) flood and drought protection; (ii) the water-food-energy nexus; and (iii) water purification. The paper shows that NBS provide additional benefits, such as improving water quality, increasing biodiversity, obtaining social co-benefits, improving urban microclimate, and the reduction of energy consumption by improving indoor climate. The paper concludes that a systemic change to NBS should be given a higher priority and be preferred over conventional water infrastructure.

Key words: climate change resilience, nature-based solutions, stormwater, urban water, wastewater treatment

INTRODUCTION

According to the 2018 Intergovernmental Panel on Climate Change (IPCC) report, global climate change will cause irreversible harm to humans, the built environment and the biosphere (IPCC 2015). In particular, the depletion and degradation of pristine water resources is expected to affect significantly human and environmental health. In addition, the rapid increase of urban areas, resulting in a higher demand for water resources as well as disruption of the natural water cycle, accentuates the importance of sustainable and resilience-based water management. Hence, it is essential for urban water management (UWM) to be an integral part of urban planning. Moreover, land use decisions affect water supply and wastewater system designs and operation, as well as measures needed for managing stormwater runoff. Furthermore, an urban infrastructure system requires energy, which in turn, typically requires water (Loucks & Van Beek 2017). Consequently, water is one of the key elements of the United Nations Sustainable Development Goals (SDGs), alone or interlinked with different aspects. For instance, several of the 17 objectives are strongly connected to urban farming and call for an economical utilisation of assets, environment rebuilding, biodiversity, carbon sequestration, feasible catchment management and soil management (Keesstra *et al.* 2016).

Urban water refers to all water that is present in urban environments which includes natural surface water, groundwater, drinking water, sewage, stormwater, flood overflow water and recycled water (a third pipe, stormwater harvesting, sewer mining, managed aquifer recharge, etc.). Furthermore, a wide range of techniques can solve urban water-related problems, for example, improving water use efficiency and water demand reduction techniques, water sensitive urban design (WSUD) techniques, living streams, environmental water and protection of natural wetlands, waterways and estuaries in urban landscapes (water.gov.au, 2017). Larsen & Gujer (1997) defined UWM as a combination of water supply, urban drainage, wastewater treatment and water-related sludge handling. Accordingly, UWM includes the plan, design and operation of infrastructure to secure drinking water and sanitation, the control of infiltration and stormwater runoff, recreational parks and the maintenance of urban ecosystems.

Sustainable urban development includes a holistic management approach consisting of the water-energy-food nexus, land use and the diversification of water sources for reliable supplies (Kalantari *et al.* 2018). Further, integrated urban water management (IUWM) provides a framework and

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objective for planning, designing, and managing urban water systems. Moreover, IUWM is a flexible process that responds to change and enables stakeholders to participate in, and predict the impacts of development decisions. Consequently, adequate IUWM includes the environmental, economic, social, technical and political aspects of UWM. It enables better land use planning and the management of its impacts on freshwater supplies, treatment and distribution; wastewater collection, treatment, reuse and disposal; stormwater collection, use and disposal; and solid waste collection, recycling and disposal systems. Accordingly, it makes urban development part of integrated basin management, which is oriented toward a more economically, socially and environmentally sustainable mixed urban-rural landscape (Loucks & Van Beek 2017; Kalantari *et al.* 2018; Arabameri *et al.* 2019). IUWM also aims to help cities progress towards a circular economy, thus closing the loop of water resource circulation, and helps to limit the discharge of liquid waste and the constantly growing need for additional water resources (High level Panel on Water 2018).

As a result of increasing urban areas, the interaction of many factors such as demographic, economic, political, environmental, cultural and social factors creates challenges related to the use and management of water resources. Several of these issues can be addressed with nature-based solutions (NBS). NBS aim to protect, sustainably manage, and restore natural or modified ecosystems. NBS address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (IUCN 2018). NBS also have the potential to underpin a sustainable water management strategy (FAO 2018).

This study is conducted under the European Cooperation in Science and Technology (COST), which funds the research Action ‘CA17133 – Implementing NBS for creating a resourceful circular city’. The circular city model recognises the importance of organising the city’s systems in an analogy to the organisation of natural systems and it incorporates the principles of the circular economy, establishing an urban system that is regenerative and accessible (Girard & Nocca 2019). This study aims to offer a brief review on NBS for UWM, together with a description of some relevant projects running within the action. In this COST Action, the definition of a common language and understanding across disciplines is seen as a crucial success factor, while circular economy (CE) concepts are seen as a key approach and NBS or green infrastructure (GI) solutions are seen as core elements of the toolbox (Langergraber *et al.* 2019). Our working group has focused on the implementation of a safe and functional water cycle within the urban biosphere, where wastewater needs to be streamlined as a source of nutrients, hazardous pollutants that should be controlled (e.g., heavy metals or emerging organic contaminants), heavy metals being phytomined, the treated water looped back for irrigation, and recreational purposes should be considered side by side with sanitation, water supply or stormwater management. Furthermore, we critically appraise the established centralised water flow, defining available resources within the water flow and risk assessment on urban water, NBS for stormwater management and wastewater treatment.

The main research question addressed in this paper is ‘How can NBS be integrated with the sustainable UWM?’ To answer this question we followed two parallel approaches: (i) a traditional literature review targeting a set of different subtopics, coupled with (ii) an overview of case studies from projects running within the framework of the COST Action. By combining both, we wish to provide not only the most complete overview of the current existing knowledge but also to discuss and challenge the current existing frameworks for NBS implementation. Therefore, the aim of this paper is to define the challenges, present benefits and future trends, provide an overview of the usage of NBS for UWM and to offer implementation recommendations for urban water utilisation towards circular cities.

The paper is organised as follows. The ‘methodology’ section presents both the framework for the literature review and the selection criteria of relevant case studies. The next section describes the review through existing NBS tools for sustainable water management, subdivided into the sections ‘stormwater management’, ‘flood protection and risk management’, ‘implementation of blue-green infrastructures’, ‘urban water in the field of food, water, and energy ecosystem’, and ‘urban water

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pollution control: constructed wetlands'. Following on, a section describes some case studies, linking them with the existing literature. The final section offers a brief discussion, and some concluding remarks are provided to point the way forward for an increased implementation of NBS for UWM.

METHODOLOGY

Owing to the broad scope of the topic, different levels of implementation of NBS and availability of international peer-reviewed literature for certain subtopics, we propose a combined approach where both existing literature and case studies were reviewed using different criteria. This section is divided into two subsections. In the first subsection, we present the details of the literature survey to collect data of relevant international peer-reviewed journals, while in the second we describe the criteria for selecting relevant case studies important for the current review.

Literature review approach

The literature survey was performed independently by different sub-groups of authors involved in this work. Therefore, the details of the literature search are described in the next paragraphs per each subsection.

For the stormwater management section, the literature was searched in Google Scholar, ResearchGate, Academia.edu, ScienceDirect and Scopus by using the key words 'stormwater management' AND 'nature based solutions', 'stormwater management' AND 'historical development', 'climate change' AND 'resilience'. A total of 40 manuscripts (i.e., 10 Google Scholar, 2 ResearchGate, 2 Academia.edu, 15 ScienceDirect, 4 Scopus and 7 other publications were retrieved by cross-checking references from the initial retrievals from the databases) were retrieved and revised. After the first screening of the abstracts, 19 papers were disregarded and 11 were read and are presently discussed in this paper.

For the flood protection and risk management section, the literature was searched in Google Scholar, ResearchGate, ScienceDirect and Scopus by using the key words 'flood' 'risk management' AND 'nature based solutions'. A total of 34 manuscripts (i.e., 12 Google Scholar, 3 ResearchGate, 10 Science Direct, 3 Scopus and 6 other publications were retrieved by cross-checking references from the initial retrievals from the databases) were retrieved and revised. After the first screening of the abstracts, 23 papers were disregarded and 11 were read and are presently discussed in this paper.

For implementation of blue-green infrastructures section for flood protection and risk management section, the literature was searched in Google Scholar, ResearchGate, ScienceDirect and Scopus by using the key words 'flood', 'risk management', AND 'nature based solutions'. A total of 45 manuscripts (i.e., 10 Google Scholar, 12 ResearchGate, 8 ScienceDirect, 10 Scopus and 5 other publications were retrieved by cross-checking references from the initial retrievals from the databases) were retrieved and revised. After the first screening of the abstracts, 26 papers were disregarded and 19 were read and are presently discussed in this paper.

For the urban water pollution control section, a total of 60 manuscripts (i.e., 20 Google Scholar, 10 ResearchGate, 15 ScienceDirect, 10 Scopus and 5 other publications) were retrieved by Google Scholar, ResearchGate, ScienceDirect and Scopus by using the key words 'nature based solutions' AND 'urban water pollution control'. Among them, 10 papers were disregarded and 50 were read and discussed.

For the water-energy-food nexus section, the literature was searched in Google Scholar, ResearchGate, ScienceDirect and Scopus by using the key words 'nature based solutions' 'water' AND 'energy' AND 'food nexus'. A total of 36 manuscripts (i.e., 4 Google Scholar, 1 ResearchGate, 12 Science Direct, 2 Scopus and 17 other publications were retrieved by cross-checking references from the

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initial retrievals from the databases) were retrieved and revised. After the first screening of the abstracts, 13 papers were disregarded and 23 were read and are presently discussed in this paper. This section also generated two supplementary tables: Table S1 overviews the existing NBS and their link with the water-food-energy nexus and Table S2 compares groundwater-based natural infrastructure solutions with grey infrastructure.

Case studies selection criteria

International projects in which the CA1733 action members are directly involved dealing with NBS and sustainable water management were selected as case studies for this article. The data related to these case studies were obtained from the researchers involved in both the projects and COST Action. Figure 1 shows the geographical location of the case studies, further detailed in the section 'Case studies'.

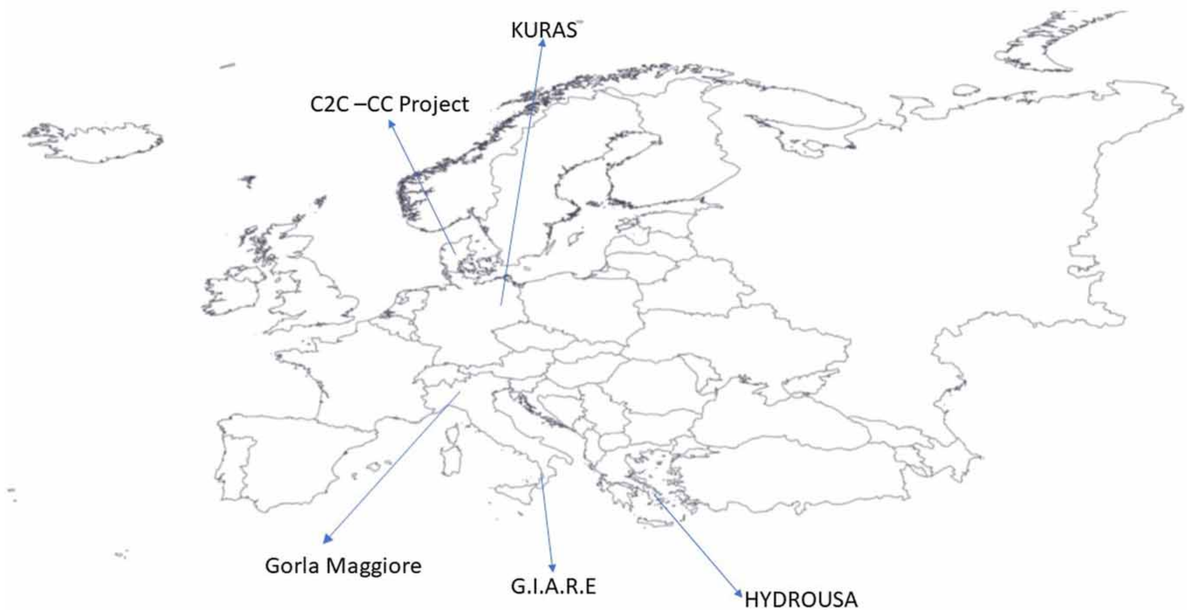

Figure 1 | Location of reviewed case studies within the COST Action.

REVIEW OF THE EXISTING NBS TOOLS FOR SUSTAINABLE WATER MANAGEMENT

In this time of anthropogenic climate change, urban regions around the world face natural disasters such as heat islands, droughts and floods, as well as urban pressures, for instance, air and water pollution along with resource management inefficiency. Consequently, the sustainable development of urban areas has resulted in decision-makers being caught in challenging situations, while simultaneously having to solve the problem of the excess of one resource and the lack of others. Therefore, based on individual cases, it seems rational to consider the possibility of implementing the concept of the circular economy in addition to connecting two problems – instead of defining them and seeing one aspect as the solution for other elements of a healthy urban socio-environmental system.

In this section, we group the sustainable water management under five categories as: (i) stormwater management, (ii) flood protection and risk management, (iii) implementation of blue-green infrastructures, (iv) urban water in the field of food, water and energy ecosystem and (v) urban water pollution control: constructed wetlands.

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Stormwater management

In recent years, stormwater management has become an increasingly multidimensional and multidisciplinary issue. Moreover, stormwater presents very distinct qualitative and quantitative characteristics from domestic sewage. It is recognised as the most important source of heavy metals, whereas wastewater constitutes the main source of organic and nitrogenous pollution (Bavor *et al.* 2001; Eriksson *et al.* 2007; Barbosa *et al.* 2012; Brown *et al.* 2013).

In many countries, separate sewer network systems are predominant, and most rainwater networks discharge rainwater directly to receiving waters, without any purification, which is a serious threat to the quality of such water. This is particularly dangerous for small watercourses flowing through cities for which rapid discharge from rainwater drainage systems exceeds the hydraulic capacities, and the introduced pollution load is a serious threat. Further, until the 1990s, it was believed that the best solution to the rainwater problem in cities should be drainage, i.e., efficiently collecting and discharging stormwater to receiving waters (Figure 2).

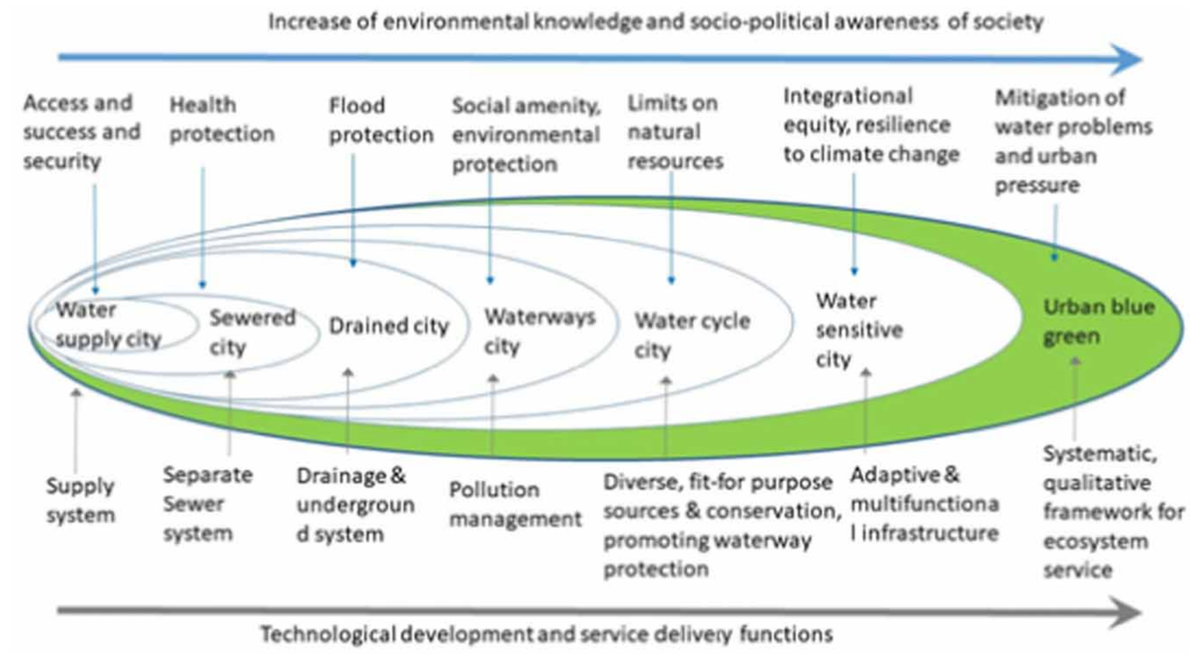

Figure 2 | Historical development of water supply and management (modified from Brown *et al.* (2009) and Blue Green Solution (2017)).

However, progressing urbanisation is inevitably connected to replacing the natural land cover with impermeable surfaces, which leads to increased surface runoff. Additionally, climate change is leading to more volatile rainfall patterns with an increasing number of extreme events, thereby causing frequent overloading of the drainage systems. As a result, floods are occurring, especially in central city districts with a high level of impervious surfaces. Such events, referred to as pluvial flash floods, are followed by long dry spells. For example, over the last 18 years in Gdańsk, Poland, more than four rainfall events with a 100-year return period (i.e., over 100 mm/day) have occurred. On 14/15 July 2016, 160 mm of rain fell within 14 hours, exceeding the total rainfall of two months. On the other hand, as mentioned above, long periods without precipitation are also causing functional problems for cities. Thus, the lack of stored rainwater increases the need for watering urban green areas with irrigation systems. Such approaches require both natural resources and financial support, thereby leading to their unsustainability (Wojciechowska *et al.* 2015).

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Despite the risks that water can pose in urban spaces, it is an integral part of the city and a vital resource for the residents. From the human health perspective, it is necessary to integrate water in the urban layout. Therefore, a modern approach to the urban planning of the so-called WSUD assumes the use of the most natural technological solutions, the so-called eco-engineering. We count green roofs, bioretention systems, 'rainforests' and hydrophyte systems that combine the function of purification and retention and provide many ecosystem services (ES), including biodiversity and returning rainwater to the local water cycle by evapotranspiration. The natural ground cover would only have 10% runoff with 40% via evapotranspiration and 50% through infiltration while the impervious cover would have 55% runoff with 30% evapotranspiration and 15% infiltration (US EPA 2003).

As presented above, existing water management systems are not sufficient in many cases, and the need to solve the problem of quantity and quality of water exists in order to implement the concept of an urban circular economy. The synergy of constantly growing urban areas with impervious surfaces and pollution associated with human activities, and climate change with an increasing number of meteorological extremes, requires a new approach for cities to become more resilient to socio-environmental pressures (Figure 3).

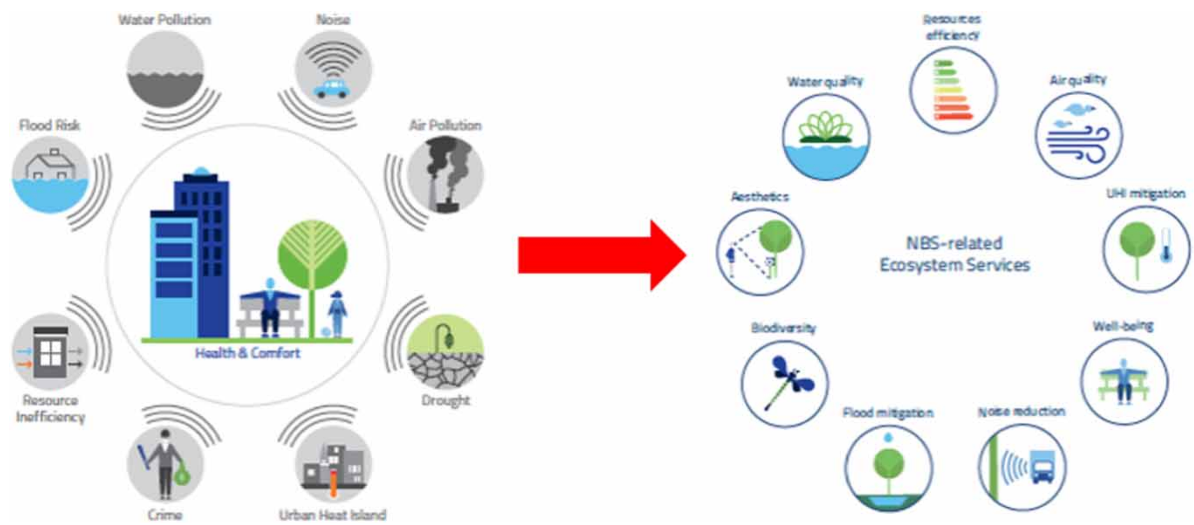

Figure 3 | Identified water problems and urban pressures and mitigation options by the application of NBS (Blue Green Solution 2017).

Therefore, based on the identified challenges, there is an urgent need to support the implementation of NBS in cities in order to contribute to climate change adaptation by reducing their vulnerability to environmental threats. NBS allow mimicking pre-development hydrologic regime and detaining runoff close to its source following the principle of low-impact development (Coffmann 1999; Bavor *et al.* 2001; Wong & Brown 2009; Hoyer *et al.* 2011) and use plants to later return the water to the local water cycle through evapotranspiration, thus supporting the plants in dry periods. Therefore, NBS become an essential feature of urban resilience managing stormwater, contributing to urban cooling through evapotranspiration and alleviating urban heat island effects while supporting urban green with local water resources.

Flood protection and risk management

Ecosystems, depending on their management, can either contribute to the problem or provide effective NBS for flood risk reduction or climate change mitigation and adaptation (Cohen-Shacham *et al.*

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2016). At the same time, the implementation of NBS depends on the state and capacity of ecosystems to provide particular regulating services (flood, erosion, climate). Their spatial dimensions provide a basis for land use management and urban planning decisions in accordance with an ecosystem-based approach for flood risk management and other aspects of urban environmental management (Szopińska *et al.* 2019). On the other hand, there are other, potentially very cost-effective ways of achieving flood protection by tapping into nature's own capacity to absorb excess waters (EC 2016b). Consequently, NBS implementation aims at preventing natural disasters to make urban areas safe and resilient, which can be achieved in combination with technological and engineering solutions if necessary.

Planning infrastructures to manage flood risk is related to connectivity (Parson *et al.* 2015), circularity (Kirchherr *et al.* 2017; Comino *et al.* 2018; Keesstra *et al.* 2018) and finding a balance between natural and urban elements (Gaines 2016). Moreover, in a fast developing city, the loss of circularity is often associated with the altered hydrological cycle, implying that water is not a natural, valuable resource, but rather a threat to the urban environment, when it flows at rates different from those of natural paths, from/toward locations that are functional to the development of human activity rather than to the environmental dynamics, through man-managed (often fast) connections, with quality standards far from those provided by natural water bodies (EPA 2005).

Consequently, the loss of circularity in the altered natural water cycle is derived from the reduction of soil infiltration capacity and resulting in fast surface runoff. The fact that the natural water cycle is replaced by the urban water cycle threatens soil, channelised urban drainage systems, receiving water bodies and downstream cities. Furthermore, the wash-off of pollutants from anthropogenic catchments poses a threat to the receiving water bodies and their biomes. The loss of infiltration and uncontrolled leakage from sewage threaten groundwater and connected surface water bodies. Subsequently, the resources, politics and awareness affect the socio-environmental dynamics and determine whether the socio-hydrological system will undergo irreversible decline or be self-sustainable (Ursino 2019).

NBS, in this context, is meant to partially recover the pre-development water fluxes and water quality, thus reducing the flood risk (WWAP 2018). Therefore, the use of NBS in this context is strongly related to the well-known concept of sustainable urban drainage, known in the literature with different key words, such as sustainable drainage systems (SuDS), WSUD or low impact development (LID), as reviewed by Fletcher *et al.* (2015). All these concepts aim to restore the water cycle within an urban catchment, from post-development back to the pre-development state (Fletcher *et al.* 2013). Thus, based on site-specific characteristics and the aim of implementation (to recover original functionality of the urban catchment or address specific issues linked to water management and risk control), NBS alone may not be able to re-establish complete circularity of the natural water cycle but rather provide multiple services to the community (e.g., mitigate flood and drought risk, affect local climate conditions, increase amenity and biodiversity). Further, based on the scale at which NBS are integrated into the so-called GI, different benefits can arise (Golden & Hoghooghi 2018). For instance, Zhang *et al.* (2019) investigated how NBS across facility, catchment and continental scales differently impact the hydrological, water quality and bioecological benefits.

Implementation of blue-green infrastructures

One of the most common ways to implement NBS is by the so-called blue-GI. Blue-green infrastructures are key elements in the holistic planning of (future) urban regions (Winker *et al.* 2019). Accordingly, blue-green infrastructures create strategically planned networks of (artificial) natural spaces in cities (Bundesamt für Naturschutz 2017). Therefore, the use of NBS seeks to minimise the effects of climate change on urban areas and create various ecosystem services with benefits

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for the society, environment and economy. NBS can help create natural circumstances in urban areas for 'alleviating urban pressures and achieve resilience to climate change' (Maksimovic *et al.* 2017).

Blue-green infrastructures establish multifunctional structures as diverse green spaces in combination with elements of WSUD (Winker *et al.* 2019) to strengthen urban sustainable development. Accordingly, 'green' infrastructural elements take essential roles in creating a healthy microclimate in cities. For instance, trees reduce flood risks and the effect of urban heat islands and expand shading while pocket parks (and streams) aesthetically attract citizens and provide space relieving mental aspects of urban pressure (Maksimovic *et al.* 2017). 'Greening' transforms cities by unsealing surfaces and is applied on building structures to lower buildings' energy level by natural cooling, which saves costs and works in aesthetical ways. Further, green rooftops have a multifunctional use within blue-green infrastructures from urban gardening to collecting spaces for rainwater. As precipitation is a scarce resource and floods and droughts will accumulate due to climate change, cities can adapt WSUD strategies which focus on managing all water streams within the city. In addition, a water supply from rainwater, stormwater and treated wastewater from a sustainable blue infrastructure for cities can relieve or replace grey infrastructure (Depietri & McPhearson 2017). For example, natural or close to natural ways of flood risk prevention such as sponge cities are more sustainable than flood walls. In combination, blue-green infrastructures provide health benefits for society and relieve the pressure on the environment and urban space. Furthermore, blue-green infrastructures are more cost-effective than the current predominant urban infrastructures. As such, a long-term sustainability approach can be pursued with regard to the design of cities of the future.

The urban blue-green infrastructures provide various valuable regulating ecosystem services in respect to global climate regulation by reduction of greenhouse gas concentrations through carbon storage and sequestration (Kazak *et al.* 2016), water flow maintenance and flood protection (Szewrański *et al.* 2018), micro and regional climate regulation (Kołecka *et al.* 2018; Ziemiańska & Kalbarczyk 2018) and improvement of air and water quality (Lakatos *et al.* 2012; Dąbrowska *et al.* 2017; Bawiec 2019). Consequently, creating well-designed built environments rich in ecosystem services provides various options for mitigation and adaptation of urban areas for the impact of climate change. Most of the adaptation measures in cities depend mainly on particular urban planning solutions and public regulations. Therefore, based on the technological solutions, local authorities can improve urban development processes by decision support systems, which effectively suggest suitable solutions in the case of many domains of environmental management (Kazak & van Hoof 2018). Identification and consideration of the dependency of the local population on the particular ecosystem services in the living areas make the valuation of the ecosystem services an important factor in sustainable landscape planning and territorial integration policymaking (Borisova 2013; Świąder *et al.* 2018).

As mentioned above, the implementation of blue-green infrastructures does not only solve the problem of water management in cities, but it supplies much more influential ecosystem services on increasing urban resilience to socio-environmental challenges. These ecosystem services can be assessed and mapped for better understanding of the environmental carrying capacity in the land management system to cope with flood hazard at all levels – region, basin and settlement (Boyanova *et al.* 2014; Larondelle *et al.* 2014; Świąder 2018). In some cases, the ecological boundaries, in terms of the area providing ecosystem services to the cities, exceed their administrative boundaries up to 1,000 times (Folke *et al.* 1997). At the same time, cities rely heavily on the capacity of the ecosystems in the urban environment provided by the green and blue areas. Thus, the interaction between biophysical and geophysical processes determines the potential capacity of natural capital to provide regulating ecosystem services. The water flow can be influenced by several natural processes and functions of the ecosystems, which contribute to the absorption of water and therefore reduce surface runoff or vice versa. The main factors of the capacity for water retention are the vegetation cover, the soil structure and texture, the presence of bare land or water bodies, the slopes and the land

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cover in the territory. In the study by Nikolova & Nedkov (2018), the flood regulation supply capacity was assessed by an Index of Capacity for Water Retention of urban ecosystems (as defined by Zhiyanski *et al.* 2017). The assessment of flood regulation services is carried out in four main steps according to the methodological framework for ecosystem services assessment developed by Burkhard *et al.* (2012):

1. identification of the urban ecosystems with potential to provide flood regulation;
2. selection of indicators for ecosystem services assessment;
3. quantification of the ecosystem services indicators;
4. assessment and mapping of flood regulating urban ecosystem services.

The results of such assessment show that the water retention capacity of residential, industrial and public areas is lower, while urban green areas have higher potential. Thus, detailed assessment gives decision-makers the exact information about the impact of future actions on biocapacity and the ecological footprint of human activity.

Urban water in the field of food, water and energy ecosystem

Liquete *et al.* (2016) as well as Leigh & Lee (2019) indicated that the future of urban water systems is shifting towards resource oriented, integrated, sustainable, distributed and NBS. Accordingly, wastewater treatment will be replaced by the production of goods. Further, one optimised system will allow multiple targets to be reached, instead of having a separate infrastructure for every purpose. This should give treated wastewater access to everybody. Multiple targets besides water treatment can be the production of fertilisers, provision of urban green, enhancing biodiversity and cooling, to name just one possible set. These targets must be defined during the concept phase in a case by case approach and their fulfilment must be measurable. According to present knowledge, this is the way forward to eliminate present untreated wastewater releases, a target set in SDG 6: clean water and sanitation (UN 2015).

NBS can help face these challenges by providing the means for cities to successfully achieve long-term sustainability in the use of resources (e.g., energy, water, land) and increase urban resilience to climate change (Maes & Jacobs 2017). Nevertheless, water-energy-food nexus relationships are complex and poorly understood, especially in urban environments, thus leading to significant potential risks. However, there are benefits if society is able to manage them adequately (Bennett *et al.* 2016). Further, Bennett *et al.* (2016) address the water-energy-food nexus and natural infrastructure investment on the entire watershed scale, taking large-scale infrastructure investment programmes into account, thus going beyond the city boundaries. Consequently, the implementation of NBS in urban areas can benefit from the water-energy-food nexus at local scales to efficiently manage natural resources for the optimal ecosystem services' delivery. Nevertheless, to the best of our knowledge, there are no literature reviews focused on the water-energy-food nexus in urban areas and how multi-functional NBS may help manage this nexus to improve the usage efficiency of these resources, thus helping to achieve long-term sustainability of cities. Some recent studies, such as those of Hansen *et al.* (2015), Lafortezza *et al.* (2018), Krauze & Wagner (2019) and Keesstra *et al.* (2018), describe NBS with multifunctional targets and affecting the water-energy-food nexus in urban areas. At the European scale, besides the main reports from the EC (2013, 2015), recent studies have analysed NBS applications in urban environments: Faivre *et al.* (2017) focus on NBS to address social, economic and environmental challenges in EU areas; Kabisch *et al.* (2016) review NBS for climate change adaptation in urban areas; Nikolaidis *et al.* (2017) study new approaches to improve regulatory instruments and demonstrate the long-term value of NBS; Raymond *et al.* (2017a) develop a framework for assessing and implementing the co-benefits of NBS in urban areas; Russo *et al.* (2017) review NBS based on edible GI for better management of the water-energy-food nexus; and the reports from

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the Naturvation project (Bockarjova & Botzen 2017; da Rocha *et al.* 2017; Hanson *et al.* 2017), which review the different dimensions of NBS implemented in urban areas, including those related to a more efficient use of natural resources and the nexus between water, energy and food in NBS.

Most frequently, NBS are designed for: (1) urban water regeneration; (2) watershed management; (3) ecosystem restoration; (4) increasing the sustainable use of matter; (5) generation of renewable energy; and (6) increasing carbon sequestration. Likewise, European authorities (EC 2013, 2015) have highlighted the multifunctional benefits of NBS to improve resource efficiency in urban areas. Among these solutions, we find: (1) urban agriculture for local food production; (2) water regeneration; (3) green roofs for climate adaptation; (4) higher energy and water efficient use; (5) regeneration of abandoned land by afforestation; (6) food production; (7) rain gardens for stormwater regulation; and (8) the use of permeable surfaces and vegetation for run-off control. Tables S1 and S2, given as the Supplementary material, present the examples of relevant NBS related to the water-energy-nexus. Finally, one of the main challenges in the topic is the assessment of the performance and impacts of NBS in addressing the objectives of higher resource efficiency and resilience in urban areas. The assessment schemes have been developed to measure performance and impacts through different indicators: Mapping and Assessment of Ecosystems and their Services (MAES) (Maes *et al.* 2013), Knowledge and Learning Mechanism on Biodiversity and Ecosystem Services (EKLIPSE) (Raymond *et al.* 2017b) and the Smart City Performance Measurement Framework (CITYkeys) (Bosch *et al.* 2017). In addition to the examples of relevant NBS related to the food-energy-nexus, the application of groundwater-based natural infrastructure solutions and comparison with the grey infrastructure also exist. Table S2 explains the function, goal and solution, which are the outcomes of the comparison.

Urban water pollution control: constructed wetlands

Urban water pollution control nowadays is predominantly carried out as an 'end of the pipe' solution with highly intensified wastewater treatment systems in order to protect downstream freshwaters from contamination and eutrophication (Finger *et al.* 2013). Yet, in addition to the benefits related to management of stormwater, flood protection and efficient use of resources in a water-energy-food nexus discussed in the previous sections, NBS offers an untapped potential for urban water pollution control. The treatment potential of NBS depends, among other factors, on the type of NBS used (infiltration basin, constructed wetland, raingarden, etc.), quantity and quality of water to be treated, and local conditions (climate, precipitation patterns, etc.).

In the concepts of GI, LID and sustainable drainage systems, water pollution controls are provided by the so-called planted/unplanted biofiltration systems. According to the definition of Fonder & Headley (2013), planted (surface) systems are a type of constructed wetlands (CWs). Among the various types of NBS, CWs are the most common and accepted NBS for pollution control nowadays, and they can be used in cities, especially for Masi *et al.* (2018):

- rainwater treatment;
- combined sewer overflow treatment;
- polishing of the outflow from existing wastewater treatment plants, including for the treatment of contaminants of emerging concern (CEC);
- greywater treatment.

In respect to water quantity and quality, stormwater presents different qualitative and quantitative characteristics compared to domestic sewage. It is recognised as the most important source of heavy metals, whereas wastewater constitutes the main source of organic and nitrogenous pollution (Barbosa *et al.* 2012). On the other hand, the quality of stormwater can vary greatly in time and between locations, especially in urban areas where over 650 substances were identified in stormwater

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(Eriksson *et al.* 2007). Table 1 displays the classification of five main groups of pollutants that can be encountered in stormwater.

Table 1 | List of main stormwater pollutant types (adapted from Eriksson *et al.* 2007)

Pollutant types	Indicator parameters
Basic parameters	Organic matter (BOD_5, COD), suspended solids, nitrogen, phosphorus, pH
Heavy metals	Zinc, cadmium, chromium (VI), nickel, lead, platinum
Polycyclic aromatic hydrocarbons	Benzopyrene, naphthalene, pyrene
Herbicides	Terbuthylazine, pendimethalin, phenmedipham, glyphosate
Organic compounds	Nonylphenol ethoxylates and degradation products, e.g., nonyl phenol, pentachlorophenol, di-2-ethylhexyl phthalate, 2,4,4′-trichlorobiphenyl (polychlorinated biphenyl 28), methyl-tert-butyl ether
Bacterial indicators	Faecal coliforms (*E. coli*), pathogens (*Pseudomonas aeruginosa*)

Typically, NBS are employed to reduce the levels of traditional pollutants such as total suspended solids (TSS), organic matter, nutrients and also heavy metals. TSS belong to the group of basic pollutants but, at the same time, are classified as being the most dangerous due to their impact, both on the aquatic environment and humans (Makepeace *et al.* 1995; Paschke 2003; Eriksson *et al.* 2007; Madrid & Zayas 2007; Ingvertsen *et al.* 2011; Gasperi *et al.* 2012; Zgheib *et al.* 2012). The concentration of TSS could vary significantly depending on the place of origin (e.g., for streets: TSS ranges from 61 to 320 mg/L; for parking: TSS ranges from 42 to 240 mg/L; and for motorways: TSS is around 200 mg/L (Boogaard 2015). It must also be considered that very often TSS are constituted or covered by organic matter which works as a binding material for the sorption of the above-mentioned emergent pollutants, allowing, therefore, their transport even for a long distance. Therefore, retention of suspended solids has been a primary function of many of the NBS. Typically, CWs can remove up to 88% of TSS, 92% of BOD_5, 83% of COD even after 20+ years of operation (Vymazal *et al.* 2019). For the nutrients, the removals vary greatly between the systems and are in the range of 46–90% for total phosphorus and 16–84% for total nitrogen (Malaviya & Singh 2012).

In addition to the removal of traditional pollutants such as suspended solids, organic matter and nutrients (Zhang *et al.* 2014a, 2014b; Machado *et al.* 2017; Arden & Ma 2018), CWs are capable of removing organic and inorganic pollutants (Verlicchi & Zambello 2014; Krzeminski *et al.* 2019). Among these, the removal of pesticides (Barceló & Petrovic 2008), heavy metals (Wang *et al.* 2017), pharmaceuticals (Li *et al.* 2014; Zhang *et al.* 2014a, 2014b; Ilyas & van Hullebusch 2019; Zraunig *et al.* 2019) and various other contaminants of emerging concern (CEC) (Imfeld *et al.* 2009; Matamoros *et al.* 2010; Gorito *et al.* 2017; Talib & Randhir 2017) have been explored in the last decade. The observed removal of heavy metals was between 23 and 97% depending on the heavy metal, CWs' type, type of water matrix and others (Malaviya & Singh 2012).

Regarding the CEC, plant-associated NBS have been reported to be crucial for the removal of different CEC (Carvalho *et al.* 2014; Zhang *et al.* 2016; Ilyas & van Hullebusch 2019), which can favour the solution of creating more 'green' in the cities. Therefore, the key removal pathways are the uptake by plants (e.g., carbamazepine), microbial degradation (e.g., ibuprofen, salicylic acid, galaxolide), adsorption and subsequent sedimentation (e.g., triclosan, tetracycline) and photodegradation (e.g., ketoprofen, naproxen, triclosan, diclofenac) (Bi *et al.* 2019).

Although treatment wetlands can achieve high removal of up to 100% of different organic and inorganic chemicals, the removal effectiveness varies significantly and the removal effectiveness of particular compounds may vary depending on the CW design, its operation mode and seasonal

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conditions (Verlicchi & Zambello 2014; Zhang *et al.* 2016; Ilyas & van Hullebusch 2019; Krzeminski *et al.* 2019; Zraunig *et al.* 2019). This indicates that for efficient removal, CWs need to be designed and/or adjusted for targeted pollutants. While CWs can be very effective, they are not able to completely remove CEC from the (waste) water. Moreover, hybrid systems combining different types of CWs, or other treatment techniques, might offer increased removal due to the synergistic effects against specific types of pollutants (Garcia-Rodríguez *et al.* 2014; Verlicchi & Zambello 2014; Zhang *et al.* 2014a, 2014b; Ilyas & Masih 2017; Zhang *et al.* 2019). Furthermore, treated water from CWs may be suitable for some reuse applications if they are well designed and maintained (Ilyas & Masih 2017; Arden & Ma 2018; Krzeminski *et al.* 2019). Nevertheless, current knowledge gaps restrict holistic evaluation of CWs' applicability and the estimation of CWs' potential for the removal of CEC.

Regarding the climatic conditions, CWs have been demonstrated to work efficiently in different climatic conditions, but tropical conditions tend to favour treatment performance due to continuous plant growth, extended sunlight exposure and increased microbial activity, these being of particular importance for more recalcitrant pollutants (Zhang *et al.* 2014a, 2014b; Machado *et al.* 2017). However, good comparable removal rates of suspended solids, organic matter and phosphorus are reported for temperate conditions, with only nitrogen removal being affected in a cold climate (Wang *et al.* 2017).

For urban water pollution control, other NBS (and GI elements) can be very effectively used in combination with CWs for purposes such as wastewater source control and separation, water reuse and other means of sustainable sanitation framework (Masi *et al.* 2018). Accordingly, one of the key concepts could be a combination of composting and vermicomposting toilets (Hill & Baldwin 2012; Anand & Apul 2014) and greywater treatment with wetlands or green walls providing the treated water for further reuse. Furthermore, as the space in cities becomes a highly valuable commodity, multipurpose NBS offering other benefits beyond the water treatment and pollution control become a viable alternative (Raymond *et al.* 2017; Frantzeskaki 2019). Multifunctionality is a key factor, as the water pollution control does not have to be the major role of NBS but can be integrated into stormwater management and biodiversity enhancement.

PROJECTS/CASE STUDIES APPROACH

In spite of the different potential for implementing NBS for UWM, the showcased projects from the COST Action members are only dealing with stormwater management. The applications range from rainwater harvesting in water-scarce areas (e.g., HYDROUSA project in Greece) to the reforestation of watersheds (e.g., Rangárvellir project in Iceland (Keesstra *et al.* 2018)). While both aforementioned cases aim at re-establishing the natural water cycle and increasing natural water retention, the means and purposes differ. Moreover, the Natural Water Retention Measures project, directed by the EU Directorate-General for Environment from 2013 to 2014, aimed to improve the water status on hydromorphology and diffuse pollution, by offering a catalogue of case studies showcasing a broad range of concepts and case studies (nwrm.eu, 2015). However, for effective selection of NBS for stormwater management planning, instruments are still needed. Within the project Concepts for urban rainwater management, drainage and sewage systems (KURAS) in Germany, an integrated planning approach for stormwater management measures was developed considering the other aspects of NBS besides water retention (Matzinger *et al.* 2017). The potential multi-functionality of NBS is an important feature, especially regarding the implementation in circular cities. The Gorla Maggiore water park project in the northern territories of Italy, which includes the use of a water park for NBS applications, and the integrated and sustainable management service for water–energy cycle in urban drainage systems (G.I.A.R.E.) project in southern Italy based on water–energy interaction in Milan, Italy are also summarised in this section. In addition to these two Italian projects, the C2C-CC project,

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which is carried out in Denmark and includes flood control, water treatment, base-flow and sustainable heat energy applications, is summarised in the section. The main purpose of explaining these five projects here in this section is to emphasise the representative of multipurpose NBS implementations for stormwater management.

Project 1: The Gorla Maggiore water park

The Gorla Maggiore water park project, located in Gorla Maggiore, northern Italy, is an urban wetland development focusing on NBS and ecosystem services. The park aims to protect the city against flooding, improving water quality, increasing biodiversity and obtaining social co-benefits (Rizzo *et al.* 2018). The park, with a total area of approximately 3 ha, comprises sections with different functionalities: (1) stormwater detention for flood prevention (1 ha); (2) domestic water treatment (0.4 ha); and (3) recreational areas (1.3 ha). Furthermore, the combined sewer overflow and excess runoff may be diverted into the park in the case of extreme rainfall events, with an expected reduction of peak flow by 86% and downstream discharge of 8,900 m^3 for events with a ten-year return period. Moreover, it reduces the downstream dissolved organic carbon load by 11.7 t/yr and nitrogen load by 0.4 t/yr, along with social and ecological benefits (Masi *et al.* 2017). In addition, the project demonstrates that the performance and costs of the park are similar or even better than the grey infrastructure for water purification and flood protection (Masi *et al.* 2017).

Project 2: coast to coast climate challenge (C2C-CC project)

The C2C-CC project (http://www.c2ccc.eu/) is a Danish cross-municipality climate adaptation project with 31 partners and 19 supportive partners working to create a climate resilient central region in Denmark. The sub-project 'Infiltration of surface water through permeable coating' has the primary aim of re-establishing the natural pre-development water cycle and preventing flooding. This is done by harvesting rainwater in the roadbed as the road is made of permeable asphalt. The roadbed is constructed using a gravel mix ensuring a porosity of 30% which can detain the volume of water generated by a 100-year-flood. Moreover, the gravel mix removes TSS and heavy metals from the water. Subsequently, the detained water transmits its heat to a geothermal tube, with a length of 800 m, connected to a nearby day-care centre for heating, which is then infiltrated into the soil. Thus, this NBS provides flood control, water treatment, base-flow and sustainable heat energy.

Project 3: HYDROUSA

HYDROUSA aims to revolutionise the water supply chain in Mediterranean regions by demonstrating innovative solutions for water/wastewater treatment and management, which will close the water loops and will also boost their agricultural and energy profile. Relevant to NBS applications, HYDROUSA demonstrates that circular NBS technologies work for wastewater treatment and nutrient recovery, while creating further environmental and societal benefits. The project offers a solution for the problem of rare water reserves in Mediterranean regions in the summer during the high tourism season. The project will not only develop and demonstrate innovative water services, but will also revolutionise the water value chains in Mediterranean areas from water abstraction and use up to sewage treatment and reuse (www.hydrousa.org, 2019). There are five water categories in the HYDROUSA project: rainwater, groundwater, wastewater, water vapour and sea water and the systems defined between these categories are harvesting, recharge and restore, wetlands, vapour condensation and tropical greenhouse. Moreover, biomimicry design concepts and fertigation are being applied to increase the efficiency of the selected NBS. Some of the recovered products of these systems are water for domestic use, irrigation water, biogas, drinking water and salt (Figure 4).

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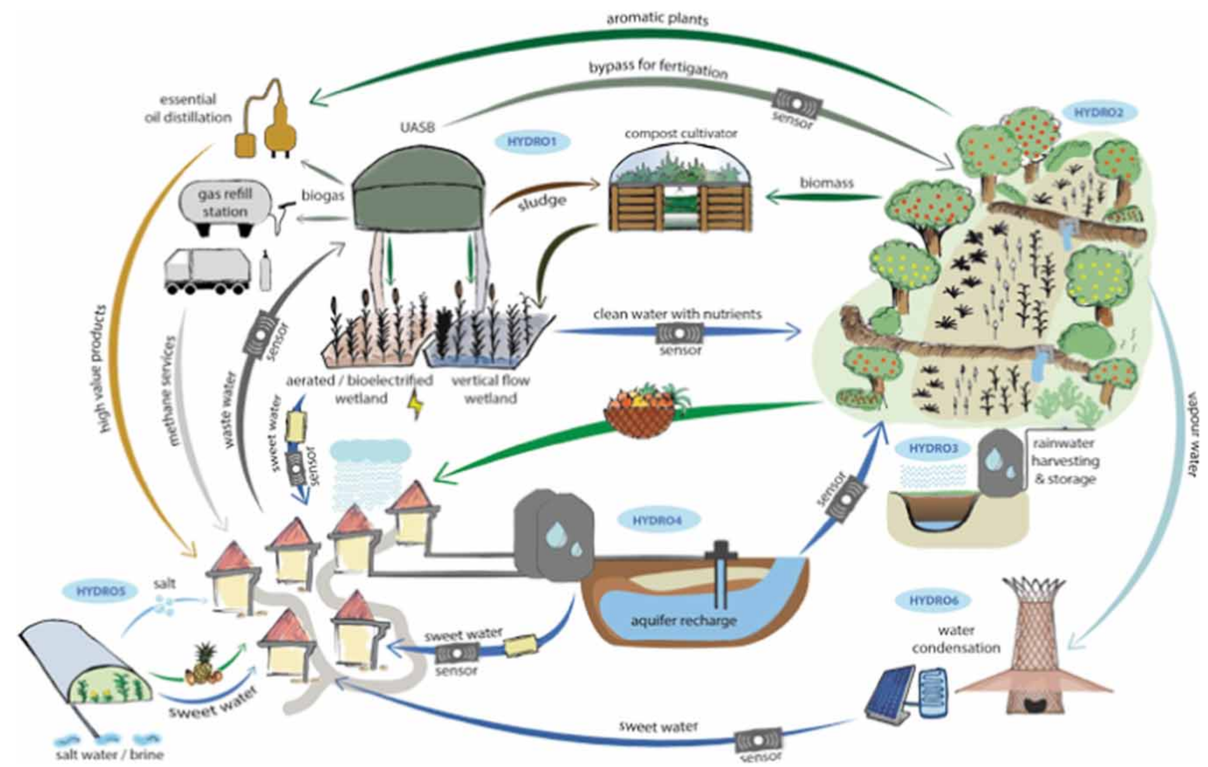

Figure 4 | The HYDROUSA project working principles and the processes (from www.hydrousa.org, 2019).

Project 4: concepts for urban rainwater management, drainage and sewage systems (KURAS)

The aim of this project is to give the answer to the question ‘How can the future wastewater discharge, water quality, urban climate and quality of life in the city be improved through intelligently coupled storm water and waste water management?’ The project consists of a network of partners from research and industry as well as the city of Berlin decision-makers. KURAS is the elaboration and exemplary demonstration of integrated concepts for a sustainable handling of wastewater and rainwater for urban locations. As mentioned in the Introduction section, NBS aim to protect, sustainably manage and restore natural or modified ecosystems. The KURAS project aims to decrease water consumption after heavy rainfall in the city and enables the sustainable management. Some of the following sub-goals, which are defined, to reach this achievement are as follows (www.watershare.eu, 2019):

- For wastewater disposal companies and operators of municipal sewer networks, which, like Berlin, have a slight gap, options for the adaptation of wastewater infrastructure to climate change and its consequences are being developed.
- Prognosis models are intended to investigate the effects of measures – e.g., to avoid deposits in the sewer system after long periods of dry weather or of mixed water overflows in waters during heavy rainfall – for real Berlin model areas.

Project 5: integrated and sustainable management service for water-energy cycle in urban drainage systems (G.I.A.R.E.)

The main objective of the project, relevant to the aim of NBS, was to develop an integrated approach for sustainable water–energy cycle management in the urban context. In this perspective, a technological platform was implemented in order to both optimise the use of water resources that rely on

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the urban drainage network such as meteoric waters deriving from the roof of buildings (40% of total urban area) and paved areas, i.e., roads, yards, etc. (35%) and to allow energy saving (Figure 5). For these purposes, experimental activities were conducted on:

- control of inflows to the drainage network;
- control of the polluting load generated;
- thermo-energy benefits;
- potential of rainwater for reuse.

Specific objectives of the project (Figure 5) are listed as follows:

- OR1: Realisation of a compact storm drain prototype device for the treatment of run-off rainwater.
- OR2: Module for management and optimisation of water–energy performance of green roof systems in Mediterranean climate.
- OR3: Urban drainage planning and design service through sustainable technologies to reduce inflows and pollutants.
- OR4: Development of a technological platform for decision-making support for the integrated and sustainable management of the water–energy cycle in the urban drainage system.

An 'Urban Hydraulic Park' was constructed as a demo site at the Vermicelli catchment (University of Calabria) where a green roof with a rainwater harvesting system, permeable pavement, a stormwater filter and a traditional sedimentation tank were connected to a treatment unit. Further, a monitoring and acquisition system was used to analyse the environmental benefits and the hydraulic and thermal efficiency of each unit.

The results of the project showed good hydraulic performance of the green roof concerning stormwater retention in Mediterranean weather conditions (Palermo *et al.* 2019; Piro *et al.* 2019a). The hydraulic behaviour of the green roof, permeable pavement and stormwater filter were also analysed by means of a modelist approach (Brunetti *et al.* 2016, 2017; Garofalo *et al.* 2016; Piro *et al.* 2019b).

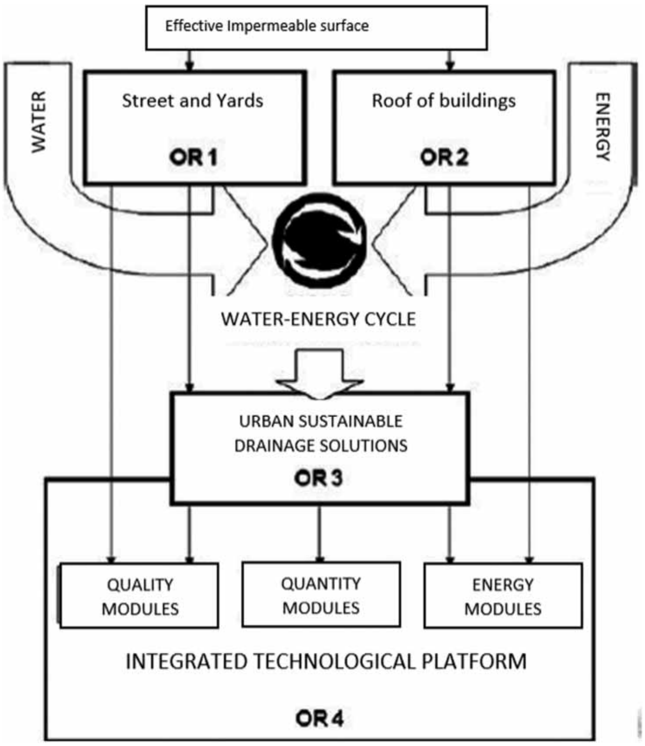

Figure 5 | The working principle of the G.I.A.R.E project (from www.giare.eu, 2019).

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Moreover, life cycle assessment (LCA) analysis of the green roof and permeable pavement highlighted the sustainability of these low-impact infrastructures (Maiolo *et al.* 2017).

DISCUSSION AND CONCLUDING REMARKS

Based on the presented literature review and case studies, three main focuses of NBS implementation could be identified: (i) stormwater management, (ii) water-food-energy nexus using water for food and energy production and (iii) water pollution control. The presented overview demonstrates that NBS are not only effective and efficient, but are also largely accepted by people neighbouring such facilities. The present review differentiates from previous studies by combining a literature review with the analysis of case studies involving different NBS applications in European cities. Table 2 presents the review of these case studies that highlight the links between the NBS approach, main services and references. For instance, stormwater management can be implemented by establishing water parks with extended retention basins that withhold rainwater during heavy precipitation events as

Table 2 | Review summary of the case studies

Case studies and implementation years	Description of the NBS	Type of water	Main services	References
The Gorla Maggiore water park, 2013–2015	Constructed wetlands for water pollution control and hydraulic risk management	Combined sewer overflow	Water pollution control; Flood mitigation; Biodiversity increase; Aesthetic/Social benefits	Liquete *et al.* (2016), Masi *et al.* (2017) and Rizzo *et al.* (2018)
HYDROUSA, 2018–present	Constructed wetlands in the Food-Water-Energy nexus; Constructed wetlands for greywater treatment and reuse; Rainwater harvesting systems; Agroforestry	Wastewater; Greywater; Rainwater; Seawater	Reuse of nutrient (N,P) rich treated wastewater; Reuse of treated greywater; Reuse of harvested rainwater; Recreation of high-biodiversity and productive agroforestry site; Removal of emerging organic micropollutants from the water phase and plant uptake in edible plants	The project is still running – www.hydrousa.org (2018–2022)
KURAS, 2016–present	Rainwater harvesting; Decreasing water consumption	Rainwater, Water sewer overflow	Avoiding deposits in the sewer system; Reuse of harvested rainwater	The project is still running – www.kuras-projekt.de
G.I.A.R.E., 2011–2014	Compact storm drain prototype device for run-off rainwater treatment; Green roof systems for support in the management of urban drainage system; Urban drainage planning and design service to inflows and pollutants reduction; Development of a technological platform	Rainwater; Stormwater	Removal of pollutants at storm drain inlet; Management and optimisation of water–energy performance; Hydraulic defence of urban area and control on dishage quality into water bodies; Decision-making support for sustainable management of water–energy cycle in urban drainage system	Brunetti *et al.* (2016), Garofalo *et al.* (2016), Brunetti *et al.* (2017), Maiolo *et al.* (2017), Palermo *et al.* (2019) and Piro *et al.* (2019a, 2019b)
C2C-CC, 2016–present	Providing flood control; Running water treatment; Waste-flow; Launching sustainable heat energy	Rainwater; Groundwater; Lakes; Rivers; Seawater	Water pollution control; Flood mitigation; Management and optimisation of water–energy performance	Project is still running – https://www.c2ccc.eu/

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illustrated in the example of Gorla Maggiore in northern Italy. Such water parks offer protection from floods but also create ecosystems within the cities. Moreover, permeable coating of streets and paths are another way of reducing flood risk in cities. These systems can also produce energy for district heating by simply using the heated surface of paved streets and paths. The Danish project, C2C-CC, is an illustrative example of such a system. The HYDROUSA project investigates options for NBS to manage water resources on Greek islands which experience increased water demand during the tourist season. The KURAS project in Berlin, Germany, focuses on NBS for stormwater and wastewater management in large urbanised areas. Water parks, permeable coating of streets and green roofs function as water retention reservoirs, slowing down the runoff during heavy precipitation events. In some cases, the water stored in these NBS can become available at later points during dry periods, thereby reducing the drought effects. The G.I.A.R.E. in Italy focuses on integrated and sustainable management service for water–energy cycle applications.

Figure 6 illustrates the suggested scheme of sustainable water management in an urban settlement with the case studies HYDROUSA and GORLA MAGGIORE and Figure 7 shows the case studies C2C-CC, KURAS and G.I.A.R.E.

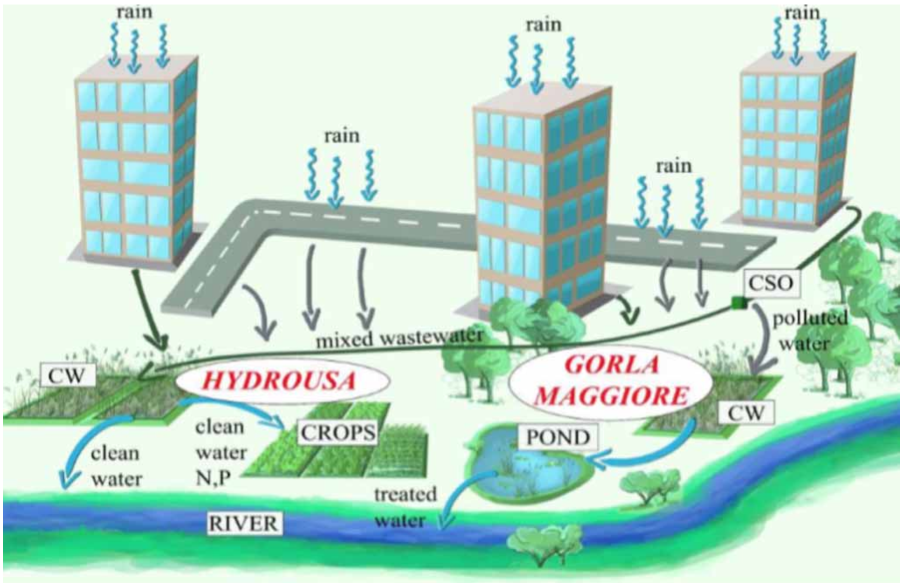

Figure 6 | Transition scheme towards a decentralised and integrated, sustainable water management in an urban settlement with the contributions of the case studies HYDROUSA and GORLA MAGGIORE highlighted (SUDS: sustainable drainage systems, CW: constructed wetlands) (adapted from Masi *et al.* 2018).

The presented review and selected case studies relevant to NBS demonstrate the advantages of NBS both in social and economic terms, i.e., creation of new jobs and saving of energy and resources. Closed-loop recycling of greywater can decrease the amount of potable water used and wastewater by up to 50–60%, reducing water production and sewage treatment costs at centralised WWTPs. Other projects have focused on NBS and the water-food-energy nexus, as summarised in the Supplementary material tables. Hence, NBS include constructed wetlands, restored wetlands, coastal Mediterranean wetlands, green walls and green roofs. NBS, moreover, act as groundwater storage, water retention, water purification and improvement of environmental value.

The most frequent NBS are constructed wetlands, which can remove nutrients and organic components, including organic micropollutants and other emerging compounds. They can be designed for water sources with very different characteristics. In addition to treating water for a particular purpose, wetlands can be designed for water storage, infiltration and evapotranspiration, important

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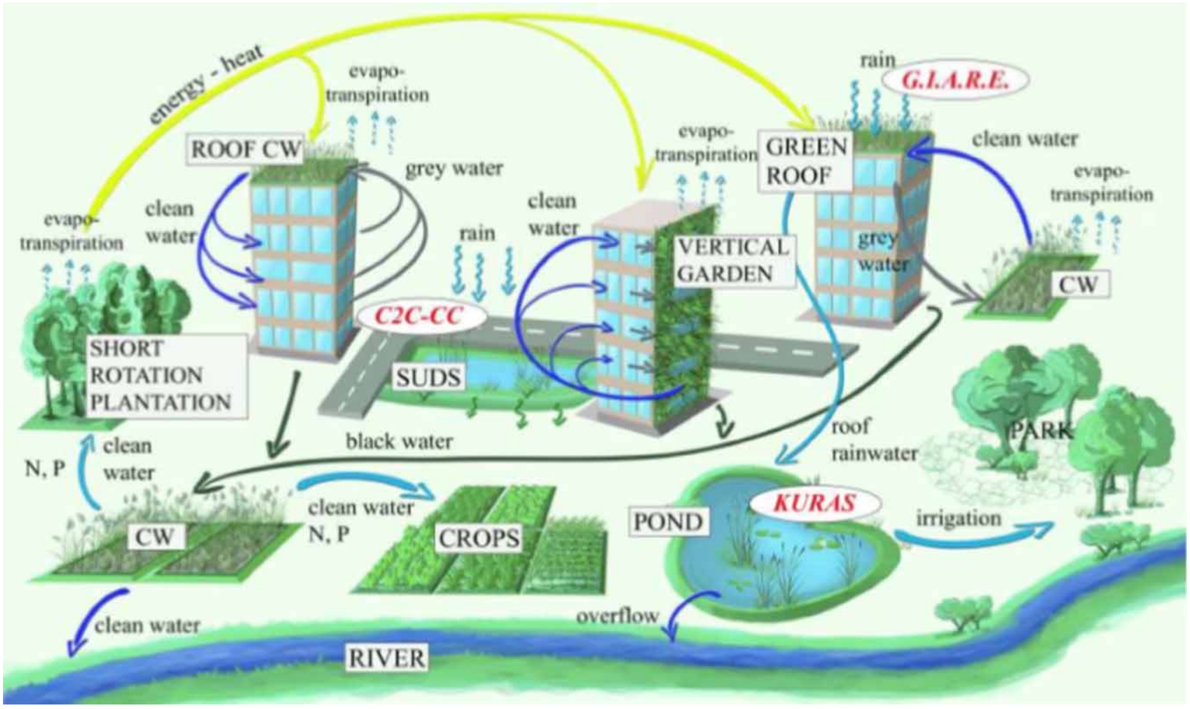

Figure 7 | Advisable scheme of decentralised and integrated, sustainable water management in an urban settlement with the contributions of the case studies C2C-CC, KURAS and G.I.A.R.E. highlighted (SUDS: sustainable drainage systems, CW: constructed wetlands) (adapted from Masi *et al.* 2018).

functions of the urban water cycle. They also provide a series of additional benefits that grey infrastructure cannot, such as providing ecological niches within urban areas, or preferred recreation and educational areas. However, most of the research and technical development of treatment wetlands historically relates to decentralised treatment, normally away from urban areas. Thus, we still have only a small number of examples and limited data on the implementation of treatment wetlands in the urban environment. In spite of the potential of other NBS implemented in the urban area, such as green walls or SUDS, to purify water, the majority of the existing examples and publications deal only with the attenuation of the heat island effect or stormwater management, respectively. It is thus clear that in order to increase the implementation of NBS in the urban environment, further research and demonstration should more effectively combine different disciplines and needs in aligning with the holistic perspectives required by the water-food-energy nexus and taking into consideration the ecosystem services provided.

The implementation of NBS applications in urban areas is, at the same time, limited by some challenges. For instance, especially in densely built urban areas or protected historical city centres, the limited space available is a major drawback. Nevertheless, while this represents a present challenge, in the future, architecture and urban planning can be adapted to more easily accommodate NBS, which provide the widest possible range of benefits. In fact, NBS present a multifunctional capacity for resource recovery and pollution control, delivering multiple benefits in this issue, although it is worth noting that NBS for UWM clearly address other challenges, such as biodiversity enhancement and a more efficient management of the water-food-energy nexus, among others.

In the future, the reliance on NBS in sustainable water use is expected to increase. Given the still-increasing effects of climate change, it is necessary that in the future, planning for city infrastructure will be based on climate change mitigation, adaptation and resilience. The most common applications for NBS will be in parallel with integrated river management practices and re-establishment of wetlands. The developments towards more holistic concepts of resources flow management imply integrated, cross-sectoral systems and approaches. In the context of UWM, pollution control is shifting towards resource recovery. The traditional separation between water supply, wastewater and stormwater is challenged towards reusing properly treated wastewater and stormwater for purposes where potable water quality is not necessarily needed. NBS implementation can support this paradigm shift.

Based on the presented literature review, the NBS case studies and the discussion above, we conclude the following:

(1) NBS help mitigate flood and drought impacts simultaneously supporting stormwater and water supply management.
(2) NBS are essential to maintain the natural hydrologic regime despite development and partial sealing of surfaces, not least to keep the natural water cycle of evapotranspiration and rainfall, but also to mitigate urban heat island effects and allow the growth of urban green with local water resources.
(3) NBS can efficiently purify very different water sources, greywater, rain water, sewer overflow or wastewater, for various purposes of further use, while generating numerous side benefits. Besides treating water, NBS can also retain stormwater, produce or irrigate for food production and save energy.
(4) NBS create very promising new opportunities to use water more effectively and efficiently, enable urban farming or mitigate energy consumption. However, the urban water-food-energy nexus is still in a very early stage of development.
(5) Ultimately, a wide application of NBS needs a systemic change from wanting to do things separately with various technologies towards learning to let nature take care of them in an integrated way that restores a close to natural local water balance and further important nature functions.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available at https://dx.doi.org/10.2166/bgs.2020.932.

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