Performance and Impact Monitoring of Nature-Based Solutions

D3.1 Deliverable

31/05/19

Laura Wendling[1], Ville Rinta-Hiiro[1], Johannes Jermakka[1], Zarrin Fatima[1], and Malin zu-Castell Rüdenhausen[1]

Ana Ascenso[2], Ana Isabel Miranda[2], Peter Roebeling[2], Ricardo Martins[2], and Rita Mendonça[2]

[1] VTT Technical Research Centre Ltd, P.O. Box 1000 FI-02044 VTT, Finland
[2] CESAM – Department of Environment and Planning, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Dissemination level		
PU	Public	X
CO	Confidential, only for members of the consortium (including the Commission Services)	

Deliverable administration						
No & name	**D3.1 NBS performance and impact monitoring protocols**					
Status	In preparation	**Due**	M24	**Date**	2019-05-31	
Author(s)						
Description of the related task and the deliverable. Extract from DoA	**T3.1.2 Develop a Suite of Defined NBS Monitoring and Evaluation Protocols (VTT, UAV, STU) M3 – 30** The effectiveness of NBS implemented in front-runner cities will be monitored and evaluated using a defined suite of protocols to enable consistent collection and management of NBS performance data during and following the UNaLab project. Monitoring and evaluation protocols will be established in co-operation with T3.2 following the co-identification of KPIs and KIIs in T3.1.1. Monitoring and evaluation protocols will include a comprehensive methodology for the routine measurement of key parameters and evaluation of NBS efficacy based on defined KPIs. The scope of the monitoring and evaluation protocol will be two-fold in order to measure the performance of implemented NBS at the Project level (i.e. demonstration areas) and City level (further scaling and replication inside city and region). This task will output D3.1. VTT will lead the task with advice from UAV (model parameter inputs) and STU (key engineering parameters of NBS system components).					
Participants	VTT, UAV, STU					
Comments	This deliverable has not yet been approved by the funding agency					

V	Date	Authors	Description
1	01.11.2018	Laura Wendling, Ville Rinta-Hiiro, Johannes Jermakka, Zarrin Fatima, Malin zu Castell Rüdenhausen	Initial draft
2	06.03.2019	Salla Leppanen, Maarit Särkilahti	Comments from Tampere: updated draft with contributions from TRE
3	29.03.2019	Sonia Zarino, Silvia Campailla	Comments from Genova: updated draft with contributions from GEN
4	31.3.2019	Ana Asceno, Ana Isabel Miranda, Peter Roebeling, Ricardo Martins, Rita Mendonça	Contribution of sections from UAV
5	29.4.2019	Laura Wendling	Draft consolidation and submission to WP3 + WP5 partners for review, to P. Spinnato for cross-check
6	10.5.2019	Silvia Vela	Feedback from internal review process - contributions from RINA
7	10.5.2019	Piersaverio Spinnato	WP4 cross-check feedback from ENG
8	23.5.2019	Tom Hawxwell	QA/QC check of document
9	25.5.2019	Abdul Sami Kazi	Final review of document

About UNaLab

The UNaLab project is contributing to the development of smarter, more inclusive, more resilient and more sustainable urban communities through the implementation of nature-based solutions (NBS) co-created with and for local stakeholders and citizens. Each of the UNaLab project's three Front-Runner Cities – Eindhoven (NL), Genova (IT) and Tampere (FI) – has a strong commitment to smart, citizen-driven solutions for sustainable urban development. The establishment of Urban Living Lab (ULL) innovation spaces in Eindhoven, Genova and Tampere supports on-going co-creation, demonstration, experimentation and evaluation of a range of different NBS targeting climate change mitigation and adaptation along with the sustainable management of water resources. The Front-Runner Cities actively promote knowledge- and capacity-building in the use of NBS to enhance urban climate and water resilience within a network of committed partner cities, including seven Follower Cities – Stavanger, Prague, Castellón, Cannes, Başakşehir, Hong Kong and Buenos Aires – and the Observers, Guangzhou and the Brazilian Network of Smart Cities. Collaborative knowledge production among this wide network of cities enables UNaLab project results to reflect diverse urban socio-economic realities, along with differences in the size and density of urban populations, local ecosystem characteristics and climate conditions. Evidence of NBS effectiveness to combat the negative impacts of climate change and urbanisation will be captured through a comprehensive monitoring and impact assessment framework. Further replication and up-scaling of NBS is supported by development of an ULL model and associated tools tailored to the co-creation of NBS to address climate- and water-related challenges, a range of applicable business and financing models, as well as governance-related structures and processes to support NBS uptake. The results of the project will be a robust evidence base and go-to-market environment for innovative, replicable, and locally-attuned NBS.

Partners

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Table of Contents

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

1. EXECUTIVE SUMMARY

Deliverable 3.1, *Performance and Impact Monitoring of Nature-Based Solutions,* is first and foremost a handbook for practitioners. The information provided herein summarises the classification and mode of action of nature-based solutions (NBS), the selection of key indicators of NBS performance and impact, design of an NBS monitoring scheme, and baseline establishment along with a suite of measurement/monitoring methods for key indicators and metrics. The primary purpose of this document is to provide a suite of performance and impact metrics and data collection procedures for consistent, transparent monitoring of NBS with time, and to facilitate comparison of NBS across different locations.

A number of the indicators and metrics herein are denoted as "common to all SCC-02-2016-2017 projects". As such, these are the primary metrics that will contribute to the European evidence base on NBS performance and impact. Common indicators and metrics have been identified to date in the areas of climate adaptation and climate change mitigation (carbon emissions, temperature); water management (flood vulnerability, drought vulnerability, water quality); green space management and biodiversity; air quality; and, economic activity and green jobs. Experts from each of the projects funded under EU Horizon 2020 call topic SCC-02-2016-2017 are currently working to identify common performance and impact metrics for urban regeneration; participatory planning and governance; social justice and social cohesion; and, health and well-being. As a result, an update to D3.1, *Performance and Impact Monitoring of Nature-Based Solutions* that includes measurement/monitoring methods for all of the indicators and metrics identified as "common" among SCC-02-2016-2017 projects will be issued at a later date.

Individual metrics used to evaluate NBS performance and impact are grouped herein by indicator category. For each of the indicator categories presented, a brief introduction is provided followed by one or more specific metrics applicable to the respective indicator. The introduction to each metric presents fundamental information about the significance of the metric: what is measured, how is it measured, and what is the 'big picture' significance of the measurement? Where more than one measurement method is provided for a given metric, any one of the methods described can be used. Particular method selection is largely dependent upon the specific NBS being monitored, resources available and the objective of the monitoring programme.

All cited references are listed in Section 7; in addition, key references for each indicator/metric are listed at the end of the respective section for convenience. Where possible, links to additional information, including both additional publications and online resources, are also provided. Guidance regarding monitoring frequency and the potential scale of measurement is provided for each metric.

2. Introduction

2.1 Purpose and target group

Performance and Impact Monitoring of Nature-Based Solutions (Deliverable 3.1) is a handbook for practitioners. It provides a suite of performance and impact metrics and data collection procedures for consistent, transparent monitoring of nature-based solutions (NBS) with time, and to facilitate comparison of NBS across different locations. The document is intended to guide the selection and implementation of indicators and metrics to evaluate the performance and impact of NBS. Rather than reproduce every measurement or monitoring protocol herein in their entirety, we briefly describe each key indicator and its associated metrics, then outline the steps necessary to acquire and process the relevant data. References to detailed standard methods or peer-reviewed publications that present the respective method are provided for each indicator/metric.

The indicators and metrics denoted as "common to all SCC-02-2016-2017 projects" (see Table 4) have been identified by NBS project representatives on the Indicator Evaluation Framework (IEF) Taskforce (also known as Taskforce 2.0) as the primary metrics that will contribute to the European evidence base on NBS performance and impact. To date, the IEF Taskforce has addressed common indicators and metrics related to: climate adaptation and climate change mitigation (carbon emissions, temperature); water management (flood vulnerability, drought vulnerability, water quality); green space management and biodiversity; air quality; and, economic activity and green jobs. Changes to the "common" indicators of NBS performance and impact in these categories is not anticipated. The IEF Taskforce has not yet identified common performance and impact metrics for the remaining categories: urban regeneration; participatory planning and governance; social justice and social cohesion; and, health and well-being. As a result, an update to this handbook that includes "common" indicators among SCC-02-2016-2017 projects for these categories are will be issued at a later date.

2.2 Contributions of partners

VTT led the preparation of D3.1 *Performance and Impact Monitoring of Nature-Based Solutions*. UAV contributed to sections 2.3, 4.2, 4.8 and 4.13. Inputs from the multi-project IEF Taskforce formed the basis for discussion and development of some monitoring/measurement methods. Feedback from front-runner cities EIN, GEN and TRE informed selection of project-specific metrics (i.e., metrics not "common" to all SCC-02-2016-2017 projects).

2.3 Baseline

The establishment of the pre-NBS Baseline requires the definition of the methodology, the data sources and the tools used to create this pre-NBS Baseline for measurable parameters relevant for co-identified key performance indicators (KPIs) and key impact indicators (KIIs) (see Martins et al., 2018).

The pre-NBS Baseline for relevant measurable parameters serves as a basis against which performance and impact of NBS implementation can be assessed. To this end, baseline data are

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

obtained for a reference period (to obtain a representative 'average' reference year) for each of the measurable parameters relevant for the co-identified KPIs and KIIs, using the best available data from municipalities, monitoring studies, statistical databases, reports, research literature sources and, when applicable, through additional measurement, interviews, workshops and questionnaires.

The established representative '2015' pre-NBS Baseline is based on average 2012-2016 data, corresponding with long-term average temperature and precipitation data, for the considered UNaLab front-runner cities (Tampere, FI; Eindhoven, NL; Genova, IT). The representative '2015' pre-NBS Baseline year intends to be a recent and representative period for the current conditions, so that the performance and impact of the NBS implementations are evaluated and analysed. The initial and obvious choice is considering a single year as the representative (e.g., 2015), however, a period of a single year is often not representative of the current state and can therefore deviate from what was representative. This was, for example, observed for temperature in 2015, which was the hottest year on record (Martins et al., 2018). Thus, we opted for a timespan of five years between 2012 and 2016. These years include the maximum (2015) as well as a local low (2012) and, hence, will be most representative for the '2015' pre-NBS Baseline.

Baseline data obtained from publicly available data sources included:
1. Urban Units and Socio-Economic;
2. Weather, Precipitation and Air Quality;
3. Water Quality;
4. Land Use;
5. Green Spaces and Water Bodies;
6. Transportation and Construction costs;
7. Urban Centres; and
8. Reported Flood Events.

Generic GIS geometrical data treatment processes were used to allow for the representation of the Baseline data, as follows: i) *Simplify* – method that relies on the reduction of number of points in a curve using a modified Douglas-Peucker algorithm (Douglas & Peucker, 1973); ii) *Unite* – method that overlays two vector maps; and iii) *Dissolve* – method that dissolves boundaries between adjacent areas sharing a common category number or attribute.

Finally, these baseline data were stored, visualized and downloadable through a Google Sites-based app (see https://sites.google.com/view/unalab/baseline-maps). In particular, Google Sites was used to create a webpage for ease of access, Google Maps was used to present data geographically, and Google Forms was used to obtain feedback from the visitors.

a) Key References[1]

Martins, R. Ascenso, A., Mendonça, R., Mendes, R., Roebeling, P., Bodilis, C., & Augusto, B. (2018). Pre-NBS Baseline Data for Front-Runner Cities. UNaLab project (https://www.unalab.eu/), Milestone Report M3.1 of 22-10-2018, CESAM – Department of Environment and Planning, University of Aveiro, Aveiro, Portugal. 32pp.

[1] All references cited herein are provided in Section 7. For ease of use, key references are are listed in each respective section along with links to additional information.

2.4 Relations to other activities

Performance and Impact Monitoring of Nature-Based Solutions (D3.1) is a stand-alone report that provides guidance to UNaLab partner cities measuring or monitoring the performance and impact of NBS implemented as part of the UNaLab project (i.e., WP5). The present document will be updated throughout the UNaLab project based on new information from the NBS Impact Evaluation Framework (IEF) Task Force, published literature and other relevant sources. The first update to D3.1 will be provided at M36, as an Appendix in the WP5 *Preliminary NBS Implementation Handbook* (D5.3). Further updates will be reported at M60 when the final version of this document is presented as an Appendix in the WP5 *UNaLab NBS Implementation Handbook* (D5.5, M60). In addition, the methods described herein will be used to evaluate performance and impacts of NBS implemented in UNaLab front-runner cities, and will be reported in the WP3 report *Performance and Impacts of NBS* (D3.4, M60).

3. NBS CLASSIFICATION AND INDICATOR APPLICABILITY

3.1 General classification of NBS

Nature-based solutions were initially introduced in 2008 (MacKinnon, Sobrevila, & Hickey, 2008; Mittermeier et al., 2008) as a means to mitigate and adapt to climate change whilst protecting biodiversity and improving sustainability of livelihoods. Although several definitions of NBS have been proposed, the most commonly accepted definitions are those from the International Union for the Conservation of Nature (IUCN) and the European Commission (EC) (Table 1). The IUCN definition necessitates that a well-managed or restored ecosystem form the basis of any NBS (Cohen-Shacham, Walters, Janzen, & Maginnis, 2016, pg. 5), whilst the somewhat broader EC definition encompasses solutions "inspired by, supported by, or copied from" nature (European Commission, 2015, pg. 5). See the *UNaLab NBS Technical Handbook* (Eisenberg & Polcher, 2018) for detail regarding the relationship between NBS and other initiatives or classes of environmental intervention, e.g. green infrastructure, water sensitive urban design, etc.

Table 1. What are nature-based solutions? International Union for the Conservation of Nature (IUCN; Cohen-Shacham et al., 2016, pg. 5) and European Commission (European Commission, 2015, pg. 5) definitions of NBS

IUCN (2016)	European Commission (2015)
"… actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits."	"… actions which are inspired by, supported by or copied from nature. ... Nature-based solutions use the features and complex system processes of nature… in order to achieve desired outcomes... Maintaining and enhancing natural capital…forms the basis for implementing solutions. These nature-based solutions ideally are energy and resource-efficient, and resilient to change…"

There is no single definitive list of NBS; however, NBS can be broadly grouped based on their objectives, or function, and level of ecosystem intervention. Eggermont et al. (2015) proposed the following NBS typology that has since been widely adopted (Figure 1):

- **Type 1** – no or minimal intervention in ecosystems, with objectives related to maintaining or improving delivery of ecosystem services within and beyond the protected ecosystems.
- **Type 2** – extensive or intensive management approaches that develop sustainable, multifunctional ecosystems and landscapes to improve delivery of ecosystem services relative to conventional interventions.
- **Type 3** – Highly intensive ecosystem management or creation of new ecosystems.

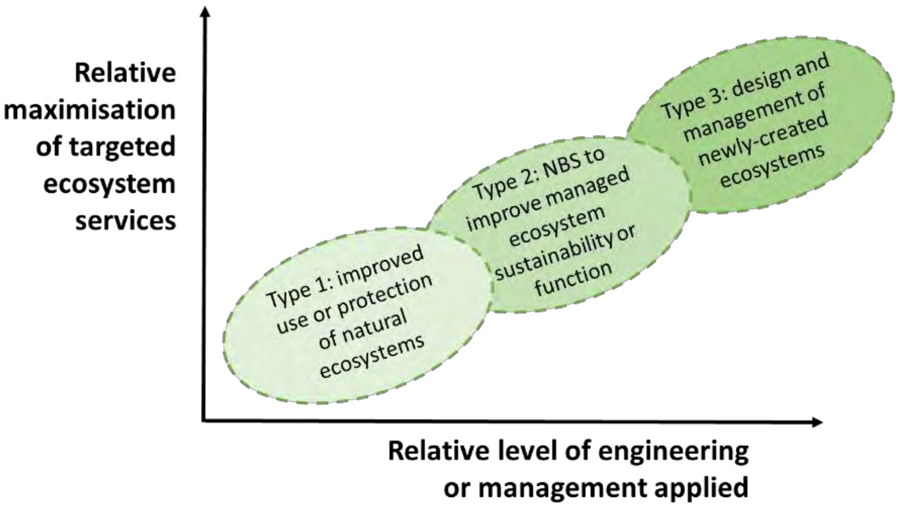


Figure 1. Schematic representation of NBS typology (adapted from Eggermont et al., 2015)

Type 1 NBS include protection and conservation strategies, urban planning strategies, and (environmental) monitoring strategies. Type 1 NBS by nature fall largely within the domain of governance, with implementation of Type 1 NBS strategies potentially limited or driven by various biophysical, social and institutional factors. Type 2 NBS are comprised of a range of different sustainable management practices. As newly-created ecosystems, Type 3 NBS are the most "visible" solutions. Examples of Types 1-3 NBS may include (Cohen-Shacham et al., 2016; Eggermont et al., 2015; European Commission, 2015; Nicolaides et al., 2019):

<u>**Type 1 NBS**</u>

- **Protection and conservation strategies**
    - Establish protected areas or conservation zones
    - Limit or prevent specific land use and/or practices
    - Ensure continuity of ecological network (protection from fragmentation)
    - Maintenance or enhancement of natural wetlands
- **Urban planning strategies**
    - Ensure continuity of ecological network
    - Control urban expansion
- **Monitoring**
    - Regular monitoring of physical, chemical or biological indicators

<u>**Type 2 NBS**</u>

- **Sustainable management protocols**
    - Integrated pest/weed management
    - Spatial and/or time and frequency aspects of integrated and ecological management plans
    - Creation and preservation of habitats and shelters to support biodiversity (e.g., insect hotels for wild bees, next boxes for native bats and birds, stopover habitat/"rest stops" for migratory birds)
    - Installation of apiaries
    - Sustainable fertiliser use

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

- Erosion control through management of grazing animal stocking density and exclusion of grazing animals from riparian areas
- Composting of organic wastes and reuse of composted material
- Integrated water resource management
- Protection of plant resources from pest and disease
- Aquifer protection form pollution and sustainable management of withdrawals

Type 3 NBS

- **Green space** - multifunctional open space characterised by natural vegetation & permeable surfaces
  - Urban parks and gardens of all sizes
  - Heritage park
  - Botanical garden
  - Rain garden
  - Community garden
  - Cemetery
  - Schoolyards and sports fields
  - Meadow
  - Green strips
  - Green transport track
  - "Multifunctional" dry detention pond or vegetated drainage basin
- **Trees and shrubs**
  - Forest (including afforestation)
  - Orchard
  - Vineyard
  - Hedges/shrubs/green fences
  - Street tree(s)
- **Soil conservation and quality management**
  - Slope revegetation
  - Cover crops
  - Windbreaks
  - Conservation tillage practices
  - Permaculture
  - Deep-rooted perennials
  - Organic matter enrichment (manure, biosolids, green manure, compost, etc.)
  - Inorganic soil conditioners and amendments (biochar, vermiculite, etc.)
- **Blue-green space establishment or restoration**
  - Riparian buffer zones
  - Mangroves
  - Saltmarsh/seagrass
  - Intertidal habitats
  - Dune structures
- **Green built environment**
  - Green roof
  - Green-blue roof
  - Green wall/façade
  - Green alley
  - Infiltration planters and tree boxes
  - Rainwater harvesting systems
  - Temporary and/or small-scale interventions including green furniture, green living rooms, etc.

- **Natural or semi-natural water storage and transport structures**
  - Surface wetland (marsh)
  - Floodplains, floodplain reconnection with rivers
  - Restoration of degraded waterbodies
  - Restoration of degraded waterways, including re-meandering of streams and river daylighting
  - Retention pond/wet detention pond
- **Infiltration, filtration, and biofiltration structures**
  - Infiltration basin
  - Vegetated filter strip
  - Rain garden
  - Wet/dry grassed swale, with or without check dams
  - Surface wetland (marsh)
  - Subsurface (constructed) wetland or filtration system
  - Bioretention basin/bioretention cell

3.2 Selecting NBS to address specific challenges

Numerous references provide information about appropriate NBS to address a given challenge; however, it is extremely difficult, if not impossible, for a single reference document to list all the different possible variations of NBS form. A general understanding of the mode of action of different kinds of NBS and a broad understanding of their form – in effect, how different forms of NBS work and what they look like – can help to select the most appropriate NBS to address a specific challenge.

Whilst it is certainly possible to 'match' local challenges with NBS using a published challenge-NBS matrix, applying a deeper understanding of NBS mode of action enables further innovation. Table 2 provides a general overview of NBS broadly grouped by form and function (mode of action), along with potential ecosystem service provision by each NBS group. The exemplar NBS provided within each group should be viewed as indicative rather than exhaustive, and are independent of NBS typology. For example, the "trees and shrubs" NBS groups could include Type 1 NBS actions to protect and conserve forest areas or urban planning to include forested areas in new urban development (Type 1), as well as protection of forest resources from pests and disease (Type 2) or planting of new trees and shrubs (Type 3).

Table 3 provides a general indication of the applicability of each broad NBS group to selected common urban challenges.

Table 2. Nature-based solutions broadly grouped by form and function or mode of action, and the potential ecosystem services provided by each

Primary Action*	NBS form	Variations on NBS form	Description and Function	Potential Ecosystem Services Provided
I, D, E, P	Green space	Urban parks and gardens of all sizes Heritage park Botanical garden Community garden Cemetery Schoolyards and sports fields Meadow Green strips "Multifunctional" dry detention pond or vegetated drainage basin	Multifunctional open space characterised by natural vegetation & permeable surfaces. May include (isolated) trees or woody vegetation in addition to open space. Intercept precipitation, increase infiltration and evapotranspiration, shallow depressions provide temporary water storage. This type of NBS can also contribute to the improvement of air quality and to the reduction of the urban heat island effect.	Provisioning: food (community gardens, wild foods); genetic resources; fresh water (via infiltration) Regulating: air quality; climate; water quantity; erosion; water quality; pollination; natural hazard Cultural: spiritual & religious; aesthetic; recreation & tourism
E, Sh, W, P	Trees and shrubs	Forest (including afforestation) Orchard Vineyard Hedges/shrubs/green fences Street tree(s)	Natural or semi-natural systems including perennial woody vegetation. Function to intercept precipitation, increase evapotranspiration, provide shade, stabilise slopes, absorb gaseous pollutants, capture particulate pollutants, capture and store CO_2. Trees and shrubs can affect atmospheric dispersion patters in the cities changing local air quality and affecting human comfort.	Provisioning: food (community orchards, wild foods); fibre (timber, wood fuel); genetic resources; fresh water (via infiltration) Regulating: air quality; climate; water quantity; erosion; water quality; pollination; natural hazard Cultural: spiritual & religious; aesthetic; recreation & tourism
I, B, P (E, W)	Soil conservation and quality management	Slope revegetation Cover crops Windbreaks Conservation tillage practices Permaculture Deep-rooted perennials Organic matter enrichment Inorganic soil conditioners and amendments	Soil conservation and quality management actions serve to reduce soil erosion, increase water infiltration, improve quality of surface runoff and receiving waterbodies, increase biodiversity of soil flora and fauna, mitigate climate change by through C sequestration and CO_2, CH_4 and N_2O emissions reduction, enable food and fibre production, and provide genetic resources. Vegetation can also provide food and habitat for pollinators.	Provisioning: food (crops, wild foods); fibre (timber, wood fuel); genetic resources; fresh water (via infiltration) Regulating: erosion; air quality; climate; water quantity; water quality; pollination; natural hazard Cultural: aesthetic
F, I, B	Blue-green space establishment or restoration	Riparian buffer zones Mangroves Saltmarsh/seagrass	Vegetated area of land adjacent to a watercourse or waterbody. Function to slow overland runoff and reduce flooding, increase	Provisioning: food (fisheries, wild foods); fibre (timber, wood fuel); fresh water (via filtration/infiltration); genetic resources

		Intertidal habitats Dune structures	infiltration and hyporheic exchange, stabilize soil at land-water interface and reduce erosion, & filter particulate materials.	Regulating: air quality; climate; water quantity; erosion; water quality; natural hazard; pollination Cultural: spiritual & religious; aesthetic; recreation & tourism
E, F/I, Ins, Sh, S, P	Green built environment	Green roof Green-blue roof Green wall/façade Green streets, alleys and parking lots Temporary and/or small-scale green structures (green furniture, green living room, etc.)	Structural (built) elements of the urban environment that incorporate vegetation in to their design to infiltrate, evapotranspirate and/or store rainwater, provide shade, and mitigate heat and pollution. Highly variable due to differences in structure, growth media & plant species/cover.	Provisioning: fresh water (via filtration/infiltration and rainwater capture); genetic resources Regulating: air quality; water quantity; erosion; water quality; climate; pollination; natural hazard Cultural: aesthetic
I, P, R/S	Natural or semi-natural water storage and transport structures	Surface wetland (marsh, reed bed, etc.) Floodplains and floodplain reconnection with rivers Restoration of degraded waterbodies Restoration of degraded waterways, including re-meandering of streams and river daylighting Retention pond/wet detention pond	Natural or constructed waterbody that increases water retention capacity and reduces flow of overland runoff by providing water storage or conveyance & facilitates particulate settling. Enhances freshwater resources via infiltration through hyporheic zone. Provides natural habitat for wildlife, and a range of recreational opportunities.	Provisioning: food (fisheries/aquaculture, wild foods); fresh water (via filtration and/or infiltration through hyporheic zone), genetic resources Regulating: water quantity; erosion; water quality; natural hazard; climate (via particulate/organic C capture) Cultural: spiritual & religious; aesthetic; recreation & tourism
I, F, B, P	Infiltration, filtration, and biofiltration structures	Infiltration basin Bioretention basin/bioretention cell Rain garden Vegetated filter strip/bioswale Wet/dry grassed swale, with or without check dams Infiltration planters and tree boxes Subsurface (constructed) wetland or filtration system	Normally dry area, possibly associated with a watercourse, which slows overland runoff water velocity and provides increased water storage capacity (reduces peak flows). Natural physical, biological and chemical processes attenuate pollutants in runoff. Captured water may infiltrate surrounding soil or engineered media and subsequently intersect with groundwater, or filtered water may be discharged via a drainage system or spillway.	Provisioning: fresh water (via runoff capture & filtration and/or infiltration) Regulating: water quantity; erosion; water quality; natural hazard; climate

**B=biofiltration; D=peak volume reduction via detention (temporary pool); E=evaporation/evapotranspiration; F=filtration; I=infiltration; Ins=insulation; P=pollutant removal or transformation; R=peak volume reduction via retention (permanent pool); S=storage, typically for later use; Sh=shade; W=windbreak.*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Table 3. Nature-based solutions grouped by form and function or mode of action, and their general applicability to exemplar challenges

	Carbon emissions	Flooding	Water scarcity	Water pollution	Coastal erosion	Soil degradation	Land instability	Air pollution	Reduced biodiversity	Compromised health and well-being	Urban decline	Building inefficiency	Poor public perception or value of nature	Declining property values
Green space	•	•	•	•		•		•	•	•	•	•	•	•
Trees and shrubs	•	•	•			•	•	•	•	•	•	•	•	•
Soil conservation and quality management	•	•	•	•		•	•	•	•	•				
Blue-green space establishment or restoration	•	•	•	•	•	•	•		•	•				
Green built environment	•	•	•	•		•		•	•	•	•	•	•	•
Natural or semi-natural water storage and transport structures		•			•				•	•	•		•	•
Infiltration, filtration, and biofiltration structures		•	•		•					•				

3.3 Assessing NBS performance and impact

3.3.1 Indicators and metrics

The way that the terms "indicator" and "metric" are defined and used varies widely. Herein, we define indicators and metrics as follows:

- **Indicator** – A quantitative or qualitative variable that provides the means to assess a particular phenomenon or attribute with respect to a specific objective
- **Metric** – an explicit calculated or composite measure, or value based upon two or more measures, e.g., before and after NBS implementation.

A single indicator may have several different, specific metrics that can potentially be used to assess NBS performance and impact.

3.3.2 Selection of indicators and specific metrics

Identification of key indicators of NBS performance and impact may begin with a group brainstorming session among all stakeholders, potentially in conjunction with co-creation workshops (e.g., Appendix I, Section 8). The large number of potential indicators of NBS performance and impact can be overwhelming, and it may thus be useful to somewhat reduce the number of potential indicators prior to discussing with stakeholder groups. In this case, a team of experts familiar with the local challenges as well as the municipality's strategies and objectives may recommend a short list of indicators for further discussion with stakeholders. In this case, there are a number of frameworks from which it is possible to source potential indicators of NBS performance and impact, such as:

- the NBS impact evaluation framework developed by the EKLIPSE Working Group on Nature-based Solutions to Promote Climate Resilience in Urban Areas (Raymond et al., 2017);
- the Mapping and Assessment of Ecosystems and their Services-Urban Ecosystems technical report and indicator framework (Maes et al., 2016; Maes, Zulian, Günther, Thijssen, & Raynal, 2019);
- the CITYkeys assessment framework for smart city projects and smart cities (Bosch et al., 2017; Huovila et al., 2017);
- the global indicator framework for UN Sustainable Development Goal 11 'Make cities and human settlements inclusive, safe, resilient and sustainable' (United Nations General Assembly, 2015, 2017; UN-Habitat et al., 2016);
- key environmental indicators identified by the Organization for Economic Development and Co-Operation (OECD) (OECD, 2008); and,
- various other NBS evaluation schemes and assessment frameworks published in the scientific literature (e.g., Calliari, Staccione & Mysiak, 2019; Faivre, Sgobbi, Happaerts, Raynal, & Schmidt, 2017; Kabisch et al., 2016; Nel, du Plessis & Landman, 2018; Wendling, Huovila, zu Castell-Rüdenhausen, Hukkalainen, & Airaksinen, 2018)

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Multiple sources may be used to develop a long list of potential indicators and metrics such as those used in the UNaLab project (Appendix II, Section 9).

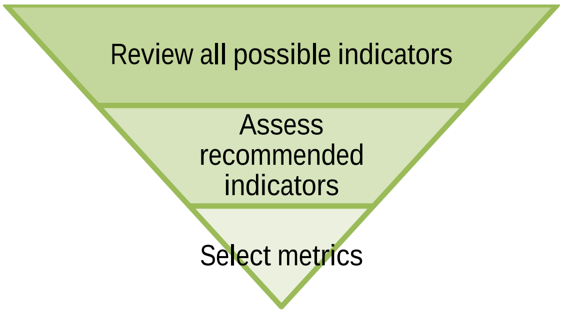


Figure 2. Schematic representation of NBS performance and impact indicator and metric selection

In the UNaLab project, a short form (Appendix I, Section 8) was used to establish a common understanding of previously identified challenges and their relative importance, as well as the expected outcomes of planned NBS implementation in each partner city. An initial meeting to assess the ‘match’ between challenges and expected NBS impacts focused broadly on big-picture concepts: the issues that each city planned to address by implementing NBS, the relative importance of these issues, and the scale at which the impact of NBS was expected. This meeting provided opportunity to clarify specific challenges and to explore the idea of scale with respect to NBS impacts. Following the initial brainstorming session, technical experts from each partner city and partner institutions worked together to select some recommended indicators for each city.

Recommended indicators can then be further refined by the selection of specific metrics. Meetings between NBS managers and other experts may be necessary to identify the most suitable metrics for assessment of suggested key indicators of NBS performance and impact based on specific objectives, project duration, and available resources. There are typically several different metrics that could potentially be used to quantify each indicator.

The final list of indicators adopted by each UNaLab partner city will likely evolve with time, and with the progress of the IEF Task Force. The current short list of indicators of NBS performance and impact for use by UNaLab partner cities is shown in Table 4.

Table 4. NBS performance and impact indicators and metrics for use by one or more UNaLab front-runner cities. Indicators/metrics denoted as “common” are shared among all NBS projects funded under H2020 call topic SCC-02-2016-2017

Indicator	Metric	Common to SCC-02-2016-2017 projects
Carbon emissions	Total amount of carbon stored in vegetation	X
	Total amount of carbon stored in soil	
	Carbon removed or stored per unit area per unit time	X
	CO_2 emissions due to building energy consumption	
	CO_2 emissions due to vehicle traffic	
Temperature	Mean or peak daytime local temperatures	X
	Heatwave risk	X
	Urban Heat Island (UHI) effect	
	Flood peak height	X

Flood vulnerability	Time to flood peak	X
	Run-off in relation to precipitation quantity	X
	Infiltration capacity	
	Evapotranspiration	
Drought vulnerability	Rainwater or greywater use for irrigation purposes	
	Depth to groundwater	
	Water Exploitation Index	
Water quality	Basic water quality (pH, temperature, EC, DO, flow rate)	
	Nitrogen and phosphorus in surface water and/or groundwater	X
	Metal pollutants in surface water and/or groundwater	X
	Total suspended solids (TSS)	
	Pollutant discharge to local waterbodies	
	Total number and species richness of aquatic macroinvertebrates	
Green space management	Distribution of public green space	X
	Accessibility of urban green spaces	X
	Proportion of road network dedicated to pedestrians and/or bicyclists	
	Ambient pollen concentration	
Biodiversity	Proportion of natural areas within a defined urban zone	
	Structural and functional connectivity	X
	Number of native species of birds within a defined urban zone	
	Changes in number of native species	
Air quality	Concentration of PM_{10}, $PM_{2.5}$, NO_2, and O_3 in ambient air	X
	Annual O_3, SO_2, NO_2, CO, and $PM_{2.5}$ capture/removal by vegetation	X
	Estimated years of life lost due to poor air quality	X
	Estimated morbidity and total mortality associated with air pollution	X
Urban regeneration	Reclamation of contaminated land (brownfields)	
	Ratio of open spaces to built form	
	Incorporation of environmental design in buildings	
	Proportion of area devoted to roads	
	Preservation of cultural heritage	
	Design for 'sense of place'	
Participatory planning & governance	Openness of participatory processes	
	Awareness of citizens regarding urban nature & ecosystem services	
	Participatory governance	
	Ease of governance of NBS	
	New forms of financing	
	Policy learning concerning adapting policies and strategic plans	
	Climate resilience strategy development	
Social justice &	Availability and equitable distribution of blue-green space	
	Safety, including indicators of crime	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

social cohesion	People reached by NBS project	
	Participation of vulnerable or traditionally under-represented groups	
	Consciousness of citizenship	
Health and well-being	Encouraging a healthy lifestyle	
	Exposure to noise pollution	
	Hospital admissions due to high temperature during extreme heat events	
Economic activity & green jobs	Establishment of new businesses in the area surrounding NBS	X
	Value of rates paid by all businesses in the area surrounding NBS	X
	Number of subsidies or tax reductions applied for (private) NBS measures	
	Number of new jobs in green sector	
	Use of ground floor building space for commercial or public purposes	
	Land and property value	X

Key References and Additional Information

Bosch, P., Jongeneel, S., Rovers, V., Neumann, H.-M., Airaksinen, M., & Huovila, A. (2017). CITYkeys indicators for smart city projects and smart cities. CITYkeys D1.4. Retrieved from http://nws.eurocities.eu/MediaShell/media/CITYkeysD14Indicatorsforsmartcityprojectsandsmartcities.pdf

Calliari, E., Staccione, A., & Mysiak. J. (2019). An assessment framework for climate-proof nature-based solutions. *Science of the Total Environment*, *656*, 691-700.

Eisenberg, B., & Polcher, V. (2018). *Nature Based Solutions Technical Handbook. UNaLab D5.1 NBS Technical Handbook 31/05/2018.* Stuttgart, Germany: University of Stuttgart Institute of Landscape Planning and Ecology. Retrieved from https://www.unalab.eu/documents/nbs-technical-handbook.

Faivre, N., Sgobbi, A., Happaerts, S., Raynal, J., & Schmidt, L. (2017). Translating the Sendai Framework into action: the EU approach to ecosystem-based disaster risk reduction. *International Journal of Disaster Risk Reduction*, *32*, 4-10.

Huovila, A., Airaksinen, M., Pinto-Seppä, I., Piira, K., Bosch, P., Penttinen, T., … Kontinakis, N. (2017). CITYkeys Smart City Performance Measurement System. *International Journal for Housing Science*, *41*(2), 113–125.

Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., … Bonn, A. (2016). Nature-based solutions to climate change adaptation and mitigation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and Society*, *21*(2), 39.

Maes, J., Zulian, G., Günther, S., Thijssen, M., & Raynal, J. (2019). *Enhancing Resilience of Urban Ecosystems through Green Infrastructure. Final Report, EUR 29630 EN.* Luxembourg: Publications Office of the European Union.

Maes, J., Zulian, G., Thijssen, M., Castell, C., Baró, F., Ferreira, A.M.., ... Teller, A. (2016). *Mapping and Assessment of Ecosystems and their Services. Urban Ecosystems.* Luxembourg: Publications Office of the European Union.

Nel, S., du Plessis, C., & Landman, K. (2018). Planning for dynamic cities: introducing a framework to understand urban change from a complex adaptive systems approach. *International Planning Studies*, *33*(3), 250-263.

Nicolaides, N., Lilli, M., Stagakis, S., Somarakis, G., Chrysoulakis, N., Lemaitre, F. & Le Roux, X. (2019). Unpublished material adapted from *Chapter 3. Classification of Nature Based Solutions*. February 2019. WP6 – Capacity Building and Materialisation of Nature Based Solutions – NBS Handbook. A deliverable of the ThinkNature Horizon 2020 Coordination and Support Action.

Organisation for Economic Co-operation and Development (OECD). (2008). *Key Environmental Indicators*. Paris, France: OECD Environment Directorate. Retrieved from https://www.oecd.org/env/indicators-modelling-outlooks/37551205.pdf

Raymond, C.M., Berry, P., Breil, M., Nita, M.R., Kabisch, N., de Bel, M., ... Calfapietra, C. (2017). *An Impact Evaluation Framework to Support Planning and Evaluation of Nature-based Solutions Projects. Report prepared by the EKLIPSE Expert Working Group on Nature-based Solutions to Promote Climate Resilience in Urban Areas*. Wallingford, United Kingdom: Centre for Ecology and Hydrology.

United Nations Environment Programme (UNEP), United Nations Educational, Scientific and Cultural Organization (UNESCO), World Health Organisation (WHO), United Nations (UN) Women, United Nations Office on Drugs and Crime (UNODC), World Bank Group … United Nations Statistics Division. (2016). *A Guide to Assist National and Local Governments to Monitor and Report on SDG Goal 11+ Indicators: Monitoring Framework, Definitions, Metadata, UN-Habitat Technical Support.* Nairobi, Kenya: UN-Habitat. Retrieved from http://unhabitat.org/sdg-goal-11-monitoring-framework/

United Nations (UN) General Assembly. (2015). *Transforming Our World: The 2030 Agenda for sustainable development. A/RES/70/1.* New York: United Nations. Retrieved from http://www.unfpa.org/sites/default/files/resource-pdf/Resolution_A_RES_70_1_EN.pdf

United Nations (UN) General Assembly (2017). Resolution adopted by the General Assembly on 6 July 2017. 71/313 Work of the Statistical Commission pertaining to the 2030 Agenda for Sustainable Development. 10 July 2017, A/RES/71/313. Retrieved from https://undocs.org/A/RES/71/313

Wendling, L.A. & Holt, E.E. 2019. Integrating engineered and nature-based solutions for urban stormwater management. In D.J. O'Bannon, (Ed.) *Women in Water Quality: Investigations by Prominent Female Engineers*. Zurich: Springer.

Wendling, L., Huovila, A., zu Castell-Rüdenhausen, M., Hukkalainen, M., & Airaksinen, M. (2018). Benchmarking Nature-Based Solution and Smart City assessment schemes against the Sustainable Development Goal indicator framework. *Frontiers in Environmental Science, 6*, 69.

3.4 Scale of application of selected indicators to NBS

The scale at which a given indicator or metric can be quantified varies a great deal. In most cases, even a metric that is measured on a hyper-local scale can be combined with other analogous measurements (e.g. measurements from a network of sensors) to yield information at a broader scale. In some cases, a 'big picture' can also be generated by modelling as a substitute for measurement data. A model essentially provides an approximation of the real-world situation. There are a few fundamental issues to consider when designing a scheme to monitor NBS performance or impact (Table 5).

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

The most critical, and arguably the most difficult element of designing a monitoring scheme is determining a realistic potential scale of impact to effectively direct monitoring and measurement efforts. Will the implemented NBS deliver benefits far beyond its borders, or is it part of a wider network of NBS? If the new NBS is part of a wider network, how can a monitoring scheme be designed so as to assess the performance or impact of the respective NBS in question? It is recommended that NBS owners work with a group of multi-disciplinary experts, and review similar NBS installations elsewhere[2], to develop a tailored monitoring scheme specific to local needs.

[2] Numerous NBS case studies are available online via the Oppla knowledge marketplace: https://oppla.eu/

Table 5. Monitoring NBS performance and impact at appropriate scale - considerations

Consideration	Brief Explanation	Example
Principal objective(s) of the NBS	Individual NBS can have multiple co-benefits, it remains essential to clearly define the main goal(s) of NBS implementation. At this stage opportunities to obtain added-value may be identified.	*An NBS consisting of roadside vegetation (vegetative barrier between road and adjacent land) with the primary objective of reducing human exposure to traffic-related pollution. An added value may be increased biodiversity via use of different native, non-invasive species.*
Definition of **"success"**	Define the level of performance or impact needed with respect to the principal objective(s) for the NBS to be considered "successful". Additional goals can also be defined in order of priority.	Annual mean targets: 15% reduction in NO_2, 30% reduction in total VOCs and 40% reduction in airborne particulates (PM_{10} + $PM_{2.5}$) measured at a height of 1.5 m and at a distance of 10 m from the road edge. Also: no significant increase in ambient pollen concentration or ground-level O_3; improved attractiveness of roadside walking/cycling paths.
Factors contributing to performance or impact of NBS	Based on the NBS implemented and its mode of action (how it works), a range of different characteristics can influence its performance and impact. Consult with relevant experts to identify the key factors.	*The type, height, and thickness of roadside vegetation, the continuity of the vegetative barrier, length of barrier relative to area of concern, and the structure of the built environment (i.e., extent of 'street canyon' environment) influence the extent of pollutant mixing and deposition.*
Potential data sources	Consider all the different types of information that can be collected to evaluate the NBS, and how it can be gathered. Look for opportunities to engage the community through, e.g. citizen science initiatives or the use of personal monitoring devices/wearable sensors.	*Fixed meteorological data & air quality measurement station(s) and samplers, mobile or wearable air quality sensors, manual measurements (leaf area index, leaf area density, height), modelling (e.g., i-Tree), epidemiological health data (morbidity, mortality)*
Available resources	Consider both the availability of baseline ('before NBS') data as well as the financial and human resources required for on-going monitoring (CAPEX + OPEX). Prioritise measurements and scale monitoring plans based on the resources available.	*What equipment is needed to conduct monitoring? Who can do the necessary manual monitoring (e.g., is it a highly skilled job, or can it be part of a citizen science initiative)? What are the expected on-going costs of, e.g., equipment maintenance? If personal monitoring devices are to be used, how many are needed to obtain an accurate representative sample of the local population?*
Realistic scale of impact	Assess the likely area of impact based on the scale of the NBS implemented. Consider results from similar case studies.	*Are existing meteorological and air quality monitoring stations sufficient to observe changes in air quality at individual site or street/neighbourhood scale or are additional (new) site-specific monitoring stations needed to provide sufficient resolution?*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4. MEASURING NBS INDICATORS

Individual metrics used to evaluate NBS performance and impact in this Section are grouped by indicator category (denoted by second-tier, e.g. "*X.X Indicator category*"). For each of the indicator categories presented, a brief introduction is provided followed by one or more specific metrics applicable to the respective indicator. Metrics are presented as third-tier headings (e.g., "*X.X.X Name of metric*"). Where multiple, significantly different measurement methods are given, these are presented as fourth-tier sub-headings (e.g., "***x)*** *Name of method*"). All cited references are listed in Section 7; in addition, key references for each indicator/metric are listed at the end of the respective section for convenience. Where possible, links to additional information, including online resources, are also provided. Guidance regarding the potential scale of measurement is provided for each metric.

4.1 Carbon Emissions

Indicator	Metric
Carbon emissions	Total amount of carbon stored in vegetation
	Total amount of carbon stored in soil
	Total amount of carbon removed or stored per unit area per unit time
	CO_2 emissions related to building energy consumption
	CO_2 emissions related to vehicle traffic

The global carbon cycle describes the deposition and release of C between soil, vegetation, atmosphere, oceans, rocks and fossil fuel emissions. Cycling of C between these different reservoirs in part defines the quantity of atmospheric carbon dioxide (CO_2). Efforts to mitigate increasing global atmospheric CO_2 concentration include emissions reduction, C storage, and C sequestration. *Carbon storage* refers to the quantity of C contained in biomass, including soil organic matter. *Carbon sequestration* refers to the process of increasing the C content of a reservoir other than the atmosphere, for example, increasing the C content of soil, plant biomass, or the oceans.

Carbon in the biosphere is divided among different reservoirs or pools as: inorganic carbon dissolved in the ocean (*ca.* 38 000 Gt C), underground fossilized carbon deposits (*ca.* 10 000 Gt C), soil organic carbon (*ca.* 2000 Gt C), atmospheric CO_2 (*ca.* 800 Gt C) and plant biomass, or phytomass (*ca.* 550 Gt C) (Riebeek, 2011; Scharlemann, Tanner, Hiederer & Kapos, 2014). An estimated 600 Gt C have been release from anthropogenic sources since 1750 as a result actions such as the burning of fossil fuels and land use change. Approximately 40% of anthropogenic C releases remain the atmosphere (260 Gt C), with the remainder partitioning between soil (165 Gt C) and ocean (175 Gt C) reservoirs (Intergovernmental Panel on Climate Change (IPCC), 2014; Le Quéré et al., 2016).

a) Carbon storage and sequestration

Atmospheric CO_2 concentration has a profound effect on the Earth's climate. Atmospheric CO_2 is relatively lesser in quantity compared with global C stocks in soil and oceans, but changes in plant biomass, soil organic C content and ocean conditions can have large effects on the atmospheric C balance. Thus, enhancing C storage in soil and biomass in urban areas and slowing C cycling help to support urban sustainability. Actions to increase C storage such as in forest conservation or protection of soil from degradation contribute can help to mitigate the impacts of climate change.

Depending on soil characteristics and climate type, soil and vegetation store very different quantities of C. Cool, moist boreal ecosystems may have >300 t C/ha in soil and only 25-50 t C/ha as biomass. In contrast, a warm, wet ecosystem such as a tropical rainforest can sustain >150 t C/ha as biomass with a relatively lesser quantity of C stored in the soil. As a general rule, the soil underlying a given area can store a greater quantity of C than the overlying vegetation, and a natural area with relatively little disturbance can store more C than an equivalent highly maintained area of lawn and trees (Hostetler & Escobedo, 2013). A greater quantity of C is generally stored in the soil relative to vegetation, but surface vegetation often serves to preserve soil C; in areas where surface biomass is removed through, e.g., deforestation, a large fraction of soil organic C is typically lost over time due to subsequent degradation and leaching (Scharlemann et al., 2014).

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

b) CO_2 emissions

Approximately half of the anthropogenic CO_2 emissions between 1750 and 2011 occurred in the most recent 40 years (IPCC, 2014). Increases in atmospheric CO_2 are driven largely by the use of fossil fuels for transport and energy production, with additional substantial greenhouse gas emissions due to land use change (particularly deforestation). Non-CO_2 greenhouse gases including methane (CH_4), nitrous oxide (N_2O) and fluorinated gases (e.g., chlorofluorocarbons, hydro chlorofluorocarbons, perfluorocarbons, and sulphur hexafluoride) comprised approximately 27% of total greenhouse gas emissions in 2010 (IPCC, 2014). For reporting purposes, emissions of all greenhouse gases are typically expressed as CO_2-equivalent emissions (CO_2e or CO_2-eq). Each greenhouse gas has a characteristic global warming potential (GWP) based on its respective ability to absorb energy (radiative efficiency) and its atmospheric lifetime (Table 6). The GWP of a gas is defined as how much energy the emissions of 1 t of the gas will absorb over a given period of time relative to the emissions of 1 t of CO_2.

Table 6. Major greenhouse gases and their global warming potential (GWP)

Greenhouse gas	Primary anthropogenic source(s)	GWP_{100}[a]
CO_2	Fossil fuel combustion	1
CH_4	Rice culture & enteric fermentation	28
N_2O	N fertiliser use, biomass burning & fossil fuel combustion	265

[a] GWP_{100}=Global warming potential over 100-year time period (AR5; IPCC, 2015)

Carbon dioxide emissions represent the largest share of greenhouse gas emissions and are used as an indicator to measure the environmental burden of a community. The estimation of the total greenhouse gas emissions of an urban community is a complex calculation including actions within and outside the boundaries of the community, they direct measurement of which is impossible. The aspects include measurement of energy use as electrical energy, heating and cooling energy, gas, oil or other combustibles, fuel used for transport, emissions from solid waste and wastewater collection and management, emissions from industrial processes and chemical use, and emissions from agriculture, land use, and forestry. Also consumption of manufactured products, whose physical emissions occur elsewhere can be calculated for the place of use or purchase. Greenhouse gas emissions are comprehensively addressed in the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (2006). Information sources for city-scale calculations include the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories - An Accounting and Reporting Standard for Cities (Fong et al., 2015).

For the purposes of NBS monitoring, a simplified indicator can be used that evaluates a single defined measure – for example, CO_{2e} emissions from building energy consumption or from vehicle traffic.

4.1.1 Carbon storage and sequestration in vegetation

***Metric:** Total amount of carbon (tonnes) stored in vegetation*

Accounting for C stored in soil and vegetation in an urban area can provide an indication of the condition of natural green spaces, total free surface area and total quantity of vegetation in the area examined. Measures of C storage and sequestration also provide a tangible connection to climate change mitigation, and the impacts of local land use, planning and management decision-making. It is important to note the substantial variation in C sequestration and storage capacity of different types of NBS.

There are several tools for modelling carbon in trees including the U.S. Forest Service Forest Inventory and Analysis Database, such as the suite of i-Tree tools (USDA Forest Service, 2019) and the CUFR Tree Carbon Calculator (CTCC). i-Tree Eco is a free ecosystem services tool developed by the USDA Forest Service and it is actively developed and adapted for further use also in Europe, and it is a good choice for calculation of carbon storage. The i-Tree Eco model inputs a database of city trees with information on location, size and species to a geographic information system platform.

The required data includes extent of vegetation cover & characteristics of vegetation (e.g., type, age and height), land use, air quality data, and meteorological data. These can be obtained from forest inventory analysis (FIA), a national land cover database (NLCD) or databases for housing density mapping. Users may need permission to gain access to national databases unless the data are open (freely available).

An urban area tree inventory database is created and provides inputs to the i-Tree program. The inventory can be created from maps and sample measurements. Municipalities often have arborists and gardeners who already have the requisite information or databases available. The i-Tree program also requires meteorological and other local information for modelling.

a) Modelling carbon storage with the i-Tree model

Download the free software application for forest assessment i-Tree Eco from https://www.itreetools.org/eco/. The i-Tree Eco model (USDA Forest Service, 2019) calculates the biomass for each measured tree using allometric equations from the literature. Biomass estimates are combined with base growth rates, based on length of growing season, tree condition, and tree competition, to derive annual biophysical accounts for carbon storage and carbon sequestration. The i-Tree model uses field survey data from the location of interest (i.e., tree inventory) to quantify the urban forest structure, and its effects on the environment and value to the community.

Once the tree inventory is sufficiently comparable to the real urban area, the tool is used to calculate the carbon stored in vegetation and this calculation can be followed as changes are made in the area and used as an indicator. The tool can also be used to model potential effects of changes to be made or situation if changes were not made by creating parallel scenarios of the same area with different tree inventories.

The i-Tree Eco model provides quantitative estimates of carbon storage and sequestration. i-Tree Eco can also calculate other parameters of interest, e.g., pollution removal, avoided runoff, volatile organic compound runoff, and oxygen production. To determine changes as a result of NBS implementation, populate the tree inventory database and run the model before and after NBS implementation. Annual updates will enable tracking of changes to C storage and sequestration with time.

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

b) Manual calculation of carbon storage

Alternatively, an estimate of C storage or sequestration in above-ground vegetation can be manually determined using a similar approach to the i-Tree Eco application. First, each above-ground vegetation polygon in a digital cartographic dataset can be classified per light detection and ranging (LiDAR) data as, e.g., *herbaceous vegetation* (grasses and non-woody plants), *shrub* (woody bushes and trees with mean height typically <2 m), *tall shrub* (woody bushes and trees with mean height generally 2-5 m), or *tree* (trees >5 m in height) after Davies, Edmonson, Heinemeyer, Leake, & Gaston (2011). Davies et al. (2011) recommend surveying to ground-truth map data and classification estimates. Species-specific allometric equations are available from the scientific literature to estimate above-ground dry weight biomass of the classified vegetation, and carbon storage calculated using conversion factors also available from the scientific literature. Where there are multiple equations for a given species, the equations can be combined to obtain a general result. Total above ground tree biomass can be converted to C storage using conversion factors based on tree type. The dry-weight of above-ground biomass of each class of vegetation along with the mean C content can also be determined via laboratory analysis.

If studying trees in quadrats or gardens, tree density can be calculated as the number of trees divided by the area of the entire land parcel. Mean C stock per tree species, estimated using allometric equations, can then be multiplied by the proportional contribution of each tree species to the total number of trees. The species-level results can then be combined to obtain an estimate of the above-ground C store associated with different land cover categories and, subsequently, for a city as a whole.

Scale of measurement: district to regional scale

Key References

Davies, Z.G., Edmonson, J.L., Heinemeyer, A., Leake, J.R., & Gaston, K.J. (2011). Mapping an urban ecosystem service: quantifying above-ground carbon storage at a city-wide scale. *Journal of Applied Ecology*, ***48***, 21125-1134.

Fong, W.K., Sotos, M., Doust, M., Schultz, S., Marques, A., & Deng-Beck, C. (2015). *Global Protocol for Community-Scale Greenhouse Gas Emission Inventories*. Washington, D.C.: World Resources Institute. Retrieved from https://www.wri.org/publication/global-protocol-community-scale-greenhouse-gas-emission-inventories

Intergovernmental Panel on Climate Change (IPCC). (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston, S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (Eds.). Hayama, Japan: Institute for Global Environmental Strategies (IGES). Retrieved from https://www.ipcc-nggip.iges.or.jp/public/2006gl/.

Intergovernmental Panel on Climate Change (IPCC). (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds.). Geneva, Switzerland: IPCC.

United States Department of Agriculture (USDA) Forest Service. (2019). i-Tree Eco Manual. Northern Research Station, USDA Forest Service. Retrieved from https://www.itreetools.org/resources/manuals/Ecov6_ManualsGuides/Ecov6_UsersManual.pdf

Additional Resources

i-Tree Eco model: https://www.itreetools.org/eco/

CUFR Tree Carbon Calculator (CTCC): https://www.fs.usda.gov/ccrc/index.php?q=tools/tree-carbon-calculator-ctcc

Rogers, K., Sacre, K., Goodenough, J., & Doick, K. (2015). *Valuing London's Urban Forest: Results of the London i-Tree Eco Project.* London: Treeconomics. Retrieved from https://www.london.gov.uk/sites/default/files/valuing_londons_urban_forest_i-tree_report_final.pdf

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.1.2 Carbon storage and sequestration in soil

Metric: *Total amount of carbon (tonnes) stored in soil*

Carbon storage in soils is dynamic on the time scale of decades, and is sensitive both to climatic and anthropogenic disturbance. The soil can serve as either a source of CO_2 emissions or as a C sink, making land use and land cover change critical to soil C sequestration. Soils and surface litter contain an estimated two- to three-times as much C as the quantity present in the Earth's atmosphere (Trumbore, 2009). Estimates of global soil organic carbon (SOC) stocks range from approximately 500 to nearly 3000 Pg C (Pg = 10^{15} g, or billion tonnes) (Scharlemann et al., 2014). The most frequently reported global SOC estimate is 1500 Pg C.

Total C in soils is the sum of inorganic and organic C. Inorganic C is largely found in carbonate minerals (e.g., $CaCO_3$), and is highest in soils that formed from calcareous parent materials under arid conditions. Approximately two-thirds of the C in soils in in organic form, referred to as SOC. Soil organic carbon consists of the cells of microorganisms, plant and animal residues at various stages of decomposition, humus synthesised from residues, and elemental forms of C such as charcoal, graphite and coal.

Carbon sequestration in soil implies transforming atmospheric CO_2 into long-lived C forms and storing it securely in soil. Organic C in soil can be returned to the atmosphere as CO_2 via biological oxidation, or as CH_4 via methanogenesis. Changes in land use or land cover can alter soil conditions such stored C is released. For example, conversion of native vegetation to cropland results in loss (as CO_2 emissions) of an estimated 60% of stored SOC in temperate regions and as much as 75% in tropical regions (Lal, 2004). Potential for SOC sequestration is mainly in restoration of degraded soils and ecosystems. Increases in SOC can also be achieved through agroforestry, addition of biochar, adoption of perennial cropping systems, reforestation and afforestation (particularly with hardwood species), and other forms of management that affect land cover and land use. Recorded SOC sequestration ranges from 0-150 kg C/ha in dry and warm climates to 100-1000 kg C/ha in humid and cool regions (Lal, 2004).

Management actions that enhance SOC stocks are those that add large quantities of biomass to the soil, involve minimal soil disturbance, protect the soil from erosion or degradation (conserve soil), enhance water use efficiency/conserve water, improve soil structure, enhance the activity and species diversity of soil fauna, and strengthen mechanisms of biogeochemical cycling. Soil C management actions must consider co-benefits and trade-offs with other ecosystem services in order to develop policies with optimal benefit.

a) Soil carbon measurement method

The most reliable and accurate method of determining soil C content is field sampling followed by laboratory analysis. Combustion is an accurate, commonly used analytical technique to quantify total C in soil – including both organic and inorganic soil C. Combustion analysis involves converting all forms of C in the soil to CO_2 by wet or dry combustion, then measuring evolved CO_2. Change in soil C content occurs most readily in the SOC fraction, so observed changes in total soil C content with time are most likely to represent changes to SOC content.

It may be challenging to detect small changes in soil C content in soils that contain substantial inorganic (mineral) C. A rapid field test of the soil's reactivity to acid can indicate whether it may be necessary to undertake more intensive analyses of soil samples to quantify both the organic and inorganic C fractions, rather than total (inorganic + organic) C by combustion. Rapid assessment of soil carbonate content involves reacting a small sample (ca. 1 g) of soil with 1-2 drops of 1 M hydrochloric acid (HCl) in a glass or porcelain container and observing the reaction for ~5 min. The reaction between soil carbonate minerals and HCl is visible as bubbles/effervescence as bubbles of CO_2 are produced. Table 7 provides guidance to evaluate the semi-quantitative reaction between soil carbonates and HCl.

Table 7. Soil carbonate estimation based on reaction with 1 M hydrochloric acid (Rowell, 2014; Soil Survey Staff, 2009)

Estimated Carbonate Content	Visible reaction
Non-calcareous (<1%)	No bubbles form
Slightly calcareous (1-2%)	Very few bubbles form, reaction just visible & confined to individual soil grains
Slightly calcareous (2-5%)	Few bubbles form
Calcareous (5-10%)	Many obvious bubbles form up to 3 mm in diameter
Very calcareous (>10%)	Very many obvious bubbles form up to 7 mm in diameter

If the HCl 'field test' indicates the presence of inorganic C then the soil sample should be pre-treated to remove inorganic C prior to determination of organic C content by wet digestion. A sample of the carbonate-containing soil should be treated at room with a mixture of dilute sulphuric acid (H_2SO_4) and ferrous sulphate ($FeSO_4$) for at least 20 min, or until effervescence appears to cease. The flask containing the soil and H_2SO_4/$FeSO_4$ mixture should then be heated over a flame and boiled slowly for 1.5 min to destroy any remaining carbonate. Finally, pulverised potassium dichromate ($K_2Cr_2O_7$) should be added to the mixture and organic C determined by chromic acid digestion (wet combustion) (Nelson & Sommers, 1996).

Scale of measurement: plot scale; it is possible to extrapolate results from small number of field samples based on soil maps to approximate soil C storage at landscape (regional) scale.

Key references

Nelson, D.W., & Sommers, L.E. (1996). Total Carbon, Organic Carbon, and Organic Matter. In D.L. Sparks (Ed.), *Methods of Soil Analysis Part 3, Chemical Methods* (pp. 961-1010). Madison, WI: Soil Science Society of America, Inc.

Rowell, D.L. (2014). *Soil Science: Methods & Applications*. New York: Routledge.

Soil Survey Staff. (2009). *Soil Survey Field and Laboratory Methods Manual. Soil Survey Investigations Report No. 51, Version 2.0. R. Burt (Ed.).* Lincoln, NE: United States Department of Agriculture, Natural Resources Conservation Service.

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.1.3 Carbon removed or stored per unit area per unit time

Metric: *Total carbon removed or stored (tonnes/ha/y or similar units)*

To evaluate C removal or storage per unit area per unit time, determine C storage in vegetation or soil as described in section 4.1.1 or 4.1.2, respectively, for the same area at two different points in time. Divide each C storage value obtained by the area assessed to determine C storage per unit area. Subtract the earlier value obtained for C storage and sequestration/unit area from the more recent value, then divide by the length of time between measures to obtain an estimate of C removal or storage per unit area per unit time.

The growth rate of a forest has significant impact on its C storage potential. Forest C sequestration (FCS) is usually estimated as a function of forest area, forest type, and forest age:

$$FCS = (FIA_{rate}/FOREST_{mean\text{-}pct}) \times NONF_{mean\text{-}pcti} \times NONF_{areai}$$

where FIA_{rate} is net forest growth rate for the most common type group in county i, $FOREST_{mean\text{-}pct}$ is mean canopy cover percentage for all forested pixels in the county i, $\mathrm{NONF}_{\mathrm{mean\text{-}pct}}$ is mean canopy cover percentage for all non-forest pixels in county i, and $NONF_{area}$ is area sum of all non-forest pixels in county i. The sum of FCS in both forested and non-forest pixels is the total net FCS by urban and community trees in county i (Zheng, Ducey, & Heath, 2013). Studies have shown that more accurate estimates of FCS are obtained by classifying forests as recently afforested or mature/remnant forest as tree growth rates vary substantially between these forest types (Smith, Heath, Skog & Birdsey, 2006; Zheng, Heath, Ducey & Smith, 2011).

Scale of measurement: plot scale to regional scale

Key References

Smith, J.E., Heath, L.S., Skog, K.E., & Birdsey, R.A. (2006). *Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States. USDA Forest Service Report GTR-NE-343*. Newtown Square, PA: Northeastern Research Station, United States Department of Agriculture, Forest Service.

Zheng, D., Ducey, M.J. & Heath, L.S. (2013). Assessing net carbon sequestration on urban and community forests of northern New England, USA. *Urban Forestry & Urban Greening*, ***12***, 61-68.

Zheng, D., Heath, L.S., Ducey, M.J. & Smith, J.E. (2011). Carbon changes in conterminous US forests associated with growth and major disturbances: 1992–2001. *Environmental Research Letters*, ***6***, 014012.

Additional Information

Bettinger, P., Boston, K., Siry, J.P. & Grebner, D.L. (2017). Chapter 2 - Valuing and Characterizing Forest Conditions. In P. Bettinger, K. Boston, J.P. Siry, & D.L. Grebner (Eds.), *Forest Management and Planning (Second Edition) (21–63)*. London: Elsevier Academic Press.

Kenway, S.J., Lant, P., & Priestly, T. (2011). Quantifying water-energy links and related carbon emissions in cities. *Journal of Water and Climate Change*, *2*, 247-259.

4.1.4 CO_2 emissions related to building energy consumption

Metric: *CO_2 emissions related to building energy consumption (direct and electricity indirect) with and without NBS implementation (kWh/y and t C/y saved)*

Building energy consumption is the fraction of greenhouse gas emissions that can be affected by nature based solutions in urban environment. This measure can be calculated from municipal data and estimates, and can indicate changes in building heating and cooling needs. The metric can be measured fairly easily, however it is not sensitive to details regarding how energy is produced. Depending on the method employed, the analysis can be lacking in accuracy and comparability between different communities and regions. Data required to assess CO_2 emissions related to building energy consumption include information about building energy sources and electrical energy use, as well as supplemental energy sources such as district heating and local combustion for heating. These data can typically be obtained from municipal sources or from records of building- or district-level energy consumption from the building owner or utility company.

a) Quantifying building emissions

The emitted GHG-equivalence of energy use can be calculated at different levels of precision. A rapid and reasonably accurate method uses a national emission factor for consumed energy (Table 8), which gives a conversion factor t CO_2/MWh to yield a value for equivalent CO_2-emissions resulting from building energy use.

First, the community housing energy sources are identified and methods for their quantification on yearly basis are recorded (IPCC, 2006). These energy sources include the electrical energy use, as well as supplemental energy sources such as district heating and local combustion for heating. Numerical values for the community as a whole (MWh) as well as population equivalent are recorded (MWh/person), thus allowing for compensation for population change. To determine changes as a result of NBS implementation, calculate before and after NBS implementation. Annual updates will enable tracking of changes to CO_2 emissions due to building energy consumption with time.

All forms of energy need to be taken into account, including electricity consumption, natural gas or thermal energy for heating and cooling, and fuels. These may be provided in different units of energy (kWh, GJ, m^3), but all must be calculated or converted to kWh of energy to add the separately calculated energy consumptions and achieve the total energy consumption. Relevant unit conversions:

- 1 J = 1 Ws
- 1 kWh= 3,600,000 J
- 1 TOE = 41.868 GJ = 11,630 kWh = 11.63 MWh.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

b) Calculation

$$Emissions_{buildings} = Energy(MWh/a) \cdot national\ emission\ factor\ (tCO_2/MWh)$$

$$Emissions_{traffic} = Estimated\ use\ of\ fuel(t) \cdot emission\ factor(t\ CO_2/t)$$

$$Decrease(\%) = 100\% - \left(\left(\frac{Emission_{buildings(+traffic)}\ (after)}{Emission_{buildings(+traffic)}\ (before)}\right) \cdot 100\%\right)$$

Scale of measurement: building, street and district scale

Key References

Intergovernmental Panel on Climate Change (IPCC). (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Prepared by the National Greenhouse Gas Inventories Programme, Eggleston, S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (Eds.). Hayama, Japan: Institute for Global Environmental Strategies (IGES). Retrieved from https://www.ipcc-nggip.iges.or.jp/public/2006gl/.

Table 8. National and European emission factors for consumed electricity (Koffi, 2017)

Country	Standard emission factor (t $C0_2$/MW)
Austria	0.209
Belgium	0.285
Germany	0.624
Denmark	0.461
Finland	0.440
France	0.216
United Kingdom	0.056
Greece	0.543
Ireland	1.149
Italy	0.732
Netherlands	0.483
Portugal	0.435
Sweden	0.369
Bulgaria	0.023
Cyprus	0.819
Czech Republic	0.874
Estonia	0.950
Hungary	0.566
Lithuania	0.153
Latvia	0.109
Poland	1.191
Romania	0.701
Slovenia	0.557
Slovakia	0.252
Eu-27	0.460

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.1.5 CO_2 emissions related to vehicle traffic

Metric: *CO_2 emissions related to vehicle traffic (t C/y reduction)*

The traffic GHG-emission are calculated typically either through fuel consumption data or travel distance data (IPCC, 2006). In a community-scale, study, only travel distance, represented by amount of traffic measurements are seen feasible. First, suitable available data source measuring the kilometre per person transport in the area should be identified, preferentially giving estimates of consumption of gasoline, diesel, ethanol and natural gas, the most common fuels used in car and rail transport (IPCC, 2006; Toledo & Rovere, 2018). These consumed fuels, as well as potential consumed electricity by electrified rail systems, are converted to emission using emission factors for different fuels. Preferred method is to locate country specific net-calorific-values and CO_2-emission factors, when available, but general default values are presented (IPCC, 2006).

Table 9. Emission factors for fuels, adapted from IPCC 2006 Guidelines Vol 2. Tables 1.2 & 1.4. (IPCC, 2006)

	Gasoline	Diesel	Ethanol	Natural gas
t CO_2/t fuel	3.07	3.19	1.91	2.69

Scale of measurement: district scale

Key references

Intergovernmental Panel on Climate Change (IPCC). (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Prepared by the National Greenhouse Gas Inventories Programme, Eggleston, S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (Eds.). Hayama, Japan: Institute for Global Environmental Strategies (IGES). Retrieved from https://www.ipcc-nggip.iges.or.jp/public/2006gl/.

4.2 Temperature

Indicator	Metric
Temperature	Mean or peak daytime local temperatures (°C)
	Heatwave risk: number of combined tropical nights (>20°C) and hot days (>35°C)
	Urban Heat Island (UHI) effect

Urban heating characteristics and the phenomenon of the Urban Heat Island (UHI), i.e. the phenomenon that temperatures in urban areas are higher than in the rural surrounding areas, have been extensively studied as the most obvious impacts of human activities on local climates. The UHI is observed where the built environment impacts the thermodynamic fluxes between the sky and the Earth through four aspects (Rizwan, Dennis & Liu, 2008): reduced vegetation, properties of urban materials, urban geometry and increased anthropogenic heat. Moreover, the UHI effect varies temporally and spatially (Leconte, Bouyer, Claverie & Pétrissans, 2017). In Europe, the UHI has been the subject of a great amount of research, of which Santamouris (2007) provided a state of the art for, in particular, Mediterranean and Central European cities.

4.2.1 Mean or peak daytime temperature

Metric: *Mean or peak daytime local temperature by direct measurement, PET calculation or modelling (°C), or by PMV-PPD calculation (unitless value)*

Green urban infrastructure can significantly affect climate change adaptation by reducing air and surface temperatures with the help of shading and through increased evapotranspiration. Conversely, green urban infrastructure can also provide insulation from cold and/or shelter from wind, thereby reducing heating requirements (Cheng, Cheung, & Chu, 2010). By moderating the urban microclimate, green infrastructure can support a reduction in energy use and improved thermal comfort (Demuzere et al., 2014).

Studies have documented changes in ambient temperature with increasing distance from a green area (Yu & Hien, 2006). The cooling effect of green space results in lower temperatures in the surrounding built environment. A simulation of the surrounding buildings showed the potential for a 10% decrease in the cooling load due to the presence of the green area in the vicinity (Yu & Hien, 2006). Use of turf as vertical greening has been reported to help reduce interior surface temperatures by >2°C. Shashua-Bar, Pearlmutter & Erell (2009) report that courtyards with shade trees and grass exhibited a daytime temperature reduction of approximately 2.5°C.

Key References

Cheng, C.Y., Cheung, K.K.S., & Chu, L.M. (2010). Thermal performance of a vegetated cladding system on facade walls. *Building and Environment*, *45*(8), 1779-1787.

Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orru, H., … Faehnle, M. (2014). Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. *Journal of Environmental Management*, *146*, 107-115.

Shashua-Bar, L., Pearlmutter, D., & Erell, E. (2009). The cooling efficiency of urban landscape strategies in a hot dry climate. *Landscape and Urban Planning*, *92*(3–4), 179-186.

Yu, C., & Hien, W.N. (2006). Thermal benefits of city parks. *Energy and Buildings*, *38*, 105-120.

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

a) Direct Measurement of Temperature

Ambient air temperature can be assessed through continuous monitoring of temperature, near the NBS intervention area, and calculation of mean and peak daytime temperature before and after NBS implementation.

Scale of measurement: plot to district scale

b) Predicted Mean Vote-Predicted Percentage Dissatisfied

Thermal comfort is described as the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE], 2013). The most commonly known approach was developed by Fanger in the 1970s based on a heat balance model of the human body for indoor environments (Fanger, 1970). The model aims to estimate the mean thermal sensation of a group of individuals and their respective percentage of dissatisfaction with the thermal environment, expressed in terms of Predicted Mean Vote-Predicted Percentage Dissatisfied (PMV-PPD). The PMV can be calculated using six variables: metabolism, clothing, indoor air temperature, indoor mean radiant temperature, indoor air velocity and indoor air humidity (Rupp, Vásquez, & Lamberts, 2015). The practical application of the PMV equation and associated variables has been described by Ekici (2016).

PMV provides a score that relates to the Thermal Sensation Scale shown in Table 10 (Fanger, 1970). If the score is zero, the occupant satisfaction regarding the environment is at the maximum level (Ekici, 2016).

Table 10. Thermal Sensation Scale (Fanger, 1970)

Scale	Description	How it feels
3	Hot	Intolerably warm
2	Warm	Too warm
1	Slightly warm	Tolerably uncomfortable, warm
0	Neutral	Comfortable
-1	Slightly cool	Tolerably uncomfortable, cool
-2	Cool	Too cool
-3	Cold	Intolerably cool

Scale of measurement: building scale

Key References

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2013). Standard 55 - Thermal environmental conditions for human occupancy. Atlanta, GA: ASHRAE.

Ekici, C. (2016). Measurement uncertainty budget of the PMV thermal comfort equation. *International Journal of Thermophysics*, *37*, 48

Ekici, C. (2013). Review of Thermal Comfort and Method of Using Fanger's PMV Equation.

Proceedings of the 5th International Symposium on Measurement, Analysis and Modelling of Human Functions, 27-29 June 2013, Vancouver, Canada. 4 pp.

Fanger, P. (1970). *Thermal comfort. Analysis and applications in environmental engineering*. Copenhagen: Danish Technical Press.

Rupp, R. F., Vásquez, N. G., & Lamberts, R. (2015). A review of human thermal comfort in the built environment. *Energy and Buildings*, *105*, 178–205.

c) Physiological Equivalent Temperature

The physiological equivalent temperature (PET) is the temperature at any given place (outdoors and indoors) that is equivalent to the air temperature at which the heat balance of the human body is maintained with the core and skin temperatures equal to those under the conditions being assessed (Höppe, 1999). Compared to PMV, PET has the advantage to use °C, which allows the results to be easily interpreted by urban or regional planners.

Several equations can be used to calculate PET. The basis is the heat-balance equation of the human body. In order to take into account the basic thermoregulatory processes, the Munich energy-balance model for individuals (MEMI) is used for calculation of PET (1). The heat balance model MEMI is based on the energy balance equation of the human body and is related to the Gagge two-node model (Gagge, Stolwijk, & Nishi, 1972). The MEMI equation is as follows:

$$M + W + R + C + E_D + E_{Re} + E_{Sw} + S = 0 \qquad (1)$$

where, M is the metabolic rate (internal energy production by oxidation of food); W is the physical work output; R is the net radiation of the body; C is the convective heat flow; E_D is the latent heat flow to evaporate water into water vapour diffusing through the skin; E_{Re} is the sum of heat flows for heating and humidifying the inspired air; E_{Sw} is the heat flow due to evaporation of sweat; and, S is the storage heat flow for heating or cooling the body mass.

As a first step, the mean surface temperature of the clothing (T_{cl}), the mean skin temperature (T_{sk}) and the core temperature (T_c) must be evaluated. These three parameters provide the basis for calculation of E_{Sw}. Two equations are necessary to describe the heat flows from the body core to the skin surface (F_{cs}) as shown in (2), and heat flows from the skin surface through the clothing layer to the clothing surface (F_{sc}) as shown in (3) (Höppe, 1999):

$$F_{CS} = v_b \cdot \rho_b \cdot c_b \cdot (T_c - T_{sk}) \qquad (2)$$

where, v_b is blood flow from body core to skin (L/s/m^2); ρ_b is blood density (kg/L); and, c_b is the specific heat (W/sK/kg).

$$F_{SC} = (1/I_{cl}) \cdot (T_{sk} - T_{cl}) \qquad (3)$$

where, I_{cl} is the heat resistance of the clothing (K/m^2/W).

Using equations (1) (2) and (3) together, it is possible to evaluate the thermal state of the human body. To calculate PET (Höppe, 1999):

- Determine the thermal conditions of the body using MEMI for a given set of climatic parameters.
- Insert calculated values for mean skin temperature (T_{sk}) and core temperature (T_c) into the

MEMI equation (1) and solve the three equations for air temperature, T_a (v = 0.1 m/s; water vapour pressure = 12 hPa; $T_{mrt} = T_a$). This temperature is equivalent to PET.

Scale of measurement: building or plot scale

Key References

Gagge, A., Stolwijk, J.A., & Nishi, Y. (1971). An effective temperature scale based on a simple model of human physiological regulatory response. *ASHRAE Transactions*, *77*(1), 247-257.

Höppe, P. (1999). The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology*, *2466*, 71-75.

Additional Information

Nicol, F., Humphreys, M.A., & Roaf, S. (2012). *Adaptive thermal comfort: principles and practice*. London: Routledge.

d) Temperature Modelling

An alternate method to measure difference in temperature is to apply a meteorological model such as the Weather Research and Forecasting model (WRF) (NCAR & UCAR, n.d.; NOAA, n.d.). Data requirements include initial and boundary conditions (MOZART model; Emmons et al., 2010), topography and land use (USGS 33 classes database; Pineda, Jorba, Jorge & Baldasano, 2004) and urban parameters (building height, width, number of road lanes). For calculation purposes, the data can be collected annually and before and after NBS implementation. The use of the WRF model allows the calculation of this indicator with an hourly resolution at the grid, neighbourhood or city scale neighbourhood. These data can be obtained through national statistics, municipal departments, Corine Land Cover, and a mapping application such as OpenStreetMap. For calculation purposes, the data can be collected annually before and after NBS implementation.

Scale of measurement: district to regional scale

References

Emmons, L.K., Walters, S., Hess, P.G., Lamarque, J.-F-, Pfister, G.G., Fillmore, D. … Kloster, S. (2010). Description and evaluation of the Model for Ozone and Related chemical Tracers, version 4 (MOZART-4). *Geoscientific Model Development*, *3*, 43-67.

National Center for Atmospheric Research (NCAR) & University Corporation for Atmospheric Research (UCAR). (n.d.). Weather Research and Forecasting (WRF) Model Users' Page. Retrieved from http://www2.mmm.ucar.edu/wrf/users/

National Oceanic and Atmospheric Administration (NOAA). (n.d.). Weather Research and Forecasting model coupled to Chemistry (WRF-Chem). Retrieved from https://ruc.noaa.gov/wrf/wrf-chem/

Pineda, N., Jorba, O., Jorge, J. & Baldasano, J.M. (2004). Using NOAA AVHRR and SPOT VGT data to estimate surface parameters: application to a mesoscale meteorological model. *International Journal of Remote Sensing*, *25*(1), 129–143.

Weather Research and Forecasting Model (WRF): https://www.mmm.ucar.edu/weather-research-and-forecasting-model

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.2.2 Heatwave Risk

Metric: *Heatwave risk: number of combined tropical nights (>20°C) and hot days (>35°C)*

Heatwave is a period of prolonged abnormally high surface temperatures relative to those normally expected. Heatwaves can be characterized by low humidity, which may exacerbate drought, or high humidity, which may exacerbate the health effects of heat-related stress such as heat exhaustion, dehydration and heatstroke. Heatwaves in Europe are associated with significant morbidity and mortality. Furthermore, climate change is expected to increase average summer temperatures and the frequency and intensity of hot days (Russo et al., 2014). In cities and urban areas, the UHI tends to exacerbate heatwave episodes. There is no universal definition of a heat wave, though the World Meteorological Organization (WMO) defines a heat wave as five or more consecutive days of prolonged heat in which the daily maximum temperature is higher than the average maximum temperature by 5°C or more.

For this project, heatwave risk is defined as the number of combined tropical nights (>20°C) and hot days (>35°C), following Fischer & Schär (2010) as cited by Baró, Haase, Gómez-Baggethun and Frantzeskaki (2015), and simulated by Carvalho, Martins, Marta-Almeida, Rocha and Borrego (2017). This indicator is assessed through continuous monitoring of temperature, and/or estimated by applying meteorological models such as the WRF (NCAR & UCAR, n.d.; NOAA, n.d.). The data requirement, data sources and potentialities are similar to those described above (Section 4.2.1).

Scale of measurement: building/plot to regional scale

Key References

Baró, F., Haase, D., Gómez-Baggethun, E., & Frantzeskaki, N. (2015). Mismatches between ecosystem services supply and demand in urban areas: A quantitative assessment in five European cities. *Ecological Indicators*, *55*, 146–158.

Carvalho, D., Martins, H., Marta-Almeida, M., Rocha, A., & Borrego, C. (2017). Urban resilience to future urban heatwaves under a climate change scenario: A case study for Porto urban area (Portugal). *Urban Climate*, *19*, 1-27.

Fischer, E.M., & Schär, C. (2010). Consistent geographical patterns of changes in high-impact European heatwaves. *Nature Geoscience*, *3*, 398–403.

National Center for Atmospheric Research (NCAR) & University Corporation for Atmospheric Research (UCAR). (n.d.). Weather Research and Forecasting (WRF) Model Users' Page. Retrieved from http://www2.mmm.ucar.edu/wrf/users/

National Oceanic and Atmospheric Administration (NOAA). (n.d.). Weather Research and Forecasting model coupled to Chemistry (WRF-Chem). Retrieved from https://ruc.noaa.gov/wrf/wrf-chem/

Russo, S., Dosio, A., Graversen, R., Sillmann, J., Carrao, H., Dunbar, M.B. …Vogt, J.V. (2014). Magnitude of extreme heat waves in present climate and their projection in a warming world. *Journal of Geophysical Research: Atmospheres*, *119*(22), 12500–12512.

Additional Information

Christensen, J.H., Boberg, F., Christensen, O.B. & Lucas-Picher, P. (2008). On the need for bias correction of regional climate change projections of temperature and precipitation. *Geophysical Research Letters*, *35*(20), L20709.

WRF. (2018). WRF Model Users' Page. Retrieved from http://www2.mmm.ucar.edu/wrf/users/

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.2.3 Urban Heat Island (UHI) effect

Metric: *Urban Heat Island (UHI) effect (°C)*

This indicator focuses on the urban heat island (UHI) effect, wherein a significant difference is observed in air temperature between the city and its surroundings. The UHI effect is caused by the absorption of sunlight by (stony) materials, reduced evaporation and the emission of heat caused by human activities. The UHI effect is greatest after sunset and reported to reach up to 9°C in some cities, e.g., Rotterdam (Van Hove et al., 2015). As a result of the UHI effect, citizens living in urban areas experience more heat stress than those living in the countryside.

The UHI effect is quantified by determining the difference between the measured temperature within the city compared with the temperature of the surrounding countryside during the summer.

1. Identify or install one or more meteorological (temperature) measurement stations within the built environment, and one measurement station outside the city that functions as a reference station.
2. Compare the hourly average air temperature measurements of the urban measurement station(s) with the station outside the city (the reference station).
3. Look for the largest temperature difference (hourly average) between urban and countryside areas during the summer months. This temperature difference is an absolute measure of the UHI effect.

Key references

Van Hove, L.W.A., Jacobs, C.M.J., Heusinkveld, B.G., Elbers, J.A., van Driel, B.L., & Holtslag, A.A.M. (2015). Temporal and spatial variability of urban heat island and thermal comfort within the Rotterdam agglomeration. *Building and Environment*, *83*, 91-103.

4.3 Flood Vulnerability

Indicator	Metric
Flood vulnerability	Flood peak height
	Time to flood peak
	Run-off in relation to precipitation quantity
	Infiltration capacity
	Evapotranspiration

4.3.1 Flood peak height & Time to flood peak

Metric: *Height of flood peak*

Metric: *Time to flood peak*

Rapid urbanisation and industrialisation have led to reduced vegetative cover and decreased water storage in the subsurface, as well as the concentration and accumulation of surface runoff in sewage systems due to reduced infiltration into the soil. As a result, the volume of surface runoff as well as the velocity and time to peak storm runoff and baseflow are all increased. Urbanisation also reduces the land coverage of forests and vegetation that help to dissipate the flow energy (Devi, Ganasri & Dwarakish, 2015; Liu, Gebremeskel, De Smedt, Hoffman & Pfister, 2004). The detrimental effects of urbanisation on hydrologic systems are expected to increase in the future due to both increasing urbanisation as well as changes to the global climate, including rising sea levels, glacial retreat, changing precipitation patterns and an increasing frequency of extreme events (Kiehl, 2011).

An expected consequence of this trend is an increase in flood peak discharges. Sewer systems are typically dimensioned for 'normal' or high-probability return rate rain events with some methods developed to augment flood management by providing additional water flow controls either upstream or in parallel with centralised sewer systems. Both 'hard' engineering solutions and natural (or nature-based) flood management solutions exist, and can be used either individually or in combination with one another. A meta-analysis by Iacob, Rowan, Brown and Ellis (2014) examined a range of different natural flood management solutions used in 25 European studies. The natural flood management systems used in the studies were broadly categorised as: (a) (re)establishment of forests and woodland; (b) drainage and drain blocking; (c) wetlands and floodplains restoration; and, (d) combined measures. To date, no universally-applicable urban flood management solution has been identified; however, hybrid measures that combine NBS with conventional 'hard' engineering solutions/grey infrastructure have been identified as the optimal mix of security provided by grey infrastructure with the multiple co-benefits of NBS (Jongman, 2018).

Assessment of the effectiveness of flood management methods can be performed by different methods. For example, the assessment of runoff can be performed by in situ measurements before and after construction of a flood management structure. In the studies reviewed by Iacob et al. (2014), the assessment of natural management methods was performed either by hydrologic and hydraulic modelling or by direct monitoring. Parameters used for the assessment of the performance of natural flood management measures were: (a) flood peak reduction for different flood event return periods (e.g., 1, 2, 25, 50, or 100 years); (b) increase in time to flood peak; and, (c) decrease in annual probability of flood risk for the selected area. Common methods for direct measurements of runoff and different modelling to estimate surface runoff are presented below.

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.3.2 Runoff in relation to rainfall

Metric: *Run-off in relation to precipitation quantity (mm/%)*

As previously noted, the extent of impermeable surfaces in urban areas is continually increasing as cities develop and expand, due to the construction of buildings, roads, streets, parking lots, etc. A significant consequence is greater runoff in urban areas, which can also lead to flooding. Many factors are affecting the quantity of surface runoff, including soil characteristics, land use and vegetative cover, hillslope, and storm properties such as rainfall duration, amount, and intensity (Sitterson et al. 2017). In general, surface runoff is generated in two ways (Yang, Li, Sun & Ni, 2014): through saturation excess, where runoff is generated when the soil becomes saturated (for example after a lengthy period of rainfall); or, through infiltration excess, where runoff is generated when the rainfall intensity exceeds the infiltration rate of water into the soil (for example during a heavy precipitation event when rain falls more rapidly than it can infiltrate the soil). Different methods for quantifying runoff described herein include direct measurement, the curve number method, the rational method, the use of intensity-duration-frequency (IDF) curves, and process-based hydraulic modelling.

a) Runoff Coefficient - Direct measurement

Weirs, flumes and orifices are some of the most common methods in open channel flow measurements. Weirs are the simplest devices to measure flow in open channels (Figure 3). Weirs can consist of vertical plates with sharp crests and constriction of the flow causes a fall of the flow over the crest. There are several types of weirs including triangular or V-Notch, rectangular, and trapezoidal (also called Cipolletti) weirs. The operation principle of the weirs is that they obstruct the flow in the channel and the head behind the weir is a function of flow velocity and flow rate through the weir.

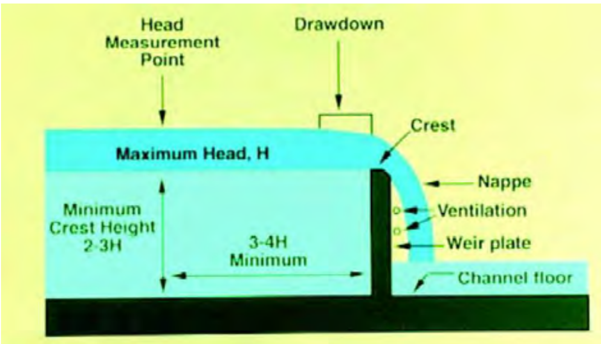


Figure 3. Weir diagram (reproduced from Adkins, 2006)

Flumes are another traditional method for open channel flow measurement (Figure 4) in a channel with converging and diverging sections. The operation principle of the flumes is that the water level is higher in the converging section than in the diverging section, and that there is direct relationship between water depth and flow rate (Adkins, 2006).

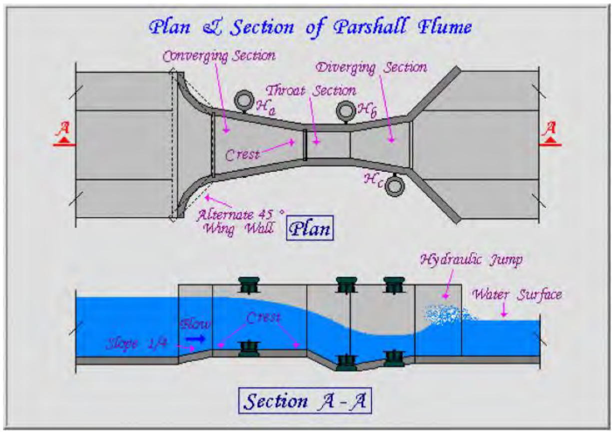


Figure 4. A Parshall flume configuration (reproduced from Adkins, 2006)

Test set-ups for studying surface runoff in urban areas have been reported by, e.g., Armson, Stringer, and Ennos (2013) and Stovin, Vesuviano, and Kasmin (2012). In one particular study by Armson et al. (2013), an urban area with a gently sloping surfaces (1:40) was mimicked and surface drains directed into tipping bucket flow gauges (Figure 5). The test plot consisted of different types of surfaces to examine surface effects on runoff rate and volume. Data loggers recorded runoff volumes as numbers of bucket tips per 24-h period. The depth of the daily runoff was then calculated by dividing the volume of daily runoff by the area of the test plot.

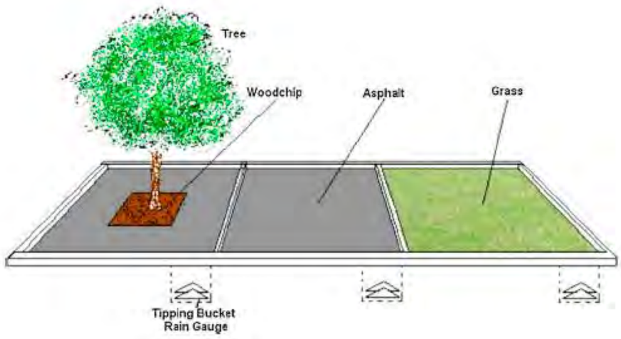


Figure 5. Test plot for measuring surface water runoff (reproduced from Armson et al., 2013)

A similar experimental design was employed by Stovin et al. (2012) to examine the hydrological performance of green roofs: a test bed was constructed and rainfall was monitored using a tipping bucket rain gauge (Figure 6). Runoff was collected into a tank below the test bed via a gutter. Continuous recording of the runoff was done by a pressure transducer which monitored the depth of water in the collection tank. The data resolution was approximately 2×10^{-4} mm in the most sensitive zone, decreasing to 7×10^{-3} mm. The collection tank was automatically emptied when the water depth reached the capacity of the tank. Data from the pressure transducer and the rain gauge was collected using a data logger at 1 min intervals.

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Figure 6. Green roof performance monitoring test bed (reproduced from Stovin et al., 2012)

In summary, direct measurement of runoff and its characteristics can be performed using weirs, orifices, flumes, etc. In smaller scale areas or test set-ups, tipping-bucket gauges, pressure transducers, etc., can be used. With data logging systems, data can be collected automatically at certain intervals. Units in which runoff is usually expressed are m^3/s, litres/s or depth-equivalent mm.

Scale of measurement: Plot or building scale to district scale.

Key references

Adkins, G.B. (2006). *Flow Measurement Devices*. Utah Division of Water Rights, Utah.

Armson, D., Stringer, P. & Ennos, A.R. (2013). The effect of street trees and amenity grass on -urban surface water runoff in Manchester, UK. *Urban Forestry & Urban Greening*, *12*, 282-286.

Stovin, V., Vesuviano, G. & Kasmin, H. (2012). The hydrological performance of a green roof test bed under UK climatic conditions. *Journal of Hydrology*, *414-415*, 148-161.

b) Runoff Coefficient – Curve Number

The most widely used modelling method to estimate runoff from rainfall is the curve number method (Zeng et al., 2017), which forms the basis for many modelling approaches. The curve number methodology is particularly useful for comparing pre- and post-development peak rates, volumes, and hydrographs. The key component of the runoff equation is the curve number (CN). The CN value is determined based on the hydrologic soil group (HSG), land use/cover, hydrologic surface condition and antecedent moisture condition (Zeng et al., 2017). The curve number method excludes time as a variable (USDA, 2004).

The curve number method is outlined in Chapter 10 of the United States Department of Agriculture's *National Engineering Handbook* (USDA, 2004). The curve number equation to estimate runoff from rainfall is:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad P > I_a$$

$$Q = 0 \qquad P \le I_a$$

where:

Q = depth of runoff, inches

P = depth of rainfall, in inches

I_a = initial abstraction, in inches

S = maximum potential retention, in inches

The initial abstraction (I_a) consists mainly of interception, infiltration during early parts of a storm, and surface depression storage. Interception and surface depression storage can be estimated from cover and surface conditions. Infiltration during the early part of the storm is highly variable and depends on many factors, including rainfall intensity, soil crusting, and soil moisture. The initial abstraction can be determined from rainfall-runoff events for small watersheds. However, estimation of the initial abstraction is not easy and I_a has been assumed to be a function of the maximum potential retention (S). An empirical relationship between I_a and S has been expressed as (USDA, 2004):

$$I_a = 0.2S$$

With this relationship, the original runoff equation can be written in a more simplified form (USDA 2004):

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad P > I_a$$

The runoff based on curve number can be determined based on graphs or tables provided by USDA (2004). The tables can give more exact solutions for the runoff. The graphical solution for the runoff equation is shown in Figure 7. The parameter CN is a transformation of potential maximum retention, S (USDA, 2004):

$$CN = \frac{1000}{10 + S}$$

This equation is for S in inches. For S in millimetres, the value for CN is (USDA 2004):

$$CN = \frac{1000}{10 + \frac{S}{25.4}}$$

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

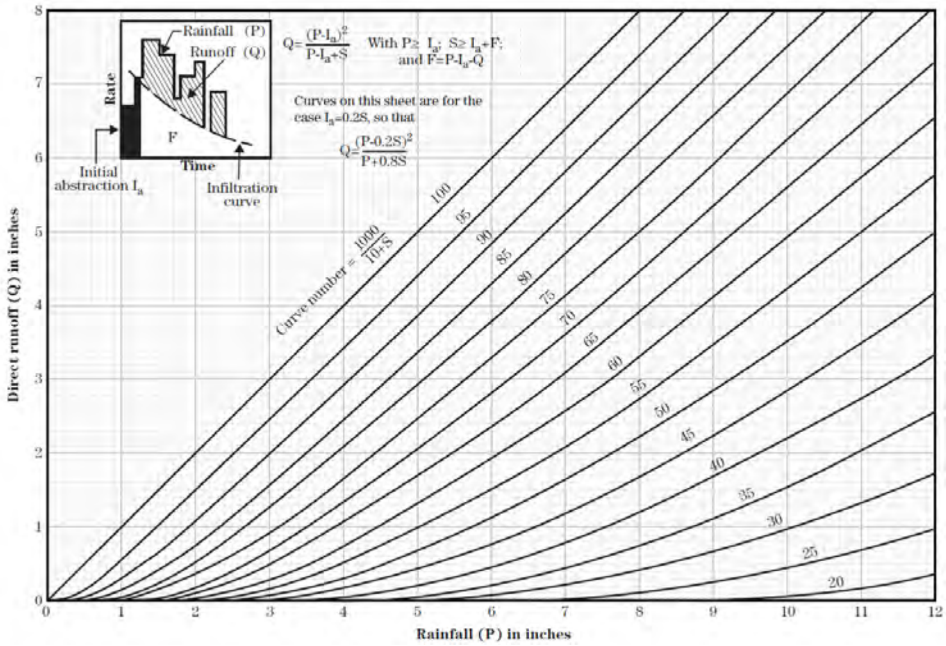


Figure 7. Graphical solution for curve number (CN) (reproduced from USDA, 2004)

Curve number varies due to differences in rainfall intensity and duration, total rainfall, soil moisture conditions, cover density, stage of growth, and temperature. In Table 9-1 of the *National Engineering Handbook* (USDA, 2004), curve number for different variations in cover type, hydrologic condition, and hydrologic soil group are given. In table 10-1 (USDA, 2004), values of *S* for different curve numbers can be determined.

Runoff based on the curve number method can be determined using the methods presented in the *National Engineering Handbook* (USDA, 2004). Steps to produce the value for the storm runoff include:

- Determining the value of *CN* for the specific cover type, hydrologic condition, and hydrologic soil group, using Table 9-1 in the USDA *National Engineering Handbook* (2004).
- Determining the value for *S* based on the *CN* value, using Table 10-1 in the USDA *National Engineering Handbook* (2004) or equation for the *CN*.
- Determining the runoff (*Q*) either using the graphical solution or tables provided by the USDA *National Engineering Handbook* (2004). For the determination, values for rainfall and *CN* are needed. Other possibility to determine the runoff is to use the runoff equation where values for rainfall and *S* are needed.

Scale of measurement: District scale to metropolitan area scale

Key references

United States Department of Agriculture (USDA). (2004). *National Engineering Handbook Part 630 Hydrology*. Washington, D.C.: United States Department of Agriculture, Natural Resources Conservation Service. Retrieved from https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/manage/hydrology/?cid=STELPRDB1043063

c) Runoff Coefficient - Rational Method

The Rational Method is a widely used method, which gives an empirical relation between rainfall intensity and peak flow (Hayes & Young 2005). The Rational Method in determining runoff coefficient uses an empirical linear equation to compute the peak runoff rate from a selected period of uniform rainfall intensity. The Rational Method was originally developed >100 years ago, but it still remains useful in estimating runoff from simple, relatively small drainage areas such as parking lots. Use of the Rational Method should be limited to drainage areas <20 acres with generally uniform surface cover & topography. The Rational Method can be used only to compute peak runoff rates. Since it is not based on a total storm duration, but rather a period of rain that produces the peak runoff rate, the method cannot compute runoff volumes unless the user assumes a total storm duration. The method is most commonly used for sizing of sewer systems ('design discharges').

The equation for the peak discharge in the Rational Method is presented by the Virginia Department of Transportation *Drainage Manual* (VDOT, 2002):

$$Q = C_f C i A$$

where:

Q = Maximum rate of runoff, cubic feet per second (cfs)

C_f = Saturation factor

C = Runoff coefficient representing a ratio of runoff to rainfall (dimensionless)

i = Average rainfall intensity for a duration equal to the time of concentration for a selected return period, inches per hour (in/hr)

A = Drainage area contributing to the point of study, acres (ac)

The equation for the Rational Method presented, e.g., by Dhakal, Fang, Asquith & Cleveland (2013), includes also a dimensional correction factor (m_0). With the correction factor, the maximum rate of runoff can be determined either in SI units or Imperial units (1/360 = 0.00278 in SI units or 1.008 in Imperial units).

The runoff coefficient (C) is a key parameter in the Rational Method. Typical values for C are listed in many reference books, textbooks and design manuals, e.g., Viessman and Lewis (2003), Virginia Department of Transportation (VDOT; 2019), and (Dhakal et al., 2013.) The Virginia Department of Transportation (2019) note that the runoff coefficient requires significant judgment and understanding from the designer. The runoff coefficient is related to slope, condition of cover, antecedent moisture condition, and other factors that may influence runoff quantities. The value for C ranges between 0 and 1.0. With the value of 0, no runoff is generated and with the value of 1.0, all of the rain becomes runoff (Hayes & Young 2005).

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Saturation factor (C_f) is a coefficient for storms with less than a 10-year recurrence interval. These higher intensity storms require modification to estimation of runoff. Saturation factors are given by reference books and design manuals, e.g., the Virginia Department of Transportation *Drainage Manual* (2019) (Table 11). Note that the saturation factor, C_f, multiplied by the runoff coefficient, C, should not exceed 1.0.

Table 11. Saturation factors (Cf) for rational formula (VDOT, 2002)

Recurrence Interval (Years)	C_f
2, 5 and 10	1.0
25	1.1
50	1.2
100	1.25

Different definitions exist for the time of concentration (T_f). One of them is that the time of concentration is the time required for water to flow from the hydraulically most remote point in the drainage area to the point of study (VDOT, 2019).

In smaller drainage areas (<200 ac, or <80.94 ha), the time of concentration usually consists of overland flow, channel flow or concentrated flow, and conveyance flow in manmade structures. For very small drainage areas, the flow time may only consist of overland flow, but for very large areas, the overland flow may not be significant and not measurable. Determining of the time of concentration for these different flows is presented by VDOT (2019). After calculating the total time of concentration, the designer should determine if the calculated value is reasonable.

The time of concentration is used in the Rational Method to estimate the average rainfall intensity (i) which can be selected from an Intensity-Duration-Frequency curve. Another possibility to estimate the rainfall intensity is to use factors B, D and E in the procedure described by VDOT (2019). In the Rational Method, the average rainfall intensity is determined for a duration equal to the time of concentration for a selected return period.

It should be noted that when using the Rational Method, several assumptions that are seldom met under natural conditions must be made (Hayes & Young, 2005):

- Precipitation is uniform over the entire basin
- Storm duration does not vary with time or space
- Storm duration is equal to the time of concentration
- Design storm of a specified frequency produces the design flood of the same frequency
- Basin area increases roughly in proportion to increase in length
- Time of concentration is relatively short and independent of storm intensity
- Runoff coefficient does not vary with storm intensity or antecedent soil moisture
- Runoff is dominated by overland flow
- Basin storage effects are negligible

A simplified outline of the necessary steps to determine peak runoff using the Rational Method is:

- Determine the runoff coefficient (*C*). Typical values are listed in textbooks and manuals (e.g., Viessman & Lewis, 2003; VDOT, 2002). If needed, use a saturation factor (C_f) for storms with a recurrence intervals less than 10 years.
- Determine the time of concentration (T_c). The methods for determining the time of concentration are described by, e.g., VDOT (2002).
- Determine the rainfall intensity (*i*). It is assumed that the duration is equal to the time of concentration. The rainfall intensity can be selected from the IDF curve.
- Solve the equation of the Rational Method to obtain the estimated peak runoff.

Scale of measurement: Plot or building scale to district scale. Used mostly for relatively small drainage areas, such as parking lots. The use should be limited to drainage areas <20 acres.

Key references

Dhakal, N., Fang, X., Asquith, W.H. & Cleveland, T. (2013). Return period adjustment for runoff coefficients based on analysis in undeveloped Texas watersheds. *Journal of Irrigation and Drainage Engineering*, June 2013

Hayes, D.C., & Young, R.L. 2005. *Comparison of Peak Discharge and Runoff Characteristic Estimates from the Rational Method to Field Observations for Small Basins in Central Virginia. Scientific Investigations Report 2005-5254*. Reston, VA: United States Geological Survey.

Viessman, W. & Lewis, G.L. (2003). Introduction to Hydrology. 5th edition. Upper Saddle River, NJ: Prentice Hall

Virginia Department of Transportation (VDOT). (2019). *Drainage Manual. Location and Design Division. Issued April 2002. Rev. March 2019.* Richmond, VA: Virginia Department of Transportation. Retrieved from http://www.virginiadot.org/business/resources/LocDes/DrainageManual/Combined_Drainage_Manual.pdf

d) Runoff Coefficient – IDF Curves

Intensity-Duration-Frequency (IDF) curves are a statistical estimation of ‘peak’ runoff rates based on recorded rainfall data (historic) and catchment characteristics (area, channel length, soil permeability). The IDF curves represent the frequency and the intensity of maximum rainfall events in different durations and they are commonly used in the design of hydrosystems (Fadhel, Rico-Ramirez, & Han, 2017). IDF analysis provides a convenient tool for summarizing regional rainfall information and thus it is useful in municipal storm water management practice. The IDF curves are created using historical rainfall data but it has to be taken into account that changes in climatic conditions may lead to changing magnitudes and frequencies of extreme rainfall (Prodanovic & Simonovic, 2007).

The IDF curves include the frequency of extreme rainfall rates corresponding to different durations, e.g., 5 min, 10 min, 15 min, 30 min, 60 min, 2 h, 6 h, 12 h, and 24 h. Return period represents the average time between years having occurrences of a rainfall event of a given magnitude, and it is

European Commission
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

usually expressed in years, i.e., 2, 5, 10, 25, 50, or 100 y (Wang & Huang, 2014). An example of an IDF curve by Al Mamoon, Joergensen, Rahman, and Qasem (2014) is presented in Figure 8.

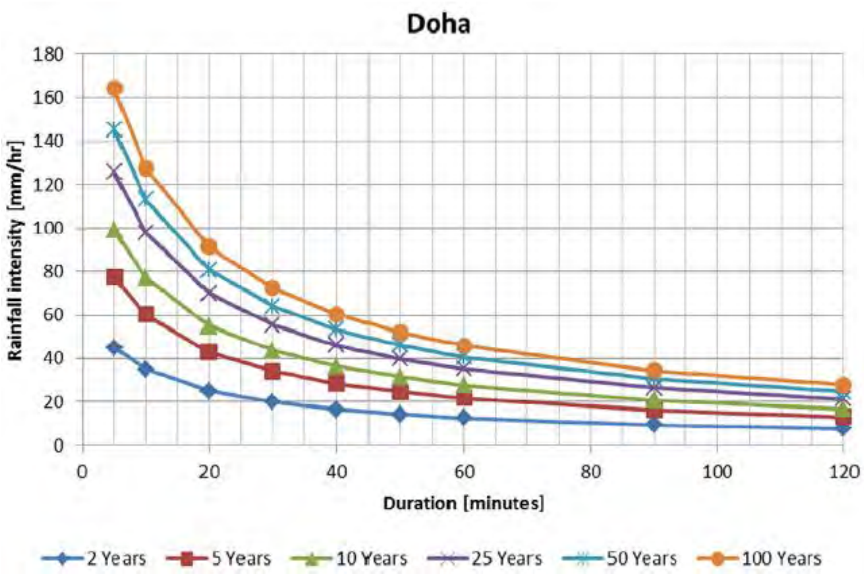


Figure 8. Intensity-Duration-Frequency (IDF) curves derived from Doha International Airport meteorological observations (reproduced from Al Mamoon et al., 2014)

The IDF analysis starts by gathering time series records of different durations and then extracting annual extremes from the record for each duration. Then a probability distribution is used to fit the annual extreme data and to estimate rainfall quantities. The purpose of fitting the probability distribution is to standardize the characteristics of point rainfall with widely varying lengths of record (Prodanovic & Simonovic 2007).

One of the most common probability distributions used in the IDF analysis is Gumbel's extreme value distribution (Wang & Huang 2004). Also other possible probability distributions can be used. In a study by Mirrhosseini, Srivastava, & Stefanova (2013), a Generalized Extreme Value distribution was used for creating IDF curves. This probability distribution combines Gumbel, Frechet, and Weibull distributions. Form and use of the Gumbel's extreme value distribution is described by Wang & Huang (2004).

Another possibility to create IDF curves is to use the following equation (MTO 1997):

$$i = A / (t_d + B)^c$$

where:

i = average rainfall intensity, mm/h

t_d = rainfall duration, min

A, B, and c are coefficients

The coefficients can be solved by least squares method described in the *Ontario Drainage Management Manual* produced by the Ministry of Transportation of Ontario (MTO, 1997). When the coefficients are solved, the above equation can be used to produce plots of rainfall intensity vs. duration for different return periods (Wang & Huang 2004).

A summary of the steps necessary to create IDF curves is given by Mirrhosseini et al. (2013):

- Obtain annual maximum series of precipitation depth for a given duration (15 min, 30 min, 45 min, 1 h, 2 h, 3 h, 6 h, 12 h, 24 h, and 48 h)
- Use a suitable probability distribution (e.g., generalized extreme value per Mirrhosseini et al., 2013) to find precipitation depths for different return periods (2, 5, 10, 25, 50, and 100 y)
- Repeat the first two steps for different durations
- Plot rainfall intensity versus duration for different frequencies

Scale of measurement: Different sizes of catchments, district scale to region scale.

Key references

Al Mamoon, A., Joergensen, N.E., Rahman, A., & Qasem, H. (2014). Derivation of new design rainfall in Qatar using L-moment based index frequency approach. *International Journal of Sustainable Built Environment*, *3*(1), 111-118.

Fadhel, S., Rico-Ramirez, M.A., & Han, D. (2017). Uncertainty of Intensity-Duration-Frequency (IDF) curves due to varied climate baseline periods. *Journal of Hydrology*, *547*, 600-612.

Ministry of Transportation of Ontario (MTO). (1997). *Ministry of Transportation of Ontario Drainage Management Manual*. Ontario, Canada: Ministry of Transportation of Ontario. Retrieved from http://www.mto.gov.on.ca/english/publications/drainage-management.shtml

Mirrhosseini, G., Srivastava, P., & Stefanova, L. (2013). The impact of climate change on rainfall Intensity-Duration-Frequency (IDF) curves in Alabama. *Regional Environmental Change*, *13*(S1), 25-33.

Prodanovic, P., & Simonovic, S.P. (2007). *Development of Rainfall Intensity Duration Curves for the City of London Under the Changing Climate. Water Resources Research Report No. 058.* London, Ontario, Canada: Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering.

Wang, X., & Huang, G. (2014). *Technical Report: Developing Future Projected IDF Curves and a Public Climate Change Data Portal for the Province of Ontario. Submitted to Ontario Ministry of the Environment.* Saskatchewan, Canada: Institute for Energy, Environment and Sustainable Communities (IEESC) of the University of Regina. Retrieved from http://www.ontarioccdp.ca/final_tech_report.pdf

e) Runoff Coefficient - Process-based hydraulic modelling.

Many limitations exist in hydrological measurements. The limitations are related to a limited range of measurement techniques and a limited range of measurements in both space and time. Due to these limitations, there is a need to extrapolate the available measurements in both space and time. Also, with measurements it is hard to estimate the future hydrological conditions which might change. Therefore, there are often needs for modelling the rainfall-runoff processes (Beven, 2012).

It is necessary to understand that modelling includes numerous simplifications and approximations. Limitations in modelling can include adequacy of process parametrizations, data limitations and uncertainty, and computational constraints on model analysis. Models can be defined in terms of process complexity (i.e., to what extent different models explicitly represent specific processes) and spatial complexity (i.e., to what extent different models explicitly represent details of the landscape and the lateral flow of water across model elements). This model diversity leads to challenges when choosing the approach to modelling (Clark et al., 2017).

In Figure 9, the modelling process is described by Beven (2012). The modelling process starts with a perceptual model, which is the summary of perceptions of how the catchment responds to rainfall under different conditions. In the conceptual model, mathematical descriptions are formed where hypotheses and assumptions are taken into account. If the equations decided in the conceptual model cannot be solved analytically given some boundary conditions for the real system, an additional stage of approximation is necessary using the techniques of numerical analysis to define a procedural model. This is given in a form of code that will run on the computer. In the next phase, the parameters used in the model needs to be calibrated. The most commonly used method in the model calibration is matching the model predictions and observations from the direct measurements if they are available. After the calibration of parameters, simulations with the model could be made. Results of the simulations should then be reviewed and the model validated. The validation can be done by comparing the results to direct measurements, e.g. observed discharges, if they are available (Beven 2012).

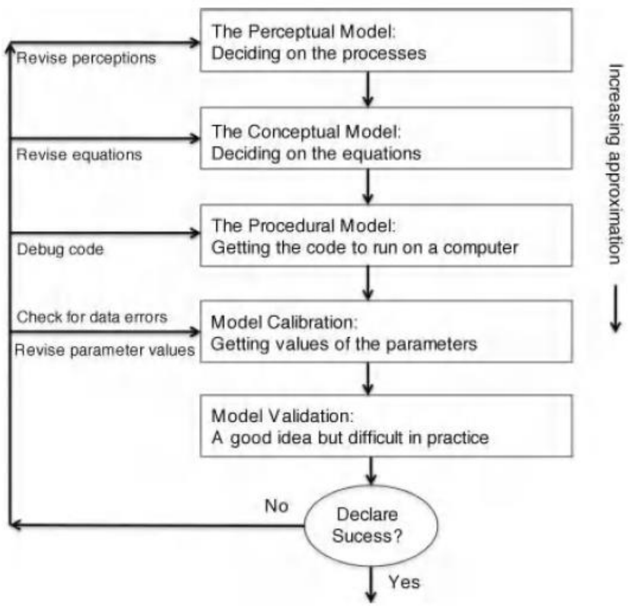


Figure 9. A schematic outline of the steps in the modelling process (reproduced from Beven, 2012)

When choosing a conceptual model, the following procedure can be used (Beven, 2012):

- Prepare a list of the models under consideration.
- Prepare a list of the variables predicted by each model. Decide if the model under consideration will give the needed output.
- Prepare a list of the assumptions made by the model. Reject models where the assumptions are estimated to be too inaccurate.
- Make a list of the inputs required by the model, for specification of the flow domain, the boundary and initial conditions and the parameter values.

- Determine whether you have any models left on your list. If not, the criteria should be reviewed again and then review the previous steps.

Different model structures exist. Model structures can be empirical, conceptual, or physical. The structure determines how runoff is calculated. In Table 12, different model structures are listed with the methods they use, strengths and weaknesses, best uses, and examples of different models (Sitterson et al., 2017).

Table 12. Comparison of the basic structure for rainfall- runoff models (adapted from Sitterson et al., 2017)

	Empirical	Conceptual	Physical
Method	Non-linear relationship between inputs and outputs, black box concept	Simplified equations that represent water storage in catchment	Physical laws and equations based on real hydrologic responses
Strengths	Small number of parameters needed, can be more accurate, fast run time	Easy to calibrate, simple model structure	Incorporates spatial and temporal variability, very fine scale
Weaknesses	No connection between physical catchment, input data distortion	Does not consider spatial variability within catchment	Large number of parameters and calibration needed, site specific
Best Use	In ungauged watersheds, runoff is the only output needed	When computational time or data are limited	Have great data availability on a small scale
Examples	Curve Number, Artificial Neural Networks[(a)]	HSPF(b), TOPMEDEL[(a)], HBV[(a)], Stanford[(a)]	MIKE-SHE[(a)], KINEROS[(c)], VIC[(a)], PRMS[(d)]

[a] Devia, Ganasri, & Dwarakish, 2015
[b] Johnson, Coon, Mehta, Steenhuis, Brooks, & Boll, 2003
[c] Woolhiser, Smith, & Goodrich, 1990
[d] Singh, 1995

Empirical models are the simplest models and physical mechanistic models are the most complicated models. The physical models are also called process-based or mechanistic models. In these physical process-based models, physical principles including water balance equations, conservation of mass and energy, momentum, and kinematics are used. Spatial and temporal variations within the catchment are incorporated into the physical model. A large number of physical and process parameters are needed to calibrate the model. However, if precise data are available and the physical properties of the hydrological processes are accurately understood, the physical models are the most realistic models since there is a good connection between model parameters and physical catchment characteristics (Sitterson et al., 2017). Short descriptions of some of the physical models are given by multiple resources, e.g., Devia, Ganasri, and Dwarakish (2015).

Scale of measurement: All scales depending on the type of model used.

Key references

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Beven, K.J. (2012). *Rainfall-Runoff Modelling: The Primer. Second Edition.* Chichester, West Sussex, U.K.: Wiley-Blackwell.

Clark, M.P., Bierkens, M.F.P., Samaniego, L., Woods, R.A., Uijlenhoet, R., Bennett, … Peters-Lidard, C.D. (2017). The evolution of process-based hydrologic models: historical challenges and the collective quest for physical realism. *Hydrology and Earth System Sciences*, *21*, 3427-3440

Devia, G.K., Ganasri, B.P., & Dwarakish, G.S. (2015). A Review on Hydrological Models. *Aquatic Procedia*, *4*, 1001-1007.

Johnson, M.S., Coon, W. F., Mehta, V.K., Steenhuis, T.S., Brooks, E.S., & Boll, J. (2003). Application of two hydrologic models with different runoff mechanisms to a hillslope dominated watershed in the northeastern US: a comparison of HSPF and SMR. *Journal of Hydrology*, *284*(1-4), 57-76.

Singh, V.P. (Ed.). (1995). *Computer Models of Watershed Hydrology*. Highlands Ranch, CO: Water Resources Publications, LLC.

Sitterson, J., Knightes, C., Parmar, R., Wolfe, K., Muche, M., & Avant, B. (2017). *An Overview of Rainfall-Runoff Model Types. EPA Report Number EPA/600/R-17/482. September 2017.* Athens, GA: Office of Research and Development National Exposure Research Laboratory.

Woolhiser, D.A., Smith, R.E., & Goodrich, D.C. (1990). *KINEROS, A kinematic runoff and erosion model: Documentation and user manual. ARS-77.* Washington, D.C.: United States Department of Agriculture, Agricultural Research Service. Retrieved from https://www.tucson.ars.ag.gov/unit/Publications/PDFfiles/703.pdf

f) Rainfall

Many different types of rain gauges for point rainfall measurements exist. Some of the most common rain gauges are a tipping-bucket gauge and a storage rain gauge. Most of the rain gauges consist of a circular collector (delineating the area of the sample) and a funnel that channels the collected rain into a measuring mechanism or into a reservoir where it may be measured at a later time. Debris clogging the mechanism and evaporation in hot weather are prevented by the narrow funnel. However, it is possible that the gauge becomes blocked, e.g., by snow (Met Office, 2010).

Storage rain gauges are standard gauges for rainfall measurements. The gauge has a sharp brass or steel rim of diameter 5 in (127 mm), sited 30 cm above ground level with a funnel that collects rain in a narrow necked bottle placed in a removable can. The storage rain gauge is non-automated, and to make the rainfall measurement, the observer empties the collected rain into a graduated glass rain measure. Due to impracticality of non-automated measurements, many rainfall measurements are nowadays done using automated measurement gauges. In Figure 10, a type of storage rain gauge widely used in the United Kingdom is presented.

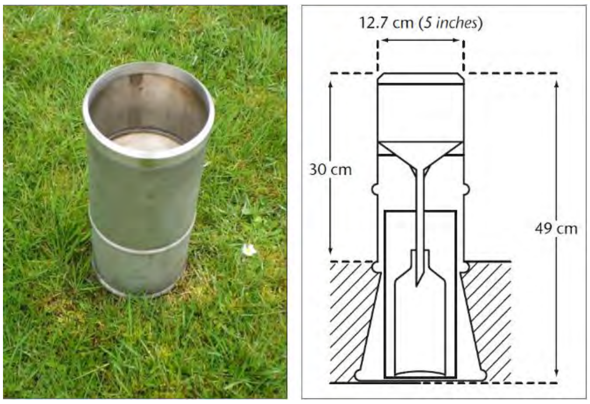


Figure 10. A 5-inch rain gauge (left) and a cross-section of the 5-inch rain gauge (right) (modified from Met Office, 2010)

Tipping-bucket gauges are used for automatic rainfall measurements (Figure 11). In the tipping-bucket gauge, a mechanism records an event each time a rainfall increment of 0.2 mm has been detected.

Figure 11. Tipping-bucket rain-gauge (reproduced from Met Office, 2010)

Rainfall measurements are used in many studies. For example, Robinson, Moore, Nisbet, and Blackie (1998), used large plastic sheet net-rainfall gauges to collect stemflow and throughfall over areas of 20-50 m^3. Also, flows from the sheets were recorded using large (1-L capacity) tipping buckets. In a study by Liu et al., (2004), a sub-basin in Luxembourg was extensively instrumented by stream gauges and rain gauges including both hourly and daily rain gauges. Daily rainfall records were disaggregated into hourly rainfall series according to the nearest hourly reference rain gauge. Rainfall was monitored using a tipping bucket gauge in a green roof test rig, reported by Stovin et al. (2012). A tipping bucket rain gauge was sited next to the test bed and the data from the rain gauge was logged using a data logger.

Scale of measurement: Building/plot to neighbourhood/district or even metropolitan scale, depending on the accuracy required.

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Key references

Liu, Y.B., Gebremeskel, S., De Smedt, F., Hoffmann, L., & Pfister, L. (2004). Simulation of flood reduction by natural river rehabilitation using a distributed hydrological model. *Hydrology and Earth System Sciences*, *8*(6), 1129-1140.

Met Office. (2010). *National Meteorological Library and Archive Fact sheet 17 - Weather observations over land.* Devon, United Kingdom: Met Office. Retrieved from https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/library-and-archive/library/publications/factsheets/factsheet_17-observations.pdf

Robinson, M., Moore, R.E., Nisbet, T.R., & Blackie, J.R. (1998). *From moorland to forest: the Coalburn catchment experiment. Report No. 133.* Wallingford, United Kingdom: Institute of Hydrology. Retrieved from http://nora.nerc.ac.uk/id/eprint/7372/

Stovin, V., Vesuviano, G., & Kasmin, H. (2012). The hydrological performance of a green roof test bed under UK climatic conditions. *Journal of Hydrology*, *414-415*, 148-161.

4.3.3 Infiltration capacity

Metric: *Infiltration capacity (%; change in precipitation infiltration capacity measured using ring infiltrometer & extrapolated/modelled for full unsealed area)*

Surface imperviousness is characteristic of urban areas and an important environmental indicator (Arnold & Gibbons, 1996; Strohbach et al., 2019). As surface imperviousness increases, the volume and velocity of surface runoff increases and there is a corresponding decrease in water infiltration. A high proportion of surfaces in urban areas are impermeable and the impermeability of surfaces in the cities is increasing as cities become more densely populated. The impermeability of urban surfaces originates from constructing buildings, roads, parking areas, etc., with materials that are not permeable to water.

According to Maes et al. (2019), 22% of the surfaces in European cities are sealed. If only soil sealing in artificial areas is considered, 58% of urban surfaces are sealed. These are average values so there are cities, and areas within cities, where the proportion of the impermeable surfaces is higher. Urban soil sealing, as an indicator, can be assessed as the surface area of sealed soil per inhabitant (Maes et al., 2019). Soil sealing can lead to significant challenges in stormwater management. In urban areas, surface runoff or flooding may occur during and after rain events depending on the extent of impermeable surfaces, capacity and functioning of the sewer system, and rainfall intensity. It should be noted that climate change is expected to increase the frequency and intensity of rain events.

One solution to mitigate surface impermeability whilst maintaining essential accessibility for emergency vehicles and disabled persons is to construct water-permeable pavements. These water-permeable pavements can decrease stormwater runoff during and after rain events and, thus, also reduce the needed capacity of the sewer system. Water-permeable pavements can be, for example, water-permeable asphalt, water-permeable concrete, or concrete blocks with water-permeable joints. The structure of the permeable asphalt and concrete is porous so water that can infiltrate through the pavement. Although broadly analogous to natural soils, the porous structure and pore size distribution of permeable asphalts and permeable concretes varies according to desired performance characteristics. For optimal management of surface water runoff, permeable asphalts and concretes are designed to contain relatively fewer microporous structures and more macroporous structures compared with natural soil, and to have relatively greater connectivity between pores. Water permeable paver blocks are typically made from impermeable concrete with joints between pavers filled with impermeable material, e.g., coarse grained rock material.

a) Measuring infiltration

Measurements of soil water flow parameters can be conducted using multiple different methods. When measuring water flow parameters in the field (field-saturated parameters), the measurements in the unsaturated or vadose zone (above the water table), are typically conducted using various ring infiltrometer and borehole or well permeameter methods. In the saturated zone (below the water table), water flow parameters (saturated parameters) are usually measured using auger hole methods, and at greater depths using piezometer methods. Saturated and field-saturated water flow parameters include, e.g., cumulative infiltration, infiltration rate, hydraulic conductivity, matric flux potential, sorptivity, the macroscopic capillary length parameter, the effective Green-Ampt wetting front pressure head, and the air-entry and water-entry pressure heads (Reynolds, Elrick, & Youngs, 2002).

Ring or cylinder infiltrometers are common methods to measure water flow in the vadose zone. The ring infiltrometers are thin-walled, open-ended metal or plastic cylinders with an outside-bevelled

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

cutting edge on the bottom end. The cylinder is usually pushed 3-10 cm into the soil, and a head of water is ponded inside. There are various possible cylinder arrangements. These arrangements include single or solitary cylinder (single-ring and pressure infiltrometers), an inner measuring cylinder centred inside an outer buffer cylinder (double- or concentric-ring infiltrometer), two adjacent cylinders (twin- or dual-ring infiltrometer), and three or more adjacent cylinders (multiple-ring infiltrometer). The measuring cylinder of the single-ring infiltrometer is typically 10-50 cm in diameter and 10-20 cm in length. The diameter of double- or concentric-ring infiltrometer's cylinder is typically 10-20 cm and it is 10-20 cm long, while the buffer cylinder diameter is typically about 50 cm and the length is the same as in the measuring cylinder. Depending on the cylinder arrangements and desired flow parameters, various one-dimensional, three-dimensional, transient, steady state, constant head, and falling head analyses can be conducted when using ring infiltrometers (Reynolds et al., 2002). A schematic of single-ring and double- or concentric-ring infiltrometers is presented in Figure 12.

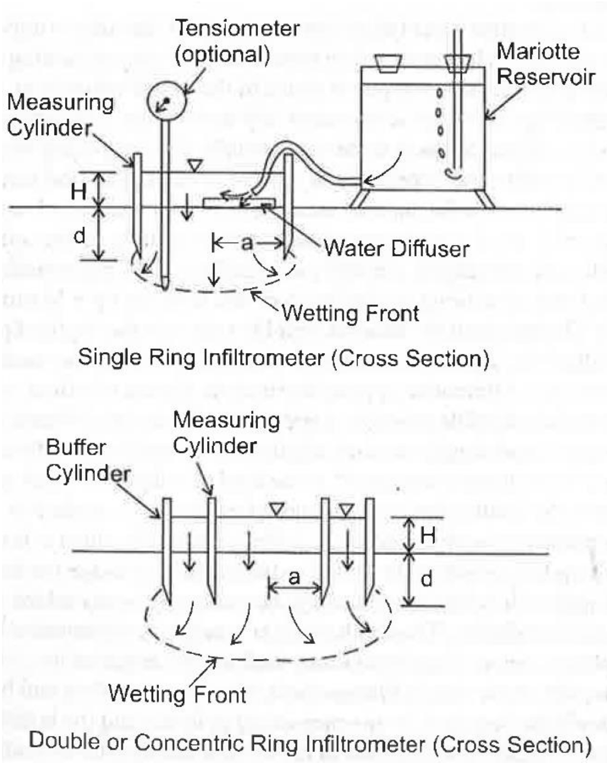


Figure 12. Schematic of the single-ring and double- or concentric-ring infiltrometers (reproduced from Reynolds et al., 2002)

According to Reynolds et al. (2002), the initial infiltration rate through a ring or cylinder infiltrometer is very high but with time it approaches a quasi-steady-state value. Description of the quasi-steady infiltration through a ring infiltrometer is in the following equation (Reynolds & Elrick, 1990):

$$q_s/K_{fs} = Q/(\pi a^2 K_{fs}) = [H/(C_1 d + C_2 a)] + \{1/[\alpha^*(C_1 d + C_2 a]\} + 1$$

where q_s (L T^{-1}) is quasi-steady infiltration rate, K_{fs} (L T^{-1}) is the field-saturated hydraulic conductivity, Q (L^3 T^{-1}) is the corresponding quasi-steady flow rate, a (L) is the ring radius, H (L) is the steady depth of ponded water in the ring, d (L) is the depth of ring insertion into the soil, C_1=0.316π and C_2=0.184π are dimensionless quasi-empirical constants that apply for $d \geq 3$ cm and $H \geq 5$ cm (Reynolds & Elrick, 1990; Youngs, Leeds-Harrison, & Elrick, 1995). The macroscopic capillary length, α (L^{-1}) can be estimated from soil structure and texture. Some values for α are presented in Table 13 (Reynolds et al., 2002).

Table 13. Soil texture-structure categories for site-estimation of the parameter "α" (Reynolds et al., 2002, adapted from Elrick, Reynolds & Tan, 1989).

Soil texture and structure category	α* (cm^{-1})
Compacted, structureless, clayey or silty materials such as landfill caps and liners, lacustrine or marine sediments	0.01
Soils that are both fine textured (clayey or silty) and unstructured; may also include some fine sands.	0.04
Most structured soils from clays through loams; also includes unstructured medium and fine sands. The category most frequently applicable for agricultural soils.	0.12
Coarse and gravelly sands; may also include highly structured or aggregated soils, as well as soils with large and/or numerous cracks, macropores.	0.36

Measurements for infiltration rate of water-permeable pavements can also be conducted using multiple methods (Kuosa, Loimula, & Niemeläinen, 2014). Some standardised methods exist for laboratory and field testing but tailored methods can also be used. However, it is important to use the same method for all relevant surfaces in order to obtain comparable results. In these methods, the surface is not broken. Some of the standards measuring permeability of pavements are listed below:

- ASTM D 3385: 2009. Test method for infiltration rate of soils in field using double-ring infiltrometers.
- ASTM C1701/C1701M-09. Standard test method for infiltration rate of in place pervious concrete.
- ASTM C1781/C1781M-13. Standard test method for surface infiltration rate of permeable unit pavement systems.
- EN 12697-19: 2012. Bituminous mixtures – Test methods for hot mix asphalt. Permeability of specimen.
- EN 12697-40: 2012: 2005. Bituminous mixtures – Test methods for hot mix asphalt – Part 40: in situ drainability.

A simple method for measuring infiltration rate is described in the standard ASTM C1701/C1701M-09. This standard is for measuring the infiltration rate of *in situ* pervious concrete. The method could be used for other types of water-permeable pavements. It should be noted that the infiltration rate is valid only for the specific area where the test is conducted. In this method, a cylindrical infiltration ring is used (Figure 13). The ring is open at both ends. In the inner surface of the ring, there should be two lines at a distance of 10 and 15 mm from the bottom of the ring. When pouring water inside the ring, the water head should stay between the lines. Non-hardening plumbers' putty can be used to seal the joint between the ring and the pavement. The infiltration rate is calculated using the following equation:

$$I = \frac{KM}{(D^2 * t)}$$

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

where:

I = Infiltration rate, mm/h

M = Mass of infiltrated water, kg

D = Inside diameter of infiltration ring, mm

t = time required for measured amount of water to infiltrate the concrete, s

K = 4 583 666 000 (converts the recorded data of *M*, *D* and *t* to the infiltration rate in mm/h)

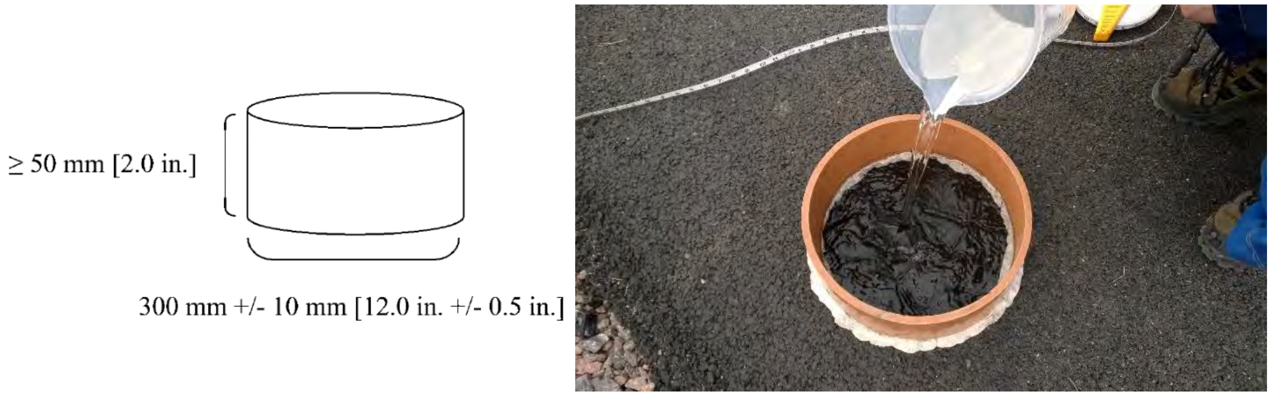


Figure 13. Left: Dimensions of the infiltration ring per ASTM C1701/C1701M-09 standard test method. Right: Infiltration rate measurements on a permeable asphalt conducted by VTT Technical Research Centre of Finland Ltd

Measurements of water flow parameters of the soil in the vadose zone using ring infiltrometers can be conducted with the following steps (Reynolds et al., 2002):

- The cylinder is inserted 3-10 cm into the soil. The contact between the soil and the inside cylinder should be lightly tamped to prevent flow or leakage around the cylinder walls.
- A constant depth of water is ponded inside the measuring cylinder and also inside the buffer cylinder if the concentric-ring infiltrometer is used. The ponding depth is usually 5-20 cm depending on the circumstances.
- The water infiltration rate through the measuring cylinder is measured. The infiltration rate through the buffer cylinder can also be measured if single-ring and concentric-ring infiltration rate results are compared. Quasi-steady flow in the near-surface soil under the measuring cylinder is assumed to occur when the discharge becomes effectively constant. The field-saturated hydraulic conductivity, K_{fs}, can be calculated using the equation presented previously. It should be noted that the parameter α can be estimated based on the soil texture and structure, or measured using independent methodology. Some values for α are given in Table 13.

The following instructions for measuring infiltration of a water permeable pavement are based on the ASTM C1701/C1701M-09 (infiltration rate of *in situ* pervious concrete). More detailed instructions are provided in the standard.

- Install the infiltration ring. The joint between the ring and the pavements should be made watertight using, e.g., plumber's putty.

- Conduct pre-wetting. Pour a total of 3.60 ± 0.05 kg of water inside the ring so that the head maintains between lines marked inside the ring. The timing starts when the water hits the surface and it stops when there is no free water left on the surface.
- Conduct the test. The test shall start within 2 min after the completion of the pre-wetting. Similar procedure for the test is used than in the pre-wetting. However, if the elapsed time in the pre-wetting was less than 30 s, a total of 18.00 ± 0.05 kg of water is used in the test.

Scale of measurement: Plot scale to street scale

Key References

Arnold, C.L., Jr., & Gibbons, C.J. (1996). Impervious surface coverage: The emergence of a key environmental indicator. *Journal of the American Planning Association*, *62*(2), 243-258.

ASTM C1701/C1701M-09. *Standard test method for infiltration rate of in place pervious concrete*.

Kuosa, H., Loimula, K., & Niemeläinen, E. (2014). Vettä läpäisevät pinnoitteet ja rakenteet - Materiaalikehitys ja simulointitestaus. Tutkumusraportti VTT-R-05001-14. VTT Technical Research Centre Ltd, Espoo, Finland. 118 pp. [Finnish] http://www.vtt.fi/files/sites/class/D2_5_CLASS_WP2_D2_Lab_and_Simulation_Results.pdf

Maes, J., Zulian, G., Günther, S., Thijssen, M., & Raynal, J. (2019). *Enhancing Resilience of Urban Ecosystems through Green Infrastructure. Final Report, EUR 29630 EN.* Luxembourg: Publications Office of the European Union. Retrieved from https://publications.europa.eu/en/publication-detail/-/publication/cc585ccd-3b0c-11e9-8d04-01aa75ed71a1/language-en/format-PDF/source-87798697

Reynolds, W.D., & Elrick, D.E. (1990). Ponded infiltration from a single ring: I. Analysis of steady flow. *Soil Science Society of America Journal*, *54*, 1233-1241.

Reynolds, W.D., Elrick, D.E., & Youngs, E.G. (2002). Ring or Cylinder Infiltrometers (Vadose Zone). In J.H. Dane & G.C. Topp (Eds.), *Methods of Soil Analysis. Part 4 Physical Methods*. Madison, Wisconsin: Soil Science Society of America, Inc.

Strohbach, M.W., Döring, A.O., Möck, M., Sedrez, M., Mumm, O., Schneider, A.-K., … Schröder, B. (2019). The "hidden urbanization": Trends of impervious surface in low-density housing developments and resulting impacts on the water balance. *Frontiers in Environmental Science*, 7, 29.

Youngs, E.G., Leeds-Harrison, P.B., & Elrick, D.E. (1995). The hydraulic conductivity of low permeability wet soils used as landfill lining and capping material: analysis of pressure infiltrometer measurements. *Journal of Soil Technology*, *8*, 153-160.

Additional References

The Copernicus Land Monitoring Service offers high-resolution pan-European maps of surface imperviousness: https://land.copernicus.eu/pan-european/high-resolution-layers/imperviousness/status-maps/2015

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

An extensive research project with water permeable pavements, “Climate Adaptive Surfaces (CLASS)”, was conducted in Finland in 2012-2014 (https://www.vtt.fi/sites/class/en/class-climate-adaptive-surfaces).

4.3.4 Evapotranspiration

Metric: *Measured or modelled evapotranspiration (typically expressed in mm per unit time)*

Evapotranspiration (ET) is a combination of two separate processes whereby water is lost from the soil surface by evaporation, and from vegetation by transpiration. Water evaporates from surfaces when sufficient heat is supplied for liquid water to transition to water vapour. Transpiration is when liquid water plant tissues vaporises and is released to the atmosphere through stomatal openings on the plant leaf. Nearly all water taken up by plants is released to the atmosphere through transpiration.

a) Measuring evapotranspiration

Evapotranspiration is challenging to measure, involving specific devices and accurate measurements of various physical parameters or the soil water balance in lysimeters. These methods are typically expensive, demanding in terms of accuracy and require specially trained personnel to operate. Methods for accurate, direct measurement of ET are not used for routine measurements but are important for validation of ET estimates obtained by more indirect methods. In practice, ET is commonly calculated using meteorological data. The Penman-Monteith equation is the FAO-recommended standard technique for calculation of reference evapotranspiration, ET_o from crops (Allen, Pereira, Raes, & Smith, 1998). Using the Penman-Monteith equation, ET from plant surfaces under standard conditions is determined using an experimentally-determined coefficient (k_c) to relate the ET for a specific crop species, ET_c, to ET_o. Thus, for a given crop species:

$$ET_c = k_c \times ET_0$$

Vegetated areas within cities present a further challenge, however; urban vegetation differs from agricultural crops in ways that can limit the applicability of the crop coefficient method to cities. In addition to the non-uniformity of urban vegetation, shading of urban vegetation by landscape trees and structures and edge effects due to the relatively small scale of urban green space in comparison to commercial crop fields can significantly influence ET (Snyder, Pedras, Montazar, Henry, & Ackley, 2015). For urban landscapes, the landscape coefficient method (LCM), which uses a different set of coefficients rather than k_c to estimate ET, may be more appropriate (Costello, Matheny, Clark, & Jones, 2000):

$$ET = k_L \times ET = k_d \times k_s \times k_{mc} \times ET_0$$

where k_L is a landscape coefficient defined as a product of k_d, a planting density factor, k_S, a species-specific factor, and k_{mc}, a microclimate factor.

Litvak and Pataki (2016) validated the LCM for ET estimation of turfgrass in California, USA. They measured the ET of turfgrass lawns using portable chambers made of clear PVC. Small data loggers inside the PVC chambers calculated ET based on temperature and humidity changes. Daily values of ET0 were obtained from local meteorological stations. The $ET_{0\ (in\ situ)}$ was calculated by substituting the net radiation (R_{N}), air temperature (T_{a}) and vapour pressure deficit of the air (D) measured at each study site in the following version of Penman-Monteith equation:

$$ET_{0\ (in\ situ)} = \frac{\Delta}{\Delta + \gamma} + \frac{R_N}{694.5(1 - 9.46 \times 10^{-4} T_a)} D(0.030 + 0.0576u)$$

Where: Δ = the slope of saturation vapour pressure as a function of temperature at the ambient temperature; γ = the psychrometric constant; and, u = wind speed at 2 m height. Assuming no soil

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

water limitation and maximum ET dependence solely on microclimate conditions, the calculation for ET was reduced to (Litvak & Pataki, 2016):

$$ET = k_{mc} \times ET_0$$

The preceding equation can be combined with a linear function to express fractional tree canopy cover (*TCC*) in order to calculate k_{mc} for shaded and non-shaded grass areas, and/or modelled using parameters derived from experimental measurements of ET (e.g., $ET_{0\,(in\,situ)}$) (Litvak & Pataki, 2016). The results of the study by Litvak and Pataki (2016) using this technique yielded approximations of the coefficients required to determine ET using the LCM method (Table 14). See Litvak and Pataki (2016) for detailed discussion of parameters and calculations.

Table 14. Coefficients for evapotranspiration (ET) calculation: k_{mc} of grass lawn based on in situ ET measurements and corresponding k_L estimates for warm- and cool-season grasses that completely cover the ground (from Litvak & Pataki, 2016). TCC is fractional tree canopy cover

<table>
<tr><th rowspan="2">Season</th><th colspan="3">Unshaded grass areas</th><th colspan="3">Shaded grass areas</th></tr>
<tr><th>k_{mc}</th><th>k_L warm season</th><th>k_L cool season</th><th>k_{mc}</th><th>k_L warm season</th><th>k_L cool season</th></tr>
<tr><td>Normal summer</td><td>1.1±0.1</td><td>0.8</td><td>1.0</td><td>0.1±0.0 to 0.9±0.2</td><td>0.1-0.6</td><td>0.1-0.8</td></tr>
<tr><td>Very dry summer</td><td>1.6±0.1</td><td>1.2</td><td>1.4</td><td rowspan="2">k_{mc} = *a*-*b* x *TCC*
a=0.90±0.09
b=0.35±0.13</td><td>-</td><td>-</td></tr>
<tr><td>Winter</td><td>0.9±0.1</td><td>0.5</td><td>0.6</td><td>0.1-0.5</td><td>0.1-0.6</td></tr>
</table>

Information about urban surface vegetation cover can be combined with measured/modelled ET to yield an estimate of ET across a varied landscape. Litvak, Manago, Hogue, and Pataki (2016) combined the empirical models of turfgrass ET and tree transpiration derived from the *in situ* measurements described above with previously developed remotely sensed estimates of vegetation cover and ground-based vegetation surveys to estimate ET at landscape scale.

b) Recommendation

Commercially-available ET monitoring stations are generally meteorological stations that calculate potential ET using monitored temperature, relative humidity, wind speed and direction, solar radiation, and precipitation data. These systems are designed to improve water use efficiency in irrigated agriculture by informing crop irrigation scheduling. Depending on the intended use of ET data, measurement of potential ET may be sufficient to show changes in ET as a function of land cover change, i.e., from sealed urban surfaces to green space. A number of different proprietary systems are available for on-site monitoring of potential ET. In addition to its simplicity, an advantage to use of an ET monitoring station is the acquisition of meteorological data from the immediate area of the NBS, which can be used to evaluate local-to-microscale changes in temperature.

Scale of measurement: plot scale, can be extrapolated using land cover data

Key References

Allen, R.G., Pereira, L.S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56*. Rome: Food and Agriculture Organization of the United Nations. http://www.fao.org/3/X0490E/x0490e00.htm#Contents

Costello, L.R., Matheny, N.P., Clark, J.R., & Jones, K.S. (2000). *A guide to estimating irrigation water needs of landscape plantings in California, the landscape coefficient method and WUCOLS III*. Berkeley, CA, USA: University of California Cooperative Extension, California Department of Water Resources. https://ucanr.edu/sites/WUCOLS/

Litvak, E., Manago, K.F., Hogue, T.S., & Pataki, D.E. (2016). Evapotranspiration of urban landscapes in Los Angeles, California at the municipal scale. *Water Resources Research*, *53*(5), 4236-4252.

Litvak, E. & Pataki, D.E. (2016). Evapotranspiration of urban lawns in a semi-arid environment: An *in situ* evaluation of microclimatic conditions and watering recommendations. *Journal of Arid Environments*, *134*, 87-96.

Snyder, R.L., Pedras, C., Montazar, A., Henry, J.M., & Ackley, D. (2015). Advances in ET-based landscape irrigation management. *Agricultural Water Management*, *147*, 187-197

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.4 Drought Vulnerability

Indicator	Metric
Drought vulnerability	Depth to groundwater
	Rainwater or greywater use for irrigation purposes

4.4.1 Depth to groundwater

Metric: *Depth from land surface reference point to top of groundwater table (m)*

Measurement of depth to groundwater in a well is frequently performed to examine changes in the level of the water table. The depth to groundwater is likely to vary with the season, so it is important to take repeated measurements over a long period of time to accurately evaluate changes in groundwater resource volume. One of the simplest ways to assess the depth from land surface to groundwater is to measure the water level in a shallow well using a chalked steel measuring tape. Blue carpenter's chalk is commonly used to mark the steel tape, which is lowered into the well until the end of the tape is wet. The level of the water will be indicated by the depth to which the chalk is wet and the colour changes from light blue to dark blue.

There are a number of different electronic water level metres marketed by different companies, any of which are suitable for routine monitoring of groundwater level in shallow wells or boreholes. These electronic instruments typically consist of a spool of dual conductor wire with a probe attached to the end and an indicator. As the probe is lowered into the well or borehole, a light or sound will indicate when the indicator comes into contact with water and the circuit is closed.

Regardless of the measurement technique employed, when measuring depth to groundwater the depth measurement should be made relative to an established reference point. This reference point is typically denoted by a permanent mark or notch on the well casing and is associated with a geodetic vertical datum established for surveying, e.g., the European Vertical Reference System or applicable local height datum.

Scale of measurement: Plot scale to street scale or greater, depending on surface topography and extent/connectivity of underlying aquifer(s)

Key References

Hopkins, J. & Anderson, B. (2016). *A Field manual for Groundwater-level Monitoring at the Texas Water Development Board. User Manual 52.* Retrieved from http://www.twdb.texas.gov/groundwater/docs/UMs/UM-52.pdf

Additional Information

American Geosciences Institute (AGI) FAQ *How can you find out how deep the water table is in a specific location?* https://www.americangeosciences.org/critical-issues/faq/how-can-you-find-out-how-deep-water-table-specific-location

Snyder, D.T. (2008). *Estimated depth to Ground Water and Configuration of the Water Table in the Portland, Oregon Area. Scientific Investigations Report 2008-5059.* Reston, Virginia: United States Geological Survey. Retrieved from https://pubs.usgs.gov/sir/2008/5059/pdf/sir20085059.pdf

4.4.2 Rainwater or greywater use for irrigation purposes

Metric: *Volume of rainwater or greywater used for irrigation purposes (L/y or similar unit)*

Scale of measurement: Plot scale to street scale

a) Rainfall capture and use

Accurate accounting of rainfall capture and use for irrigation requires use of a water level sensor to measure the volume of water contained within a given rainwater storage unit at any time. If the storage unit is completely sealed and the water level can be easily recorded each time it is opened (and again after water is discharged for use), it may be possible to manually record and calculate the volume of water captured and used for irrigation purposes.

An alternate solution is to equip the discharge point of the rainwater storage unit/tank with a water meter, and record the volume of water used over a specific period of time. This is well-suited to applications with multiple water storage tanks and/or in situations where it may be challenging to accurately quantify water use manually. The water meter(s) may be connected to an automatic meter reading (AMR) device that enables remote communication of water usage between the water meter and a central point. An AMR is similar to a smart water meter; smart meters use a centralised data communication hub to make water usage data available in real time to anyone authorised to access the data. In the present application, where the Living Lab is the 'owner' of the water resource as well as the 'user', AMR technology functions much the same as a smart water meter. Use of AMR technology or a smart water meter could be a good choice to communicate with stakeholders regarding the benefits of rainwater capture and use for irrigation.

b) Greywater re-use

Domestic wastewater consists of greywater, the wastewater discharged from hand basins, showers and baths, dishwashers, and laundry machines, and blackwater from toilets. Depending on local regulations, water from the kitchen sink be regarded as greywater or blackwater. One person generates 90-120 L greywater each day depending on lifestyle, living standard, age, gender, and other factors. Greywater comprises 50-80% of all domestic wastewater but contains a relatively small fraction of the total pollutant load (Antonopoulou, Kirkou, & Stasinakis, 2013; Donner et al., 2010; Li, Wichmann, & Otterpohl, 2009). Separation of domestic greywater from blackwater and on site re-use for toilet flushing or irrigation of non-edible vegetation provides an alternative water source in areas facing water shortage. On-site greywater re-use can reduce potable water use by as much as 50% (Gross, Shmueli, Ronen, & Raveh, 2007).

There are no practical limitations for the use of greywater to flush toilets; however, there are concerns about the potential for bacterial growth when nutrient-rich wastewater remains untreated for a period of time. In particular, human health risks associated with faecal coliform (*Escherichia coli*) and antibiotic-resistant bacteria have been identified where raw (untreated) greywater is discharged to open ditches in densely populated urban areas (Nuñez, Tornello, Puentes, & Moretton, 2012). Antibiotic resistance has also been detected in bacterial communities of some greywater-irrigated soils (Troiano, Beneduce, Gross, & Ronen, 2018).

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

It is recommended that domestic greywater is filtered (e.g., sand and/or granular activated carbon filter and/or treatment in vertical subsurface-flow wetland or reed bed, etc.) prior to use for irrigation of non-edible vegetation such as landscaping.

Key References

Antonopoulou, G., Kirkou, A. & Stasinakis, A.S. (2013). Quantitative and qualitative greywater characterization in Greek households and investigation of their treatment using physicochemical methods. *Science of the Total Environment*, *454-455*, 426-432.

Donner, E., Eriksson, E., Revitt, D.M., Scholes, L., Holten Lützhøft, H.-C. & Ledin, A. (2010). Presence and fate of priority substances in domestic greywater treatment and reuse systems. *Science of the Total Environment*, *408*(12), 2444-2451.

Gross, A., Shmueli, O., Ronen, Z., & Raveh, E. (2007). Recycled vertical flow constructed wetland (RVFCW)-a novel method of recycling greywater for irrigation in small communities and households. *Chemosphere*, *66*(5), 916-623.

Li, Y., Wichmann, K., & Otterpohl, R. (2009). Review of the technological approaches for grey water treatment and reuses. *Science of the Total Environment*, *407*(11), 3439-3449.

Nuñez, L., Tornello, C., Puentes, N., & Moretton, J. (2012). Health risks associated with the presence of antibiotic resistant bacteria in greywater. *Ambiente e Agua*, *7*(1), 235-243.

Troiano, E., Beneduce, L., Gross, A., & Ronen, Z. (2018). Antibiotic-resistant bacteria in greywater and greywater-irrigated soils. *Frontiers in Microbiology*, *9*, 2666

Additional Information

Alcalde Sanz, L. & Gawlik, B.M. (2014). Water Reuse in Europe: Relevant guidelines, needs for and barriers to innovation. A synoptic overview. JRC Science and Policy Report. Brussels: Publications Office of the European Union. http://publications.jrc.ec.europa.eu/repository/handle/JRC92582

European Commission. (2018). Proposal for a Regulation of the European Parliament and of the Council on minimum requirements for water reuse. Brussels, 28.5.2018. COM(2018) 337 final. 2018/0169 (COD), plus Annexes. Retrieved from http://ec.europa.eu/environment/water/pdf/water_reuse_regulation.pdf, http://ec.europa.eu/environment/water/pdf/water_reuse_regulation_annex.pdf.

European Commission, Directorate-General for Environment. (2018) *Proposal for a Directive of the European Parliament and of the Council on the quality of water intended for human consumption (recast). COM/2017/0753 final - 2017/0332 (COD)*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52017PC0753&from=EN

Mekonnen, M. & Hoekstra, A.Y. (2011). *National water footprint accounts: the green, blue and grey water footprint of production and consumption*. (Value of water research report 50; No. 50). Delft, the Netherlands: UNESCO-IHE Institute for Water Education. Retrieved from http://doc.utwente.nl/76913/1/Report50-NationalWaterFootprints-Vol1.pdf

United States EPA - Water recycling and reuse http://www3.epa.gov/region9/water/recycling/

4.4.3 Water Exploitation Index

Metric: *Annual total water abstraction as a proportion (%) of available long-term freshwater resources in the geographically relevant area (basin) from which the municipality obtains its water.*

The Water Exploitation Index (WEI) compares the volume of water consumed each year to the available freshwater resources. More specifically, the WEI presents total annual freshwater extraction as a proportion (%) of the long-term annual average freshwater available from renewable resources. The WEI warning threshold of 20% distinguishes a water-stressed area from one not suffering water scarcity. Severe scarcity is defined as WEI >40%. The European Environment Agency (EEA) uses the WEI to evaluate water scarcity across major river basins in Europe with time (https://www.eea.europa.eu/data-and-maps/indicators/use-of-freshwater-resources-2/assessment-3).

The WEI can be applied at smaller scale to assess the sustainability of water usage in a selected geographically-relevant area such as a river basin or sub-basin. The WEI is calculated as follows (European Environment Agency [EEA], 2018a):

$$WEI = \left(\frac{Volume\ of\ water\ abstraction}{Volume\ of\ renewable\ freshwater\ resources}\right) \times 100$$

An advanced version of the WEI, called the WEI+, accounts for recharge of available freshwater supplies, or water return (EEA, 2018a):

$$WEI+ = \left(\frac{Volume\ of\ water\ abstraction - Volume\ of\ water\ returns}{Volume\ of\ renewable\ freshwater\ resources}\right) \times 100$$

The volume of long-term renewable freshwater resources in a natural or semi-natural geographically relevant area (e.g., basin or sub-basin) is calculated as (EEA, 2018a):

$$Long\ term\ renewable\ freshwater\ resources = ExIn + P - ETa - \Delta S$$

where $ExIn$ = external inflow, P = precipitation, Eta = actual evapotranspiration and ΔS = change in storage (lakes and reservoirs).

The equation for renewable freshwater resources can be simplified as follows for highly-modified (i.e., not natural or semi-natural) river basins or sub-basins (EEA, 2018a):

$$Long\ term\ renewable\ freshwater\ resources = outflow + (abstraction - return) - \Delta S$$

where outflow = downstream flow or discharge to sea and ΔS = change in storage (lakes and reservoirs).

Necessary information about annual volumes of water abstraction (groundwater, surface water) from a given basin or sub-basin can be obtained from records of water supply companies and city documents relating to water abstraction permits. Wastewater treatment companies, water supply companies and municipal environment/environmental management departments are sources of information related to annual volumes of water returns. Information about long term renewable water resources can be obtained from local water boards, municipal departments and/or national environment agencies.

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Key References

European Environment Agency (EEA). (2018a). *Use of freshwater resources.* Copenhagen: European Environment Agency. Retrieved from https://www.eea.europa.eu/data-and-maps/indicators/use-of-freshwater-resources-2/assessment-3

4.5 Water Quality

Indicator	Metric
Water quality	Basic water quality (pH, temperature, EC, DO, flow rate)
	Nitrogen and phosphorus in surface water and/or groundwater
	Metal pollutants in surface water and/or groundwater
	Total suspended solids (TSS)
	Pollutant discharge to local waterbodies
	Total number and species richness of aquatic macroinvertebrates

Water quality can profoundly impact both aquatic and terrestrial ecosystems. Changes to the quality of water may occur due to many different factors, including human activities. It is therefore important to monitor water quality in environments likely to be affected by anthropogenic activity, or in particularly sensitive aquatic ecosystems. Commonly measured water quality parameters include, e.g.: pH; temperature; dissolved oxygen (DO) content; electrical conductivity (EC); turbidity, total suspended solids (TSS) and/or total dissolved solids (TDS); dissolved organic carbon (DOC) content; nutrient concentration, generally including total nitrogen (TN), total phosphorus (TP) and/or various N and P species; the concentration of selected metal contaminants such as cadmium (Cd), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), and/or zinc (Zn) (Lundy, Ellis, & Revitt, 2012); organic pollutants, such as solvents or pesticides; and selected organisms, or biological indicators of water quality. The EEA (Kristensen & Bøgestrand, 1996) groups water quality variables into broad categories to simplify selection of water quality monitoring parameters (Table 15).

Table 15. Categories of water quality variables (adapted from Kristensen & Bøgestrand, 1996)

Group	Examples
Basic variables for general water quality characterisation	- pH - Temperature - Electrical conductivity - Dissolved oxygen - Flow rate or discharge
Suspended particulate matter	- Total suspended solids (TSS) - Total dissolved solids (TDS) - Turbidity - Total organic matter (TOC) - Biochemical oxygen demand (BOD) - Chemical oxygen demand (COD)
Organic pollution indicators	- Dissolved oxygen - Biochemical oxygen demand (BOD) - Chemical oxygen demand (COD) - Ammonium (NH_4^+)
Indicators of eutrophication: nutrients and biological effect indicators	- Nitrogen - Phosphorus - Chlorophyll a - Secchi disc transparency - Phytoplankton - Zoobenthos
Indicators of acidification	- pH - Alkalinity

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

	- Electrical conductivity - Sulphate (SO_4^{2-}) - Nitrate (NO_3^-) - Aluminium - Phytoplankton and diatom sampling
Specific major ions that are essential factors in determining water suitability for various uses	- Chloride (Cl^-) - Sulphate (SO_4^{2-}) - Sodium (Na) - Potassium (K) - Calcium (Ca) - Magnesium (Mg)
Metals	- Cadmium (Cd) - Copper (Cu) - Lead (Pb) - Mercury (Hg) - Nickel (Ni) - Zinc (Zn)
Organic micropollutants such as pesticides and chemicals used in industrial processes	- Polychlorinated biphenols (PCBs) - Hexachlorocyclohexane (HCH) group compounds - Polycyclic aromatic hydrocarbons (PAHs)
Indicators of radioactivity	- Total alpha and/or beta activity - ^{137}Cs - ^{90}Sr
Microbiological indicators	- Total coliform bacteria - Faecal coliform bacteria - Faecal streptococci bacteria
Biological indicators of ecosystem condition	- Phytoplankton - Zooplankton - Zoobenthos - Fish - Frogs - Aquatic macrophytes - Birds and other animals associated with surface waters

Multiple water quality parameters are typically monitored due to the wide range of potential pollutants. Some parameters can be measured directly whilst others require analysis in a laboratory. Herein, we briefly address some of the more common water quality monitoring variables; however, the information here is not comprehensive and may augment but should not take the place of a locally or nationally mandated water quality monitoring programme. Reviewing the alignment between the monitored water quality parameters and locally applicable environmental legislation facilitates assessment of water quality and supports identification of potential areas of concern.

Fundamental considerations when developing a water monitoring program include:

- What is the purpose of water quality monitoring?
- Which parameters will be monitored?
- Where will monitoring sites be located?
- How will the selected parameters be monitored (monitoring or measurement techniques)?

- How often will the parameters be measured, and how does the timing of sample collection potentially influence the accuracy of the data obtained?
- When will monitoring occur?

Selection of the sampling sites is one the most important elements in the monitoring effort. Location of the water quality monitoring must be selected so that the monitoring provides the most useful information. The methods for water sampling and analysis will be selected based mostly on the accuracy and cost requirements. The selection of specific techniques to analyse different pollutants in water is largely dependent upon the objectives of the water quality testing and the resources available. To determine the most appropriate water quality testing protocol, first review any relevant existing water quality data and identify pollutants of particular concern. Then consider how new data from water quality monitoring will be used. Consider the necessary sampling frequency to obtain sufficiently detailed information about each pollutant of concern, and review the availability of continuous monitoring devices for each pollutant or pollutant class. The timing of the sampling needs to take into account factors including goals of the monitoring program, accessibility of the sampling site, local weather conditions, the respective number of sites and monitoring personnel, and the water quality measures to be measured.

Some of the most commonly monitored water quality parameters are listed below along with brief descriptions of the respective sampling methods. A number of standard methodologies for water testing are available from, e.g., the International Organization for Standardization (ISO), American Public Health Association (APHA), the European Environment Agency (EEA), and others. Consult applicable water quality regulations to determine the acceptable measurement or monitoring techniques for the local area when planning the water quality monitoring programme. Underpinning the EU Water Framework Directive (European Parliament, 2000) and other "primary" Directives related to water quality adopted by the EU are complemented by national regulations issued by EU Member States. Local or national water quality regulations may be more stringent than those adopted by the EU; check locally-applicable guideline and limit values for pertinent water quality parameters when selecting monitoring parameters and methodologies.

Key References

Kristensen, P. & Bogestrand, J. (1996). *Surface Water Quality Monitoring. Topic Report 2/96*. Copenhagen: European Environment Agency.

Additional Information

European Parliament, Council of the European Union. (2000). *EU Water Framework Directive: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy.* Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02000L0060-20140101

European Parliament, Council of the European Union. (2008). *Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy, amending and subsequently repealing Council Directives 82/176/EEC, 83/513/EEC, 84/156/EEC, 84/491/EEC, 86/280/EEC and amending Directive 2000/60/EC of the European Parliament and of the Council.* Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0105

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.5.1 Basic water quality: pH, EC, DO, temperature & flow rate

Metric: *Basic water quality parameters (pH, EC, DO, temperature, flow rate)*

Scale of measurement: Plot scale

Basic water quality parameters include pH, temperature, electrical conductivity (EC), dissolved oxygen (DO) content and flow rate. Each of these parameters is usually quantified using a meter (i.e., via electrometry) both in the field and in samples collected in the field and transported to the laboratory for analysis.

a) pH

One of the most important quality parameters of water is pH, which is a measure of the relative acidity or alkalinity of a solution. The pH is considered a 'master variable' as the pH, together with oxidative-reductive potential, determines the chemical speciation, behaviour and fate of (bio)chemical compounds in the environment. Solution pH is also a critical factor in aquatic ecosystem health. Water's pH can be affected by, e.g., mineral dissolution, atmospheric dust and aerosol deposition, anthropogenic releases, and the release or alteration of chemical compounds by flora and fauna through photosynthesis and respiration. The pH range of natural waters varies from ca. 4.5 in peat-influenced waters to as high as 10.0 in systems influenced by intense algal photosynthetic activity. The typical pH range of natural waters is 6.5-8.0.

Measuring of the pH is simple and is usually done using either a colorimetric method (visual or electronic) or electronic meters. Steps in the determination of pH include:

- Checking the equipment. Some of the following equipment should be used: pH colorimeter field kit, pH meter with built-in temperature sensor, or colorimeter with reagents.
- Measuring the pH values.
    - In the colorimetric method (both visual and electronic), indicators that change colour according to the pH of the solution are used. With colorimetric kits, chemical or two (reagents) are added to the water sample, and the resulting colour is compared to the colour standards of known pH values.
    - With the calibrated pH meter, the electrode is placed in the water and the pH is recorded.

The recommended method of pH measurement is electrometry/use of a pH electrode. A summary of recommended or mandatory limit values per applicable primary EU water quality related Directives is given in Table 16.

Table 16. Recommended or mandatory pH limit values

EU Directive	Guideline value	Limit value
Freshwater Fish Directive [2006/44/EC]		≥6.0 and ≤9.0†
Shellfish Directive [79/923/EEC]		7.0-9.0
Drinking Water Directive [98/83/EC]		≥6.5 and ≤9.5

† Values are applicable to both salmonid and cyprinid waters

b) Electrical Conductivity (EC)

Electrical Conductivity, or conductivity, reflects a water's dissolved (ionisable) mineral salt content. The EU Drinking Water Directive (98/83/EC; European Parliament, Council of the European Union, 1998) together with subsequent amendments establishes an upper EC limit of 2500 µS/cm for waters intended for human consumption. The EC (in µS/cm) provides a rough approximation of the total dissolved solids (TDS, in mg/L) content, via the equation:

$$Conductivity \times \frac{2}{3} = Total\ dissolved\ solids$$

c) Dissolved Oxygen (DO) and Temperature

The significance of DO content of natural waters is the requirement for sufficient oxygen to support aquatic life. As a general "rule of thumb", water with quality that is suitable for fish is also suitable for most other beneficial uses. A summary of recommended or mandatory limit values per applicable primary EU water quality related Directives is given in Table 17.

Table 17. Recommended or mandatory limit values for dissolved oxygen (DO)

EU Directive	Units of analysis	Guideline value	Limit value
Freshwater Fish Directive [2006/44/EC]-salmonids	mg/L O_2	50% ≥9	50% ≥9
	mg/L O_2	100% ≥7	
Freshwater Fish Directive [2006/44/EC]-cyprinids	mg/L O_2	50% ≥8	50% ≥7
	mg/L O_2	100% ≥5	
Shellfish Directive [79/923/EEC]	% O_2 saturation	≥80	≥70

The DO content of water is inversely related to temperature, with decreasing O_2 solubility in water as temperature increases (Table 18). Thus, DO and temperature should always be measured together to ensure accuracy. Many DO meters have an in-built temperature probe and will display DO content in mg/L as well as the per cent (%) O_2 saturation, along with the measured water temperature (in °C).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Table 18. Maximum dissolved oxygen concentration (100% saturation) at standard 1 atm/760 mm Hg pressure

Temperature (°C)	DO (mg/L)	Temperature (°C)	DO (mg/L)
0	14.6	13	10.5
1	14.2	14	10.3
2	13.8	15	10.1
3	13.5	16	9.9
4	13.1	17	9.7
5	12.8	18	9.5
6	12.4	19	9.3
7	12.1	20	9.1
8	11.8	21	8.9
9	11.6	22	8.7
10	11.3	23	8.6
11	11.0	24	8.4
12	10.8	25	8.3

The Freshwater Fish Directive (2006/44/EC; European Parliament, Council of the European Union, 2006) specifies maximum temperatures of 21.5°C and 28.0°C for salmonid and cyprinid waters, respectively. There is an additional 10°C temperature limit during the breeding periods of species that require cold water for reproduction applicable only to waters inhabited by such species.

d) Flow rate

The flow rate of a stream cannot be measured directly using a meter; rather, continuous flow measurements are obtained by measuring water height at a selected point in the stream (stage) and velocity, then calculating the flow of water past that point. The most common approach to continuous streamflow monitoring involves installation of a stilling well in or near the stream where an intake pipe maintains the water level within the stilling well at the same elevation as the stream (Figure 14).

Discharge can be calculated by multiplying the area of the channel at the selected point in the stream (cross-sectional area) by current velocity. First, the area of the channel is calculated based on manual measurements, typically using cable or steel measuring tape and a wading rod in shallow streams and suspended sounding weights in deeper waters. A current meter is then used to measure stream velocity. Alternately, an acoustic Doppler current profiler can be used to measure water depth and velocity at the same time. When the acoustic Doppler profiler or current meter are not available, floats or volumetric measurements provide an accessible but less accurate method for measuring velocity.

A stage-discharge relationship unique to a given stream can be generated by logarithmic plotting stream stage (in m, y-axis) as a function of stream discharge (in m^3/s, x-axis). This stage-discharge relationship can then be used to calculate the flow rate (discharge, in m^3/s) at any measured stream height (stage), or extrapolate the ratings.

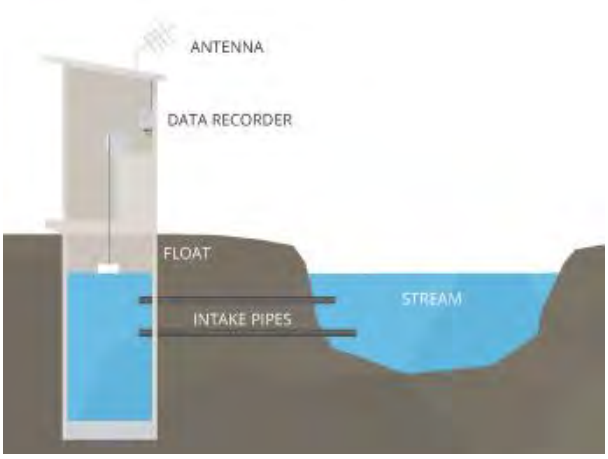


Figure 14. Schematic of a stilling well installed in a streambank to continuously record and transmit stream stage data for flow rate determination.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.5.2 Nitrogen and phosphorus concentration or load

Metric: *Nitrogen and phosphorus in surface water and/or groundwater (%, expressed as total annual N or P load and/or reduction of maximum annual concentration)*

Nutrients, including nitrogen (N) and phosphorus (P), can have significant impact on water quality, including effects on plant growth, oxygen concentration, water clarity, and sedimentation rates. Some major anthropogenic sources of nutrients are agricultural and industrial emissions, discharged wastewater and atmospheric deposition. Nitrogen and phosphorus are present in water in many different forms, or as many different chemical species. The forms of N and P that are quantified can include some or all of the following:

- Nitrogen: total N (N_{tot}), total Kjeldahl N (TKN), dissolved organic N (DON), nitrate (NO_3^-), nitrite (NO_2^-) and ammonia/ammonium (NH_3/NH_4^+)
- Phosphorus: total P (P_{tot}), acid-hydrolysable P (AHP), orthophosphate (PO_4^{3-})

An understanding of each of these nutrient fractions' typical abundance in natural waters and common analytical methods can help to inform a water quality sampling programme.

- **Nitrate (NO_3^-)** – the main oxidised form of inorganic N in natural waters. *Note that sometimes analyses for NO_3^-- also include NO_2^-, based on the assumption that NO_2^- comprises an insignificant proportion of the oxidised form of inorganic N.* In the laboratory, NO_3^- is traditionally determined by flow injection analysis following conversion to NO_2^-, usually via passage of the sample through a column filled with copper-coated cadmium granules. The NO_2^- is then treated with sulphanilamide ($H_2NSO_2NH_2$) and coupled with N-(1-naphthyl)ethlyenediaminie dihydrochloride (Greiss reagent) to form a highly coloured azo dye. The absorbance of the product is measured colourimetrically using a photometer. This analysis yields a value for NO_3^- + NO_2^-; to determine NO_3^- only, NO_2^- must be quantified separately and this value (NO_2^-) subtracted from the value obtained for NO_3^- + NO_2^-. The EU Drinking Water Directive (98/83/EC; European Parliament, Council of the European Union, 1998) together with subsequent amendments establishes an upper regulatory limit of 50 mg/L NO_3^- in waters intended for human consumption, equivalent to 11 mg/L N as NO_3^-.

- **Nitrite (NO_2^-)** – typically present at very low concentrations in natural waters, NO_2^- is determined in the laboratory using the same procedure as NO_3^- without the copperised cadmium column treatment. Any waters containing appreciable (e.g., >0.03 mg/L) NO_2^- are generally considered of questionable quality. Guideline and limit values for NO_2^- per applicable EU water quality related Directives are given in Table 19.

Table 19. Recommended or mandatory limit values for nitrite (NO_2^-)

EU Directive	Units of analysis	Guideline value	Limit value
Freshwater Fish Directive [2006/44/EC] – salmonid waters	mg/L NO_2^-	≤0.01	-
Freshwater Fish Directive [2006/44/EC] – cyprinid waters	mg/L NO_2^-	≤0.03	-
Drinking Water Directive [98/83/EC]	mg/L NO_2^-	N/A	0.50

- **Nitrate-Nitrite (NO_x)** – NO_3^- and NO_2^- are frequently reported as nitrate-nitrite, oxidised inorganic N, or NO_x. This is because NO_2^- is typically present as an insignificant fraction of the NO_3^- concentration.

- **Ammonia/Ammonium (NH_3/NH_4^+)** – ammonia (NH_3) and ammonium (NH_4^+) are two forms of reduced inorganic N (ammoniacal N), and exist in equilibrium in water. In general, NH_4^+ is the form of reduced inorganic N measured in natural waters because at pH ≤8.0 the proportion of ammoniacal N present as NH_3 is ≤10%. *It is important to note, however, that the equilibrium shifts towards NH_3 at pH ≥9.0, and that low concentrations of NH_3 (e.g., 0.1 mg/L and greater) may be damaging to aquatic life*. Ammoniacal N is determined colourimetrically in the laboratory by flow injection analysis following treatment with salicylate and dichloroisocyanurate. A single value reported for ammonia/NH_3 is usually the sum of both NH_4^+ and NH_3. Guideline and limit values for ammoniacal N, NH3 and NH4+, per applicable EU water quality related Directives are given in Table 20.

Table 20. Recommended or mandatory limit values for ammoniacal nitrogen

EU Directive	Units of analysis	Guideline value	Limit value
Freshwater Fish Directive [2006/44/EC] – salmonid waters	mg/L NH_3	≤0.005	≤0.025
	mg/L NH_4^+	≤0.04	<1
Freshwater Fish Directive [2006/44/EC] – cyprinid waters	mg/L NH_3	≤0.005	≤0.025
	mg/L NH_4^+	≤0.2	<1
Drinking Water Directive [98/83/EC]	mg/L NH_4^+	N/A	0.5

- **Dissolved organic N (DON)** – typically determined by subtracting inorganic forms of N (NO_3^-, NO_2^- and NH_4^+) from N_{tot}. Dissolved organic N can also be measured directly via wet chemical oxidation. The relative importance of DON in natural water samples varies between locations, but it is possible for DON to comprise a substantial proportion of the total N content.

- **Total Kjeldahl N (TKN)** – TKN = NH_4^+ + DON. The traditional laboratory test to determine TKN uses sulphuric acid (H_2SO_4) and a digestion catalyst to convert organic forms of N to the NH_4^+ form. The NH_4^+ is then quantified by titration or colourimetrically using flow injection analysis (per ammoniacal N procedure). Note that the digestion procedure does <u>not</u> convert NO_2^- or NO_3^- to NH_4^+.

- **Total N (N_{tot})** – total N is the sum of NO_3^-, NO_2^-, NH_4^+ and organic N. N_{tot} is usually determined in the laboratory via flow injection colourimetric analysis following alkaline persulfate digestion, passage of the sample through a column filled with copper-coated cadmium granules, treatment with sulphanilamide ($H_2NSO_2NH_2$) and coupling to N-(1-naphthyl)ethlyenediaminie dihydrochloride (Greiss reagent) to form a coloured azo dye.

- **Orthophosphate (PO_4^{3-})** – may also be referred to as “phosphate”, “reactive phosphorus” or “soluble reactive phosphorus”. Orthophosphate can be measured directly in samples filtered to 0.45 µm using a colourimetric technique based on the reaction of orthophosphate with molybdate (MoO_4^{2-}). In the ascorbic acid (’molybdate blue’) technique, the chemical reaction of PO_4^{3-} with MoO_4^{2-} generates a blue colour. In contrast, the molybdovanadate technique produces a yellow solution. In either case, the intensity of the colour generated indicates the concentration of orthophosphate in the sample. The limit values for total P, expressed as PO_4^{3-}, are indicative in order to reduce eutrophication (Table 21; European Parliament, 2006).

European Commission

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Table 21. Indicative limit values for total phosphorus, expressed as phosphate (PO_4^{3-})

EU Directive	Units of analysis	Indicative limit value
Freshwater Fish Directive [2006/44/EC] – salmonid waters	mg/L PO_4^{3-}	≤0.2
Freshwater Fish Directive [2006/44/EC] – cyprinid waters	mg/L PO_4^{3-}	≤0.4

- **Acid hydrolysable P (AHP)** – this fraction includes condensed phosphates, or multiple orthophosphate molecules condensed together, such as metaphosphate, pyrophosphate and polyphosphate. These compounds are sometimes used for corrosion control in drinking water distribution systems. To analyse AHP, the condensed phosphate molecules must first be treated with sulphuric acid (H_2SO_4) and heat (150°C for 30 min) to convert them to orthophosphate. Analysis of the digested sample will give the concentration of condensed phosphates + orthophosphate, so to determine only the AHP fraction the quantity of orthophosphate (in a sample not treated with H_2SO_4 and heat) must be subtracted.
- **Total P (P_{tot})** – total P includes orthophosphates, acid hydrolysable P, and organic forms of P. Organic forms of P are not readily broken down and require oxidation in addition to acid and heat treatment. Organic P digestion typically involves addition of a strong oxidant such as potassium persulphate ($K_2S_2O_8$) as well as H_2SO_4 and heat. This process converts all forms of P to PO_4^{3-}. After digestion, the same technique as used to quantify orthophosphate (ascorbic acid or molybdovanadate method) can be used to quantify all forms of P in the sample, yielding the 'total' P concentration.

Different nitrogen and phosphorus species can be quantified in a water sample either in the field, using a test kit or ion selective electrode (ISE), or via laboratory analyses. Sample analysis by an accredited laboratory analysis is the most accurate way to obtain information about nutrient concentration in waters. A full suite of laboratory analyses for multiple chemical species of N and P can be quite costly. A less expensive alternative may be the use of one or more ISEs to detect selected N and/or P species. Whilst ISEs for various N species (NO_2^-, NO_3^-, NH_3/NH_4^+) are readily available from multiple suppliers, ISEs for phosphate are less common. Ion selective electrodes are analogous to a pH electrode and are used in much the same way as a pH electrode (pH electrodes are essentially ion selective electrodes that are sensitive to the H^+ ion). An advantage of ISEs is their ease of use, and potential for permanent installation at a given sampling point. It is possible to program a data logger connected to an *in-situ* ISE to measure and record a value at a prescribed frequency.

Test kits are usually used on site (in the field) to obtain a rapid result, but are in general less accurate than analyses performed in an accredited laboratory. Test kits typically involve the addition of chemical reagents to a water sample and yield results based on test strip colour comparison, solution colour comparison to a colour wheel or colour chart, or measurement with a photometer. The spectrophotometer measures the quantity of a chemical based on its characteristic absorption spectrum. Photometers are generally quite accurate but can be expensive to purchase and maintain. Test kits based on colour comparison, either of test strips or solutions, are relatively less costly but can have limited accuracy at low nutrient concentrations (Table 22).

Table 22. Comparative summary of nutrient test kit types for water quality analyses (adapted from Reedyk & Forsyth, 2006)

	Test Strips	Visual Comparison	Photometer
Applicability to low concentrations	Poor	Average	Good
Degree of subjectivity in result interpolation	High	Average	Low
Relative cost	Low	Average	High
Relative ease of use	Very easy	Easy	Easy
Recommended application	Awareness	Awareness & general monitoring	General or dedicated monitoring

Scale of measurement: Plot scale to district scale, depending on location of sampling point

Key References

Orhel, R.L., & Register, K.M. (2006). *Volunteer Estuary Monitoring. A Methods Manual. Second edition.* Washington, D.C: United States Environmental Protection Agency.

Reedyk, S., & Forsyth, A. (2006). *Using field chemistry kits for monitoring nutrients in surface water. Publication number PRO-121-2006-1.* Ottawa, Ontario, Canada: Agriculture and Agri-Food Canada PFRA. Retrieved from http://pfra.ca/doc/Water%20Quality/Water%20Quality%20Protection/using_field_chem_kits_final.pdf

Additional Information

European Parliament, Council of the European Union. (1991). *Council Directive 91/271/EEC of 21 May 1991 concerning urban waste water treatment.* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31991L0271&from=EN

European Parliament, Council of the European Union. (1991). *Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources.* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31991L0676

European Parliament, Council of the European Union. (1998). *Council directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption.* Retrieved from https://eur-lex.europa.eu/eli/dir/1998/83/2015-10-27

European Parliament, Council of the European Union. (2000). *EU Water Framework Directive: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy.* Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02000L0060-20140101

European Parliament, Council of the European Union. (2006). *Council Directive 2006/44/EC of 6 September 2006 on the quality of fresh waters needing protection or improvement to support*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

fish life. Retrieved from https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:264:0020:0031:EN:PDF

European Parliament, Council of the European Union. (2008). *Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy, amending and subsequently repealing Council Directives 82/176/EEC, 83/513/EEC, 84/156/EEC, 84/491/EEC, 86/280/EEC and amending Directive 2000/60/EC of the European Parliament and of the Council.* Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0105

European Parliament, Council of the European Union. (2013). Directive 2013/39/EU of the European Parliament and of the Council of 12 August 2013 amending Directives 2000/60/EC and 2008/105/EC as regards priority substances in the field of water policy (Text with EEA relevance). *OJ L 226, 24.8.2013, 1–17*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32013L0039

European Commission, Directorate-General for Environment. (2018) *Proposal for a Directive of the European Parliament and of the Council on the quality of water intended for human consumption (recast). COM/2017/0753 final - 2017/0332 (COD).* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52017PC0753&from=EN

Maximum dissolved oxygen concentration saturation table: https://lakestewardsofmaine.org/wp-content/uploads/2014/01/Maximum-Dissolved-Oxygen-Concentration-Saturation-Table.pdf

4.5.3 Metal concentration or load

Metric: *Metal pollutants in surface water and/or groundwater (%, expressed as total annual metal pollutant load and/or reduction of maximum annual concentration)*

Metals and metalloids (herein referred to simply as metals) are ubiquitous in the natural environment and can potentially accumulate to toxic levels as metals do not degrade with time. As such, metals can have a significant impact on water quality and its fit-for-purpose use. Natural sources of metals include weathering of geologic materials (rocks and soil) and volcanic activity. The primary reservoir of metals is geological substrate. Human activity has greatly accelerated natural biogeochemical cycles, resulting in anthropogenic emissions of metals to the atmosphere one to three orders of magnitude greater than natural fluxes. Anthropogenic sources of metals include point sources such as mining and industrial activities, and non-point sources such as fossil fuel combustion and agricultural activities. Some of the more common metal pollutants are: aluminium (Al), arsenic (As), barium (Ba), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), molybdenum (Mo), nickel (Ni), lead (Pb) and mercury (Hg), selenium (Se), vanadium (V) and zinc (Zn).

Metals in water samples are typically quantified in an accredited laboratory using a suite of standardised analyses. Ion-coupled plasma spectrophotometry (ICP) coupled with atomic emission spectrometry or mass spectrometry (ICP-AES or ICP-MS, respectively) is widely considered the 'gold standard' for analysis of metals in water. ICP analyses are highly precise and accurate to very low concentrations. Multiple elements can be analysed from a single sample, and a relatively small sample volume is required (typically 100 mL or less). A disadvantage of ICP analysis of metals in water samples is that it can be quite costly, and there is usually a significant delay between the time of sample collection and receipt of water quality data from the laboratory. The nature of ICP analyses means that the analysed samples represent a single point in time (the time at which the sample was collected), and metal concentrations may vary substantially in urban waters due to the contribution of run-off from urban surfaces.

Field test kits are available for on-site testing of some metals (e.g., As, Cd, Cu, Pb, Mo, etc.) whilst other metals can be detected using an ion-selected electrode (ISE; e.g., Cd, Pb, Zn, etc.). Field test kits vary greatly and range from semi-quantitative paper test strips for multiple metals, to quantitative colourimetric-type analyses. Some field test kits may involve the use of portable laboratory equipment such as a photometer, fluorometer or similar. The primary advantage of field test kits and ISEs is the ability to rapidly obtain results and, in the case of ISEs, potentially install a testing unit in-situ to take measurements at regular intervals and save results to a data logger or upload to a central data repository. The main disadvantage of field test kits and ISEs is that a separate kit or ISE is required for each element of interest, and the limit of detection for a given element of interest may be substantially higher than the respective accredited laboratory analysis technique. In addition, analysis of individual metals using field test kits can be time-intensive and/or require trained personnel to conduct the tests.

Results of metal analyses are typically interpreted via comparison with applicable legislation, monitoring changes in the concentration of individual metals with time and noting when and for what duration (how long) an individual metal pollutant was detected at concentrations greater than regulatory limits or guideline values. Combining metal concentration with measurements of flow rate can be used to estimate the total load of individual metal pollutants delivered to receiving waterbodies. Alternatively, a metal pollution index (e.g., Chaturvedi, Bhattacharjee, Singh, & Kumar, 2018; Chaturvedi et al., 2019; Mohan, Nithila, & Reddy, 1996) can be used to compare concentrations of selected metals to a particular water quality standard and to calculate an overall index value for

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

metal pollution based on these values. The objectives of the water quality monitoring programme will largely determine how data regarding metal pollution are used.

Scale of measurement: Plot scale to district scale, depending on location of sampling point

Key References

Chaturvedi, A., Bhattacharjee, S., Mondal, G.C., Kumar, V., Singh, P.K., & Singh, A.K. (2019). Exploring new correlation between hazard index and heavy metal pollution index in groundwater. *Ecological Indicators*, *97*, 239-246.

Chaturvedi, A., Bhattacharjee, S., Singh, A.K., & Kumar, V. (2018). A new approach for indexing groundwater heavy metal pollution. *Ecological Indicators*, *87*, 323-331.

European Parliament, Council of the European Union. (2000). *EU Water Framework Directive: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy.* Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02000L0060-20140101

Mohan, S.V., Nithila, P., & Reddy, J. (1996). Estimation of heavy metals in drinking water and development of heavy metal pollution index. *Journal of Environmental Science and Health. Part A: Environmental Science and Engineering and Toxicology*, *31*(2), 283-289.

4.5.4 Total suspended solids (TSS)

Metric: *Total suspended solids (TSS) or turbidity (% and total, units dependent upon measurement technique)*

Total suspended solids (TSS) can affect the health and productivity of the aquatic ecosystem. Sources of TSS include, e.g., sediment runoff from agricultural fields, logging activities, construction sites, roadways, waste discharge, or excessive algal growth. The TSS content often increases sharply during and immediately following a rainfall event. The EU Freshwater Fish Directive (2006/44/EC) recommends ≤25 mg/L TSS for salmonid and cyprinid fish health (European Parliament, 2006), whilst the concentration of TSS in wastewater treatment plant effluents is limited to ≤35 mg/L by Wastewater Directive 91/271/EEC (European Parliament, Council of the European Union, 1991).

Total suspended solids are typically quantified in the laboratory using a gravimetric process, yielding TSS measurement in units of mass per volume (e.g., mg/L or ppm). Measurement of TSS involves filtration of a water sample followed by drying and weighing of the particulates removed. This laboratory measurement of TSS directly quantifies the amount of fine particulate material suspended in water but is relatively time-intensive. To directly quantify TSS, collect samples and analyse gravimetrically in a laboratory.

A semi-quantitative, rapid assessment of TSS can be accomplished by evaluating sample turbidity, a measure of the relative transparency of a water sample. Turbidity measurements are more semi-quantitative and rely on comparison of light scattering with that of standard solutions (turbidity meter) or visual assessment (Secchi disk, transparency tube). Turbidity meters use a light beam with defined characteristics to provide a semi-quantitative measure of the particulates present in the water, providing an integrated measure of light scattering and absorption. The measurement is provided in nephelometric turbidity units (NTU). Turbidity (in NTU) can be directly related to TSS (in mg/L) via creation of a standard curve (TSS versus turbidity) for a given location/type of fine particulate material.

- Measuring turbidity *in-situ*:
  - Secchi disk, which is lowered into the water and the level where the disk disappears is registered. Secchi disk is very commonly used visual method because it is easy to use, inexpensive, and relatively accurate.
  - Turbidity meter consists of a light source that illuminates a water sample and a photoelectric cell that measures the intensity of light scattered at a 90° angle by the particles in the sample. The turbidity meter method is very accurate.
  - Transparency tube is a clear, narrow plastic tube marked in units with a light and dark pattern painted on the bottom. Water is poured into the tube until the pattern disappears, and the depth is recorded.

Scale of measurement: Plot scale to district scale

Key References

Orhel, R.L., & Register, K.M. (2006). *Volunteer Estuary Monitoring. A Methods Manual. Second edition.* Washington, D.C: United States Environmental Protection Agency.

Additional Information

European Parliament, Council of the European Union. (1991). *Council Directive 91/271/EEC of 21 May 1991 concerning urban waste water treatment.* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31991L0271&from=EN

European Parliament, Council of the European Union. (2000). *EU Water Framework Directive: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy.* Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02000L0060-20140101

European Parliament, Council of the European Union. (2006). *Council Directive 2006/44/EC of 6 September 2006 on the quality of fresh waters needing protection or improvement to support fish life.* Retrieved from https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:264:0020:0031:EN:PDF

4.5.5 Total pollutant discharge to local waterbodies

Metric: *Water quality status according to WFD as determined by pollutant discharge monitoring*

In the EU, all waterbodies are classified by quality status based on guidelines set in the Water Framework Directive (WFD), Directive 2000/60/EC (European Parliament, Council of the European Union, 2000). The WFD outlines biological, physico-chemical and hydromorphological quality elements. Comparison of measured water quality parameters for a given waterbody with standard values outlined in the WFD allows classification of the status of a waterbody from high to bad. Parameters taken into account include a large number of variables including, e.g., plankton counts, aquatic flora, invertebrates, hydrological continuity and conditions, thermal conditions, oxygen conditions, salinity, nutrient conditions and prevalence of priority pollutants and other specific pollutants. Many of these parameters are waterbody specific and the determination of stress caused by a pollution source depends on the type and size of the waterbody (European Parliament, Council of the European Union, 2000).

Persistent quality monitoring of the receiving waterbody is a good way of following the environmental impacts of the pollutant discharges of urban communities, but they depend heavily on the condition and size of the receiving waterbody and the whole catchment area. To monitor changes in specific urban pollutant discharge and potential changes caused by NBS implementation, more precise and limited metrics are required. Measuring urban runoff is challenging as it consists of point and non-point sources, it can be highly heterogeneous in place and time, and it is potentially heavily affected by rainfall and storm events, as well as seasonal changes such as snowmelt (Allen Burton & Pitt, 2010). As a result, selecting proper sampling procedures as well as measured variables to capture a representative figure of the pollution discharge loading is challenging.

Typical parameters to consider when assessing urban runoff water quality include faecal bacteria, *Escherichia coli* and *Enterococcus feacalis*, which measure the prevalence of faeces or wastewater. Nutrients, including total nitrogen (N_{tot}), ammonium (NH_4^+), nitrate (NO_3^-) and total phosphorus (P_{tot}) are related to the runoff from lawns, gardens and parks, chemical discharges, or accumulated residues in streambanks or sediments released by storm surges. Oil, grease, petroleum hydrocarbons, rubber particles, asphalt dust, soot, polycyclic aromatic hydrocarbons (PAHs), as well as the metals nickel (Ni), copper (Cu), zinc (Zn), cadmium (Cd), and lead (Pb) are typical pollutants emerging from roads and parking lots. Legislators in the EU and the United States have identified lists of priority pollutants that should be monitored; the EU list includes 33+8 chemicals (European Parliament, Council of the European Union, 2008), or 48 chemicals in a newer edition to be confirmed (European Parliament, Council of the European Union, 2012). These chemicals in particular, but any other chemical pollutant as well, should be monitored if they are discharged in the catchment area. The overall water quality is most often followed using physical and chemical indicators and composite indicators that follow indirect measures of quality. These include physical and chemical indicators such as temperature, colour, turbidity, conductivity, oxidative-reductive potential (ORP), dissolved oxygen (DO), pH, buffering capacity and salinity. Composite indicators include total suspended solids (TSS), biological oxygen demand (BOD), chemical oxygen demand (COD) and total organic carbon (TOC) (Allen Burton & Pitt, 2010; European Parliament, Council of the European Union, 2000; United States Environmental Protection Agency, 2017; Zumdahl & DeCoste, 2012).

For the purpose of NBS monitoring, a simple, but informative metric is required. As the aim is not to protect the receiving waterbody, to catch hazardous pollutants or inclusively map the total quality of the runoff, a selection of parameters indicating runoff from road surfaces, faecal contamination, nutrient loading and physico-chemical parameters are sufficient.

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Table 23. Parameters for pollutant discharge monitoring

	Parameter	Method	Indicator value
1	Intestinal enterococci	ISO 7899 or equivalent	Faecal contamination
2	Total nitrogen	ISO 29441 or equivalent	Nutrient runoff
3	Total phosphorus	ISO 6878 or equivalent	Nutrient runoff
4	pH	ISO 10523 or equivalent	Chemical balance
5	Redox potential, ORP		Chemical balance
6	Turbidity	ISO 7027-1 or equivalent	Indicator for suspended solids
7	Conductivity	ISO 7888 or equivalent	Ionic strength
8	Dissolved oxygen, DO	ISO 17289 or equivalent	Chemical/biological balance
9	Temperature		Environmental indicator
10	Polycyclic aromatic hydrocarbons	ISO 28540 or equivalent	Pollution from traffic
11	Chemical Oxygen Demand, COD	ISO 6060 or equivalent	Organic content
12	Biochemical Oxygen Demand, BOD	ISO 5815 or equivalent	Organic content

The parameters are standardized and simple to determine from a sample, but the temporal and regional heterogeneity of runoff volume and quality makes determination of overall quality challenging. These parameters allow for qualitative analysis of change and scale of pollution from runoff to be estimated, but are only indicatively suitable for comparison between different areas.

Pollutant discharge is estimated by taking samples from urban runoff from the target area and comparing the time series of the selected parameters. First, sampling sites are selected to represent the catchment urban area in question as comprehensively as possible. Ideally, sampling sites can be streams, ditches or runoff sewers collecting from a large catchment area in the urban area of interest, but not yet mixing with a larger waterbody. A sampling schedule is determined and followed. Ideally, continuous automatic aggregate samplers are used with flowmeters, providing the most reliable estimates of parameter yearly aggregates. Alternate sampling method is systematic sampling in which samples are taken with identical time steps (e.g., every 2 months) regardless of conditions, like rainfall, traffic or temperature. All non-continuous sampling procedures inflict bias into results, and will only capture a fraction of the actual runoff quality, which makes results invariably noisy.

On-site measurements, sampling and laboratory analysis are to be performed by personnel and in premises with experience in water sampling and analysis using standardized methods, chemicals and equipment. For technical details, please refer to standard methods or equivalent methods available at the laboratory performing the analysis.

As the details of each urban environment and NBS can differ substantially, and as parameters described here are often only indicative of water quality, potential change in pollution discharge is presented in a Likert-type scale (Table 24).

Table 24. Likert scale for evaluating change in discharge water quality

1	Several of the parameters indicate significantly worse water quality, or more than half of the parameters indicate somewhat worse water quality
2	One of the parameters indicate significantly worse water quality, or some of the parameters indicate somewhat worse water quality
3	The parameters indicate no change in the water quality
4	One of the parameters indicate significantly better water quality, or some of the parameters indicate somewhat better water quality
5	Several of the parameters indicate significantly better water quality, or more than half of the parameters indicate somewhat better water quality

Scale of measurement: District scale

Key References

Allen Burton, G., Jr., & Pitt, R.E. (2010). *Stormwater Effects Handbook. A Toolbox for watershed Managers, Scientists, and Engineers.* Boca Raton, FL: Lewis Publishers, CRC Press.

European Parliament, Council of the European Union. (2000). *EU Water Framework Directive: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy.* Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02000L0060-20140101

European Parliament, Council of the European Union. (2008). *Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy, amending and subsequently repealing Council Directives 82/176/EEC, 83/513/EEC, 84/156/EEC, 84/491/EEC, 86/280/EEC and amending Directive 2000/60/EC of the European Parliament and of the Council.* Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0105

European Parliament, Council of the European Union. (2009). *Commission Directive 2009/90/EC of 31 July 2009 laying down, pursuant to Directive 2000/60/EC of the European Parliament and of the Council, technical specifications for chemical analysis and monitoring of water status (Text with EEA relevance). OJ L 201, 1.8.2009, p. 36–38* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009L0090

European Parliament, Council of the European Union. (2012). *Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directives 2000/60/EC and 2008/105/EC as regards priority substances in the field of water policy. /* COM/2011/0876 final - 2011/0429 (COD) */.* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52011PC0876

United States Environmental Protection Agency (US EPA). (2017). *Water Quality Standards Handbook: Chapter 3: Water Quality Criteria. EPA-823-B-17-001.* Washington, D.C.: EPA Office of Water, Office of Science and Technology. Retrieved from https://www.epa.gov/sites/production/files/2014-10/documents/handbook-chapter3.pdf

Zumdahl, S.S., & DeCoste, D.J. (2012). *Chemical Principles*. *Seventh Edition.* Boston, MA: Cengage Learning.

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.5.6 Total number & species richness of aquatic macroinvertebrates

Metric: *Total number and species richness of aquatic macroinvertebrates (unitless)*

Aquatic macroinvertebrates are animals that do not have a backbone, can be observed without magnification and spend at least part of their life in water. Most macroinvertebrates spend part of all of their life attached to submerged rocks, logs and vegetation. They are good indicators of the health of aquatic ecosystems because:

- Macroinvertebrates are affected by physical, chemical and biological conditions of the stream
- Macroinvertebrates are relatively long-lived and cannot escape pollution, so can therefore reflect changes to stream conditions across space and time
- Macroinvertebrates are ubiquitous in perennial aquatic systems
- Macroinvertebrates are a critical part of the food web in streams
- Macroinvertebrates have a range of different life history strategies (e.g., mode of respiration, feeding strategy, reproduction) that can be used to evaluate causes of aquatic ecosystem impairment
- Macroinvertebrates can easily be sampled and identified in a cost-effective manner

Macroinvertebrate monitoring can not only provide information about how changes to the landscape or stream characteristics affect the health of the biological community, but also yields an opportunity for community members to engage in environmental monitoring. It is recommended that an aquatic biologist assist in the design of a biosurvey programme and provide a locally-adapted macroinvertebrate identification key. Monitoring approaches typically involve the establishment of a transect-type study area or sampling 'reach' and macroinvertebrate sample collection along with habitat assessment. The relative intensity of the biosurvey and level of supervision by professional aquatic biologists depends upon the programme objective. It is generally recommended that macroinvertebrate sampling programmes start with the simplest, least resource-intensive approach and work towards increasing complexity depending on the available resources, expertise and volunteer interest. An example of a macroinvertebrate sampling programme is given below. Additional details of macroinvertebrate sampling and exemplar Field Data Sheets are provided in Appendix III, Section 10.

(1) Establish sample location (sample station)

1. Establish a sampling location on the upstream side of any road crossing.
2. Measure a distance of at least 10 m upstream and away from the road crossing to ensure the sampling reach is established outside of the influence of the roadway. Record the distance from the road crossing to the start of the sampling reach on the Field Data Sheet and place a piece of flagging tape or other noticeable landmark (e.g., a stick or rock) on the stream bank to mark the start of the sampling reach.
3. Measure 100 m from the start of the sampling reach by measuring the distance within the stream channel or immediately on the stream bank. Place a piece of flagging tape or other noticeable landmark on the stream bank to mark the end of the sampling reach.
4. If re-sampling a previously established site, review a previous Field Data Sheet in order to establishing the sampling reach the same manner as done previously.

(2) Estimate habitat proportions

5. Note the types of habitats available within the sampling reach and their relative abundance.

6. Estimate the relative proportion of each habitat type and record on a Field Data Sheet the respective percentages of each habitat type and the number of macroinvertebrate samples to be collected within each habitat type (collect a total of 10 macroinvertebrate samples, with collection from each habitat type proportional to its relative abundance).

(3) Collect macroinvertebrate samples

7. Work from the downstream end of the sampling reach towards the upstream end.

8. A single jab (to collect a sample of macroinvertebrates) consists of forcefully thrusting the collection net into the habitat for a distance of 30-60 cm, accompanied by sweeping the area with the net to capture all dislodged macroinvertebrates. A single jab in hard bottom habitats is accomplished by positioning the net and disturbing the substrate for a distance of 30-60 cm upstream of the net. A jab into a leaf pack involves positioning the net downstream and dislodging the leaf pack over about a 30-60 cm distance into the net.

9. Ensure that the organisms present in each 30-60 cm area sampled are thoroughly disturbed and dislodged. A jab within a given area may be repeated to ensure that the habitat has been thoroughly sampled. If the sampling net becomes clogged to the extent that it may hinder obtaining an appropriate sample, discard the material in the net and redo that portion of the sample in the same habitat type but in a different location.

10. After each jab is collected, dump the net contents into a wide pan. Inspect the inside of the net and place any macroinvertebrates clinging onto the net in the pan.

(4) Clean and preserve the sample

11. Collected samples will likely contain rocks, leaves, sticks, sand, and other material. Carefully pick the macroinvertebrates from each sample and place into a glass sample container half-filled with 70% ethanol. Discard the other material. Ensure that all macroinvertebrates are picked from teach jab sample before discarding the debris.

12. Fill out a sample label with pencil and place it inside the collection jar.

(5) Habitat assessment and estimation of flow

13. Evaluate the stream bed composition. Estimate the proportion of the stream bed within the 100 m sampling run comprised of bedrock, boulder, cobble, gravel, sand, silt or organic material, respectively, and record on a Field Data Sheet.

14. Estimate the proportion of rocks covered by sand, silt or mud (embeddedness) and record.

15. Measure flow at one spot within the 100 m sampling run. Find a straight stretch of stream and measure a distance of 3 m with a measuring tape. Drop a float (i.e., an apple, orange, or a small stick) and measure the time it takes the float to travel 3 m.

16. Take a total of four flow measurements at the same spot in the stream - two from high velocity water and two from low velocity water.

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

17. Measure the wetted width of the stream in this section and take depth measurements at one-foot intervals across the stream at this location. Record your measurements on the Field Data Sheet.

(6) Generate a site sketch

18. Sketch major features and mark the areas from which samples were taken.

Results of macroinvertebrate surveys should be evaluated to assess changes with time, or changes relative to undisturbed conditions. The comparison between the sampled site and a reference site representing undisturbed conditions yields an evaluation of biological status (Table 25). Consult the local water management department and/or national environmental agency to obtain locally-applicable information about biological indicators of water quality.

Table 25. Guide to biological quality assessment per Water Framework Directive (European Parliament, Council of the European Union, 2000)

Status	Characteristics of macrophytes
High	Taxonomic composition corresponds entirely or almost entirely to undisturbed conditions. There are no detectible changes in the average macrophytic abundance.
Good	Slight changes in composition and abundance of macrophytic taxa compared with type-specific communities. Changes do not indicate accelerated growth of phytobenthos or higher forms of plant life resulting in undesirable disturbances to the balance of organisms present in the water body, or to the physico-chemical quality of the water.
Moderate	The composition of macrophytic taxa differs moderately from the type-specific community and is significantly more distorted than at good status. Moderate changes in the average macrophytic abundance are evident.

Scale of measurement: Plot to neighbourhood/district scale.

Key References

European Parliament, Council of the European Union. (2000). *EU Water Framework Directive: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy.* Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02000L0060-20140101

4.6 Green Space Management

Indicator	Metric
Green space management	Distribution of public green space
	Accessibility of urban green space
	Proportion of road network dedicated to pedestrians and/or bicyclists
	Ambient pollen concentration

4.6.1 Distribution of public green space

Metric: *Distribution of public green space expressed as a proportion of total urban surface area or per capita*

Multiple studies have documented the positive impact on quality of life that is derived from accessible urban green spaces, including parks, street trees, school green areas, public institutions' gardens, residential gardens, cemeteries, sportsgrounds, squares, urban forests, green spaces of the industrial and commercial production, green roofs, vertical gardens, arable lands, vacant lands, and greenhouses (e.g., Badiu et al., 2016). Some of the benefits of urban green spaces include improvements in air quality and local climate regulation (e.g., Rafael, Vicente, Rodrigues, Miranda, Borrego & Lopes, 2018); opportunities for nature experience, recreation and sports activities (e.g., Langemeyer, Baró, Roebeling & Gómez-Baggethun, 2015); real-estate value (e.g., Roebeling et al., 2017); and stormwater runoff control.

It is important that within cities, the urban green spaces are equally distributed. The European Environment Agency defines the distribution of green urban areas as the relationship between green area boundaries (edges) and all the other elements in the city. With unequal distribution of urban green areas, benefits are focused on fewer city elements (neighbourhoods, streets, buildings or houses) and it also prevents connectivity of all the available green spaces in the ecological network. (EEA network.) There are two fundamental ways by which the distribution of green space within a city can be evaluated, namely the total surface area and the per capita area of green space:

a) Total surface

- The categories of green spaces considered from the Urban Atlas (which have a minimum extent of 0.5 ha and a minimum width of 10 m) were urban green spaces and sports and leisure facilities (Badiu et al., 2016)
- Percentage of green space (urban green, agricultural green, forests and nature areas) (de Vries, Verheij, Groenewegen & Spreeuwenberg, 2003)

b) Per capita

- Green space per capita: distance to the road (Badiu et al., 2016)
- Surface of green public spaces expressed as area per inhabitant or per every 1000 inhabitants (Chiesura, 2004)
- Assessing health factors (smoking, obesity, etc.) as a function of distance between green space and home in metres (Tamosiunas et al., 2014)
- Proximity → public park at 5 min walk from home or work (Yes/No) (Madureira, Nunes, Oliveira, Cormier & Madureira, 2011)

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

- Percentage of the area in the Census Area Statistics (CAS) Ward of the participant's residence that is comprised of green space (Roe et al., 2013)
- Percentage of green space within a 1 km and 3 km radius around the postal code coordinates, derived from an existing database and calculated for each household (Maas, Verjeij, Groenewegen, de Vries & Spreeuwenberg, 2006)
- Urbanicity → The indicator is based on the number of households per square kilometre (Maas et al., 2006)
- Normalized Difference Vegetation Index (NDVI) → NDVI is an indicator of greenness based on land surface reflectance of visible (red) and near-infrared parts of spectrum. NDVI ranges between –1 and +1 with higher numbers indicating more greenness (Dadvand et al., 2012)

The same type of procedure can be used to determine the accessibility of specific types of public green space, such as sportsgrounds or urban forest areas.

The EEA's interactive map for green infrastructure indicators (https://www.eea.europa.eu/themes/sustainability-transitions/urban-environment/urban-green-infrastructure/urban-green-infrastructure-1) presents indicators, including the share of green urban areas (Figure 15) and distribution of green urban areas for multiple European cities. Share of green urban areas defines a proportion of green urban areas inside the core cities (proportion of all vegetated areas within the city boundaries in relation to the total area). Distribution of green urban areas presents the ratio of the length of the urban area perimeter (in m) to the urban area (in ha). This measure defines how equally the green areas are distributed in the city.

Another possibility to define the distribution of green urban areas is to calculate the area of green space per capita. For example, in a study by Badiu et al. (2016) the green spaces per capita in different Romanian cities were estimated based on four different data source which were aerials images, TEMPO Database (National Institute of Statistics), Environmental Protection Agencies, and the Urban Atlas.

Data sources for EEA's interactive map include Natura 2000 (https://www.eea.europa.eu/data-and-maps/data/natura-9) and the Urban Atlas (https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-urban-atlas). The European Urban Atlas provides high-resolution land use maps and it is based on Copernicus satellite data on land use in urban areas.

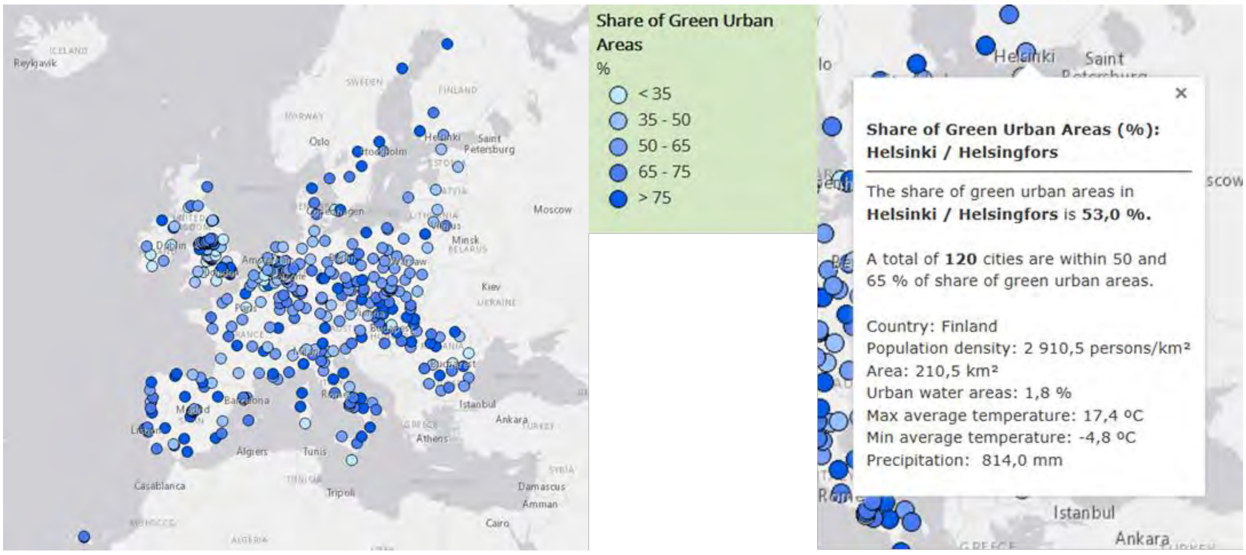


Figure 15. Screenshots from the EEA's Interactive map of green infrastructure indicators. On the left and middle, share of green urban areas in different European cities are presented and on the right, detailed information from the City of Helsinki is shown

Scale of measurement: District scale to city scale

Key references

Badiu, D.L., Ioja, C.I., Patroescu, M., Breuste, J., Artmann, M., Nita, M.R., Gradinaru, S.R., Hossu, C.A., & Onose, D.A. (2016). Is urban green space per capita a valuable target to achieve cities' sustainability goals? Romania as a case study. *Ecological Indicators*, *70*, 53-66.

Chiesura, A. (2004). The role of urban parks for the sustainable city. *Landscape and Urban Planning*, *68*(1), 129-138.

Dadvand, P., de Nazelle, A., Triguero-Mas, M., Schembari, A., Cirach, M., Amoly, E., … Nieuwenhuijsen, M. (2012). Surrounding greenness and exposure to air pollution during pregnancy: An analysis of personal monitoring data. *Environmental Health Perspectives*, *120*, 1286–1290.

Langemeyer, J., Baró, F., Roebeling, P., & Gómez-Baggethun, E. (2015). Contrasting values of cultural ecosystem services in urban areas: the case of park Montjuïc in Barcelona. *Ecosystem Services*, 12, 178-186.

Maas, J., Verheij, R.A., Groenewegen, P.P., de Vries, S., & Spreeuwenberg, P. (2006). Green space, urbanity, and health: how strong is the relation? *Journal of Epidemiology and Community Health*, *60*, 587-592.

Madureira, H., Nunes, F., Oliveira, J. V, Cormier, L., & Madureira, T. (2015). Urban residents' beliefs concerning green space benefits in four cities in France and Portugal. *Urban Forestry & Urban Greening*, *14*(1), 56-64.

Rafael, S., Vicente, B., Rodrigues, V., Miranda, A.I., Borrego, C., & Lopes, M. (2018). Impacts of green infrastructures on aerodynamic flow and air quality in Porto's urban area. *Atmospheric*

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Environment, *190*, 317-330.

Roe, J.J., Ward Thompson, C., Aspinall, P.A., Brewer, M.J., Duff, E.I., Miller, D., … Clow, A. (2013). Green space and stress: Evidence from cortisol measures in deprived urban communities. *International Journal of Environmental Research and Public Health*, *10*, 4086-4103.

Roebeling, P., Saraiva, M., Palla, A., Gnecco, I., Teotónio, C., Fidélis, T., … Rocha, J. (2017). Assessing the socio-economic impacts of green/blue space, urban residential and road infrastructure projects in the Confluence (Lyon): a hedonic pricing simulation approach. *Journal of Environmental Planning and Management*, 60(3), 482-499.

Tamosiunas, A., Grazuleviciene, R., Luksiene, D., Dedele, A., Reklaitiene, R., Baceviciene, … Niewenhuijsen, M.J. (2014). Accessibility and use of urban green spaces, and cardiovascular health: findings from a Kaunas cohort study. *Environmental Health*, *13*(1), 20.

Additional Information

The European Environment Agency's interactive map for green infrastructure indicators: https://www.eea.europa.eu/themes/sustainability-transitions/urban-environment/urban-green-infrastructure/urban-green-infrastructure-1

4.6.2 Accessibility of urban green spaces

Metric: *Accessibility (measured as distance or time) of urban green spaces*

One way to estimate the impacts of urban green space is to evaluate green space accessibility. As one of the indicators in EEA's Interactive map for Green infrastructure indicators, effective green infrastructure is presented. EEA defines effective green infrastructure as a potential distribution of green infrastructure element in the territory or in the neighbouring area.

a) Exposure to green space - distance to city parks

Accessibility to green spaces can also be determined as a distance to the green spaces or time to reach the green spaces. In a study by Tamosiunas et al. (2014), spatial land cover sets for Kaunas city were obtained from the municipality, and they were processed using an ArcGIS software for green space exposure. City parks larger than 1 ha were included. Distances to the nearest city park were estimated by geocoding home addresses of the survey responders and using SAS and GIS software.

- Data requirements:
  - Land use map
  - Green space map
  - Green space qualification
  - Road network map
- Data source and availability:
  - Municipal departments
  - Corine Land Cover
  - OpenStreetMap

Sample time/data collection interval: Before and after the NBS implementation

Scale of measurement: District scale to city scale

b) Percentage of the green space in the living environment

Many different methods exist and have been used in studies estimating the amount of green space in the living environment. In studies by de Vries et al. (2003), Maas et al. (2006), and Maas et al. (2009), a National Land Cover Classification database (LGN3 and LGN4 in The Netherlands) was used as a data source for green space exposure evaluation. In the study by de Vries et al. (2003), additional sources were used including, for example, infrastructure and noise levels. All the environmental data used were combined in a single geographical information system (GIS). Living environments were defined as circles with radius of 1 km or 3 km.

In studies by Ward Thompson et al. (2012) and Roe et al. (2013) the study participants' living environment was defined as the area in the Census Area Statistics (CAS), which is a geographical unit used in the administration of the United Kingdom's decennial census. Green space were obtained

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

from the website of the Centre for Research on Environment Society and Health (CRESH). The green spaces included parks, woodlands, scrub and other natural environments, but not private gardens.

Sample time/data collection interval: Before and after the NBS implementation

Scale of measurement: District scale to city scale

Key references

de Vries, S., Verheij, R.A., Groenewegen, P.P., & Spreeuwenberg, P. (2003). Natural Environments – healthy environments? An exploratory analysis of the relationship between greenspace and health. *Environment and Planning*, *35*, 1717-1731.

Maas, J., Verheij, R.A., de Vries, S., Spreeuwenberg, P., Schellevis, F.G., & Groenewegen, P.P. (2009). Morbidity is related to a green living environment. *Journal of Epidemiology and Community Health*, *63*(12), 967-973.

Maas, J., Verheij, R.A., Groenewegen, P.P., de Vries, S., & Spreeuwenberg, P. (2006). Green space, urbanity, and health: how strong is the relation? *Journal of Epidemiology and Community Health*, *60*, 587-592.

Roe, J.J., Ward Thompson, C., Aspinall, P.A., Brewer, M.J., Duff, E.I., Miller, D., … Clow, A. (2013). Green space and stress: Evidence from cortisol measures in deprived urban communities. *International Journal of Environmental Research and Public Health*, *10*, 4086-4103.

Tamosiunas, A., Grazuleviciene, R., Luksiene, D., Dedele, A., Reklaitiene, R., Baceviciene, M., … Niewenhuijsen, M.J. (2014). Accessibility and use of urban green spaces, and cardiovascular health: findings from a Kaunas cohort study. *Environmental Health*, *13*(1), 20.

Ward Thompson, C.W., Roe, J., Aspinall, P., Mitchell, R., Clow, A., & Miller, D. (2012). More green space is linked to less stress in deprived communities: Evidence from salivary cortisol patterns. *Landscape and Urban Planning*, *105*, 221 – 229.

4.6.3 Proportion of road network dedicated to pedestrians and/or bicyclists

Metric: *Proportion of road network dedicated to pedestrians and/or bicyclists (% of network)*

Increase in pedestrian and bicycle traffic is regarded beneficial for its economic, environmental, health and life quality effects. Availability of pedestrian paths and bicycle lanes can decrease the dependency on automobile ownership and use and related costs, free space from automobile traffic and congestion, reduce air pollution, increase physical activity and related health benefits and improve social activity and interaction within communities.

Pedestrian and/or bicycle path length gives a numeric indicator to follow the development the relative development of green transport routes in the community. It is easy to obtain and can be compared to different areas of interest. Path length is as a variable indicates only the relative availability of green transport routes (i.e., pedestrian and bicycle paths), but does not yield information regarding their use, utility, or perceived value by the community, which depend for instance on their coverage, consistency, terrain, safety and connectivity.

Increase in pedestrian/bicycle path length is measured as percentage increase of the length of pedestrian/cycling paths in the whole urban community in question. The pedestrian/bicycle paths are roads or lanes designated and marked for use by pedestrians and/or bicycles. The calculation can be performed from a map with adequate markings of path types and lengths, from which pedestrian/bicycle paths are summed before and after NBS implementation. Pedestrian paths and bicycle routes can be considered together or separately, depending on the specific metric desired.

$$Increase\ (\%) = \left(\frac{Length\ of\ cycling\ paths_{after}}{Length\ of\ cycling\ paths_{before}} \cdot 100\%\right) - 100\%$$

In the case of a new development, a business-as-usual model plan can be used to compare the difference in pedestrian/bicycle path length achieved to the state-of-art achieved in the project.

Scale of measurement: Street to metropolitan scale

European Commission

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.6.4 Ambient pollen concentration

Metric: *Number of grains of pollen per cubic metre of air (pollen grains/m^3)*

Urban green spaces frequently have a limited number of plant species, including a higher proportion of non-native species in comparison with rural areas (McKinney, 2002). The low species diversity in many urban areas is directly linked to the formation of concentrated pollen emission sources. In particular, large-scale use of a small number of roadside tree species results in production of large quantities of a single species of pollen. Areas of concentrated pollen may not be readily dispersed by air currents. Some studies indicate that urban citizens are 20% more likely to suffer airborne pollen allergies than people living in rural areas, largely due to the uniformity of green spaces, where a small number of species that have proved highly suited to urban environmental conditions are overwhelmingly used, and the interaction of pollen with air pollutants (Cariñanos & Casares-Porcel, 2011).

The volumetric Hirst-type pollen and spore trap designed in 1952 remains one of the devices most commonly used for pollen and spore monitoring (Buters et al., 2018). The Hirst-type trap is standard in pollen monitoring networks in Europe. The Hirst-type pollen and spore trap uses a vacuum pump to continuously draw air at a known rate (e.g., 10 L/min). A wind vane attached to the sampler head ensures that the trap inlet is always facing the prevailing wind. Depending on the configuration of the trap, pollen and spores are captured on adhesive coated transparent plastic tape (Melinex) or on a microscope slide coated with an adhesive. Adhesive tapes are attached to a metal drum that rotates with time.

Pollen traps can be fitted with a drum specific to a 24-h or a 7-day sampling period. At the conclusion of the sampling period, the tape with adhered pollen and spores is cut into pieces representing 24-h periods of time and mounted on a microscope slide. Where the pollen and spores are captured directly on a microscope slide, the slide must be changed every 24 h. These slides are examined by microscopy for counting and identification of pollen and spores. This traditional method of identifying and characterising trapped pollen and spores is time-consuming and requires considerable expertise, but the results are widely accepted and known to be consistent.

Scale of measurement: plot to neighbourhood scale

Key References

Buters, J.T.M., Antunes, C., Galveias, A., Bergmann, K.C., Thibaudon, M., Galán, C. … & Oteros, J. (2018). Pollen and spore monitoring in the world. *Clinical and Translational Allergy*, *8*, 9.

Cariñanos, P., & Casares-Porcel, M. (2011). Urban green zones and related pollen allergy: A review. Some guidelines for designing spaces with low allergy impact. *Landscape and Urban Planning*, *101*(3), 205-214.

McKinney, M. (2002). Urbanization, Biodiversity, and Conservation: The impacts of urbanization on native species are poorly studied, but educating a highly urbanized human population about these impacts can greatly improve species conservation in all ecosystems. *BioScience*, *52*(10), 883-890.

Additional Information

D'Amato, G., Cecci. L., Bonini, S., Nunes, C., Annesi-Maesano, I., Behrendt, H., … Van Cauwenberge, P. (2007). Allergenic pollen and pollen allergy in Europe. *Allergy*, *62*, 976-990.

Instructions for the use of a Hirst-type pollen and spore trap: https://aaaai.confex.com/aaaai/2013/recordingredirect.cgi/.../Burkard%20Directions.pdf

Interactive on-line map of pollen monitoring sites around the world: https://www.zaum-online.de/pollen-map.html; http://www.eaaci.org/patients/resources/; https://oteros.shinyapps.io/pollen_map/

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.7 Biodiversity

Indicator	Metric
Biodiversity	Proportion of natural areas within a defined urban zone
	Structural and functional connectivity of green spaces
	Bird species in urban area
	Changes in native species numbers

Biodiversity is the measure of biological variety in the environment and it has an important role in functioning ecosystems services and health of environment and society. Urbanisation affects biodiversity through urban sprawl/habitat fragmentation, loss of fertile agricultural lands, and the spread of invasive alien species (International Standardization Organization [ISO], 2018). Biodiversity is an aspect of natural environment that is most directly affected by anthropogenic influence and loss of biodiversity can have significant effects for sustainability of resilience. Biodiversity loss poses a widespread threat to society, including issues as diverse as, e.g., food security, quality of recreational and tourism-based opportunities, and potential for new medicinal innovations or novel products. Biodiversity loss can have significant detrimental impacts on essential ecological function, such as nutrient transformation, carbon sequestration and air purification by vegetation. Biodiversity is typically evaluated based on variability and variety of species and forms of life, as well as environments and their connectivity. City biodiversity is seen as an important aspect of sustainable and resilient urban development.

United Nations Convention on Biological Diversity has developed a City Biodiversity Index (a.k.a. Singapore Index). It is a quantitative self-assessment tool for cities to follow progress in conserving biodiversity (Chan et al., 2014). The index is comprised of 23 separate measured indicators, ten concentrating on native biodiversity, four on ecosystems services and nine on governance and management actions.

For monitoring effects of NBS on biodiversity, selecting metrics from the City Biodiversity Index focusing on native biodiversity has many benefits. The methodology has been developed in coordination with a consortium of scientists and cities with varied ecological and urban environments, methodology is freely available, and other cities for comparison are easily available. The collection of this data further facilitates the completion of the full City Biodiversity Index, if seen beneficial by the participatory cities. While some aspects of the index are seen not ideally representative, the index as a whole is seen as a powerful tool for increasing the visibility of urban biodiversity, and in particular can support acquisition of information about the changes is biodiversity (Kohsaka et al., 2013).

Key References

Chan, L., Hillel, O., Elmqvist, T., Werner, P., Holman, N., Mader, A., & Calcaterra, E. (2014). *User's Manual on the Singapore Index on Cities' Biodiversity (also known as the City Biodiversity Index)*. Singapore: National Parks Board, Singapore.

International Organization for Standardization (ISO). (2018). Sustainable cities and communities - Indicators for city services and quality of life (ISO 37120:2018). Available from https://www.iso.org/standard/68498.html

Kohsaka, R., Pereira, H.M., Elmqvist, T., Chan, L., Moreno-Peñaranda, R., Morimoto, Y., … Pearsell, G. (2013). Indicators for Management of Urban Biodiversity and Ecosystem Services: City Biodiversity Index. In *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities* (pp. 699–718). Dordrecht: Springer Netherlands.

4.7.1 Proportion of natural area

Metric: *Proportion of natural areas within a defined urban zone (fraction or %)*

Natural areas are defined as ecosystems, which are not significantly influenced by human actions and comprise mainly of native species in natural environments. Such environments are important in preserving biodiversity as natural areas typically harbour much larger biodiversity than urban or constructed green spaces. Natural areas include forests, swamps, streams, lakes, etc., but exclude parks and green infrastructure. Re-naturalized areas can be included.

Data on zones in natural or naturalized condition in the urban area of interest from, e.g., government agencies, municipalities, nature groups, universities, etc. The area can be calculated using mapping tools, including satellite images from Google Maps. Calculate the share of the sum of natural and naturalized areas to the total area to get the indicator value.

Scale of measurement: District to region scale

Key references

Chan, L., Hillel, O., Elmqvist, T., Werner, P., Holman, N., Mader, A., & Calcaterra, E. (2014). *User's Manual on the Singapore Index on Cities' Biodiversity (also known as the City Biodiversity Index)*. Singapore: National Parks Board, Singapore.

Additional Information

City Biodiversity Index (or Singapore Index): https://www.cbd.int/subnational/partners-and-initiatives/city-biodiversity-index

User's Manual for the City Biodiversity Index: https://www.cbd.int/doc/meetings/city/subws-2014-01/other/subws-2014-01-singapore-index-manual-en.pdf

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.7.2 Structural and functional connectivity

Metric: *Degree of connectivity between natural environments within a defined urban area*

The fragmentation of natural environments is a major threat to biodiversity as scattered and non-connected natural areas are much less efficient in preserving biodiversity than large and connected areas. To estimate fragmentation, natural areas are defined and then an estimation is made about their connections. The definition of connectivity is based on movement of fauna - can animals move freely between areas of natural habitats? The areas are considered connected if they are less than 100 m apart and not divided by barriers such as roads, modified rivers, walls, etc.

A mesh indicator value is calculated. Natural areas are categorized into separate interconnected patches. The area of each patch is summed, squared and these squares are summed and divided by the total area of natural areas.

$$Mesh\ indicator = \left(\frac{A_1^2 + A_2^2 + \cdots + A_n^2}{A_1 + A_2 + \cdots A_n}\right)$$

This index (in hectares) is a metric - mesh indicator - used in the indicator value.

Scale of measurement: District to region scale

Key references

Chan, L., Hillel, O., Elmqvist, T., Werner, P., Holman, N., Mader, A. & Calcaterra, E. (2014). *User's Manual on the Singapore Index on Cities' Biodiversity (also known as the City Biodiversity Index)*. Singapore: National Parks Board, Singapore.

Additional Information

de Groot, R. (2006). Function-analysis and valuation as a tool to assess land use conflicts in planning for sustainable, multi-functional landscapes. *Landscape and Urban Planning*, *75*, 175-186.

de Groot, R.S., Alkemade, R., Braat, L., Hein. L., & Willemen, L. (2010). Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological Complexity*, *7*, 260-272.

Iojă, C.I., Grădinaru, S.R., Onose, D.A., Vânău, G.O., & Tudor, A.C. (2014). The potential of school green areas to improve urban green connectivity and multifunctionality. *Urban Forestry and Urban Greening*, *13*(4), 704–713.

Mallarach, J.M., & Marull, J. (2006). Impact assessment of ecological connectivity at the regional level: recent developments in the Barcelona Metropolitan Area. *Impact Assessment and Project Appraisal*, *24*(2), 127-137.

Marull, J., Pino, J., Mallarach, J.M., & Cordobilla, M.J. (2007). A Land Suitability Index for Strategic Environmental Assessment in metropolitan areas. *Landscape and Urban Planning*, *81*(3), 200-212.

Marull, J., Pino, J., Tello, E., & Cordobilla, M.J. (2010). Social metabolism, landscape change and land-use planning in the Barcelona Metropolitan Region. *Land Use Policy*, *27*(2), 497-510.

Marulli, J., & Mallarach, J.M. (2005). A GIS methodology for assessing ecological connectivity: application to the Barcelona Metropolitan Area. *Landscape and Urban Planning*, *71*, 243–262.

European Commission

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.7.3 Number of native bird species within an urban area

Metric: *Number of different native species of birds within a defined urban area*

Bird species numbers act as an indicator about changes in the diversity of the urban environment. Birds are relatively easy to detect and monitor and are present in various, also urban environments.

Total native bird species detected in built areas are counted. The count census numbers can be obtained from city council archives or bird watch organizations. While considered a universally good indicator of biodiversity change, the data can be difficult to obtain, it has high variability and requires long timescales to show significant trends. The number of species acts as the indicator value.

Scale of measurement: District to region scale

Key references

Chan, L., Hillel, O., Elmqvist, T., Werner, P., Holman, N., Mader, A. & Calcaterra, E. (2014). *User's Manual on the Singapore Index on Cities' Biodiversity (also known as the City Biodiversity Index)*. Singapore: National Parks Board, Singapore.

4.7.4 Change in number of native species

Metric: *The number of native species detected in the urban area, compared to a baseline number of species.*

The definition of biodiversity is the presence of different species of different taxonomic groups. The net change in the number of species in a municipality is an indication of biological diversity loss or gain. A more comprehensive sample of the biodiversity in an area can be obtained through a census of species in different groups. Vascular plants, birds, and butterflies have been defined in the City Biodiversity Index as core taxonomic groups to be followed in all cities. On top of these, cities are encouraged to select two supplementary taxonomical groups chosen to best reflect local biodiversity. The supplementary taxonomical groups can include e.g. bryophytes, fungi, amphibians, reptiles, fish, beetles, spiders, seagrasses or others.

The goal of species bookkeeping is to encourage reintroduction of lost native species to urban areas through active development or protection.

Counts of animal and plant species found on the whole urban area of interest are used. Data on the species counts can be available through municipalities, government agencies, environmental organizations, bird watch organizations or universities. As focus in this metric is increasing biodiversity and reintroducing broader array of natural species, it can be sufficient to select a certain biotypes or areas and a selection of species for monitoring. The indicator value is the number of new native species detected in the urban area, compared to a baseline species number.

Scale of measurement: District to region scale

Key references

Chan, L., Hillel, O., Elmqvist, T., Werner, P., Holman, N., Mader, A. & Calcaterra, E. (2014). *User's Manual on the Singapore Index on Cities' Biodiversity (also known as the City Biodiversity Index)*. Singapore: National Parks Board, Singapore.

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.8 Air Quality

Indicator	Metric
Air quality	Concentration of particulate matter (PM_{10} and $PM_{2.5}$), NO_2, and O_3 in ambient air
	Air pollutant capture/removal by vegetation
	Estimated years of life lost (YLL) due to poor air quality
	Estimated morbidity and total mortality associated with air pollution

Air pollution is considered the single largest environmental health risk in the world, causing an estimated 2-6 million or more yearly deaths globally (Health Effects Institute [HEI], 2018; World Health Organisation [WHO], 2016). An important focus of research has been on the role of urban vegetation in the formation and removal of air pollutants in cities (e.g., Miranda et al., 2017) and the associated impacts of air pollution on morbidity, mortality and life-expectancy (e.g., Costa et al., 2014). The most relevant pollutants in air are particulate matter of different sizes ($PM_{2.5}$, PM_{10}), ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), polycyclic aromatic hydrocarbons (PAHs), carbon monoxide (CO), benzene (C_6H_6) and toxic metals (As, Cd, Ni, Pb and Hg) (EEA, 2018b). Whilst different pollutants can have large local effects, the most prevalent pollutants with most serious health effects are particulate matter, ozone and nitrogen dioxide, which are selected for metrics here.

Measuring ambient air quality parameters is typically done with stationary measuring station located near traffic, in an urban background location, in an industrial location or in a rural location for different kind of statistics (EEA, 2018b). Temporary measuring stations can be deployed, but longer measuring periods are always required for meaningful analysis. Continuous measurements are often complemented with larger scale models for larger area estimation of air quality parameters - stationary station data is globally freely available in real time in sources such as Real-time Air Quality Index (https://waqi.info/) and AirVisual Earth (https://www.airvisual.com/earth). The separate parameters are also combined into different air quality indexes. The stationary nature of air quality measurements requires careful planning, sizeable investment, constant management and upkeep, rendering measurements unaffordable for smaller municipalities.

The largest sources of air pollution are agriculture, solids combustion from households and energy production, emissions and particles from transport and industrial sources. These sources are not typically affected by urban NBS, rendering the potential effect of NBS for air quality limited. NBS can affect local air quality through for instance air purification through filtering, as air moves through foliage and particulate matter contacts plant surfaces. Air quality can however also worsen due to green solutions as they can reduce air mixing and flow, trapping pollutants in urban areas. (Baró et al., 2014; Janhäll, 2015) NBSs are not expected to have a significant impact in urban air quality directly, while NBS inflicted changes in pollution sources, for instance in traffic quality or pattern, can have significant impacts.

4.8.1 Concentration of particulate matter (PM_{10} and $PM_{2.5}$), NO_2 and O_3 in ambient air

Air pollution is influenced by various factors, including background, natural and anthropogenic emissions, climate and weather conditions, topography and land use, and boundary conditions (Miranda et al., 2015). Given the increasingly recognized health issues associated with air pollution (see Section 4.8.3), air quality indicators need to be established and measured.

Air pollution concentrations can be estimated based on measured and/or modelled concentrations in ambient air (O_3, NO_x, VOC, PM_{10} and $PM_{2.5}$) near the NBS intervention area. Data can be retrieved from air quality monitoring stations or from measured values during experimental campaigns. Data can also be estimated by applying air quality models, such as the WRF-Chem model (National Oceanic and Atmospheric Administration [NOAA], n.d.), which estimates 3D concentration fields with an hourly resolution at the grid, neighbourhood or city scale.

a) Particulate matter (PM_{10} and $PM_{2.5}$) concentration

Metric: *Concentration of $PM_{2.5}$ and PM_{10} ($\mu g/m^3$) in ambient air*

Particulate matter is the most globally harmful air pollutant (WHO, 2016). Fine particulate matter is defined as particles <2.5 µm in diameter ($PM_{2.5}$). $PM_{2.5}$ occurs naturally as, e.g., desert dust and sea salt droplets. A typical anthropogenic source of $PM_{2.5}$ is household level combustion, and other combustion in general. Fine particulates are harmful as they can easily enter lungs and human circulatory system. Long term exposure has negative health effects even in very low concentrations. Coarse particulate matter is defined as particles between 2.5 and 10 µm in diameter (PM_{10}) and typically originates from traffic, crushing and grinding operations, construction, agriculture, industry or other anthropogenic activities (EEA, 2018b). The annual average limits given by EU Ambient Air Quality Directive (European Parliament, Council of the European Union, 2008) and WHO air quality guidelines (WHO, 2006) are 25 and 10 $\mu g/m^3$ for $PM_{2.5}$ and 40 and 20 $\mu g/m^3$ for PM_{10}, respectively. Whilst EU limits are higher than WHO guidelines, the EU has acknowledged the existing long term health burden from particulate matter even at low levels (EEA, 2018b).

Particulate matter is measured using an air sampler that draws ambient air at a constant flow rate through a specially shaped inlet onto a filter that is weighed periodically to measure the accumulated particle load. The inlet defines the particle size cut-off (2.5 or 10 µm).

A stationary measuring station is placed in a representative traffic, urban, industrial or rural location and continuous measurement of particulate matter using standardized air sampler equipment is undertaken. Daily averages are averaged over a year to reach a yearly average, which acts as the indicator (ISO, 2018).

Scale of measurement: District to region scale

Key references

Baró, F., Chaparro, L., Gómez-Baggethun, E., Langemeyer, J., Nowak, D. J. & Terradas, J. (2014). Contribution of ecosystem services to air quality and climate change mitigation policies: the case of urban forests in Barcelona, Spain. *Ambio*, *43*(4), 466-479.

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Costa, S., Ferreira, J., Silveira, C., Costa, C., Lopes, D., Relvas, H., … Teixeira, J.P. (2014). Integrating Health on Air Quality Assessment - Review Report on Health Risks of Two Major European Outdoor Air Pollutants: PM and NO_2. *Journal of Toxicology and Environmental Health - Part B Critical Reviews*, *17*(6), 307-340.

European Environment Agency. (2018b). *Air quality in Europe – 2018 report. EEA Report No. 12/2018.* Luxembourg: Publications Office of the European Union. Retrieved from https://www.eea.europa.eu/publications/air-quality-in-europe-2018

European Parliament, Council of the European Union. (2008). *Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. OJ L 152, 11.6.2008, p. 1-44.* Retreived from https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32008L0050

Health Effects Institute (HEI). (2018). *State of Global Air 2018. Special Report.* Boston, MA: Health Effects Institute.

International Organization for Standardization (ISO). (2018). Sustainable cities and communities — Indicators for city services and quality of life (ISO 37120:2018). Available from https://www.iso.org/standard/68498.html

Janhäll, S. (2015). Review on urban vegetation and particle air pollution – Deposition and dispersion. *Atmospheric Environment*, *105*, 130-137.

Miranda, A.I., Martins, H., Valente, J., Amorim, J.H., Borrego, C., Tavares, R., … Alonso, R. (2017). Case Studies: modeling the atmospheric benefits of urban greening, In D. Pearlmutter, C. Calfapietra, R. Samson, L. O'Brien,S. Ostoic, G. Sanesi, R. Alonso (Eds.), *The Urban Forest. Cultivating Green Infrastructures for People and the Environment* (pp. 89-99). New York: Springer International Publishing.

National Oceanic and Atmospheric Administration (NOAA). (n.d.). Weather Research and Forecasting model coupled to Chemistry (WRF-Chem). Retrieved from https://ruc.noaa.gov/wrf/wrf-chem/

World Health Organization. (2006). *Air Quality Guidelines: Global Update 2005 - particulate matter, ozone, nitrogen dioxide and sulphur dioxide*. Copenhagen: WHO Regional Office for Europe. Retrieved from http://www.euro.who.int/__data/assets/pdf_file/0005/78638/E90038.pdf?ua=1

World Health Organization (WHO). (2016). *Ambient air pollution: A global assessment of exposure and burden of disease.* Geneva: World Health Organization. Retrieved from https://www.who.int/phe/publications/air-pollution-global-assessment/en/

Additional Information

Real-time Air Quality Index: https://waqi.info/

AirVisual Earth: https://www.airvisual.com/earth

b) Nitrogen dioxide (NO_2) concentration

Metric: *Concentration of NO_2 ($\mu g/m^3$) in ambient air*

Nitrogen dioxide (NO_2) is a major air pollutant that is toxic in large concentrations and has long term health effects and environmental effects in low concentrations. Nitrogen dioxide also acts as an air pollution marker because it is typically found with other pollutants including organic pollutants, ozone and nitrogen oxide (NO). Nitrogen dioxide usually originates as nitrogen oxide during combustion, which quickly oxidizes into nitrogen dioxide. Nitrogen dioxide in contact with ultraviolet light and hydrocarbons produces ozone, and is the main source of tropospheric ozone - another significant air pollutant (EEA, 2018b; WHO, 2006).

Nitrogen oxides contribute to the formation of smog and acid rain, increase the prevalence of respiratory diseases and asthma and are toxic in high concentrations (EEA, 2018b; WHO, 2006). While traffic, energy production and industry all contribute to ambient NO_2 concentrations, road traffic is the most prevalent and near source in urban environments. Especially heavy traffic and diesel engines contribute to high NO_2 concentrations. Communities using solid or gas combustion heaters or ovens, indoor NO_2 exposure can be significant and have major health effects. (EEA, 2018b; WHO, 2006) The calendar year average limit set by EU Ambient Air Quality Directive (European Parliament, Council of the European Union, 2008) and WHO air quality guideline (WHO, 2006) is 40 $\mu g/m^3$ for NO_2.

To quantify nitrogen dioxide $_2$, a stationary measuring station is placed in a representative traffic, urban, industrial or rural location and continuous measurement of nitrogen dioxide using standardized equipment is undertaken. An average of hourly averages is used to calculate a daily average and daily averages to calculate a yearly average, which acts as the indicator (ISO, 2018).

Scale of measurement: District to region scale

Key references

European Environment Agency. (2018b). *Air quality in Europe – 2018 report. EEA Report No. 12/2018.* Luxembourg: Publications Office of the European Union. Retrieved from https://www.eea.europa.eu/publications/air-quality-in-europe-2018

European Parliament, Council of the European Union. (2008). *Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. OJ L 152, 11.6.2008, p. 1-44.* Retrieved from https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32008L0050

International Organization for Standardization (ISO). (2018). Sustainable cities and communities — Indicators for city services and quality of life (ISO 37120:2018). Available from https://www.iso.org/standard/68498.html

World Health Organization. (2006). *Air Quality Guidelines: Global Update 2005 - particulate matter, ozone, nitrogen dioxide and sulphur dioxide*. Copenhagen: WHO Regional Office for Europe. Retrieved from http://www.euro.who.int/__data/assets/pdf_file/0005/78638/E90038.pdf?ua=1

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

c) Ground-level ozone (O_3) concentration

Metric: *Concentration of ground-level O_3 ($\mu g/m^3$) in ambient air*

Ozone is a major pollutant inducing significant functional and biological damage to respiratory tract as well as environmental harm (WHO, 2008; WHO, 2016). Ozone is a secondary pollutant, it is formed from anthropogenic precursor gases (mainly NO_x and volatile organic compounds, VOCs) with sunlight. The reaction paths and presence is complex as same constituents that produce ozone can also reduce its content and typically high ozone concentrations are linked with a multitude of combined anthropogenic and weather parameters including for instance local production of precursors, long-range transport of precursors, UV-radiation and mixing of ozone from stratosphere. (WHO, 2016a). While large industrial and urban agglomerations are major ozone precursor emitters, the resulting ozone air pollution exposure can be spatially disconnected, even on a different continent (WHO, 2016a).

Daily maximum 8-hour mean limits for ground-level ozone set by the EU Ambient Air Quality Directive (European Parliament, Council of the European Union, 2008) and WHO air quality guidelines (WHO, 2006) are 120 $\mu g\ O_3/m^3$ and 100 $\mu g\ O_3/m^3$, respectively.

A stationary measuring station is placed in a representative traffic, urban, industrial or rural location and continuous measurement of ozone using standardized equipment is undertaken. The convention for ozone measurement is to calculate a daily maximum 8-hour mean. Yearly average of this daily 8-hour mean acts as the indicator (ISO, 2018).

Scale of measurement: District to region scale

Key references

European Parliament, Council of the European Union. (2008). *Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. OJ L 152, 11.6.2008, p. 1-44.* Retrieved from https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32008L0050

International Organization for Standardization (ISO). (2018). Sustainable cities and communities — Indicators for city services and quality of life (ISO 37120:2018). Available from https://www.iso.org/standard/68498.html

World Health Organization. (2006). *Air Quality Guidelines: Global Update 2005 - particulate matter, ozone, nitrogen dioxide and sulphur dioxide*. Copenhagen: WHO Regional Office for Europe. Retrieved from http://www.euro.who.int/__data/assets/pdf_file/0005/78638/E90038.pdf?ua=1

World Health Organization. (2008). *Health risks of ozone from long-range transboundary air pollution*. Copenhagen: World Health Organization. Retrieved from http://www.euro.who.int/__data/assets/pdf_file/0005/78647/E91843.pdf

World Health Organization. (2016). *Ambient air pollution: A global assessment of exposure and burden of disease*. Geneva: World Health Organization. Retrieved from https://apps.who.int/iris/bitstream/handle/10665/250141/9789241511353-eng.pdf?sequence=1

4.8.3 Annual air pollutant capture/removal by vegetation

***Metric:** Annual capture of O_3, SO_2, NO_2, CO and $PM_{2.5}$ by trees and shrubs and grass (all expressed in units of mass)*

Vegetation can remove air pollutants (particles and gases) by the process of dry deposition. Deposition is the transport from a point in the air to a plant surface, which is mainly related to near-surface pollutant concentration, weather conditions and vegetation properties. Most plants have a large surface area per unit volume, increasing the probability of deposition compared with the smooth, manufactured surfaces present in urban areas. For example, 10-30 times faster deposition has been reported for sub-micrometre (<µm) particles on synthetic grass compared with glass and cement surfaces (Air Quality Expert Group [AQEG], 2013; Roupsard, Amielh, Maro, Coppalle, & Branger, 2013). To estimate the magnitude of this contribution models are commonly used.

The chemical transport model WRF-Chem (National Oceanic and Atmospheric Administration [NOAA], n.d.) has a dry deposition model that can estimate the amount of pollutants removed by vegetation (O_3, NO_X, VOC, PM_{10} and $PM_{2.5}$) with an hourly resolution per grid cell. As input data WRF-Chem requires:

i) high resolution inventory of anthropogenic emissions;

ii) biogenic emissions (MEGAN model; Guenther et al., 2006);

iii) initial and boundary conditions (MOZART model; Emmons et al., 2010); and,

iv) topography and land use (United States Geological Survey [USGS] 33 classes database; Pineda et al., 2004).

These results can be used to calculate the annual amount of pollutants removed by vegetation at the grid, neighbourhood or city scale.

The i-Tree Eco model (USDA Forest Service, 2019) can also be applied to estimate the air pollutants removed by vegetation. Although it does not provide spatial variability, it is able to calculate hourly amounts of pollutants removed by urban forests, and the associated percentage of air quality improvement throughout a year. Pollution removal is calculated for ozone (O_3), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO) and particulate matter ($PM_{2.5}$). To apply the i-Tree Eco model, the following data is required:

i) extent of vegetation cover and characteristics (e.g., type, age and height);

ii) land use;

iii) air quality; and,

iv) meteorology.

Results can be used to calculate the annual amount of pollutants removed by vegetation at the local scale.

Scale of measurement: Street to metropolitan scale

Key references

Air Quality Expert Group [AQEG]. (2018). *Impacts of Vegetation on Urban Air Pollution.* Prepared for Department for Environment, Food and Rural Affairs, Scottish Government, Welsh

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Government, and Department of the Environment in Northern Ireland. Carlisle, UK: Department for Environment, Food and Rural Affairs. Retrieved from https://uk-air.defra.gov.uk/assets/documents/reports/cat09/1807251306_180509_Effects_of_vegetation_on_urban_air_pollution_v12_final.pdf.

Emmons, L.K., Walters, S., Hess, P.G., Lamarque, J.-F-, Pfister, G.G., Fillmore, D. … Kloster, S. (2010). Description and evaluation of the Model for Ozone and Related chemical Tracers, version 4 (MOZART-4). *Geoscientific Model Development*, *3*, 43-67.

Guenther, A., Karl, T., Harley, P., Wiedinmyer, C., Palmer, P.I., & Geron, C. (2006). Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature). *Atmospheric Chemistry and Physics*, *6*(11), 3181–3210.

United States Department of Agriculture (USDA) Forest Service. (2019). i-Tree Eco Manual. Northern Research Station, USDA Forest Service. Retrieved from https://www.itreetools.org/resources/manuals/Ecov6_ManualsGuides/Ecov6_UsersManual.pdf

National Oceanic and Atmospheric Administration (NOAA). (n.d.). Weather Research and Forecasting model coupled to Chemistry (WRF-Chem). Retrieved from https://ruc.noaa.gov/wrf/wrf-chem/

Pineda, N., Jorba, O., Jorge, J., & Baldasano, J.M. (2004). Using NOAA AVHRR and SPOT VGT data to estimate surface parameters: application to a mesoscale meteorological model. *International Journal of Remote Sensing*, *25*(1), 129–143.

Roupsard, P., Amielh, M., Maro, D., Coppalle, A., & Branger, H. (2013). Measurement in a wind tunnel of dry deposition velocities of submicron aerosol with associated turbulence onto rough and smooth urban surfaces. *Journal of Aerosol Science*, *55*, 12-24.

4.8.4 Morbidity, Mortality and Years of Life Lost due to poor air quality

Metric: *Reduction in years of life (y) due to premature mortality in comparison with standard life expectancy*

Air pollution has been related to numerous adverse health effects, typically expressed in several morbidity and mortality endpoints (see Costa et al., 2014). In particular, an increasing amount of epidemiological and clinical studies observes that exposure to air pollution is associated with increased risk of heart disease, myocardial infarction and stroke as well as lung cancer (e.g., Costa et al., 2014). While the impact of these health effects may appear low at the individual level, the overall public-health burden is sizable as the entire population is exposed (Pascal et al., 2011).

The general approach in heath impact assessment is to use exposure-response functions, linking the concentration of pollutants to which the population is exposed to the number of health events occurring in that population (Costa et al., 2014; Silveira et al., 2016). Therefore, the following aspects are usually considered: i) involved pollutants and their air concentration levels, ii) health indicators analysed in terms of morbidity and mortality, iii) affected age groups, and iv) exposure time. The health response is usually calculated by:

$$\Delta R = IR \times CRF \times \Delta C \times Pop$$

Where,

- ΔR is the response as a result of the number of the unfavourable implications (cases, days or episodes) over all health indicators;
- *IR* is the baseline morbidity/mortality annual rate (%); this information is available in the national statistical institute of each country;
- *CRF* is the correlation coefficient between the pollutant concentration variation and the probability of experiencing a specific health indicator (%; i.e. Relative Risk (RR) associated with a concentration change of 1 $\mu g \cdot m^{-3}$);
- ΔC indicates the change in the pollutant concentration ($\mu g \cdot m^{-3}$) after adoption of the adaptation/mitigation measure;
- *Pop* is the population units per age group exposed to pollution.

a) Morbidity and Mortality

Metric *(Morbidity): Long-term (annual) incidence of chronic bronchitis due to poor air quality calculated using atmospheric NO_2 and PM_{10} data*

Morbidity (chronic bronchitis) due to poor air quality is calculated using NO_2 and PM_{10} to determine *CRF* and ΔC in the preceding equation.

Metric *(Mortality): Long-term (annual) incidence of mortality due to poor air quality calculated using atmospheric $PM_{2.5}$, PM_{10}, O_3 and NO_2 data*

Mortality, assessed as total mortality, is calculated using PM_{10}, $PM_{2.5}$, O_3 and NO_2 to determine *CRF* and ΔC in the preceding equation.

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Both morbidity and mortality are based on long-term (annual) effects (Table 26). Where air quality data are derived from WRF-Chem results can be calculated on a daily/weekly/monthly/annual basis at the grid, neighbourhood or city scale.

Scale of measurement: Street to metropolitan scale

b) Years of Life Lost

Years of life lost (YLL) is an often-used health indicator, and refers to the total number of years of reduced life due to premature mortality. Using the mortality indicator, the YLL can be calculated as the number of deaths multiplied by a standard life expectancy at the age at which death occurs (see Gardner & Sanborn, 1990).

Scale of measurement: Street to metropolitan scale

Table 26. Air pollutant health indicators (WHO, 2013)

Pollutant	Health outcome	Age group
PM_{10}	Chronic bronchitis (incidence)	>18 y
	Chronic bronchitis (prevalence)	6-18 y
	Total mortality	<1 y
		>30 y
$PM_{2.5}$	Total mortality	>30 y
NO_2	Total mortality	>30 y
	Prevalence of bronchitic symptoms in asthmatic children	5–14 y
O_3 (April-September)	Total mortality (respiratory diseases)	>30 y

Key references

Costa, S., Ferreira, J., Silveira, C., Costa, C., Lopes, D., Relvas, H., … Teixeira, J.P. (2014). Integrating Health on Air Quality Assessment-Review Report on Health Risks of Two Major European Outdoor Air Pollutants: PM and NO_2. *Journal of Toxicology and Environmental Health - Part B Critical Reviews*, *17*(6), 307-340.

Gardner, J.W., & Sanborn, J.S. (1990). Years of potential life lost (YPLL) – what does it measure? *Epidemiology (Cambridge, Mass.)*, *1*(4), 322–329.

Pascal, M., Corso, M., Ung, A., Declercq, C., Medina, S. & Aphekom. (2011). *APHEKON-Improving knowledge and communication for decision making on air pollution and health in Europe, Guidelines for assessing the health impacts of air pollution in European cities, Work Package 5, Deliverable D5.* Saint-Maurice, France: French Institute for Public Health Surveillance.

Silveira C., Roebeling P., Lopes M., Ferreira J., Costa S., Teixeira J.P., ... Miranda A.I. (2016). Assessment of health benefits related to air quality improvement strategies in urban areas: An Impact Pathway Approach. *Journal of Environmental Management*, *183*, 694-702.

United States Department of Agriculture (USDA) Forest Service. (2019). i-Tree Eco Manual. Northern Research Station, USDA Forest Service. Retrieved from https://www.itreetools.org/resources/manuals/Ecov6_ManualsGuides/Ecov6_UsersManual.pdf

World Health Organization (WHO). (2013). *Health risks of air pollution in Europe—HRAPIE project recommendations for concentration–response functions for cost–benefit analysis of particulate matter, ozone and nitrogen dioxide.* Copenhagen: World Health Organization, Regional Office for Europe.

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.9 Urban Regeneration

Indicator	Metric
Urban regeneration	Reclamation of contaminated land (brownfields)
	Ratio of open spaces to built form (ratio)
	Incorporation of environmental design in buildings (% of total building stock)
	Percentage of site/defined area devoted to roads (%)

4.9.1 Reclamation of contaminated land

Metric: *Reclamation of contaminated land (brownfields), expressed as total area, area per capita or % of contaminated area reclaimed*

Brownfield land refers to urban developed areas that are currently idle. Typically they are sites of previous commercial or industrial activities, which might have detected or suspected pollution and soil contamination problems, hindering their future development. Redeveloping brownfields can safe pristine green spaces from development as well as reclaim unused spaces into meaningful application (University of the West of England [UWE] Science Communication Unit, 2013).

The metric for brownfield reclamation is the proportion of brownfield redeveloped each year into use, and the absolute area of identified brownfield remaining. The indicator is simple and easy to calculate, and provides a measure that can be easily followed. The definition and classification of areas as brownfield is not rigorously defined, and thus comparison between areas and countries can be misleading without closer case studies.

Idle, developed areas within the community are identified and their combined surface area is calculated using maps. This is done yearly and the percentage change in the area is reported, as well as the actual area remaining.

Scale of measurement: Street to metropolitan scale

Key references

University of the West of England (UWE) Science Communication Unit. (2013). *Science for Environment Policy (issue 39): Brownfield Regeneration.* Bristol, United Kingdom: University of the West of England Science Communication Unit.

4.9.2 Ratio of open spaces to built form

Metric: *Ratio of open spaces to built form within a defined urban area (ratio)*

Urban space and environment can have an effect in resident health, resilience to weather events and even crime rate, and access to green urban space is seen as positive. Several terms and definitions have been used including green space, open space, public space, urban greenery and public park. Benefits of open spaces relate to both their materials and functions: the increased biodiversity and ecosystem services that increased vegetation and soil permeability and water retention can offer, as well as the potential increased social benefits of open meeting spaces, areas for recreation, sports and relaxation (WHO, 2016b). As the potential benefits of urban open spaces can depend strongly on the type and quality of the individual spaces, it can be difficult to define urban open spaces as they can include different kind of green or grey areas. The simplest method is to measure the proportional area physically occupied by buildings. This method however does not take into account any other form of non-building space that not considered beneficial open space, such as roads and parking lots. Another simple method would be to calculate the green space of urban area, based on surface type counting hard impermeable surfaces as grey areas and soft permeable surfaces as green areas. This method misses all covered parks and terraces, which can form a large portion of open areas in urban environments, even if they are not green areas (Jim, 2004).

For the purpose of this indicator, a suitable parameter is the selection of all urban green areas, added with selected open 'grey' open areas, such as public squares or pedestrian precincts. The total area covered by buildings is calculated from maps or appropriate sources. The green area is calculated and selected grey open areas are added. The ratio of the open area to the building area is calculated.

Scale of measurement: Street to metropolitan scale

Key references

University of the West of England (UWE) Science Communication Unit. (2013). *Science for Environment Policy (issue 39): Brownfield Regeneration.* Bristol, United Kingdom: University of the West of England Science Communication Unit.

Jim, C. (2004). Green-space preservation and allocation for sustainable greening of compact cities. *Cities*, *21*(4), 311-320.

World Health Organization. (2016b). *Urban green spaces and health: A review of evidence*. Copenhagen: WHO Regional Office for Europe. Retrieved from http://www.euro.who.int/__data/assets/pdf_file/0005/321971/Urban-green-spaces-and-health-review-evidence.pdf?ua=1

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.9.3 Incorporation of environmental design in buildings

Metric: *Degree to which buildings are designed to be environmentally-friendly with respect to energy efficiency, water consumption, waste production, indoor environmental quality, and implementation of NBS (unitless value).*

Environmental design is a broad concept concerning the structural, design and systemic features of buildings defining their impact on their environment. It is related to the concept of green buildings, which refers to environmentally sustainable design, construction, operation, maintenance and end of life of buildings. Green building -concept is typically manifested through building ratings made via numerous certification systems, most common of which are Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), and Comprehensive Assessment System for Building Environmental Efficiency (CASBEE). Ratings are typically implemented to large office buildings, where environmental questions have offered publicity and commercial benefits, but similar tools are available for different construction-types and neighbourhood-scale evaluations (Doan et al., 2017; Sharifi & Murayama, 2013, 2014).

Green building -terminology has typically focused on environmental parameters and green building labelling has been given to buildings that are less ecologically damaging than typical practice. A newer term, sustainable building, incorporates the environmental aspect of green building, but includes also social, economic and institutional perspectives, potentially further including additional aspects (Doan et al., 2017).

Environmental design in buildings concentrates on energy efficiency, water consumption, waste production and recycling, good environmental quality and nature based solutions. As practical methods and features addressing these components are numerous and their applicability strongly depends on the building and environment, a semi-quantitative metric is used in which each building or block is assessed based on its efforts in incorporating environmental aspects in each category.

The area is divided into buildings, groups of buildings or blocks that represent similar building stock, as seen suitable. Each component is assessed on its environmental design considering incorporated environmental design considering (Table 27): 1. Energy efficiency; 2. Water consumption; 3. Waste production; 4. Environmental quality; and, 5. Nature Based Solutions. The building(s) being assessed are scored from 0 to 1 with respect to each parameter. The average point score (0 to 5) of a building provides the indicator value, i.e., the degree to which buildings are designed to be environmentally-friendly with respect to energy efficiency, water consumption, waste production, indoor environmental quality, and implementation of NBS.

Table 27. Parameters for environmental design in buildings (or groups of buildings)

	Parameter	Methods to consider (examples)	Scoring
1	Energy efficiency	Improved insulation Reflecting windows Improved ventilation Heat exchangers in ventilation Smart lighting, smart electronics Renewable electricity (solar/wind) Heat pumps	0 points: No design incorporated 0.5 points: Some measures taken 1 point: Good measures taken
2	Water consumption	Low water toilets Separate greywater collection Rainwater collection and use	As no. 1
3	Waste production	Waste separation On-site composting Building material demolition design	As no. 1
4	Environmental quality	Indoor air quality measure/control Indoor/outdoor noise level control Indoor/outdoor lighting level control	As no. 1
5	Nature-based solutions	Incorporation of NBS A green roof Rain garden	As no. 1
	Environmental design		Sum of points

Scale of measurement: District to metropolitan scale

Key references

Doan, D. T., Ghaffarianhoseini, A., Naismith, N., Zhang, T., Ghaffarianhoseini, A., & Tookey, J. (2017). A critical comparison of green building rating systems. *Building and Environment*, 123, 243–260.

Sharifi, A., & Murayama, A. (2013). A critical review of seven selected neighborhood sustainability assessment tools. *Environmental Impact Assessment Review*, *38*, 73–87.

Sharifi, A., & Murayama, A. (2014). Neighborhood sustainability assessment in action: Cross-evaluation of three assessment systems and their cases from the US, the UK, and Japan. *Building and Environment*, *72*, 243–258.

Additional Information

Laprise, M., Lufkin, S., & Rey, E. (2015). An indicator system for the assessment of sustainability integrated into the project dynamics of regeneration of disused urban areas. *Building and Environment*, *86*, 29–38.

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.9.4 Area devoted to roads

Metric: *Total proportion of a defined urban area devoted to roadways for motorised vehicle use only (ratio or fraction)*

Roads are open areas, but depending on the road type, typically do not yield the same positive effects associated with the open urban areas/urban public spaces referred to in section 4.9.2. Roadways are generally non-permeable, and depending on the road type, are inaccessible and potentially dangerous, produce air, light and noise pollution, and form barriers to movement and ecological compartmentalization. Determination of the effects of roads for the urban environment depends for instance on the road type, speed, congestion, traffic type and structure. Road area is a metric indicating certain structural choices in an urban environment and changes in road area can indicate changes towards more natural and healthy environment. Roads can be thought to cover only the hard surfaces for cars or it can cover also green sections between and around lanes, road edges, side slopes, fences and embankments and areas around junctions, intersections, bridges and roundabouts, which cover a larger surface area in total. It can also cover sidewalks, bicycle paths and pedestrian roads.

The purpose of nature-based systems is to support alternative transport options to private cars. Also green areas related to roads for cars can have ecosystems service functions and nature-based solutions within road structures can be a major part of e.g. urban green storm water infrastructure. A suitable metric for measuring area devoted to roads is to measure the non-permeable grey area of roads for car travel, including parking lots.

The total area covered by grey roads for cars is calculated from maps or estimated from appropriate sources and the ratio to the total area is calculated.

Scale of measurement: Street to metropolitan scale

4.9.5 Preservation of cultural heritage

Metric: *The extent to which preservation of local cultural heritage is considered during urban planning (unitless value).*

Unlike ecological, economic and social sustainability, culture is not institutionalised as an aspect of sustainable development at present. Hawkes (2001) introduced cultural sustainability as a "fourth pillar" of sustainable development and emphasised the role of cultural heritage in urban planning. Extensive discourse (e.g., UNESCO, 2001; UNESCO, 2005) on the relationship between culture and sustainable development together with numerous scientific studies exploring social and cultural dimensions of sustainability indicate that cultural sustainability is linked to issues such as social equity and social justice, participation and engaged governance, social cohesion, and social capital (Soini & Birkeland, 2014).

Preservation of cultural heritage, including built heritage as well as the cultural landscapes that give a place a unique character, is key to maintaining the cultural identity of the community during urban development (Tweed & Sutherland, 2007). The extent to which urban design and heritage conservation are integrated within urban development so that it enhances or connects to the existing character of the place, e.g. preservation, restoration and/or adaptive re-use of historic buildings and cultural landscapes, can be qualitatively assessed using a five-point Likert scale:

Not at all – 1 — 2 — 3 — 4 — 5 — Very much

1. **Not at all**: no attention has been paid to existing cultural heritage in urban planning.
2. **Fair**: heritage places have received some attention in urban planning, but not as an important element.
3. **Moderate**: some attention has been given to the conservation of heritage places.
4. **Much**: heritage places are reflected in urban planning
5. **Very much**: preservation of cultural heritage and connections to existing heritage places are a key element of urban planning.

Scale of measurement: District to regional scale

Key references

Bosch, P., Jongeneel, S., Rovers, V., Neumann, H.-M., Airaksinen, M., & Huovila, A. (2017). CITYkeys indicators for smart city projects and smart cities. CITYkeys D1.4. Retrieved from http://nws.eurocities.eu/MediaShell/media/CITYkeysD14Indicatorsforsmartcityprojectsandsmartcities.pdf

Hawkes, J. (2001). *The Fourth Pillar of Sustainability: Culture's essential role in public planning.* Melbourne, VIC: Common Ground Publishing Pty Ltd in association with the Cultural Development Network (Vic.). Retrieved from https://www.researchgate.net/profile/Jon_Hawkes/publication/200029531_The_Fourth_Pillar_of_Sustainability_Culture%27s_essential_role_in_public_planning/links/09e4150bde47d6a5c4000000.pdf

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Soini, K., & Birkeland, I. (2014). Exploring the scientific discourse on cultural sustainability. *Geoforum*, *51*, 213-223.

Tweed, C., & Sutherland, M. (2007). Built cultural heritage and sustainable urban development. *Landscape and Urban Planning*, *83*(1), 62-69.

United Nations Educational, Scientific and Cultural Organization (UNESCO). (2001). UNESCO Universal Declaration on Cultural Diversity. Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000124687.page=67

United Nations Educational, Scientific and Cultural Organization (UNESCO). (2005). Convention on the Protection and Promotion of the Diversity of Cultural Expressions. Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000142919

4.9.6 Design for sense of place

Metric: *The extent to which 'sense of place' is considered during urban planning or during the planning and implementation of a specific project (unitless value).*

The phrase "design for a sense of place" relates to a complex concept involving the embodiment of tangible and intangible qualities in the design that make a place distinctive (create an identity). The unique place identity, or sense of place in turn fosters authentic human attachment and a feeling of belonging. The sense pf place concept arises from the examination of people's connectedness and identity with the built environment, in parallel with evaluation of people's perceptions and experiences of the built environment through design (Hu & Chen, 2018).

Design principles to foster a sense of place include preserving existing elements, ensuring safety and focusing on the creation of places that (Bosch et al., 2017):

- Are welcoming and respond to, or express the values of groups within the community for whom the place is designed;
- Are comprised of several physical and social settings for events and activities that make places pleasant and culturally relevant;
- Are scaled and proportioned to facilitate easy navigation, interaction and overview by the users; and,
- Have identifiable features, landmarks or historical places to enhance visual appeal and orientation.

The extent to which a given NBS project has considered design for a sense of place can be qualitatively rated on a five-point Likert scale:

Not at all – 1 — 2 — 3 — 4 — 5 — Very much

1. **Poor**: no attention has been paid to the idea of creating a sense of place in the design of the NBS project; residents are not able identify any distinctive elements.
2. **Fair**: the idea of creating a sense of place has received some attention in the NBS project, but not as an important element.
3. **Average**: some attention has been given in the NBS project design to the idea of creating a sense of place.
4. **Good**: Much attention has been given to the idea of creating a sense of place in the NBS project design.
5. **Very good**: The focus on creating a sense of place in the design is clearly and recognizably present in the NBS project, even for outsiders.

Scale of measurement: building to municipality scale

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Key references

Bosch, P., Jongeneel, S., Rovers, V., Neumann, H.-M., Airaksinen, M., & Huovila, A. (2017). CITYkeys indicators for smart city projects and smart cities. CITYkeys D1.4. Retrieved from http://nws.eurocities.eu/MediaShell/media/CITYkeysD14Indicatorsforsmartcityprojectsandsmartcities.pdf

Hu, M., & Chen, R. (2018). A framework for understanding sense of place in an urban design context. *Urban Science*, *2*(2), 34.

Additional Information

Casakin, H., & Bernardo, F. (Eds.). (2012). *The Role of Place Identity in the Perception, Understanding, and Design of Built Environments*. Sharjah, United Arab Emirates: Bentham Science Publishers.

4.10 Participatory Planning and Governance

Indicator	Metric
Participatory planning and governance	Openness of participatory processes
	Citizens' awareness regarding urban nature and ecosystem services
	Participatory governance
	Ease of governance of NBS
	New forms of financing
	Policy learning concerning adapting policies and strategic plans by integrating ecosystem services
	Climate resilience strategy development

4.10.1 Openness of participatory processes

***Metric:** The proportion of public participation processes in a given municipality per 100 000 residents per year (expressed as %).*

Public participation in NBS projects encompasses a wide range of different opportunities for citizens, nongovernmental organizations, businesses, and other stakeholders co-create, co-implement and co-manage NBS, concomitantly creating a sense of ownership. The integral role of citizens and other stakeholders in NBS projects can influence the openness of other processes managed by the municipality. Increasing the openness of processes such as policy planning and implementation strengthens the connections between government agencies and the public they serve. This metric provides an indication of the alignment between citizens need and desires and the decision-making processes in a municipality. Openness of participatory processes (%) is calculated as (Bosch et al., 2017):

$$\left(\frac{Total\ number\ of\ open\ public\ participation\ processes}{Population\ of\ city/100000}\right) \times 100$$

In addition, citizen and other stakeholder involvement in NBS planning and implementation can be qualitatively evaluated using separate Likert scales to assess community involvement.

a) Community involvement in planning phase

***Metric:** The extent to which citizens and other stakeholders have been involved in the planning phase of a given project (qualitative, unitless).*

Stakeholder involvement has been shown to positively influence agreement on solutions and acceptance of policy interventions, largely through raising citizens' awareness (Driessen, Glasbergen and Verdaas 2001). A five-point Likert scale based on the ladder of citizen participation (Arnstein, 1969) can be used to qualitatively assess the success of community involvement in NBS planning. The Likert scale follows Arnstein's ladder from non-participation (1) through degrees of tokenism (2-3) to citizen empowerment via partnership (4) or citizen control (5):

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

No involvement – 1 — 2 — 3 — 4 — 5 — High involvement

1. **Not at all**: No community involvement.
2. **Inform and consult**: A relatively complete project plan is announced to the community for information only, or for the purpose of receiving community feedback. The consultation process primarily seeks community acceptance of the plan.
3. **Advise**: A project plan is drafted by a project team then presented to community actors, who are invited to ask questions, provide feedback and give advice. Based on this input the planners may alter the project plan.
4. **Partnership**: Community actors are invited by project planners to participate in the planning process by prioritising issues and planning actions. The local community is able to influence the planning process.
5. **Community self-development**: Project planners empower community actors to outline their needs and to make actionable plans.

Scale of measurement: district to municipality scale (project-based)

Key references

Arnstein, S.R. (1969). A ladder of citizen participation. *Journal of the American Planning Association*, *35*(4), 216-224.

Driessen, P.P.J., Glasbergen, P., & Verdaas, C. (2001.) Interactive policy-making: A model of management for public works. *European Journal of Operational Research*, *128*, 322-337.

b) Community involvement in implementation phase

Metric: *The extent to which citizens and other stakeholders have been involved in the implementation phase of a given project (qualitative, unitless).*

Involvement of citizens and other stakeholders during project implementation ensures establishment of a common understanding of the project's longer-term maintenance or management needs, and provides NBS managers and developers with critical input regarding the NBS project's performance relative to stakeholder expectations. As above, a five-point Likert scale based on Arnstein's (1969) ladder of citizen participation can be used to evaluate the extent of citizen's power in determining the implementation program:

No involvement – 1 — 2 — 3 — 4 — 5 — High involvement

1. **Not at all**: No community involvement.
2. **Inform and consult**: An essentially complete project is presented to the community for information only, or in order to receive community feedback. The consultation process primarily seeks community acceptance of the project at the implementation stage.
3. **Advise**: The project implementation is done by a project team. Community actors are invited to ask questions, provide feedback and give advice. Based on this input the planners may alter how the project is implemented.
4. **Partnership**: Community actors are invited by project managers and developers to participate in the implementation process. The local community is able to influence the implementation process.
5. **Community self-development**: The project planners empower community actors to manage the project implementation and evaluate the results.

Scale of measurement: district to municipality scale (project-based)

Key references

Arnstein, S.R. (1969). A ladder of citizen participation. *Journal of the American Planning Association*, *35*(4), 216-224.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.10.2 Citizens' awareness regarding urban nature & ecosystem services

Metric: *The extent to which a project has used opportunities to increase citizen's awareness of urban nature and ecosystem services, and educate urban citizens about sustainability and the environment.*

A core concept underpinning NBS is that of ecosystem services. The conservation, rehabilitation or restoration of ecosystems and ecological processes is a key strategy to maintain, enhance or recover the natural capital, or ecosystem services, provided by intact natural systems. Nature-based solutions can provide a successful strategy to protect, restore or recover ecosystem services; implementation of NBS in urban areas can serve to enhance the connection between cities and the natural ecosystems that sustain them. An understanding of ecosystem functions and processes is needed to co-create NBS to address specific challenges. Nature-based solution projects are uniquely placed to contribute to citizens' awareness regarding the multiple co-benefits of urban nature, and the connection between re-naturing cities and the provision of ecosystem services.

> "*In the end we will conserve only what we love; we will love only what we understand; and we will understand only what we are taught.*" – Baba Dioum, 1968

Awareness of environmental issues is a critical first step in creating support for environmental projects and programs. The extent to which a project exploits opportunities to increase citizens' awareness of NBS and ecosystem services, or to more generally educate citizens about sustainability and the environment, can be evaluated using a five-point Likert scale (Bosch et al., 2017):

Not at all – 1 – 2 – 3 – 4 – 5 – very much

1. **Not at all**: opportunities to increase environmental awareness were not taken into account in the project communication
2. **Poor**: opportunities to increase environmental awareness were slightly taken into account in the project communication.
3. **Somewhat**: opportunities to increase environmental awareness were somewhat taken into account in the project communication, at key moments in the project there was attention for this issue.
4. **Good**: opportunities to increase environmental awareness were sufficiently taken into account in the project communication, the project utilized many possibilities to address this issue in their communications.
5. **Excellent**: opportunities to increase environmental awareness were taken into account in the project communication, the project utilized every possibility to address this issue both in online and offline communications.

Scale of measurement: metropolitan scale (project based)

Key references

Bosch, P., Jongeneel, S., Rovers, V., Neumann, H.-M., Airaksinen, M., & Huovila, A. (2017). CITYkeys indicators for smart city projects and smart cities. CITYkeys D1.4. Retrieved from http://nws.eurocities.eu/MediaShell/media/CITYkeysD14Indicatorsforsmartcityprojectsandsmartcities.pdf

4.10.3 Participatory governance

Metric: *The extent to which the NBS project has contributed to the active engagement of citizens in public decision-making (qualitative, unitless).*

Participatory or inclusive governance, wherein municipalities partner with citizens to develop and manage solutions to contemporary challenges, focuses on enhancing citizen engagement in municipal governance by providing opportunity for citizens to play a direct role in public decision-making. The increased engagement of citizens in urban governance and decision-making is a primary objective of the European Innovation Partnership on Smart Cities and Communities (EIP-SCC). The importance of participatory governance is highlighted in the EIP-CC Strategic Implementation Plan (EIP-SCC, 2012, pp. 12):

> *"Citizens are at the heart of a city and also at the heart of the challenges cities face through on-going urbanisation and demographic mix, consumption habits as well as increasing expectations as regards quality of life. Citizens must therefore also be at the heart of the solution. Yet presently, citizens are insufficiently engaged, motivated or empowered to contribute. And cities do not have a deep enough understanding of their citizens to actively and effectively engage them. A fundamental change is required, without which we simply cannot sustain current norms. With a better understanding of citizen's motivations, cities and their partners could define effective strategies and tools to equip citizens to be actors in smart city systems: ensure that they are informed, motivated to act responsibly, proactive and participative, or even co-create. If smartly mobilized, the effect of citizen's behaviour, choices, creativity and entrepreneurship could be enormous, offering huge untapped potential."*

The proportion (%) of citizens involved in participatory governance is calculated on an annual basis, as:

$$\left(\frac{No.\, of\ citizens\ enaged\ in\ relevant\ projects\ in\ a\ given\ year}{Total\ population\ of\ the\ city}\right) \times 100$$

Municipalities maintain records of the number of citizens involved in face-to-face meetings or other activities. Evaluation of citizen engagement should take into account not only direct/face-to-face interactions between citizens and decision-makers, but should also account for online (internet- or app/smartphone-based) engagement. Software providers and/or platform hosts can provide metrics related to the number of unique visitors for use in calculating digital citizen engagement.

Scale of measurement: municipality scale

Key references

European Innovation Partnership on Smart Cities and Communities (EIP SCC). (2013.) *Strategic Implementation Plan. Issues 14.10.2013.* Brussels: EIP SCC. Retrieved from https://smartcities.at/assets/Uploads/sip-final-en2.pdf

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.10.4 Ease of governance of NBS

Metric: *The extent to which the NBS project has contributed to, or inspired, the development of new forms of NBS governance in the form of changes to rules or regulations (qualitative, unitless).*

Existing municipal rules and regulations based upon centralised or top-down systems of management, traditional construction processes, etc., may serve as a barrier to innovations like NBS. Projects may be able to forge a new path, or shift the paradigm within which municipalities operate in order to better support innovative actions that challenge the status quo. There is growing recognition of the critical importance of citizen engagement in sustainable urban development. Long-term climate change mitigation and adaptation planning has been identified as a key area for participatory or inclusive governance, wherein municipalities partner with citizens to develop and manage solutions (Brink & Wamsler, 2018).

The extent to which an NBS project has contributed to, or inspired, the development of new forms of NBS governance in the form of changes to rules or regulations can be evaluated qualitatively using a five-point Likert scale (Bosch et al., 2017):

No impact– 1 — 2 — 3 — 4 — 5 — High impact

1. No impact: the project has not, at any level, inspired changes in rules and regulations.
2. Little impact: the project has led to a localised discussion about the suitability of the current rules and regulations.
3. Some impact: the project has led to a public discussion, leading to a change in rules and regulations.
4. Notable impact: the project has led to a public discussion, leading to a change in rules and regulations. This in its turn has sparked a discussion amongst other administrations about the suitability of the current rules and regulations.
5. High impact: the project has led to a public discussion, leading to a change in rules and regulations. This in turn has inspired other administrations to reconsider their rules and regulations

Scale of measurement: municipal scale

Key references

Bosch, P., Jongeneel, S., Rovers, V., Neumann, H.-M., Airaksinen, M., & Huovila, A. (2017). CITYkeys indicators for smart city projects and smart cities. CITYkeys D1.4. Retrieved from http://nws.eurocities.eu/MediaShell/media/CITYkeysD14Indicatorsforsmartcityprojectsandsmartcities.pdf

Brink, E., & Wamsler, C. (2018). Collaborative governance for climate change adaptation: Mapping citizen-municipality interactions. *Environmental Policy & Governance*, *28*, 82-97.

4.10.5 New forms of financing

Metric: *The extent to which the NBS project has contributed to, or inspired, the development of new forms of financing (qualitative, unitless).*

Despite widespread recognition of the multiple co-benefits offered by NBS, financing for urban green spaces remains a common barrier to NBS implementation. Kabisch et al. (2016) note that "EU-funding instruments are available for cities, but they are complicated to apply for (requiring additional administrative staff and time) and, more importantly, require co-financing, which many cities cannot afford" (p. 7). Close partnerships between municipal governments, businesses and citizens (public-private-people partnerships, PPPPs) are one example of a new business and financing model that yields resource and governance synergies that can support NBS implementation. Other examples include new financial products such as 'green mortgages' or revolving funds for sustainable investments. This metric uses a five-point Likert scale to qualitatively evaluate the extent to which a given NBS project has contributed to the development of innovative forms of financing (Bosch et al., 2017):

No impact on new forms of financing– 1 — 2 — 3 — 4 — 5 — High impact

1. No impact: the project used a new form of financing but this is not known to the outside world.
2. Little impact: the project used a new form of financing but is hardly known for this
3. Some impact: the project used a new form of financing and received some professional attention because of this.
4. Notable impact: the project is (one of the first) to develop and use a new form of financing and has attracted a lot of professional attention because of this, which has led to a few further experiments with the new way of financing.
5. High impact: the project developed and used a new form of financing and has attracted a lot of public and professional attention because of this, which has led to several further experiments with the new way of financing.

Scale of measurement: municipality scale

Key references

Bosch, P., Jongeneel, S., Rovers, V., Neumann, H.-M., Airaksinen, M., & Huovila, A. (2017). CITYkeys indicators for smart city projects and smart cities. CITYkeys D1.4. Retrieved from http://nws.eurocities.eu/MediaShell/media/CITYkeysD14Indicatorsforsmartcityprojectsandsmartcities.pdf

Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., … Bonn, A. (2016). Nature-based solutions to climate change adaptation and mitigation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and Society*, *21*(2), 39.

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.10.6 Policy learning concerning adapting policies and strategic plans

Metric: *The extent to which the NBS project has contributed to, or inspired, changes in municipal rules and regulations to support implementation and "mainstreaming" of NBS (qualitative, unitless).*

Policy learning to systemically incorporate ecosystem-based adaptation into climate change strategies and ecosystem services into municipal planning is a critical step in shifting the prevailing paradigm of dealing with risk and disaster (Wamsler, Luederitz & Brink, 2014). Existing municipal rules and regulations based upon centralised or top-down systems of management, traditional construction processes, etc., may serve as a barrier to innovations like NBS. Projects may be able to forge a new path, or shift the paradigm within which municipalities operate in order to better support innovative actions that challenge the status quo. Implementation of NBS in the absence of policy and planning support may be challenging, as bottom-up and decentralised processes are inherent within the concept. Where NBS projects result in policy learning and adaptation to new processes that align with the concept and practices of NBS co-creation, co-implementation and co-governance, the potential for NBS up-scaling and replication increases. Policy learning can also create windows of opportunity for other, similar urban innovations.

The extent of policy learning during or as a result of an NBS project can be qualitatively evaluated using a five-point Likert scale (Bosch et al., 2017):

No impact– 1 — 2 — 3 — 4 — 5 — High impact

1. **No impact**: the NBS project has not, at any level, inspired changes in municipal rules and regulations.
2. **Little impact**: the NBS project has led to localised discussion about the suitability of the current municipal rules and regulations.
3. **Some impact**: the NBS project has led to public discussion, leading to a change in municipal rules and regulations.
4. **Notable impact**: the NBS project has led to public discussion, leading to a change in municipal rules and regulations. This, in turn, has sparked discussion amongst other administrations about the suitability of current rules and regulations.
5. **High impact**: the NBS project has led to public discussion, leading to a change in municipal rules and regulations. This, in turn, has inspired other administrations to reconsider their respective rules and regulations

Scale of measurement: municipality scale (project based metric)

Key references

Bosch, P., Jongeneel, S., Rovers, V., Neumann, H.-M., Airaksinen, M., & Huovila, A. (2017). CITYkeys indicators for smart city projects and smart cities. CITYkeys D1.4. Retrieved from http://nws.eurocities.eu/MediaShell/media/CITYkeysD14Indicatorsforsmartcityprojectsandsmartcities.pdf

Wamsler, C., Luederitz, C., & Brink, E. (2014). Local levers for change: Mainstreaming ecosystem-based adaptation into municipal planning to foster sustainability transitions. *Global Environmental Change*, *29*, 189-201.

4.10.7 Climate resilience strategy development

Many climate resilience strategies are linked with disaster and risk reduction as the impacts of climate change are commonly experienced in urban areas as flooding and/or drought, and over-heating (urban heat island effect). Nature-based solutions are a key tool for use in urban climate change mitigation and adaptation efforts. In particular, urban areas are particularly vulnerable to flooding because where the soil surface is covered by impenetrable materials, like roads, parking lots, sidewalks, and buildings, the water cannot infiltrate the underlying soil. Nature-based solutions offer multi-faceted solutions that can enhance stormwater infiltration (reduce flooding and improve groundwater recharge), provide shading and/or insulation from solar radiation (mitigate UHI effect), and create habitat for native wildlife (enhance biodiversity) whilst concomitantly delivering recreational, social and cultural opportunities. Projects involving NBS can increase awareness of ecosystem based adaptation to climate change and encourage the development of municipal climate resilience strategies that incorporate natural solutions to climate change impacts.

a) Degree of development of climate resilience strategy

Metric: *The extent to which the city has developed and implemented a climate resilience strategy.*

This metric qualitatively assesses the extent to which a municipality has a climate resilience strategy and action plan. The metric is evaluated using a seven-point Likert scale based on the steps suggested by the “Mayors adapt” initiative for climate change adaptation in urban areas (Bosch et al., 2017; Climate Adapt, n.d.):

No action – 1 — 2 — 3 — 4 — 5 — 6 – 7 – Implementation, monitoring and evaluation

1. No action has been taken yet
2. The ground for adaptation has been prepared (the basis for a successful adaptation process)
3. Risks and vulnerabilities have been assessed
4. Adaptation options have been identified
5. Adaptation options have been selected
6. Adaptation options are being implemented
7. Monitoring and evaluation is being carried out.

Scale of measurement: municipality scale

Key references

Bosch, P., Jongeneel, S., Rovers, V., Neumann, H.-M., Airaksinen, M., & Huovila, A. (2017). CITYkeys indicators for smart city projects and smart cities. CITYkeys D1.4. Retrieved from http://nws.eurocities.eu/MediaShell/media/CITYkeysD14Indicatorsforsmartcityprojectsandsmartcities.pdf

Climate Adapt. (n.d.). About the Urban Adaptation Support Tool. https://climate-adapt.eea.europa.eu/knowledge/tools/urban-ast/step-0-1

European Commission

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Additional Information

Climate-ADAPT: http://climate-adapt.eea.europa.eu/

Covenant of Mayors for Climate and Energy: https://www.covenantofmayors.eu/en/

EU Strategy on adaptation to climate change: https://ec.europa.eu/clima/policies/adaptation/what_en#tab-0-1; https://ec.europa.eu/clima/sites/clima/files/docs/eu_strategy_en.pdf

b) Alignment of climate resilience strategy with UNISDR-defined elements

In addition, the evaluation of Climate Resilience Strategy Development can rely on the assessment proposed by the United Nations Office for Disaster Risk Reduction (UNISDR) that allows local governments and to assess their disaster resilience and to enable the development of a local disaster risk reduction strategy (resilience action plans).

Metric: *The extent to which the city has implemented the "Ten Essentials for Making Cities Resilient" included in the Sendai Framework for Disaster Risk Reduction.*

This metric qualitatively assess the extent to which a city has implemented a disaster risk reduction strategy aligned with the Ten Essentials for Making Cities Resilient. Such Essentials are able to cover many of the issues that cities need to address to become more disaster resilient and they are able to address multiple perspectives, such as governance and financial capacity, planning and disaster preparation and disaster response and post-event recovery (United Nations Office for Disaster Risk Reduction [UNISDR], 2017).

The metric is evaluated using UNISDR Disaster Resilience Scorecard for Cities, which is a tool that allows local governments to monitor and review progress and challenges in the Implementation of the Sendai Framework for Disaster Risk Reduction and to enable the development of a local disaster risk reduction strategy. The assessment is performed with respect to a selected climate hazard (e.g., the most severe, the most probable) and can be made at two levels: preliminary and detailed. In detail, for each of the Essentials, a number of issues is identified within the tool, and for each of the issue a score must be assigned. Final results include an overall score, a representation of results focused on the score obtained for each essential in graphical form and also a representation of results focused on the score obtained for each sub-issue of each essential in graphical form.

Scale of measurement: municipality scale

Key references

United Nations Office for Disaster Risk Reduction (UNISDR). (2017). Disaster Resilience Scorecard for Cities – Preliminary level assessment. Retrieved from https://www.unisdr.org/campaign/resilientcities/toolkit/article/disaster-resilience-scorecard-for-cities

4.11 Social Justice & Social Cohesion

Indicator	Metric
Social justice & social cohesion	Availability and equitable distribution of blue-green space
	Safety, including indicators of crime
	People reached by NBS project
	Participation of vulnerable or traditionally under-represented groups
	Consciousness of citizenship

4.11.1 Availability and equitable distribution of blue-green space

Metric: *The availability and distribution of blue-green space with respect to specific individual or household socioeconomic profiles and landscape design*

It is widely accepted that access to urban green space improves the quality of life for urban residents, facilitating social cohesion, democracy, and equity whilst enhancing physical and psychological health and well-being. Urban green spaces also contribute to the economic vitality of urban neighbourhoods by increasing property values and encouraging tourism (Ibes, 2015). A number of recent studies have highlighted inequitable access to green space in cities around the world. Spatial analysis of metropolitan areas can reveal the relationship between green space access and socio-economic status.

The overall methodology involves selecting relevant characteristics and datasets, then overlaying these dataset using GIS (see the Distribution of Green Space metric in section 4.6.1). Statistical analyses of spatially-explicit variables are then used to explore the relationship between urban green space availability and selected socio-economic characteristics. Additional factors, such as size or type of green space, biodiversity value, etc. can also be evaluated. Some examples and further references are given below.

Step 1: Separate the metropolitan area of interest into its respective spatial/administrative units

The spatial unit layer selected becomes a common spatial grid for further analyses. Cohen, Baudoin, Palibrk, Persyn, and Rhein (2012) and Ibes (2015) used local census block groups to define spatial units in Paris (FR) and Phoenix (USA), respectively. Kabisch and Haase (2014) used “living environment areas”, which represent the base for urban planning, prognosis, observation and administration in Berlin (DE). In each of these studies, the selected spatial/administrative unit provided clearly defined areas with readily available data regarding population density, demographics, median household income, level of home ownership, etc. Additional information regarding dominant building type (single family and multi-family residences, buildings for retail or commercial/industrial use, mean or maximum building height, etc.) can be obtained from municipality records for each spatial/administrative unit.

Step 2: Using GIS, overlay the spatial units with available urban landscape data

For example, Cohen et al. (2012) obtained high resolution urban landscape data (1 m) from the Paris Urban Planning Agency that described the spatial distribution of: vegetation patches per strata (i.e., <1 m, 1–10 m, >10 m); (2) water bodies, bare soil and asphalt; and, built up areas based on the median height of buildings and the period of construction. This layer was intersected with the census block group data to view distribution patterns of urban landscapes.

‘Park neighbourhoods’, or areas with urban green space accessibility, can be evaluated at this stage by mapping the area within 400 m or a 5-min walk of each identified green space (Ibes, 2015). Ibes

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

(2015) classified each public green space by size, available amenities and facilities, and distance from the city centre, as these green space characteristics affect green space quality, accessibility, biodiversity potential, and the frequency and nature of visits to the green space.

The biodiversity value of each green space can be characterised in this, or a separate, map layer using available data from botanical surveys (Cohen et al., 2012). Statistically different types of public green space can then be identified according to the botanical composition, biological traits and floral richness of each green space, per Cohen et al. (2012).

Step 3: Statistically analyse spatially-explicit data to evaluate green space availability (and green space type and size and/or biodiversity value, if desired) as a function of socio-economic factors in order to determine equity of green space distribution

A number of different statistical methods may be employed to evaluate the equity of public green space distribution. Cohen et al. (2012) used available botanical information for each of the census block groups, calculating the mean household income per botanical and landscape class cluster. They also assessed the correlation between mean revenue, floral richness, the ecological diversity index and building density (see Cohen et al., 2012).

Ibes (2015) first employed principal component analysis (PCA) to identify statistically-independent dimensions, or principal components. A two-step cluster analysis was then used to characterise park types with respect to the key attributes identified in PCA. Park type was then analysed with respect to neighbourhood social variables including income, population density, and ethnicity (see Ibes, 2015).

Scale of measurement: metropolitan scale

Key references

Cohen, M., Baudoin, R., Palibrk, M., Persyn, N., & Rhein, C. (2012). Urban biodiversity and social inequalities in built-up cities: New evidences, next questions. The example of Paris, France. *Landscape and Urban Planning*, *106*, 277–287.

Ibes, D.C. (2015). A multi-dimensional classification and equity analysis of an urban park system: A novel methodology and case study application. *Landscape and Urban Planning*, *137*, 122–137.

Kabisch, N. & Haase, D. (2014). Green justice or just green? Provision of urban green spaces in Berlin, Germany. *Landscape and Urban Planning*, *122*, 129–139.

4.11.2 Safety, including indicators of crime

Metric: *Number of violent incidents, nuisances and crimes per 100 000 population*

The number of violent incidents, reportable nuisances and other crimes is a primary indicator of feelings of personal safety (ISO, 2018). For simplicity, the crime rate of a given metropolitan area can be assessed before and after NBS implementation to determine the impact of NBS actions on local crime. Individual surveys are necessary to directly assess citizens' feelings of personal safety, but the crime rate can provide an easily quantifiable metric of actual crime in a given area.

In this context, violence refers to the intentional use of physical force or power, threatened or actual, against oneself, another person or against a group or community, which either results in or has a high likelihood of resulting in injury, death, psychological harm, maldevelopment or deprivation (e.g., murder) per the World Health Organisation definition. Crime refers to an action or offense punishable by law, such as theft or vandalism. Nuisances are not necessarily illegal but cause offense or inconvenience. Examples of nuisances frequently reported to the local authorities are indecent conduct, littering, and loud noises or objectionable odours.

The crime rate is defined as the number of violent incidents, annoyances and crimes per 100 000 population. It is calculated as:

$$\frac{Total\ number\ of\ crimes\ reported}{(City's\ total\ population/100\ 000)}$$

The result is expressed as the number of crimes per 100 000 population.

Scale of measurement: district to metropolitan scale

Key References

Bosch, P., Jongeneel, S., Rovers, V., Neumann, H.-M., Airaksinen, M., & Huovila, A. (2017). CITYkeys indicators for smart city projects and smart cities. CITYkeys D1.4. Retrieved from http://nws.eurocities.eu/MediaShell/media/CITYkeysD14Indicatorsforsmartcityprojectsandsmartcities.pdf

International Organization for Standardization (ISO). (2018). *Sustainable cities and communities — Indicators for city services and quality of life (ISO 37120:2018).* Retrieved from https://www.iso.org/standard/68498.html

Additional Information

https://www.who.int/violenceprevention/approach/definition/en/

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.11.3 People reached by NBS project

Metric: *Percentage of people in the target group that have been reached and/or are activated by the NBS project.*

Much of a project's success depends on reaching the "right" people. In many instances the reach of a project is assessed by the total number of people reached, or the total number of people from vulnerable or under-represented groups who become involved. The strength of the "people reached by NBS project" metric is that it provides a quantitative measure of the project's engagement of people within the target group, enabling rapid assessment of how successful the project has been in this regard. Conversely, the weakness of the metric is that the target group must be clearly defined in order to quantify the size of the target audience. This could be particularly challenging in NBS projects as the co-creation process is driven equally by project planners and stakeholders, meaning that the target audience can change with time as the NBS is co-defined. Evaluation of the target audience, identification of critical stakeholders and quantification of the total target audience should, therefore, be an on-going process in an NBS project. Note that this metric does not consider how people are reached, or identify limitations to citizen engagement.

People reached by an NBS project can be calculated as:

$$\left(\frac{Number\ of\ citizens\ reached}{Total\ no.citizens\ in\ target\ group}\right) \times 100$$

Scale of measurement: district to metropolitan scale

Key References

Bosch, P., Jongeneel, S., Rovers, V., Neumann, H.-M., Airaksinen, M., & Huovila, A. (2017). CITYkeys indicators for smart city projects and smart cities. CITYkeys D1.4. Retrieved from http://nws.eurocities.eu/MediaShell/media/CITYkeysD14Indicatorsforsmartcityprojectsandsmartcities.pdf

4.11.4 Participation of vulnerable or traditionally under-represented groups

Metric: *The extent to which the NBS project has led to the increased participation by groups of people who are typically not well represented in the society.*

Definitions of "vulnerable" and "under-represented" groups in society vary somewhat, but in general the following groups can be considered vulnerable to discrimination and/or under-represented:

- Women and girls
- Children
- Refugees
- Internally displaced persons
- Stateless persons
- National minorities
- Indigenous peoples
- Migrant workers
- Disabled persons
- Elderly persons
- HIV positive persons and those suffering from AIDS
- Roma/Gypsies/Sinti
- Lesbian, gay, bisexual, transgender, queer, and differently gendered people (LGBTQ+)

Particular effort is necessary to ensure that these groups receive equal representation and opportunity to become involved in NBS projects. Specifically engaging vulnerable and/or under-represented groups in NBs projects enhances social cohesion and diversity whilst tapping into underdeveloped social capital.

Opportunities to increase the participation of vulnerable or under-represented groups may involve physical, digital, financial or organisational efforts, such as:

- Physical - e.g., improved accessibility for wheelchairs;
- Digital - e.g., facilitating online access or providing information pages online
- Financial - e.g., providing financial aid to participate in sports or cultural activities
- Organisational - e.g., through targeted actions to engage specific underrepresented groups (for example via NBS-related activities in collaboration with elder care facilities, schools, refugee centres, etc.)

The participation of vulnerable or traditionally under-represented groups in NBS projects or specific NBS project activities can be qualitatively assessed using a five-point Likert scale:

Not at all – 1 — 2 — 3 — 4 — 5 — Excellent

1. **Not at all**: the project has not increased participation of groups not well represented in society.
2. **Poor**: the project has achieved little when it comes to participation of groups not well represented in society.
3. **Fair**: the project has somewhat increased the participation of groups not well represented in society.
4. **Good**: the project has significantly increased the participation of groups not well represented in society.
5. **Excellent**: Participation of groups not well represented in society has clearly been hugely improved due to the project.

Information used to evaluate the performance of a particular NBS project with regard to the participation of vulnerable or traditionally under-represented groups can be obtained from project documentation and/or interviews with the project leaders and stakeholders (including representatives of the groups targeted).

Scale of measurement: district to metropolitan scale

Key References

Bosch, P., Jongeneel, S., Rovers, V., Neumann, H.-M., Airaksinen, M., & Huovila, A. (2017). CITYkeys indicators for smart city projects and smart cities. CITYkeys D1.4. Retrieved from http://nws.eurocities.eu/MediaShell/media/CITYkeysD14Indicatorsforsmartcityprojectsandsmartcities.pdf

4.11.5 Consciousness of citizenship

***Metric:** The extent to which the NBS project has contributed in increasing consciousness of citizenship (qualitative, unitless)*

Consciousness of citizenship can be described as an individual's awareness of their community, civic rights and responsibilities and their relationship with the community, state or nation. An individual with consciousness of citizenship is aware of how the community functions and their respective role in the community. As such, consciousness of citizenship contributes to a sense of community. According to Ng (2015), civic consciousness includes the following elements:

- **Personal identity and citizenship**: characteristics such as personal awareness, pride, obedience to the law, and a sense of equality
- **National identity**: respect for national authorities, belief in the legitimacy of the current political system, sense of the nation as a cohesive whole
- **Moral consciousness**: upholding family and social normative values in public and in private, willingness to promote public welfare
- **Ecological consciousness**: awareness of the finite nature of natural resources, consideration of the environmental consequences of personal actions
- **Global citizenship**: actively concerned with others at home and abroad

The extent to which an NBS project seeks to contribute to the local consciousness of citizenship can be qualitatively rated on a five-point Likert scale, from no effort to substantial effort:

No increase – 1 — 2 — 3 — 4 — 5 — High increase

1. **None**: The NBS project has made no effort to increase civic consciousness.
2. **Little**: The NBS project has made a small effort to increase civic consciousness.
3. **Somewhat**: The NBS project has developed some initiatives to increase civic consciousness.
4. **Significant**: The NBS project has executed several activities to increase civic consciousness
5. **High**: increasing civic consciousness was (one of) the main goals of the NBS project and substantial effort has been made to enhance civic consciousness.

Scale of measurement: district to metropolitan scale

Key References

Bosch, P., Jongeneel, S., Rovers, V., Neumann, H.-M., Airaksinen, M., & Huovila, A. (2017). CITYkeys indicators for smart city projects and smart cities. CITYkeys D1.4. Retrieved from http://nws.eurocities.eu/MediaShell/media/CITYkeysD14Indicatorsforsmartcityprojectsandsmartcities.pdf

Ng, J.A.I. (2015). Scale on Civic Consciousness (SCC) for the National Service Training Program. *International Journal of Humanities and Management Sciences*, *3*(3), 161-165.

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.12 Health and Well-Being

Indicator	Metric
Health and well-being	Encouraging a healthy lifestyle
	Exposure to noise pollution
	Hospital admissions due to high temperature during extreme heat events

4.12.1 Encouraging a healthy lifestyle

Metric: *Extent to which the NBS project and associated activities serve to promote a healthy lifestyle among local residents (qualitative, unitless).*

A core co-benefit of NBS is the encouragement of healthy lifestyles for urban residents. Many different measures can be employed to encouraging a healthy lifestyle, such as:

- Increasing bicycling opportunities in the neighbourhood - network of bicycle paths covering an area between residences and businesses/services
- Increasing walking opportunities in the neighbourhood - network of pedestrian walkways covering an area between residences and businesses/services
- Increasing the number, diversity or accessibility public sports facilities
- Increasing the extent or accessibility of community gardening facilities
- Designating public areas as non-smoking zones

The overall process of NBS co-creation, co-implementation and co-management with stakeholders provides ample opportunity to specifically target NBS interventions that provide opportunities for local citizens to adopt healthier lifestyles. The extent to which this is considered during NBS planning and implementation is assessed qualitatively using a five-point Likert scale from not at all (1, no encouragement of healthy lifestyles) to excellent (extensive online and offline encouragement):

Not at all – 1 — 2 — 3 — 4 — 5 — Excellent

1. **Not at all:** no measures were taken to encourage a healthy lifestyle.
2. **Poor:** there was little encouragement of a healthy lifestyle.
3. **Somewhat:** there was some encouragement of a healthy lifestyle with the implementation of some measures.
4. **Good:** a sufficient encouragement of a healthy lifestyle was translated into several offline (biking facilities, public sports facilities) and online (i.e., reminder app) initiatives.
5. **Excellent:** a healthy lifestyle was extensively encouraged offline (biking facilities, public sports facilities, pedestrian networks) and online (i.e., exercise apps).

Scale of measurement: district to metropolitan scale

Key References

Bosch, P., Jongeneel, S., Rovers, V., Neumann, H.-M., Airaksinen, M., & Huovila, A. (2017). CITYkeys indicators for smart city projects and smart cities. CITYkeys D1.4. Retrieved from http://nws.eurocities.eu/MediaShell/media/CITYkeysD14Indicatorsforsmartcityprojectsandsmartcities.pdf

Additional Information

http://heapro.oxfordjournals.org/content/current

http://www.healthpromotionresource.ir/attachment/912.pdf)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.12.2 Exposure to noise pollution

Metric: *The per cent (%) reduction of noise level at night measured at the receiver, or the number of inhabitants exposed to noise >55 dB(A) at night, before and after NBS implementation.*

Prolonged exposure to noise, such as the environmental noise pollution caused by road, rail and airport traffic, industry, construction, and other outdoor activities, can lead to significant physical and mental health effects (ISO, 2018). Environmental noise pollution is any disturbing noise that interferes with or harms humans or wildlife.

Noise pollution is commonly measured in level of decibels (dB), which means that noise reduction can be calculated as:

$$\left(\frac{dB\ level\ after\ NBS\ implementation}{dB\ level\ before\ NBS\ implementation}\right) \times 100 = \%\ change\ in\ noise\ level$$

An alternative calculation involves an estimation of the share of the population of a defined urban area that is affected by noise >55 dB during the night:

$$\left(\frac{No.\,inhabitatants\ esposed\ to\ noise > 55\ dB}{Total\ number\ of\ inhabitants}\right) \times 100 = \%\ population\ affected\ by\ noise$$

Regardless of the calculation used, the noise level should be measured (or modelled) at the object receiving the noise. In urban areas, “night” hours are defined differently depending on jurisdiction but typically involve a specific time range, e.g. 22:00-07:00, rather than the meteorological definition of night as the period between dusk and dawn.

Scale of measurement: street to district scale

Key References

International Organization for Standardization (ISO). (2018). *Sustainable cities and communities — Indicators for city services and quality of life (ISO 37120:2018).* Retrieved from https://www.iso.org/standard/68498.html

Additional Information

European Parliament, Council of the European Union. (2002). *Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise - Declaration by the Commission in the Conciliation Committee on the Directive relating to the assessment and management of environmental noise*. Retrieved from http://ec.europa.eu/environment/noise/directive_en.htm

4.12.3 Hospital admissions due to high temperature during extreme heat events

Metric: *Change in the number of hospital admissions due to high temperature during extreme heat events from baseline values*

Heat waves ate the most significant weather-related cause of human mortality worldwide (Agarwal, Dwivedi & Ghanshyam, 2018). This metric can easily be evaluated using public health data regarding daily emergency room admissions. These data can be used either to evaluate total emergency room admissions, or to assess hospital admissions for specific disease categories such as heat stroke, dehydration and cardiac arrest (e.g., Davis & Novicoff, 2018). Further disaggregation of data may include separation by population demographic (e.g., Gronlund, Zanobetti, Schwartz, Wellenius & O'Neill, 2014).

Key References

Agarwal, A.K., Dwivedi, S. & Ghanshyam, A. (2018). Summer heat: Making a consistent health impact. *Indian Journal of Occupational and Environmental Medicine*, *22*(1), 57-58.

Davis, R.E., & Novicoff, W.M. (2018). The impact of heat waves on emergency department admissions in Charlottesville, Virginia, U.S.A. *International Journal of Environmental Research and Public Health*, *15*(7) 1436.

Gronlund, C.J., Zanobetti, A., Schwartz, J.D., Wellenius, G.A., & O'Neill, M.S. (2014). Heat, heat waves, and hospital admissions among the elderly in the United States, 1992-2006. *Environmental Health Perspectives*, *122*(11), 1187-1192.

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.13 Economic Activity & Green Jobs

Indicator	Metric
Economic activity & green jobs	Establishment of new businesses in the area surrounding NBS
	Value of rates paid by businesses established in the area surrounding NBS
	Subsidies applied for private NBS measures
	Number of new jobs in green sector
	Use of ground floor building space for commercial or public purposes in the area surrounding implemented NBS
	Land and property prices

4.13.1 Establishment of new businesses

Metric: *Number of new businesses established in the area surrounding implemented NBS*

Urban regeneration can lead to improvement in the economic, physical, and social conditions of an area that has witnessed negative changes (Tallon, 2013). As such, it can include aspects such as development of business, housing, and a positive change on the community level (Tyler, Warnock, Provins, & Lanz, 2013). Nature-based solutions also provide a ground for 'Green businesses' to flourish (Organisation for Economic Co-operation and Development [OECD], 2013).

A report by Gore, Ozdemiroglu, Eadson, Gianferrara, and Phang (2013) states that gross domestic product (GDP) and gross value added (GVA) metrics alone cannot accurately estimate the contribution of green infrastructure/NBS to economic growth. Some methods to measure success can include occupation of premises in local areas or taking up of vacated spaces, changes in taxation, increase in start-ups, increase in visitors, new and expanding producer and retail firms, direct employment in development, maintenance and servicing, indirect employment in supporting firms, and attracting and retaining the workforce.

The major indicator is the number of established businesses located around the implemented NBS and also the rates paid for occupying that particular space (Gore et al., 2013). However, this will require gathering data over a period of months to understand the trend and business activities, both before and after the NBS implementation. Data can be derived annually from municipalities, planning departments and interviews with local businesses.

Understanding and identifying the buffer zone surrounding NBS and assessing the number of new businesses in parallel is a critical component. It may be useful to define the area surrounding the NBS similarly as green space distribution as defined in Section 4.6.1, e.g., land or properties with a 5 min walk from NBS (Madureira et al., 2011). Alternatively, proximity of land or property to NBS could be defined similarly to urban green space accessibility as in Section 4.6.2, i.e., land or properties within a 300-500 m distance from NBS (Tamosiunas et al., 2014). The type and size of a given NBS, and the different recreational opportunities and aesthetic values associated with the NBS, will largely determine the extent (in distance or time) and magnitude of its impact on local business development.

Scale of measurement: district to regional scale

Key References

Gore, T., Ozdemiroglu, E., Eadson, W., Gianferrara, E., & Phang, Z. (2013). *Green Infrastructure's contribution to economic growth: A review. A Final Report for Department for Defra and*

Natural England. July 2013. London: eftec. http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=19056

Madureira, H., Nunes, F., Oliveira, J. V, Cormier, L., & Madureira, T. (2015). Urban residents' beliefs concerning green space benefits in four cities in France and Portugal. *Urban Forestry & Urban Greening*, *14*(1), 56-64.

Organisation for Economic Co-operation and Development (OECD). (2013). *Green Growth in Cities*. Paris, France: OECD Environment Directorate. Retrieved from https://doi.org/10.1787/9789264195325-en

Tallon, A. (2013). *Urban Regeneration in the UK*. Abingdon, Oxon: Routledge.

Tamosiunas, A., Grazuleviciene, R., Luksiene, D., Dedele, A., Reklaitiene, R., Baceviciene, M., … Niewenhuijsen, M.J. (2014). Accessibility and use of urban green spaces, and cardiovascular health: findings from a Kaunas cohort study. *Environmental Health*, *13*(1), 20.

Tyler, P., Warnock, C., Provins, A., & Lanz, B. (2013). Valuing the benefits of urban regeneration. *Urban Studies*, *50*, 169-190.

4.13.2 Value of rates paid by businesses

Metric: *Value of rates paid by businesses established in the area surrounding implemented NBS*

The major indicator is the total value of rates paid by businesses within a defined area surrounding implemented NBS for occupying that particular space (Gore et al., 2013). To accurately determine the impact of NBS implementation on the value of rates paid by nearby businesses, it is necessary to gather data over a period of months to understand trends and business activities before and after NBS implementation. Data can be derived annually from municipalities, planning departments and interviews with local businesses.

Understanding and identifying the buffer zone surrounding NBS and assessing the number of new businesses in parallel is a critical component. It may be useful to define the area surrounding the NBS similarly as green space distribution as defined in Section 4.6.1, e.g., land or properties with a 5 min walk from NBS (Madureira et al., 2011). Alternatively, proximity of land or property to NBS could be defined similarly to urban green space accessibility as in Section 4.6.2, i.e., land or properties within a 300-500 m distance from NBS (Tamosiunas et al., 2014). The type and size of a given NBS, and the different recreational opportunities and aesthetic values associated with the NBS, will largely determine the extent (in distance or time) and magnitude of its impact on local business development.

Scale of measurement: district to regional scale

Key References

Gore, T., Ozdemiroglu, E., Eadson, W., Gianferrara, E., & Phang, Z. (2013). *Green Infrastructure's contribution to economic growth: A review. A Final Report for Department for Defra and Natural England.* July 2013. London: eftec. http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=19056

Madureira, H., Nunes, F., Oliveira, J. V, Cormier, L., & Madureira, T. (2015). Urban residents' beliefs concerning green space benefits in four cities in France and Portugal. *Urban Forestry & Urban Greening*, *14*(1), 56-64.

Tamosiunas, A., Grazuleviciene, R., Luksiene, D., Dedele, A., Reklaitiene, R., Baceviciene, M., … Niewenhuijsen, M.J. (2014). Accessibility and use of urban green spaces, and cardiovascular health: findings from a Kaunas cohort study. *Environmental Health*, *13*(1), 20.

4.13.3 Subsidies applied for private NBS measures

Metric: *Number or total value (in EUR) of direct (cash) subsidies or tax concessions applied to private NBS measures.*

For the purposes of this metric, “subsidies applied for private NBS measures” are narrowly defined as direct (cash) subsidies or tax concessions (exemptions or credits) awarded to an individual or organisation to implement, or following implementation of, an NBS on privately-owned property. Local and national governments, as well as the individuals or organisations receiving the aforementioned subsidies, serve as sources of information for this metric. The subsidies applied for private NBS measures can be expressed either the number of subsidies, or as a monetary value (in EUR).

Together with the total number or value of subsidies awarded, tracking the availability of subsidies for private NBS measures along with the number of applications for available subsidies can provide a qualitative measure of changing demand for NBS in the private sector.

Scale of measurement: district to regional scale

European Commission

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.13.4 New jobs in green sector

Metric: *Total number or proportion of (new) jobs related to environmental service activities that contribute substantially to preserving or restoring environmental quality*

'Green jobs' in areas directly connected to the environment such as resource conservation, waste management, water and green space management, and air quality can support economic growth and development. Smart cities are expected to show a significant growth in green jobs. The United Nations Environment Programme (UNEP), International Labour Organization (ILO), International Organisation of Employers (IOE), and International Trade Union Confederation (ITUC) (2008, pp. 3) define green jobs as "work in agricultural, manufacturing, research and development (R&D), administrative and service activities that contribute substantially to preserving or restoring environmental quality. Specifically, but not exclusively, this includes jobs that help to protect ecosystems and biodiversity; reduce energy, materials, and water consumption through high efficiency strategies; de-carbonize the economy; and minimize or altogether avoid generation of all forms of waste and pollution." The employing company or organisation can either be in a 'green' sector (e.g., green infrastructure design), or in a conventional sector (e.g., engineering services) but be making genuine and substantial efforts to green its operations.

The number of jobs, or number of new jobs, in the green sector can be counted or estimated for a given municipality based on business registrations and/or administrative documents. The proportion of green jobs, or new green jobs, is calculated as:

$$\left(\frac{Number\ of\ (new)\ green\ jobs}{Total\ number\ of\ (new) jobs}\right) \times 100$$

Scale of measurement: district to regional scale

Key References

Madureira, H., Nunes, F., Oliveira, J. V, Cormier, L., & Madureira, T. (2015). Urban residents' beliefs concerning green space benefits in four cities in France and Portugal. *Urban Forestry & Urban Greening*, *14*(1), 56-64.

Tamosiunas, A., Grazuleviciene, R., Luksiene, D., Dedele, A., Reklaitiene, R., Baceviciene, M., … Niewenhuijsen, M.J. (2014). Accessibility and use of urban green spaces, and cardiovascular health: findings from a Kaunas cohort study. *Environmental Health*, *13*(1), 20.

Tyler, P., Warnock, C., Provins, A., & Lanz, B. (2013). Valuing the benefits of urban regeneration. *Urban Studies*, *50*, 169-190.

United Nations Environment Programme (UNEP), International Labour Organization (ILO), International Organisation of Employers (IOE), & International Trade Union Confederation (ITUC). (2008). *Green Jobs: Towards Decent Work in a Sustainable, Low-Carbon World.* Nairobi, Kenya: United Nations Publishing Services Section. Retrieved from https://www.ilo.org/global/topics/green-jobs/publications/WCMS_158727/lang--en/index.htm

4.13.5 Ground floor usage

Metric: *Proportion of ground floor surface of buildings within a specified distance from implemented NBS that is used for commercial or public purposes, expressed as percentage of total ground floor surface*

The atmosphere of a neighbourhood and its overall liveability are influenced by the use of ground floor spaces for commercial and public purposes. The availability of amenities not only enhances the consumer experience, but also contributes to successful retail and commerce by supporting small businesses and retailers (Arlington Economic Development, 2014). Residential and office buildings generally have the most potential for increased use of ground floor space. This metric is calculated as:

$$\left(\frac{Ground\ floor\ space\ for\ commerical\ or\ public\ use\ (m^2)}{Total\ ground\ floor\ space\ (m^2)}\right) \times 100$$

This indicator may be limited to a defined urban area within a specific distance from NBS (e.g., an area with a given distance or walking time from implemented NBS). Data about ground floor space usage can be obtained from administrative documents and/or from interviews with the department for urban planning within the local municipality.

Scale of measurement: neighbourhood or district scale

Key References

Arlington Economic Development. (2014). *Ground Floor Retail and Commerce: Policies, Guidelines and Action Plan. Draft – September 2014.* Arlington, VA: Arlington Economic Development Department, Real Estate Development Group. Retrieved from https://www.arlingtoneconomicdevelopment.com/index.cfm?LinkServID=6E1B9F23-AA29-D1AC-1DFE1072C67F5C64&showMeta=0

Bosch, P., Jongeneel, S., Rovers, V., Neumann, H.-M., Airaksinen, M., and Huovila, A. (2017). CITYkeys indicators for smart city projects and smart cities. CITYkeys project D1.4. http://nws.eurocities.eu/MediaShell/media/CITYkeysD14Indicatorsforsmartcityprojectsandsmartcities.pdf

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

4.13.6 Land and property value

***Metric:** Mean or median value of land and property within a specified distance from NBS*

The change in attractiveness of an area due to the presence of public green space or other NBS can be determined by an individual's willingness to pay for, and thus the sale price or value of, land or property located in proximity to the NBS (Gore et al., 2013). Hedonic analysis can be used to understand the effect of NBS on property value. This method enables analysis of property sale data, yielding the difference in sale prices as a function of various attributes that are thought to affect the price. As a result, hedonic analysis can identify the price premium associated with the presence of and access to NBS (Crompton, 2005; Troy & Grove, 2008).

Similar effects are likely to occur when implementation of NBS encourages development of new housing areas. A survey of real estate developers and consultants from across Europe revealed that 95% of respondents believe that open space readily adds value to commercial. On average, property developers would be willing to pay ≥3% more for the opportunity to be near public open space, with some putting the premium as high as 15-20% (Gensler, the Urban Land Institute [ULI], & the Urban Investment Network [UIN], 2011; Roebeling et al., 2017).

Change in mean and median land and property prices following implementation of NBS can also be assessed (Forest Research, 2005). The change in mean or median land and property prices can be measured as a percentage or monetary value; however, information may need to be gathered over a period months to gain a full understanding of the change in value. Data required include real estate values in the area defined as "surrounding the NBS". These data can be extracted annually from municipalities, cadastre and real estate agencies, both before and after the NBS implementation.

Understanding and identifying the buffer zone surrounding NBS and assessing the change in property value in parallel is a critical component. It may be useful to define the area surrounding the NBS similarly as green space distribution as defined in Section 4.6.1, e.g., land or properties with a 5 min walk from NBS (Madureira et al., 2011). Alternatively, proximity of land or property to NBS could be defined similarly to urban green space accessibility as in Section 4.6.2, i.e., land or properties within a 300-500 m distance from NBS (Tamosiunas et al., 2014). The type and size of a given NBS, and the different recreational opportunities and aesthetic values associated with the NBS, will largely determine the extent (in distance or time) and magnitude of its impact on local land and property values.

Scale of measurement: neighbourhood or district scale

Key References

Crompton, J.L. (2005). The impact of parks on property values: empirical evidence from the past two decades in the United States. *Managing Leisure*, *10*(4), 203-218.

Gore, T., Ozdemiroglu, E., Eadson, W., Gianferrara, E., & Phang, Z. (2013). *Green Infrastructure's contribution to economic growth: A review. A Final Report for Department for Defra and Natural England.* July 2013. London: eftec. Retrieved from http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=19056

Forest Research. (2005). *Regeneration of previously developed land: Bold Colliery Community Woodland: district valuer's report on property values.* Cockermouth, Cumbria: North West England Conservancy. Retrieved from https://www.forestresearch.gov.uk/tools-and-resources/urban-regeneration-and-greenspace-partnership/greenspace-in-practice/planning-integrated-landscapes/brownfield-regeneration/

Gensler, the Urban Land Institute (ULI), & the Urban Investment Network (UIN). (2011). *Open Space: An asset without a champion?* San Francisco, CA: Gensler. Retrieved from https://www.gensler.com/uploads/document/220/file/Open_Space_03_08_2011.pdf

Madureira, H., Nunes, F., Oliveira, J. V, Cormier, L., & Madureira, T. (2015). Urban residents' beliefs concerning green space benefits in four cities in France and Portugal. *Urban Forestry & Urban Greening*, *14*(1), 56-64.

Roebeling, P., Saraiva, M., Palla, A., Gnecco, I., Teotónio, C., Fidélis, T., … Rocha, J. (2017). Assessing the socio-economic impacts of green/blue space, urban residential and road infrastructure projects in the Confluence (Lyon): a hedonic pricing simulation approach. *Journal of Environmental Planning and Management*, *60*(3), 482-499.

Tamosiunas, A., Grazuleviciene, R., Luksiene, D., Dedele, A., Reklaitiene, R., Baceviciene, M., … Niewenhuijsen, M.J. (2014). Accessibility and use of urban green spaces, and cardiovascular health: findings from a Kaunas cohort study. *Environmental Health*, *13*(1), 20.

Troy, A., & Grove, J.M. (2008). Property values, parks, and crime: A hedonic analysis in Baltimore, MD. *Landscape and Urban Planning*, *87*(3), 233-245.

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

5. CONCLUSIONS

Many of the key indicators of NBS performance and impact can be evaluated using a number of different techniques. There are several considerations in the selection of a particular measurement or monitoring method depends, key among these is the purpose, or objective, of the measurement/monitoring scheme. How will the data acquired be used, and how is "success" defined? Principal considerations for the design of a monitoring scheme are outlined in Table 5, but there are additional factors to assess when selecting monitoring or measuring equipment, such as:

- End-user acceptance of data acquisition technique
- Accuracy of device, and need for absolute versus relative accuracy
- Cost of device, including installation, operation and maintenance
- Range of operation (metric of interest, temperature, etc.)
- Operating requirements and adaptability to site conditions
- Device standardisation/calibration requirements
- Frequency of measurement
- Sensitivity to interference (from sediment, debris, etc.)
- Installation/setup requirements
- Expected lifespan of the device and maintenance requirements
- Need for and availability of expert personnel to conduct on-going verification, troubleshooting and repair
- Susceptibility to vandalism (for monitoring equipment to be installed *in situ*)

Chief among these factors are cost and the accuracy of measurement. In general, the cost of acquiring data increases with increasing accuracy of those data. Thus, it is useful to consider the accuracy required. Is an accurate, absolute value needed for a given metric, or are relative values that track changes in the metric over time sufficient? Evapotranspiration is an example of a metric where relative values may be sufficient: monitoring changes in evapotranspiration at a specific site before and after NBS implementation, and as a function of other changes to the environment, may be adequate and can substantially reduce the equipment and personnel costs associated with data acquisition.

The broad range of co-benefits provided by NBS is an additional, significant factor for consideration in design of a monitoring scheme. There are multiple opportunities to optimise data acquisition and cost as some unique metrics apply the same data/measurement(s) to different calculations. This broad range of potential NBS co-benefits also presents a challenge with respect to the many different areas of expertise needed to inform a holistic monitoring scheme. It is beneficial to establish a team of experts to devise an NBS monitoring scheme and to consult widely with both internal and external experts.

5.1 Additional Sources of Information

Additional sources of information are provided along with an outline of the applicable methodology for each of the indicators/metrics addressed herein. Wherever possible, we have provided citations of accepted standard methods got a given metric. Where multiple, equally "standard" techniques are available to evaluate NBS performance and/or impact we have briefly outlined each of the methods to facilitate selection of the measurement or monitoring technique that is most suitable for a given situation. Many methods, e.g. carbon emissions calculations, have been comprehensively addressed elsewhere and the methodology published in readily-accessible form. Thus, rather than reproduce every measurement or monitoring protocol in its entirety herein, we have provided a brief overview of each key indicator and associated metrics then provided references to standard methods or other accessible publications that present the respective method in detail.

5.2 Monitoring Impact with Time

The simplest metrics are those that involve a single assessment of NBS impact relative to baseline (pre-NBS) conditions. Numerous project-based metrics require a single, sometimes qualitative, evaluation at the conclusion of the NBS project. Other metrics require substantially more frequent monitoring in order to obtain useful data. In particular, continuous monitoring of biophysical parameters is recommended wherever possible as point-in-time sampling can introduce significant error where parameters vary with time. The widespread availability of sensors for a multitude of parameters of interest, along with data storage and/or transmission and data processing technologies, enable real-time or near-real-time data acquisition and processing. This is particularly beneficial in terms of stakeholder engagement: where possible, *in situ* monitoring and (near-)real-time presentation of data is desirable to maintain an on-going connection with stakeholders and to support educational opportunities.

5.3 Lessons Learned

There is a lack of internationally-recognised, standard methods for some of the metrics selected for use by UNaLab front-runner cities. Herein, methods have been described based upon peer-reviewed literature where a standardised method was not available. Many of the techniques used in research, however, are excessively complex and require very expensive equipment and/or high-level expertise. In addition, access to standardised methods (e.g., from ISO) is not universal and can be costly. Further exploration of grey literature should be undertaken in order to update this document with simplified monitoring or measurement methods, and links to readily-accessible (e.g., free, online) documents that provide additional details and examples.

Several indicator categories require further exploration of specific metrics, in particular those indicators that remain under discussion by the IEF Taskforce at this time. The IEF Taskforce has not yet identified common performance and impact metrics for the remaining categories: urban regeneration; participatory planning and governance; social justice and social cohesion; and, health and well-being. Additional metrics common to all SCC-02-2016-2017 projects may be identified by the IEF Taskforce following submission of this report. Thus, D3.1 *Performance and Impact Monitoring of Nature-Based Solutions* will be updated following the establishment of a finalised list of NBS performance/impact metrics common to all SCC-02-2016-2017 projects. In addition, learnings from the UNaLab project will be integrated within D3.1 *Performance and Impact Monitoring of Nature-Based Solutions* will be updated presented as an Appendix in the final report of WP5, the *NBS Implementation Handbook* (D5.5), to be delivered in M60 (May 2022).

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

6. Acronyms and terms

ADHD	Attention deficit hyperactivity disorder
AGI	American Geosciences Institute
AHP	Acid-hydrolysable phosphorus
Al	Aluminium
AMR	Automatic meter reading
APHA	American Public Health Association
ArcGIS	Geographic information software
As	Arsenic
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
Ba	Barium
BEI	Barrier Effect Index
BOD	Biological oxygen demand
BOD_5	Biochemical oxygen demand calculated over 5 days
BREEAM	Building Research Establishment Environmental Assessment Method
C	Carbon
C_6H_6	Benzene
CAS	Census area statistics
CASBEE	Comprehensive Assessment System for Building Environmental Efficiency
Cd	Cadmium
CH_4	Methane
CN	Curve number
Co	Cobalt
CO	Carbon monoxide (gas)
CO_2	Carbon dioxide (gas)
CO_2-eq	Carbon dioxide equivalent
COD	Chemical oxygen demand
Cr	Chromium
CRESH	Centre for Research on Environment Society and Health
CTCC	CUFR Tree Carbon Calculator
Cu	Copper
DO	Dissolved oxygen
DOC	Dissolved organic carbon
DON	Dissolved organic nitrogen
ECI	Ecological Connectivity Index

EEA	European Environment Agency
EC	European Commission or electrical conductivity (check context)
EIN	City of Eindhoven
EIP-SCC	European Innovation Partnership on Smart Cities and Communities
ENN	Euclidian nearest neighbour
ET	Evapotranspiration
EU	European Union
FCS	Forest carbon sequestration
FEA	Functional ecological areas
FIA	Forest inventory analysis
GDP	Gross domestic product
GEN	City of Genova
GHG	Greenhouse gas
GI	Green infrastructure
GIS	Geographic information system
GVA	Gross value added
GWP	Global warming potential
H_2SO_4	Sulphuric acid
HCL	Hydrochloric acid
HEI	Health Effects Institute
Hg	Mercury
HSG	Hydrologic soil group
IDF	Intensity-frequency-duration
IEF	Indicator Evaluation Framework
IPC	Ion-coupled plasma spectrophotometry
ICP-AES	Ion-coupled plasma spectrophotometry – atomic emission spectrometry
ICP-MS	Ion-coupled plasma spectrophotometry – mass spectrometry
IPCC	Intergovernmental Panel on Climate Change
ISE	Ion selective electrode
ISO	International Organization for Standardization
IUCN	International Union for the Conservation of Nature
$K_2Cr_2O_7$	potassium dichromate
KPI	Key Performance Indicator
KII	Key Impact Indicator
LCM	Landscape coefficient method

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

LEED	Leadership in Energy and Environmental Design
LiDAR	Light detection and ranging
MEMI	Munich energy-balance model for individuals
Mo	Molybdenum
MTO	
MWh	Megawatt hours, unit of energy
N	Nitrogen
N_2O	Nitrous oxide
N_{tot}	Total nitrogen
NBS	Nature-based solution
NCAR	National Center for Atmospheric Research
NCLD	National land cover database
NDVI	Normalised difference vegetation index
NH_3	Ammonia
NH_4^+	Ammonium
Ni	Nickel
NO_2	Nitrogen dioxide (gas)
NO_2^-	Nitrite
NO_3^-	Nitrate
NO_x	Nitrogen oxides (gaseous mixture)
NOAA	National Oceanic and Atmospheric Administration
N_{tot}	Total nitrogen
NTU	Nephelometric turbidity units
O_3	Ozone (gas)
OECD	Organisation for Economic Co-operation and Development
ORP	Oxidative-reductive potential
P	Phosphorus
P_{tot}	Total phosphorus
PAHs	Polycyclic aromatic hydrocarbons
Pb	Lead
PET	Physiological equivalent temperature
$PM_{2.5}$	Particulate matter less than 2.5 µm in diameter (atmospheric)
PM_{10}	Particulate matter less than 2.5 µm in diameter (atmospheric)
PMV	Predicted Mean Vote
PMV-PPT	Predicted Mean Vote-Predicted Percentage Dissatisfied
PO_4^{3-}	Phosphate, or orthophosphate

PROX	Proximity Index
PVC	Polyvinylchloride
SAS	Statistical analysis suite software
Se	Selenium
SGA	School green area
SOC	Soil organic carbon
SOM	Soil organic matter
SO_2	Sulphur dioxide (gas)
SO_X	Sulphur oxides (gaseous mixture)
SUDS	InfoWorks for Sustainable Drainage Systems model
SuDS	Sustainable urban drainage systems
SWMM	Stormwater Management Model
TCC	Tree canopy cover
TDS	Total dissolved solids
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorus
TRE	City of Tampere
TSS	Total suspended solids
UCAR	University Corporation for Atmospheric Research
UHI	Urban heat island
USDA	United States Department of Agriculture
US EPA	United States Environmental Protection Agency
USFS	United States Forest Service
USGS	United States Geological Survey
V	Vanadium
VDOT	Virginia Department of Transportation
VOCs	Volatile organic compounds (atmospheric)
WEI	Water Exploitation Index
WFD	Water Framework Directive
WHO	World Health Organisation
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting model
WRF-Chem	Weather Research and Forecasting model coupled with Chemistry model

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

YLL	Years of life lost
Zn	Zinc

7. REFERENCES

Adkins, G.B. (2006). *Flow Measurement Devices*. Salt Lake City, UT: Utah Division of Water Rights.

Agarwal, A.K., Dwivedi, S. & Ghanshyam, A. (2018). Summer heat: Making a consistent health impact. *Indian Journal of Occupational and Environmental Medicine*, *22*(1), 57-58.

Air Quality Expert Group [AQEG]. (2018). *Impacts of Vegetation on Urban Air Pollution.* Prepared for Department for Environment, Food and Rural Affairs, Scottish Government, Welsh Government, and Department of the Environment in Northern Ireland. Carlisle, UK: Department for Environment, Food and Rural Affairs. Retrieved from https://uk-air.defra.gov.uk/assets/documents/reports/cat09/1807251306_180509_Effects_of_vegetation_on_urban_air_pollution_v12_final.pdf.

Allen Burton, G., Jr., & Pitt, R.E. (2010). *Stormwater Effects Handbook. A Toolbox for watershed Managers, Scientists, and Engineers.* Boca Raton, FL: Lewis Publishers, CRC Press.

Alcalde Sanz, L. & Gawlik, B.M. (2014). Water Reuse in Europe: Relevant guidelines, needs for and barriers to innovation. A synoptic overview. JRC Science and Policy Report. Brussels: Publications Office of the European Union. http://publications.jrc.ec.europa.eu/repository/handle/JRC92582

Al Mamoon, A., Joergensen, N.E., Rahman, A. & Qasem, H. (2014). Derivation of new design rainfall in Qatar using L-moment based index frequency approach. *International Journal of Sustainable Built Environment*, August 2014

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2013). Standard 55 - Thermal environmental conditions for human occupancy. Atlanta, GA: ASHRAE.

Antonopoulou, G., Kirkou, A. & Stasinakis, A.S. (2013). Quantitative and qualitative greywater characterization in Greek households and investigation of their treatment using physicochemical methods. *Science of the Total Environment*, *454-455*, 426-432.

Armson, D., Stringer, P. & Ennos, A.R. (2013). The effect of street trees and amenity grass on urban surface water runoff in Manchester, UK. *Urban Forestry & Urban Greening*, *12*, 282-286.

Arnold, C.L., Jr., & Gibbons, C.J. (1996). Impervious surface coverage: The emergence of a key environmental indicator. *Journal of the American Planning Association*, *62*(2), 243-258.

Arnstein, S.R. (1969). A ladder of citizen participation. *Journal of the American Planning Association*, *35*(4), 216-224.

Badiu, D.L., Ioja, C.I., Patroescu, M., Breuste, J., Artmann, M., Nita, M.R., Gradinaru, S.R., Hossu, C.A., & Onose, D.A. (2016). Is urban green space per capita a valuable target to achieve cities' sustainability goals? Romania as a case study. *Ecological Indicators*, *70*, 53-66.

Baró, F., Chaparro, L., Gómez-Baggethun, E., Langemeyer, J., Nowak, D. J. & Terradas, J. (2014). Contribution of ecosystem services to air quality and climate change mitigation policies: the case of urban forests in Barcelona, Spain. *Ambio*, *43*(4), 466-479.

Baró, F., Haase, D., Gómez-Baggethun, E., & Frantzeskaki, N. (2015). Mismatches between ecosystem services supply and demand in urban areas: A quantitative assessment in five European cities. Ecological Indicators, 55, 146–158.

Bettinger, P., Boston, K., Siry, J.P. & Grebner, D.L. (2017). Chapter 2 - Valuing and Characterizing Forest Conditions. In P. Bettinger, K. Boston, J.P. Siry, & D.L. Grebner (Eds.), *Forest Management and Planning (Second Edition) (21–63)*. London: Elsevier Academic Press.

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Beven, K.J. (2012). *Rainfall-Runoff Modelling: The Primer. Second Edition.* Chichester, West Sussex, U.K.: Wiley-Blackwell.

Bosch, P., Jongeneel, S., Rovers, V., Neumann, H.-M., Airaksinen, M., & Huovila, A. (2017). CITYkeys indicators for smart city projects and smart cities. CITYkeys D1.4. Retrieved from http://nws.eurocities.eu/MediaShell/media/CITYkeysD14Indicatorsforsmartcityprojectsandsmartcities.pdf

Brink, E., & Wamsler, C. (2018). Collaborative governance for climate change adaptation: Mapping citizen-municipality interactions. *Environmental Policy & Governance*, *28*, 82-97.

Buters, J.T.M., Antunes, C., Galveias, A., Bergmann, K.C., Thibaudon, M., Galán, C. … Oteros, J. (2018). Pollen and spore monitoring in the world. *Clinical and Translational Allergy*, *8*, 9.

Calliari, E., Staccione, A., & Mysiak. J. (2019). An assessment framework for climate-proof nature-based solutions. *Science of the Total Environment*, *656*, 691-700.

Cariñanos, P., & Casares-Porcel, M. (2011). Urban green zones and related pollen allergy: A review. Some guidelines for designing spaces with low allergy impact. *Landscape and Urban Planning*, *101*(3), 205-214.

Carvalho, D., Martins, H., Marta-Almeida, M., Rocha, A., & Borrego, C. (2017). Urban resilience to future urban heatwaves under a climate change scenario: A case study for Porto urban area (Portugal). *Urban Climate*, *19*, 1-27.

Casakin, H., & Bernardo, F. (Eds.). (2012). *The Role of Place Identity in the Perception, Understanding, and Design of Built Environments*. Sharjah, United Arab Emirates: Bentham Science Publishers.

Chan, L., Hillel, O., Elmqvist, T., Werner, P., Holman, N., Mader, A., & Calcaterra, E. (2014). *User's Manual on the Singapore Index on Cities' Biodiversity* (also known as the City Biodiversity Index). Singapore: National Parks Board, Singapore.

Chaturvedi, A., Bhattacharjee, S., Mondal, G.C., Kumar, V., Singh, P.K., & Singh, A.K. (2019). Exploring new correlation between hazard index and heavy metal pollution index in groundwater. *Ecological Indicators*, *97*, 239-246.

Chaturvedi, A., Bhattacharjee, S., Singh, A.K., & Kumar, V. (2018). A new approach for indexing groundwater heavy metal pollution. *Ecological Indicators*, *87*, 323-331.

Cheng, C.Y., Cheung, K.K.S., & Chu, L.M. (2010). Thermal performance of a vegetated cladding system on facade walls. *Building and Environment*, *45*(8), 1779-1787.

Chiesura, A. (2004). The role of urban parks for the sustainable city. *Landscape and Urban Planning*, *68*(1), 129-138.

Christensen, J.H., Boberg, F., Christensen, O.B., & Lucas-Picher, P. (2008). On the need for bias correction of regional climate change projections of temperature and precipitation. *Geophysical Research Letters*, *35*(20), GL035694.

Clark, M.P., Bierkens, M.F.P., Samaniego, L., Woods, R.A., Uijlenhoet, R., Bennett, … Peters-Lidard, C.D. (2017). The evolution of process-based hydrologic models: historical challenges and the collective quest for physical realism. *Hydrology and Earth System Sciences*, *21*, 3427-3440

Climate Adapt. (n.d.). About the Urban Adaptation Support Tool. https://climate-adapt.eea.europa.eu/knowledge/tools/urban-ast/step-0-1

Cohen, M., Baudoin, R., Palibrk, M., Persyn, N., & Rhein, C. (2012). Urban biodiversity and social inequalities in built-up cities: New evidences, next questions. The example of Paris, France. *Landscape and Urban Planning*, *106*, 277–287.

Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (Eds.). (2016). *Nature-based Solutions to address global societal challenges*. Gland, Switzerland: International Union for the Conservation of Nature.

Costa, S., Ferreira, J., Silveira, C., Costa, C., Lopes, D., Relvas, H., … Teixeira, J.P. (2014). Integrating Health on Air Quality Assessment-Review Report on Health Risks of Two Major European Outdoor Air Pollutants: PM and NO_2. *Journal of Toxicology and Environmental Health - Part B Critical Reviews*, *17*(6), 307-340.

Crompton, J.L. (2005). The impact of parks on property values: empirical evidence from the past two decades in the United States. *Managing Leisure*, *10*(4), 203-218.

D'Amato, G., Cecci. L., Bonini, S., Nunes, C., Annesi-Maesano, I., Behrendt, H., … Van Cauwenberge, P. (2007). Allergenic pollen and pollen allergy in Europe. *Allergy*, *62*, 976-990.

Dadvand, P., de Nazelle, A., Triguero-Mas, M., Schembari, A., Cirach, M., Amoly, E., … Nieuwenhuijsen, M. (2012). Surrounding greenness and exposure to air pollution during pregnancy: An analysis of personal monitoring data. *Environmental Health Perspectives*, *120*, 1286–1290.

Davies, Z.G., Edmondson, J.L., Heinemeyer, A., Leake, J.R., & Gaston, K.J. (2011). Mapping an urban ecosystem service: Quantifying above-ground carbon storage at a city-wide scale. *Journal of Applied Ecology*, *48*(5), 1125-1134.

Davis, R.E., & Novicoff, W.M. (2018). The impact of heat waves on emergency department admissions in Charlottesville, Virginia, U.S.A. *International Journal of Environmental Research and Public Health*, *15*(7) 1436.

Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orru, H., … Faehnle, M. (2014). Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. *Journal of Environmental Management*, *146*, 107-115.

Devia, G.K., Ganasri, B.P., & Dwarakish, G.S. (2015). A review on hydrological models. *Aquatic Procedia*, *4*, 1001-1007.

Dhakal, N., Fang, X., Asquith, W.H., & Cleveland, T. (2013). Return period adjustment for runoff coefficients based on analysis in undeveloped Texas watersheds. *Journal of Irrigation and Drainage Engineering*, 139(6), 476-482.

Doan, D. T., Ghaffarianhoseini, A., Naismith, N., Zhang, T., Ghaffarianhoseini, A., & Tookey, J. (2017). A critical comparison of green building rating systems. *Building and Environment*, 123, 243–260.

Donner, E., Eriksson, E., Revitt, D.M., Scholes, L., Holten Lützhøft, H.-C., & Ledin, A. (2010). Presence and fate of priority substances in domestic greywater treatment and reuse systems. *Science of the Total Environment*, *408*(12), 2444-2451.

Douglas, D., & Peucker, T. (1973). Algorithms for the reduction of the number of points required to represent a digitized line or its caricature. *The Canadian Cartographer*, *10*(2), 112–122.

Driessen, P.P.J., Glasbergen, P., & Verdaas, C. (2001.) Interactive policy-making: A model of management for public works. *European Journal of Operational Research*, *128*, 322-337.

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

de Groot, R. (2006). Function-analysis and valuation as a tool to assess land use conflicts in planning for sustainable, multi-functional landscapes. *Landscape and Urban Planning*, *75*, 175-186.

de Groot, R.S., Alkemade, R., Braat, L., Hein. L., & Willemen, L. (2010). Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological Complexity*, *7*, 260-272.

de Vries, S., Verheij, R.A., Groenewegen, P.P., & Spreeuwenberg, P. (2003). Natural environments – healthy environments? An exploratory analysis of the relationship between greenspace and health. *Environment and Planning*, *35*, 1717-1731.

Eggermont, H., Balian, E., Azevedo, J.M.N., Beumer, V., Brodin, T., Claudet, J., …Le Roux, X. (2015). Nature-based solutions: New influence for environmental management and research in Europe. *GAIA*, *24*(4), 243-248.

Eisenberg, B., & Polcher, V. (2018). *Nature Based Solutions Technical Handbook. UNaLab D5.1 NBS Technical Handbook 31/05/2018.* Stuttgart, Germany: University of Stuttgart Institute of Landscape Planning and Ecology. Retrieved from https://www.unalab.eu/documents/nbs-technical-handbook.

Ekici, C. (2016). Measurement uncertainty budget of the PMV thermal comfort equation. *International Journal of Thermophysics*, *37*, 48.

Ekici, C. (2013). Review of Thermal Comfort and Method of Using Fanger's PMV Equation. *Proceedings of the 5th International Symposium on Measurement, Analysis and Modelling of Human Functions, 27-29 June 2013, Vancouver, Canada*. 4 pp.

Elrick, D.E., Reynolds, W.D., & Tan, K.A. (1989). Hydraulic conductivity measurements in the unsaturated zone using improved well analyses. *Groundwater Monitoring and Remediation*, *9*, 184-193.

Emmons, L.K., Walters, S., Hess, P.G., Lamarque, J.-F-, Pfister, G.G., Fillmore, D. … Kloster, S. (2010). Description and evaluation of the Model for Ozone and Related chemical Tracers, version 4 (MOZART-4). *Geoscientific Model Development*, *3*, 43-67.

European Commission. (2015). *Towards an EU Research and Innovation policy agenda for Nature-Based Solutions & Re-Naturing Cities. Final Report of the Horizon 2020 Expert Group on 'Nature-Based Solutions and Re-Naturing Cities'*. Luxembourg: Publications Office of the European Union. Retrieved from https://publications.europa.eu/en/publication-detail/-/publication/fb117980-d5aa-46df-8edc-af367cddc202

European Commission, Directorate-General for Environment. (2018). *Proposal for a Directive of the European Parliament and of the Council on the quality of water intended for human consumption (recast). COM/2017/0753 final - 2017/0332 (COD).* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52017PC0753&from=EN

European Environment Agency (EEA). (2018a). *Use of freshwater resources.* Copenhagen: European Environment Agency. Retrieved from https://www.eea.europa.eu/data-and-maps/indicators/use-of-freshwater-resources-2/assessment-3

European Environment Agency (EEA). (2018b). *Air quality in Europe – 2018 report. EEA Report No. 12/2018.* Luxembourg: Publications Office of the European Union. Retrieved from https://www.eea.europa.eu/publications/air-quality-in-europe-2018

European Innovation Partnership on Smart Cities and Communities (EIP SCC). (2013). *Strategic Implementation Plan. Issues 14.10.2013.* Brussels: EIP SCC. Retrieved from https://smartcities.at/assets/Uploads/sip-final-en2.pdf

European Parliament, Council of the European Union. (1991). *Council Directive 91/271/EEC of 21 May 1991 concerning urban waste water treatment.* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31991L0271&from=EN

European Parliament, Council of the European Union. (1991). *Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources.* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31991L0676

European Parliament, Council of the European Union. (1998). *Council directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption.* Retrieved from https://eur-lex.europa.eu/eli/dir/1998/83/2015-10-27

European Parliament, Council of the European Union. (2000). *EU Water Framework Directive: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy.* Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02000L0060-20140101

European Parliament, Council of the European Union. (2002). *Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise - Declaration by the Commission in the Conciliation Committee on the Directive relating to the assessment and management of environmental noise*. Retrieved from http://ec.europa.eu/environment/noise/directive_en.htm

European Parliament, Council of the European Union. (2006). *Council Directive 2006/44/EC of 6 September 2006 on the quality of fresh waters needing protection or improvement to support fish life.* Retrieved from https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:264:0020:0031:EN:PDF

European Parliament, Council of the European Union. (2008). *Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy, amending and subsequently repealing Council Directives 82/176/EEC, 83/513/EEC, 84/156/EEC, 84/491/EEC, 86/280/EEC and amending Directive 2000/60/EC of the European Parliament and of the Council.* Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0105

European Parliament, Council of the European Union. (2008). *Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. OJ L 152, 11.6.2008, p. 1-44.* Retrieved from https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32008L0050

European Parliament, Council of the European Union. (2009). *Commission Directive 2009/90/EC of 31 July 2009 laying down, pursuant to Directive 2000/60/EC of the European Parliament and of the Council, technical specifications for chemical analysis and monitoring of water status (Text with EEA relevance). OJ L 201, 1.8.2009, p. 36–38* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009L0090

European Parliament, Council of the European Union. (2012). *Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directives 2000/60/EC and 2008/105/EC as regards priority substances in the field of water policy. /* COM/2011/0876 final - 2011/0429 (COD) */.* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52011PC0876

European Parliament, Council of the European Union. (2013). Directive 2013/39/EU of the European Parliament and of the Council of 12 August 2013 amending Directives 2000/60/EC and

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

2008/105/EC as regards priority substances in the field of water policy (Text with EEA relevance). *OJ L 226, 24.8.2013, 1–17*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32013L0039

European Telecommunications Standards Institute (ETSI). (2017a). ETSI TS 103 463 V1.1.1 (2017-07). Technical Specification for Access, Terminals, Transmission and Multiplexing (ATTM); Key Performance Indicators for Sustainable Digital Multiservice Cities. Valbonne – Sophia Antipolis: ETSI. Retrieved from http://www.etsi.org/deliver/etsi_ts/103400_103499/103463/01.01.01_60/ts_103463v010101p.pdf

European Telecommunications Standards Institute (ETSI). (2017b). ETSI GS OEU 019 V1.1.1 (2017-08). Group Specification for Operational energy Efficiency for Users (OEU); KPIs for Smart Cities. Valbonne – Sophia Antipolis: ETSI. Retrieved from http://www.etsi.org/deliver/etsi_gs/OEU/001_099/019/01.01.01_60/gs_OEU019v010101p.pdf

Fadhel, S., Rico-Ramirez, M.A., & Han, D. (2017). Uncertainty of Intensity-Duration-Frequency (IDF) curves due to varied climate baseline periods. *Journal of Hydrology*, *547*, 600-612.

Faivre, N., Sgobbi, A., Happaerts, S., Raynal, J., & Schmidt, L. (2017). Translating the Sendai Framework into action: the EU approach to ecosystem-based disaster risk reduction. *International Journal of Disaster Risk Reduction*, *32*, 4-10.

Fanger, P. (1970). *Thermal comfort. Analysis and applications in environmental engineering*. Copenhagen: Danish Technical Press.

Fischer, E.M., & Schär, C. (2010). Consistent geographical patterns of changes in high-impact European heatwaves. *Nature Geoscience*, *3*, 398–403.

Fong, W.K., Sotos, M., Doust, M., Schultz, S., Marques, A., & Deng-Beck, C. (2015). *Global Protocol for Community-Scale Greenhouse Gas Emission Inventories.* Washington, D.C.: World Resources Institute. Retrieved from https://www.wri.org/publication/global-protocol-community-scale-greenhouse-gas-emission-inventories

Forest Research. (2005). *Regeneration of previously developed land: Bold Colliery Community Woodland: district valuer's report on property values.* Cockermouth, Cumbria: North West England Conservancy. Retrieved from https://www.forestresearch.gov.uk/tools-and-resources/urban-regeneration-and-greenspace-partnership/greenspace-in-practice/planning-integrated-landscapes/brownfield-regeneration/

Gagge, A., Stolwijk, J.A., & Nishi, Y. (1971). An effective temperature scale based on a simple model of human physiological regulatory response. *ASHRAE Transactions*, *77*(1), 247-257.

Gardner, J.W., & Sanborn, J.S. (1990). Years of potential life lost (YPLL) – what does it measure? *Epidemiology (Cambridge, Mass.)*, *1*(4), 322–329.

Gensler, the Urban Land Institute (ULI), & the Urban Investment Network (UIN). (2011). *Open Space: An asset without a champion?* San Francisco, CA: Gensler. Retrieved from https://www.gensler.com/uploads/document/220/file/Open_Space_03_08_2011.pdf

Gore, T., Ozdemiroglu, E., Eadson, W., Gianferrara, E., & Phang, Z. (2013). *Green Infrastructure's contribution to economic growth: A review. A Final Report for Department for Defra and Natural England.* July 2013. London: eftec. Retrieved from http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=19056

Gronlund, C.J., Zanobetti, A., Schwartz, J.D., Wellenius, G.A., & O'Neill, M.S. (2014). Heat, heat waves, and hospital admissions among the elderly in the United States, 1992-2006. *Environmental Health Perspectives*, *122*(11), 1187-1192.

Gross, A., Shmueli, O., Ronen, Z., & Raveh, E. (2007). Recycled vertical flow constructed wetland (RVFCW)-a novel method of recycling greywater for irrigation in small communities and households. *Chemosphere*, *66*(5), 916-623.

Guenther, A., Karl, T., Harley, P., Wiedinmyer, C., Palmer, P.I., & Geron, C. (2006). Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature). *Atmospheric Chemistry and Physics*, *6*(11), 3181–3210.

Hawkes, J. (2001). *The Fourth Pillar of Sustainability: Culture's essential role in public planning.* Melbourne, VIC: Common Ground Publishing Pty Ltd in association with the Cultural Development Network (Vic.). Retrieved from https://www.researchgate.net/profile/Jon_Hawkes/publication/200029531_The_Fourth_Pillar_of_Sustainability_Culture%27s_essential_role_in_public_planning/links/09e4150bde47d6a5c4000000.pdf

Hayes, D.C., & Young, R.L. 2005. *Comparison of Peak Discharge and Runoff Characteristic Estimates from the Rational Method to Field Observations for Small Basins in Central Virginia. Scientific Investigations Report 2005-5254*. Reston, VA: United States Geological Survey.

Health Effects Institute (HEI). (2018). *State of Global Air 2018. Special Report.* Boston, MA: Health Effects Institute.

Hopkins, J., & Anderson, B. (2016). *A Field manual for Groundwater-level Monitoring at the Texas Water Development Board. User Manual 52*. Retrieved from http://www.twdb.texas.gov/groundwater/docs/UMs/UM-52.pdf

Hostetler, M., & Escobedo, F. (2013). *What types of urban green space are better for carbon dioxide sequestration? Publication EC279, Department of Wildlife Ecology and Conservation, UF/IFAS Extension.* Original publication date March 2010. Revised January 2013. Reviewed February 2019. Retrieved from https://edis.ifas.ufl.edu/pdffiles/UW/UW32400.pdf

Hu, M., & Chen, R. (2018). A framework for understanding sense of place in an urban design context. *Urban Science*, *2*(2), 34.

Huovila, A., Airaksinen, M., Pinto-Seppä, I., Piira, K., Bosch, P., Penttinen, … H.-M., Kontinakis, N. (2017). CITYkeys Smart City Performance Measurement System. *International Journal for Housing Science*, *41*(2), 113–125.

Höppe, P. (1999). The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology*, *2466*, 71-75.

Iacob, O., Rowan, J.S., Brown, I.M., & Ellis, C. (2014). Evaluating wider benefits of natural flood management strategies: An ecosystem-based adaptation perspective. *Hydrology Research*, *45*(6), 774-787.

Ibes, D.C. (2015). A multi-dimensional classification and equity analysis of an urban park system: A novel methodology and case study application. *Landscape and Urban Planning*, *137*, 122–137.

Intergovernmental Panel on Climate Change (IPCC). (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Prepared by the National Greenhouse Gas Inventories Programme, Eggleston, S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (Eds.). Hayama, Japan: Institute for Global Environmental Strategies (IGES). Retrieved from https://www.ipcc-nggip.iges.or.jp/public/2006gl/.

Intergovernmental Panel on Climate Change (IPCC). (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the*

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Intergovernmental Panel on Climate Change. Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds.). Geneva, Switzerland: IPCC.

International Organization for Standardization (ISO). (2018). *Sustainable cities and communities — Indicators for city services and quality of life (ISO 37120:2018).* Retrieved from https://www.iso.org/standard/68498.html

Iojă, C.I., Grădinaru, S.R., Onose, D.A., Vânău, G.O., & Tudor, A.C. (2014). The potential of school green areas to improve urban green connectivity and multifunctionality. *Urban Forestry and Urban Greening*, *13*(4), 704–713.

Janhäll, S. (2015). Review on urban vegetation and particle air pollution – Deposition and dispersion. *Atmospheric Environment*, *105*, 130-137.

Jim, C. (2004). Green-space preservation and allocation for sustainable greening of compact cities. *Cities*, *21*(4), 311-320.

Johnson, M.S., Coon, W.F., Mehta, V.K., Steenhuis, T.S., Brooks, E.S., & Boll, J. (2003). Application of two hydrologic models with different runoff mechanisms to a hillslope dominated watershed in the northeastern US: a comparison of HSPF and SMR. *Journal of Hydrology*, *284*(1-4), 57-76.

Jongman, B. (2018). Effective adaptation to rising flood risk. *Nature Communications*, *9*, 1986.

Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., … Bonn, A. (2016). Nature-based solutions to climate change adaptation and mitigation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and Society*, *21*(2), 39.

Kabisch, N. & Haase, D. (2014). Green justice or just green? Provision of urban green spaces in Berlin, Germany. *Landscape and Urban Planning*, *122*, 129–139.

Kenway, S.J., Lant, P., & Priestly, T. (2011). Quantifying water-energy links and related carbon emissions in cities. *Journal of Water and Climate Change*, *2*, 247-259.

Kiehl, J. (2011). Lessons from Earth's past. *Science*, *331*(6104), 158-159.

Koffi, B. (2017). *Covenant of Mayors Default Emission Factors.* Brussels: European Commission. Retrieved from https://www.eumayors.eu/IMG/pdf/technical_annex_en.pdf

Kohsaka, R., Pereira, H.M., Elmqvist, T., Chan, L., Moreno-Peñaranda, R., Morimoto, Y., … Pearsell, G. (2013). Indicators for Management of Urban Biodiversity and Ecosystem Services: City Biodiversity Index. In *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities* (pp. 699–718). Dordrecht: Springer Netherlands.

Kuosa, H., Loimula, K., & Niemeläinen, E. (2014). *Vettä läpäisevät pinnoitteet ja rakenteet - Materiaalikehitys ja simulointitestaus. Tutkumusraportti VTT-R-05001-14*. Espoo, Finland: VTT Technical Research Centre Ltd. [Finnish] Retrieved from http://www.vtt.fi/files/sites/class/D2_5_CLASS_WP2_D2_Lab_and_Simulation_Results.pdf

Kristensen, P., & Bogestrand, J. (1996). *Surface Water Quality Monitoring. Topic Report 2/96*. Copenhagen: European Environment Agency. Retrieved from https://www.eea.europa.eu/publications/92-9167-001-4

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, *304*(5677), 1623-1627.

Langemeyer, J., Baró, F., Roebeling, P., & Gómez-Baggethun, E. (2015). Contrasting values of cultural ecosystem services in urban areas: the case of park Montjuïc in Barcelona. *Ecosystem Services*, *12*, 178-186.

Laprise, M., Lufkin, S., & Rey, E. (2015). An indicator system for the assessment of sustainability integrated into the project dynamics of regeneration of disused urban areas. *Building and Environment*, *86*, 29–38.

Leconte, F., Bouyer, J., Claverie, R., & Pétrissans, M. (2017). Analysis of nocturnal air temperature in districts using mobile measurements and a cooling indicator. *Theoretical and Applied Climatology*, *130*(1-2), 365-376.

Le Quéré, C., Andrew, R.M., Canadell, J.G., Sitch, S., Korsbakken, J.I., Peters, G.P.,… Zaehle, S. (2016). Global carbon budget 2016. *Earth System Science Data*, *8*, 1-45.

Li, Y., Wichmann, K., & Otterpohl, R. (2009). Review of the technological approaches for grey water treatment and reuses. *Science of the Total Environment*, *407*(11), 3439-3449.

Liu, Y.B., Gebremeskel, S., De Smedt, F., Hoffmann, L., & Pfister, L. (2004). Simulation of flood reduction by natural river rehabilitation using a distributed hydrological model. *Hydrology and Earth System Sciences*, *8*(6), 1129-1140.

Lundy, L., Ellis, J.B., & Revitt, D.M. (2012). Risk prioritisation of stormwater pollutant sources. *Water Research*, *46*, 6589-6600.

Maas, J., Verheij, R.A., Groenewegen, P.P., de Vries, S., & Spreeuwenberg, P. (2006). Green space, urbanity, and health: how strong is the relation? *Journal of Epidemiology and Community Health*, *60*, 587-592.

Maas, J., Verheij, R.A., de Vries, S., Spreeuwenberg, P., Schellevis, F.G., & Groenewegen, P.P. (2009). Morbidity is related to a green living environment. *Journal of Epidemiology and Community Health, 63*(12), 967-973.

MacKinnon, K., Sobrevila, C., & Hickey, V. (2008). *Biodiversity, climate change and adaptation: Nature-based solutions from the Word Bank portfolio.* Washington, D.C.: World Bank. Retrieved from https://openknowledge.worldbank.org/handle/10986/6216?locale-attribute=fr

Madureira, H., Nunes, F., Oliveira, J.V, Cormier, L., & Madureira, T. (2015). Urban residents' beliefs concerning green space benefits in four cities in France and Portugal. *Urban Forestry & Urban Greening*, *14*(1), 56-64.

Maes, J., Zulian, G., Günther, S., Thijssen, M., & Raynal, J. (2019). *Enhancing Resilience of Urban Ecosystems through Green Infrastructure. Final Report, EUR 29630 EN.* Luxembourg: Publications Office of the European Union. Retrieved from https://publications.europa.eu/en/publication-detail/-/publication/cc585ccd-3b0c-11e9-8d04-01aa75ed71a1/language-en/format-PDF/source-87798697

Maes, J., Zulian, G., Thijssen, M., Castell, C., Baró, F., Ferreira, A.M.., ... Teller, A. (2016). *Mapping and Assessment of Ecosystems and their Services. Urban Ecosystems.* Luxembourg: Publications Office of the European Union. Retrieved from http://ec.europa.eu/environment/nature/knowledge/ecosystem_assessment/pdf/102.pdf

Mallarach, J.M., & Marull, J. (2006). Impact assessment of ecological connectivity at the regional level: recent developments in the Barcelona Metropolitan Area. *Impact Assessment and Project Appraisal*, *24*(2), 127-137.

Martins, R., Ascenso, A., Mendonça, R., Mendes, R., Roebeling, P.C., Bodilis, C. & Augusto, B. (2018). *Pre-NBS Baseline Data for Front-Runner Cities. UNaLab Project, Milestone Report M3.1*. Aveiro, Portugal: CESAM & Department of Environment and Planning, University of Aveiro.

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Marull, J., Pino, J., Mallarach, J.M., & Cordobilla, M.J. (2007). A Land Suitability Index for Strategic Environmental Assessment in metropolitan areas. *Landscape and Urban Planning*, *81*(3), 200-212.

Marull, J., Pino, J., Tello, E., & Cordobilla, M.J. (2010). Social metabolism, landscape change and land-use planning in the Barcelona Metropolitan Region. *Land Use Policy*, *27*(2), 497-510.

Marulli, J., & Mallarach, J.M. (2005). A GIS methodology for assessing ecological connectivity: application to the Barcelona Metropolitan Area. *Landscape and Urban Planning*, *71*, 243–262.

McKinney, M. (2002). Urbanization, Biodiversity, and Conservation: The impacts of urbanization on native species are poorly studied, but educating a highly urbanized human population about these impacts can greatly improve species conservation in all ecosystems. *BioScience*, *52*(10), 883-890.

Mekonnen, M., & Hoekstra, A.Y. (2011). *National water footprint accounts: the green, blue and grey water footprint of production and consumption. Value of water research report 50; No. 50.* Delft, the Netherlands: UNESCO-IHE Institute for Water Education. Retrieved from http://doc.utwente.nl/76913/1/Report50-NationalWaterFootprints-Vol1.pdf

Met Office. (2010). National Meteorological Library and Archive Fact sheet 17 - Weather observations over land. Devon, United Kingdom: Met Office. Retrieved from https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/library-and-archive/library/publications/factsheets/factsheet_17-observations.pdf

Milne, R., & Brown, T.A. (1997). Carbon in the vegetation and soils of Great Britain. *Journal of Environmental Management*, *49*(4), 413–433.

Ministry of Transportation of Ontario (MTO). (1997). Ministry of Transportation of Ontario Drainage Management Manual. Ontario, Canada: Ministry of Transportation of Ontario. Retrieved from http://www.mto.gov.on.ca/english/publications/drainage-management.shtml

Miranda, A.I., Martins, H., Valente, J., Amorim, J.H., Borrego, C., Tavares, R., … Alonso, R. (2017). Case Studies: modeling the atmospheric benefits of urban greening, In D. Pearlmutter, C. Calfapietra, R. Samson, L. O'Brien, S. Ostoic, G. Sanesi, R. Alonso (Eds.), *The Urban Forest. Cultivating Green Infrastructures for People and the Environment* (pp. 89-99). New York: Springer International Publishing.

Miranda, A.I., Silveira, C., Ferreira, J., Monteiro, A., Lopes, D., Relvas, H., ... Roebeling, P. (2015). Current air quality plans in Europe designed to support air quality management policies. *Atmospheric Pollution Research*, *6*, 434-443.

Mirrhosseini, G., Srivastava, P., & Stefanova, L. (2013). The impact of climate change on rainfall Intensity-Duration-Frequency (IDF) curves in Alabama. *Regional Environmental Change*, *13*(S1), 25-33.

Mittermeier, R.A., Totten, M., Pennypacker, L.L., Boltz, F., Mittermeier, C.G., Midgley, G., … Langrand, O. (2008). *A Climate For Life: Meeting the Global Challenge.* Arlington: Conservation International CEMEX.

Mohan, S.V., Nithila, P., & Reddy, J. (1996). Estimation of heavy metals in drinking water and development of heavy metal pollution index. *Journal of Environmental Science and Health. Part A: Environmental Science and Engineering and Toxicology*, *31*(2), 283-289.

National Center for Atmospheric Research (NCAR) & University Corporation for Atmospheric Research (UCAR). (n.d.). Weather Research and Forecasting (WRF) Model Users' Page. Retrieved from http://www2.mmm.ucar.edu/wrf/users/

National Oceanic and Atmospheric Administration (NOAA). (n.d.). Weather Research and Forecasting model coupled to Chemistry (WRF-Chem). Retrieved from https://ruc.noaa.gov/wrf/wrf-chem/

Nelson, D.W., & Sommers, L.E. (1996). Total Carbon, Organic Carbon, and Organic Matter. In D.L. Sparks (Ed.), *Methods of Soil Analysis Part 3, Chemical Methods* (pp. 961-1010). Madison, WI: Soil Science Society of America, Inc.

Ng, J.A.I. (2015). Scale on Civic Consciousness (SCC) for the National Service Training Program. *International Journal of Humanities and Management Sciences*, *3*(3), 161-165.

Nicol, F., Humphreys, M. A., & Roaf, S. (2012). *Adaptive thermal comfort: principles and practice*. London: Routledge.

Nicolaides, N., Lilli, M., Stagakis, S., Somarakis, G., Chrysoulakis, N., Lemaitre, F. & Le Roux, X. (2019). Unpublished material adapted from *Chapter 3. Classification of Nature Based Solutions*. February 2019. WP6 – Capacity Building and Materialisation of Nature Based Solutions – NBS Handbook. A deliverable of the ThinkNature Horizon 2020 Coordination and Support Action.

Nuñez, L., Tornello, C., Puentes, N., & Moretton, J. (2012). Health risks associated with the presence of antibiotic resistant bacteria in greywater. *Ambiente e Agua*, *7*(1), 235-243.

Organisation for Economic Co-operation and Development (OECD). (2013). *Green Growth in Cities*. Paris, France: OECD Environment Directorate. Retrieved from https://doi.org/10.1787/9789264195325-en

Organisation for Economic Co-operation and Development (OECD). (2008). *Key Environmental Indicators*. Paris, France: OECD Environment Directorate. Retrieved from https://www.oecd.org/env/indicators-modelling-outlooks/37551205.pdf

Orhel, R.L., & Register, K.M. (2006). *Volunteer Estuary Monitoring. A Methods Manual. Second edition.* Washington, D.C: United States Environmental Protection Agency.

Pascal, M., Corso, M., Ung, A., Declercq, C., Medina, S. & Aphekom. (2011). *APHEKON-Improving knowledge and communication for decision making on air pollution and health in Europe, Guidelines for assessing the health impacts of air pollution in European cities, Work Package 5, Deliverable D5.* Saint-Maurice, France: French Institute for Public Health Surveillance.

Pineda, N., Jorba, O., Jorge, J., & Baldasano, J.M. (2004). Using NOAA AVHRR and SPOT VGT data to estimate surface parameters: application to a mesoscale meteorological model. *International Journal of Remote Sensing*, *25*(1), 129–143.

Prodanovic, P., & Simonovic, S.P. (2007). *Development of Rainfall Intensity Duration Curves for the City of London Under the Changing Climate. Water Resources Research Report No. 058.* London, Ontario, Canada: Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering.

Rafael, S., Vicente, B., Rodrigues, V., Miranda, A.I., Borrego, C., & Lopes, M. (2018). Impacts of green infrastructures on aerodynamic flow and air quality in Porto's urban area. *Atmospheric Environment*, *190*, 317-330.

Raymond, C.M., Berry, P., Breil, M., Nita, M.R., Kabisch, N., de Bel, M., ... Calfapietra, C. (2017). *An Impact Evaluation Framework to Support Planning and Evaluation of Nature-based Solutions Projects. Report prepared by the EKLIPSE Expert Working Group on Nature-based Solutions to Promote Climate Resilience in Urban Areas*. Wallingford, United Kingdom: Centre for Ecology and Hydrology.

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Reedyk, S., & Forsyth, A. (2006). *Using field chemistry kits for monitoring nutrients in surface water. Publication number PRO-121-2006-1.* Ottawa, Ontario, Canada: Agriculture and Agri-Food Canada PFRA. Retrieved from http://pfra.ca/doc/Water%20Quality/Water%20Quality%20Protection/using_field_chem_kits_final.pdf

Reynolds, W.D., & Elrick, D.E. (1990). Ponded infiltration from a single ring: I. Analysis of steady flow. *Soil Science Society of America Journal*, *54*, 1233-1241.

Reynolds, W.D., Elrick, D.E., & Youngs, E.G. (2002). Ring or Cylinder Infiltrometers (Vadose Zone). In J.H. Dane & G.C. Topp (Eds.), *Methods of Soil Analysis. Part 4 Physical Methods*. Madison, Wisconsin: Soil Science Society of America, Inc.

Riebeek, H. (2011) The Carbon Cycle: Feature Article. NASA Earth Observatory. Home. Web. 02 August 2011. http://earthobservatory.nasa.gov/Features/CarbonCycle/

Rizwan, A.M., Dennis, L.Y.C., & Liu, C., 2008. A review on the generation, determination and mitigation of Urban Heat Island. *Journal of Environmental Sciences*, *20*(1): 120-128.

Robinson, M., Moore, R.E., Nisbet, T.R., & Blackie, J.R. (1998). From moorland to forest: the Coalburn catchment experiment. Report No. 133. Wallingford, United Kingdom: Institute of Hydrology. Retrieved from http://nora.nerc.ac.uk/id/eprint/7372/

Roe, J.J., Ward Thompson, C., Aspinall, P.A., Brewer, M.J., Duff, E.I., Miller, D., … Clow, A. (2013). Green space and stress: Evidence from cortisol measures in deprived urban communities. *International Journal of Environmental Research and Public Health*, *10*, 4086-4103.

Roebeling, P., Saraiva, M., Palla, A., Gnecco, I., Teotónio, C., Fidélis, T., … Rocha, J. (2017). Assessing the socio-economic impacts of green/blue space, urban residential and road infrastructure projects in the Confluence (Lyon): a hedonic pricing simulation approach. *Journal of Environmental Planning and Management*, *60*(3), 482-499.

Rogers, K., Sacre, K., Goodenough, J., & Doick, K. (2015). *Valuing London's Urban Forest: Results of the London i-Tree Eco Project.* London: Treeconomics. Retrieved from https://www.london.gov.uk/sites/default/files/valuing_londons_urban_forest_i-tree_report_final.pdf

Roupsard, P., Amielh, M., Maro, D., Coppalle, A., & Branger, H. (2013). Measurement in a wind tunnel of dry deposition velocities of submicron aerosol with associated turbulence onto rough and smooth urban surfaces. *Journal of Aerosol Science*, *55*, 12-24.

Rowell, D.L. (2014). *Soil Science: Methods & Applications*. New York: Routledge.

Rupp, R. F., Vásquez, N. G., & Lamberts, R. (2015). A review of human thermal comfort in the built environment. *Energy and Buildings*, *105*, 178–205.

Russo, S., Dosio, A., Graversen, R., Sillmann, J., Carrao, H., Dunbar, M.B. …Vogt, J.V. (2014). Magnitude of extreme heat waves in present climate and their projection in a warming world. *Journal of Geophysical Research: Atmospheres*, *119*(22), 12500–12512.

Santamouris, M. (2007). Heat island research in Europe: The state of the art. *Advances in Building Energy Research, 1*(1), 123-150.

Scharlemann, J.P.W., Tanner, E.V.J., Hiederer, R., & Kapos, V. (2014). Global soil carbon: understanding and managing the largest terrestrial carbon pool. *Carbon Management*, *5*(1), 81-91.

Sharifi, A., & Murayama, A. (2013). A critical review of seven selected neighborhood sustainability assessment tools. *Environmental Impact Assessment Review*, *38*, 73–87.

Sharifi, A., & Murayama, A. (2014). Neighborhood sustainability assessment in action: Cross-evaluation of three assessment systems and their cases from the US, the UK, and Japan. *Building and Environment*, *72*, 243–258.

Shashua-Bar, L., Pearlmutter, D., & Erell, E. (2009). The cooling efficiency of urban landscape strategies in a hot dry climate. *Landscape and Urban Planning*, *92*(3-4), 179-186.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N.W., Clark, D.B., … Kabat, P. (2014). Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, *111*, 3245-3250.

Silveira C., Roebeling P., Lopes M., Ferreira J., Costa S., Teixeira J.P., ... Miranda A.I. (2016). Assessment of health benefits related to air quality improvement strategies in urban areas: An Impact Pathway Approach. *Journal of Environmental Management*, *183*, 694-702.

Singh, V.P. (Ed.). (1995). *Computer Models of Watershed Hydrology*. Highlands Ranch, CO: Water Resources Publications, LLC.

Sitterson, J., Knightes, C., Parmar, R., Wolfe, K., Muche, M., & Avant, B. (2017). *An Overview of Rainfall-Runoff Model Types. EPA Report Number EPA/600/R-17/482. September 2017.* Athens, GA: Office of Research and Development National Exposure Research Laboratory.

Smith, J.E., Heath, L.S., Skog, K.E., & Birdsey, R.A. (2006). *Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States. USDA Forest Service Report GTR-NE-343*. Newtown Square, PA: Northeastern Research Station, United States Department of Agriculture, Forest Service.

Snyder, D.T. (2008). *Estimated depth to Ground Water and Configuration of the Water Table in the Portland, Oregon Area. Scientific Investigations Report 2008-5059*. Reston, Virginia: United States Geological Survey. Retrieved from https://pubs.usgs.gov/sir/2008/5059/pdf/sir20085059.pdf

Soil Survey Staff. (2009). *Soil Survey Field and Laboratory Methods Manual. Soil Survey Investigations Report No. 51, Version 2.0. R. Burt (Ed.)*. Lincoln, NE: United States Department of Agriculture, Natural Resources Conservation Service.

Soini, K., & Birkeland, I. (2014). Exploring the scientific discourse on cultural sustainability. *Geoforum*, *51*, 213-223.

Stovin, V., Vesuviano, G., & Kasmin, H. (2012). The hydrological performance of a green roof test bed under UK climatic conditions. *Journal of Hydrology*, *414-415*, 148-161.

Strohbach, M.W., Döring, A.O., Möck, M., Sedrez, M., Mumm, O., Schneider, A.-K., … Schröder, B. (2019). The "hidden urbanization": Trends of impervious surface in low-density housing developments and resulting impacts on the water balance. *Frontiers in Environmental Science*, 7, 29.

Tallon, A. (2013). *Urban Regeneration in the UK*. Abingdon, Oxon: Routledge.

Tamosiunas, A., Grazuleviciene, R., Luksiene, D., Dedele, A., Reklaitiene, R., Baceviciene, M., … Niewenhuijsen, M.J. (2014). Accessibility and use of urban green spaces, and cardiovascular health: findings from a Kaunas cohort study. *Environmental Health*, *13*(1), 20.

Toledo, A.L.L., & La Rovere, E.L. (2018). Urban mobility and greenhouse gas emissions: Status, public policies, and scenarios in a developing economy city, Natal, Brazil. *Sustainability (Switzerland)*, *10*(11), 3995.

European Commission
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052
Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

Troiano, E., Beneduce, L., Gross, A., & Ronen, Z. (2018). Antibiotic-resistant bacteria in greywater and greywater-irrigated soils. *Frontiers in Microbiology*, *9*, 2666

Troy, A., & Grove, J.M. (2008). Property values, parks, and crime: A hedonic analysis in Baltimore, MD. *Landscape and Urban Planning*, *87*(3), 233-245.

Trumbore, S. (2009). Radiocarbon and soil carbon dynamics. *Annual Review of Earth and Planetary Sciences*, *37*, 47-66.

Tweed, C., & Sutherland, M. (2007). Built cultural heritage and sustainable urban development. *Landscape and Urban Planning*, *83*(1), 62-69.

Tyler, P., Warnock, C., Provins, A., & Lanz, B. (2013). Valuing the benefits of urban regeneration. *Urban Studies*, *50*, 169-190.

United Nations Educational, Scientific and Cultural Organization (UNESCO). (2001). UNESCO Universal Declaration on Cultural Diversity. Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000124687.page=67

United Nations Educational, Scientific and Cultural Organization (UNESCO). (2005). Convention on the Protection and Promotion of the Diversity of Cultural Expressions. Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000142919

United Nations Environment Programme (UNEP), International Labour Organization (ILO), International Organisation of Employers (IOE), & International Trade Union Confederation (ITUC). (2008). *Green Jobs: Towards Decent Work in a Sustainable, Low-Carbon World.* Nairobi, Kenya: United Nations Publishing Services Section. Retrieved from https://www.ilo.org/global/topics/green-jobs/publications/WCMS_158727/lang--en/index.htm

United Nations Environment Programme (UNEP), United Nations Educational, Scientific and Cultural Organization (UNESCO), World Health Organisation (WHO), United Nations (UN) Women, United Nations Office on Drugs and Crime (UNODC), World Bank Group … United Nations Statistics Division. (2016). *A Guide to Assist National and Local Governments to Monitor and Report on SDG Goal 11+ Indicators: Monitoring Framework, Definitions, Metadata, UN-Habitat Technical Support.* Nairobi, Kenya: UN-Habitat. Retrieved from http://unhabitat.org/sdg-goal-11-monitoring-framework/

United Nations (UN) General Assembly. (2015). *Transforming Our World: The 2030 Agenda for sustainable development. A/RES/70/1.* New York: United Nations. Retrieved from http://www.unfpa.org/sites/default/files/resource-pdf/Resolution_A_RES_70_1_EN.pdf

United Nations (UN) General Assembly (2017). Resolution adopted by the General Assembly on 6 July 2017. 71/313 Work of the Statistical Commission pertaining to the 2030 Agenda for Sustainable Development. 10 July 2017, A/RES/71/313. Retrieved from https://undocs.org/A/RES/71/313

United Nations Office for Disaster Risk Reduction (UNISDR). (2017). Disaster Resilience Scorecard for Cities – Preliminary level assessment. Retrieved from https://www.unisdr.org/campaign/resilientcities/toolkit/article/disaster-resilience-scorecard-for-cities

United States Department of Agriculture (USDA). (2004). *National Engineering Handbook Part 630 Hydrology*. Washington, D.C.: United States Department of Agriculture, natural Resources Conservation Service. Retrieved from https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/manage/hydrology/?cid=STELPRDB1043063

United States Department of Agriculture (USDA) Forest Service. (2019). i-Tree Eco Manual. Northern Research Station, USDA Forest Service. Retrieved from https://www.itreetools.org/resources/manuals/Ecov6_ManualsGuides/Ecov6_UsersManual.pdf

United States Environmental Protection Agency (US EPA). (2017). *Water Quality Standards Handbook: Chapter 3: Water Quality Criteria. EPA-823-B-17-001.* Washington, D.C.: EPA Office of Water, Office of Science and Technology. Retrieved from https://www.epa.gov/sites/production/files/2014-10/documents/handbook-chapter3.pdf

University of the West of England (UWE) Science Communication Unit. (2013). *Science for Environment Policy (issue 39): Brownfield Regeneration.* Bristol, United Kingdom: University of the West of England Science Communication Unit.

Van Hove, L.W.A., Jacobs, C.M.J., Heusinkveld B.G., Elbers, J.A., van Driel, B.L., & Holtslag, A.A.M. (2015). Temporal and spatial variability of urban heat island and thermal comfort within the Rotterdam agglomeration. *Building and Environment*, *83*, 91-103.

Viessman, W., & Lewis, G.L. (2003). *Introduction to Hydrology. 5th Edition*. Upper Saddle River, NJ: Prentice Hall.

Virginia Department of Transportation (VDOT). (2019). *Drainage Manual. Location and Design Division. Issued April 2002. Rev. March 2019.* Richmond, VA: Virginia Department of Transportation. Retrieved from http://www.virginiadot.org/business/resources/LocDes/DrainageManual/Combined_Drainage_Manual.pdf

Wamsler, C., Luederitz, C., & Brink, E. (2014). Local levers for change: Mainstreaming ecosystem-based adaptation into municipal planning to foster sustainability transitions. *Global Environmental Change*, *29*, 189-201.

Wang, X., & Huang, G. (2014). *Technical Report: Developing Future Projected IDF Curves and a Public Climate Change Data Portal for the Province of Ontario. Submitted to Ontario Ministry of the Environment.* Saskatchewan, Canada: Institute for Energy, Environment and Sustainable Communities (IEESC) of the University of Regina. Retrieved from http://www.ontarioccdp.ca/final_tech_report.pdf

Ward Thompson, C.W., Roe, J., Aspinall, P., Mitchell, R., Clow, A., & Miller, D. (2012). More green space is linked to less stress in deprived communities: Evidence from salivary cortisol patterns. *Landscape and Urban Planning*, *105*, 221-229.

Wendling, L.A., & Holt, E.E. 2019. Integrating engineered and nature-based solutions for urban stormwater management. In D.J. O'Bannon, (Ed.) *Women in Water Quality: Investigations by Prominent Female Engineers*. Zurich: Springer.

Wendling, L., Huovila, A., zu Castell-Rüdenhausen, M., Hukkalainen, M. & Airaksinen, M. (2018.) Benchmarking Nature-Based Solution and Smart City assessment schemes against the Sustainable Development Goal indicator framework. *Frontiers in Environmental Science*, *6*, 69.

Wood, S.L.R., Jones, S.K., Johnson, J.A., Brauman, K.A., Chaplin-Kramer, R., Fremier, A., … DeClerck, F.A. (2018). Distilling the role of ecosystem services in the Sustainable Development Goals. *Ecosystem Services*, *29*(Part A), 70-82.

Woolhiser, D.A., Smith, R.E., & Goodrich, D.C. (1990). *KINEROS, A kinematic runoff and erosion model: Documentation and user manual. ARS-77.* Washington, D.C.: United States Department of Agriculture, Agricultural Research Service. Retrieved from https://www.tucson.ars.ag.gov/unit/Publications/PDFfiles/703.pdf

European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

World Health Organization (WHO). (2006). *Air Quality Guidelines: Global Update 2005 - particulate matter, ozone, nitrogen dioxide and sulphur dioxide*. Copenhagen: WHO Regional Office for Europe. Retrieved from http://www.euro.who.int/__data/assets/pdf_file/0005/78638/E90038.pdf?ua=1

World Health Organization (WHO). (2008). *Health risks of ozone from long-range transboundary air pollution*. Copenhagen: World Health Organization. Retrieved from http://www.euro.who.int/__data/assets/pdf_file/0005/78647/E91843.pdf

World Health Organization (WHO). (2016a). *Ambient air pollution: A global assessment of exposure and burden of disease.* Geneva: World Health Organization. Retrieved from https://www.who.int/phe/publications/air-pollution-global-assessment/en/

World Health Organization (WHO). (2018). *Ambient (outdoor) air quality and health. Fact sheet 2 May 2018.* Geneva: World Health Organization. Retrieved from https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

World Health Organization (WHO). (2013). *Health risks of air pollution in Europe—HRAPIE project recommendations for concentration–response functions for cost–benefit analysis of particulate matter, ozone and nitrogen dioxide.* Copenhagen: World Health Organization, Regional Office for Europe.

World Health Organization (WHO). (2016b). *Urban green spaces and health: A review of evidence.* Copenhagen: World Health Organization, Regional Office for Europe.

World Health Organization (WHO). (2008). *Health risks of ozone from long-range transboundary air pollution.* Copenhagen: World Health Organization, Regional Office for Europe.

Yang, W-Y., Li, D., Sun, T., & Ni, G-H. (2015). Saturation-excess and infiltration-excess runoff on green roofs. *Ecological Engineering*, *74*, 327-336.

Youngs, E.G., Leeds-Harrison, P.B., & Elrick, D.E. (1995). The hydraulic conductivity of low permeability wet soils used as landfill lining and capping material: analysis of pressure infiltrometer measurements. *Journal of Soil Technology*, *8*, 153-160.

Yu, C., & Hien, W.N. (2006). Thermal benefits of city parks. *Energy and Buildings*, *38*, 105-120.

Zeng, Z., Tang, G., Hong, Y., Zeng, C. & Yang, Y. (2017). Development of an NRCS curve number global dataset using the latest geospatial remote sensing data for worldwide hydrologic applications. *Remote Sensing Letters*, *8*(6), 528-526.

Zheng, D., Ducey, M.J., & Heath, L.S. (2013). Assessing net carbon sequestration on urban and community forests of northern New England, USA. *Urban Forestry & Urban Greening*, *12*(1), 61-68.

Zheng, D., Heath, L.S., Ducey, M.J., & Smith, J.E. (2011). Carbon changes in conterminous US forests associated with growth and major disturbances: 1992–2001. *Environmental Research Letters*, ***6***, 014012.

Zumdahl, S.S., & DeCoste, D.J. (2012). *Chemical Principles*. *Seventh Edition.* Boston, MA: Cengage Learning.

8. Appendix I: NBS performance & impact assessment brainstorming

Every city has unique water- and climate-related challenges. In UNaLab WP5, we are implementing co-created NBS in front-runner cities to help mitigate the impacts of climate change. How will we assess the performance and impact of these NBS? How do we identify the most important considerations?

Please review the following table and rate each category as “low”, “moderate”, or “high” with respect to its relative importance in your city and/or likelihood that it will be affected by your planned NBS implementation.

	Low	Moderate	High
Air pollution			
Water pollution			
Water scarcity			
Flooding or storm sewer overflows			
Urban heating/heat island effect			
Coastal erosion			
Greenhouse gas emissions			
Biodiversity			
Noise pollution			
Accessibility of recreational (green) space			
Social cohesion			
Social justice			
Urban regeneration			
Outdoor educational opportunities			
Creation of new green business opportunities			

One more consideration that is important is the scale of the planned NBS intervention. For each of the categories that you identified as highly importance and/or highly affected by NBS, at what scale will your NBS intervention most likely have impact? (Only fill out the categories relevant to you)

	Building-Plot	Street-Neighborhood	District-City
Air pollution			
Water pollution			
Water scarcity			
Flooding or storm sewer overflows			
Urban heating/heat island effect			
Coastal erosion			
Greenhouse gas emissions			
Biodiversity			
Noise pollution			
Accessibility of recreational (green) space			
Social cohesion			
Social justice			
Urban regeneration			
Outdoor educational opportunities			
Creation of new green business opportunities			

European Commission

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 730052

Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions

9. Appendix II: Long list of potential indicators of NBS performance and impact

9.1 Potential indicators for use by all SCC-02-2016-2017 NBS projects

Indicator - Climate change adaptation and mitigation	Unit of measure	Metric	Source
Carbon sequestration	tonnes	Tonnes of carbon removed or stored per unit area (hectare) per unit time (year) (Zheng et al., 2013)	EKLIPSE
	tonnes	Total amount of carbon (tonnes) stored in vegetation (Davies et al., 2011)	EKLIPSE
Temperature reduction	°C	Decrease in mean or peak daytime local temperatures (°C) (Demuzere et al., 2014)	EKLIPSE
CO_2 emissions reduction	t / y	Reduction in carbon emissions from reduced building energy consumption	EKLIPSE
Energy savings	kWh / y	Reduction in energy usage from reduced building energy consumption	EKLIPSE
Indicator - Water management	**Unit of measure**	**Metric**	**Source**
Stormwater runoff	mm / %	Run-off coefficient in relation to precipitation quantities (Armson et al., 2013; Getter et al., 2007; Iacob et al., 2014; Scharf et al., 2012)	EKLIPSE
Water quality	TO BE DEFINED	SUGGESTED PARAMETERS AS APPROPRIATE BASED ON LOCAL CONDITIONS: pH; oxidative-reductive potential (ORP) or dissolved O_2 (DO); electrical conductivity (EC); turbidity, as indicator of total suspended solids (TSS); nitrate (NO_3^-); phosphate (PO_4^{3-}); chemical oxygen demand (COD); 5-day biological oxygen demand (BOD_5); total coliform bacteria by membrane filtration or MPN. Suggest monitoring/measurement of WQ parameters only as appropriate, e.g. option to not measure parameter(s) that are not applicable or not affected by NBS implementation. TF2.0 TO REVIEW WFD CHEMICAL PARAMETERS	
Indicator - Green space management	**Unit of measure**	**Metric**	**Source**
Accessibility of urban green spaces	time or distance	Average journey time for residents/employees by foot or average distance to green space (Tamosiunas et al., 2014)	

Public green space	total area or area per capita	Green space area (total area) or green space area (e.g. hectares) per city population	
Increased connectivity		Changes in the pattern of structural and functional connectivity (Iojă et al., 2014)	EKLIPSE
		Ecological connectivity (Pino and Marull, 2012)	EKLIPSE
Increase in pollinators	TO BE DEFINED	Suggested - total pollinator biomass or total number of pollinators per unit area (Tiago Freitas, personal communication, 16.3.2018)	
Conservation	Number per unit area	Number and abundance of species of conservation interest (#/ha)	MAES
Species diversity	Number per unit area	Number and abundance of, e.g., species of birds (#/ha)	MAES
Indicator - Air quality	**Unit of measure**	**Definition**	**Source**
Atmospheric pollutant flux		Flux of relevant atmospheric pollutants (PM_{10}, $PM_{2.5}$, NO_x, etc.) per area per year (Manes et al., 2016; Tallis et al., 2011)	EKLIPSE
Indicator - Economic opportunities and green jobs	**Unit of measure**	**Definition**	**Source**
Subsidies or tax deductions for NBS	Number	Number of subsidies or tax reductions applied for (private) NBS measures (Meulen et al., 2013).	EKLIPSE
Change in property value	% or €	Change in mean or median land and property prices (Forestry Commission, 2005).	EKLIPSE
Job creation	Number	Number of jobs created (Forestry Commission, 2005)	EKLIPSE
	€ / capita	Gross value added (Forestry Commission, 2005).	EKLIPSE
Ground floor usage OR Increased use of ground floors	% of m2	Percentage of ground floor surface of buildings that is used for commercial or public purposes as percentage of total ground floor surface OR Increase in ground floor space for commercial or public use due to the project as percentage of total ground floor surface	CITYkeys

Carbon sequestration	Built environment
Description incl. justification	Urban trees and green areas enhance climate resilience through direct carbon storage in plants and soils, which eventually decreases the energy demand for cooling, especially in warmer climates and reduces associated carbon emissions (from EKILPSE). Quantifying carbon sequestration can give the opportunity to mitigate GHG effects (Zheng et al., 2013), (Davies et al., 2011).
Definition	Tonnes of carbon removed or stored per unit area (hectare) per unit time (year) (Zheng et al., 2013) Total amount of carbon (tonnes) stored in vegetation (Davies et al., 2011)
Calculation	The i-Tree Eco model calculates the biomass for each measured tree using allometric equations from the literature. Biomass estimates are combined with base growth rates, based on length of growing season, tree condition, and tree competition, to derive annual biophysical accounts for carbon storage and carbon sequestration (Baró et al. (2015) Vegetation survey: Using GIS and dividing vegetation into categories in order to determine the vegetation height that is indicative of biomass (Davies et al. 2011) Biomass & carbon storage in trees: Allometric equations (Davies et al. 2011) Total above-ground tree biomass was transformed to a carbon storage figure using conversion factors of 0.48 for broadleaf and 0.42 for coniferous trees (Milne & Brown 1997 cited in Davies et al. 2011) Carbon storage in Herbaecous vegetation: biomass samples oven dried at 105°C for 24 hours, milling them into powder form and redrying at 105°C and the carbon content determined using a C:N analyser. The carbon stock per 25 · 25 cm quadrat was then calculated by multiplying the percentage carbon with the dry-weight of the sample. Carbon storage in woody vegetation: The carbon stored within woody vegetation was therefore estimated using a conversion factor of 18 t C ha)-1 taken from a study by Patenaude et al. (2003) (cited in Davies et al. 2011) Forest carbon sequestration (FCS) is usually estimated as a function of forest area, forest type, and forest age $\frac{FIArate}{FORESTmean-pct}$ x NONmean-pcti) x NONFareai where FIArate is net forest growth rate for the most common type group in county i (Smith et al., 2006), FORESTmean-pct is mean canopy cover percentage for all forested pixels in the county i, NONFmean-pct is mean canopy cover percentage for all nonforest pixels in county i, and NONFarea was area sum of all nonforest pixels in county i. (Zheng et al., 2013)
Strengths and weaknesses	Strengths Weaknesses: Access to reliable and accurate data could be an obstacle
Data requirements	
Expected data source	Forest Inventory Analysis, National Land Cover Database (NLCD), databases for housing density map
Expected availability	Fair?
Collection interval	Every year, every few years?
Expected reliability	Depends on the frequency of updates and accuracy of updates in the database
Expected accessibility	Users may need permission to gain access to national databases unless it is open data
References IPCC (2007) Calfapietra et al., 2015; Van Vuuren et al., 2011, (Davies et al., 2011; Pataki et al., 2006). (Zheng et al., 2013)	

Temperature reduction	Built Environment
Description incl. justification	It is evident that urban areas face temperature extremes NBS aim to enhance the cities resilience to such extremities. As an example, evapotranspiration of plants will reduce temperatures by creating a cooling effect that will subsequently reduce the energy demand for cooling and ameliorate heat island effects and heat stress
Definition	Decrease in mean or peak daytime local temperatures (°C) (Demuzere et al., 2014)
Calculation	Measures of human comfort e.g. ENVIMET PET — Personal Equivalent Temperature, or PMV — Predicted Mean Vote. Heatwave risks (number of combined tropical nights (>20°C) and hot days (>35°C) following Fischer, Schär, 2010, cited by Baró et al. (2015). Measurement (modelling) of day and night mean max and min. temperatures, with respect to baseline values (from EKLIPSE)
Strengths and weaknesses	Strengths: Changes at the micro level can be easily identified Weaknesses:
Data requirements	
Expected data source	National meteorological database
Expected availability	Good. Permission maybe required if accessing large quantities of data and the duration for which the data will be assessed
Collection interval	Yearly
Expected reliability	Good
Expected accessibility	Good.
References	

CO_2 emissions reduction	Built environment
Description incl. justification	Addressing CO2 emissions is a way to mitigate climate change i.e. mitigation improves a parameter's or driver's status through active or passive behaviour
Definition	Reduction in carbon emissions from reduced building energy consumption (tonnes/y)
Calculation	With reference to a baseline situation, the energy not consumed can be accounted for as a reduction of CO2 emissions
Strengths and weaknesses	Strengths: Holds the potential to dramatically affect climate resilience Weaknesses:
Data requirements	
Expected data source	Energy producers, Building Codes to understand how buildings are built (structure, insulation etc.) in the country in question
Expected availability	Good
Collection interval	Yearly
Expected reliability	Good. However, it requires data from all building typologies in order to know the overall CO2 savings
Expected accessibility	Permission will be needed from building companies and building energy suppliers to access the data
References EKILPSE	

Energy savings	Built Environment
Description incl. justification	The COP21 in Paris highlighted that as the world becomes more urbanized, local action is becoming increasingly important (UNFCCC, 2016). European Commission's Covenant of Mayors obliges European cities to establish an Action Plan to reduce their carbon emissions by over 20%, including by using NBS and through the sustainable management of green space. Each city will need to aim for carbon-neutral urban development.
Definition	Reduction in energy usage from reduced building energy consumption (kWh / y)
Calculation	With reference to a base line situation, the costs of energy not consumed (= saved) is accounted for as a benefit
Strengths and weaknesses	Strengths: Holds the potential to dramatically affect climate resilience and lead to cost savings Weaknesses:
Data requirements	
Expected data source	Energy producers, Building Codes to understand how buildings are built (structure, insulation etc.) in the country in question
Expected availability	Good
Collection interval	Yearly
Expected reliability	Good. However, it requires data from all building typologies in order to know the overall energy savings
Expected accessibility	Permission will be needed from building companies and building energy suppliers to access the data
References	

Stormwater runoff	Built Environment
Description incl. justification	Growing urban populations, pollution, and economic activities in urban areas place water resources under severe stress (Carter, 2011). Climate change is expected to exacerbate existing problems connected to urban water resources by changing rainfall patterns and temperature regimes. Intense precipitation events will more frequently produce run-off quantities which exceed the capacities of urban sewerage systems, and cities along rivers and coastlines are at increased risk of flooding, whereas in some regions changes in rainfall patterns will further increase the risk of water scarcity in urban areas.
Definition	Run-off coefficient in relation to precipitation quantities measured in mm/% (Armson et al., 2013; Getter et al., 2007; Iacob et al., 2014; Scharf et al., 2012)
Calculation	Methods for assessing the impacts of NBS relating to the management of urban water are based mainly on the modelling of water dynamics impacting the urban environment (water quantity and quality, flow and flow velocity, including evapotranspiration and infiltration, etc.). However, here assessment of run-off coefficients in relation to precipitation quantities (mm/%) (Armson et al., 2013; Getter et al., 2007; Iacob et al., 2014; Scharf et al., 2012) will be used.
Strengths and weaknesses	Strengths: Maintenance of urban green areas in hotter climates requires irrigation, contributing to increases in urban water demand (Pataki et al., 2011); this represents a potential opportunity for water re-use schemes. Weaknesses: Reduction of run-off requires spaces for storing the water in urban areas, which competes with other urban space needs.
Data requirements	
Expected data source	Weather data to be gathered from the national meteorology center, other data such as area information may be collected from city water management, building management or district authorities.
Expected availability	Good
Collection interval	Yearly
Expected reliability	Good.
Expected accessibility	Good
References	

Accessibility of urban green spaces	Built Environment, Transport
Description incl. justification	Green and blue spaces are useful instruments for urban planners in achieving a sustainable urban structure, and they have a significant cultural and social dimension. They can provide elements characterizing the heritage and aesthetics of the area (Madureira et al., 2011; Niemelä, 2014), as well as being valued for recreation (Fors et al., 2015), social interaction (Kaźmierczak, 2013), education (Krasny et al., 2013) and supporting healthy living (Carrus et al., 2015).
Definition	Average journey time for residents/employees by foot or average distance to green space (Tamosiunas et al., 2014)
Calculation	Accessibility (measured as distance or time) of urban green spaces for population (Tamosiunas et al., 2014).
Strengths and weaknesses	Strengths: Studies have shown the positive effects of urban green spaces on urban residents through psychological relaxation and stress relief (Roe et al., 2013; Ward Thompson et al., 2012) and enhanced opportunities for physical activity (Sugiyama and Ward Thompson, 2007). Studies have also identified positive health associations between distance to urban green spaces and potential health benefits, suggesting that being in proximity to urban green spaces (Maas et al., 2006) and viewing greenery (Dravigne et al., 2008; Ulrich, 1984; Ulrich, 2002) have positive health effects. Additional benefits include reduced depression (Bratman et al., 2015a) and improved mental health (Hartig et al., 2014; van den Berg et al., 2015; Vries et al., 2003); reduced cardiovascular morbidity and mortality (Gascon et al., 2016; Tamosiunas et al., 2014); improved pregnancy outcomes (Dadvand et al., 2012); and reduced obesity (Kim et al., 2014) and diabetes (Maas et al., 2009). Urban green space also provides opportunities for exploratory behaviour in children and improved functioning of the immune system (Kuo, 2015; Lynch et al., 2014) Weaknesses: allergic reactions, or vector-borne diseases, because of increased exposure to allergenic pollen or increased disease vectors in urban green environments (Bai et al., 2013; Calaza-Martinez and Iglesias-Díaz, 2016; Cariñanos and Casares-Porcel, 2011).
Data requirements	
Expected data source	Local city or district authorities
Expected availability	Good
Collection interval	Yearly
Expected reliability	Good
Expected accessibility	Good
References (Madureira et al., 2011; Niemelä, 2014), (Kaźmierczak, 2013), (Krasny et al., 2013), (Carrus et al., 2015), (Tamosiunas et al., 2014), (Roe et al., 2013; Ward Thompson et al., 2012), (Sugiyama and Ward Thompson, 2007), (Maas et al., 2006), (Dravigne et al., 2008; Ulrich, 1984; Ulrich, 2002), (Bratman et al., 2015a), (Hartig et al., 2014; van den Berg et al., 2015; Vries et al., 2003, (Gascon et al., 2016; Tamosiunas et al., 2014), (Dadvand et al., 2012), (Kim et al., 2014), (Maas et al., 2009), (Bai et al., 2013; Calaza-Martinez and Iglesias-Díaz, 2016; Cariñanos and Casares-Porcel, 2011)	

Public green space	Built Environment
Description incl. justification	Green and blue spaces (which are sometimes referred to as just “green spaces” for brevity) are areas based on natural and semi-natural elements which provide a range of ecological (Elmqvist et al., 2015), economic (Claus and Rousseau, 2012) and societal benefits (Gómez-Baggethun and Barton, 2013). A large variety of green and blue spaces exists, but all of them provide, to a greater or lesser extent, ecosystem services required for the resilience and sustainability of urban areas (Badiu et al., 2016).
Definition	Green space area (total area) or green space area (e.g. hectares) per city population
Calculation	Distribution of public green space – total surface or per capita (Badiu et al., 2016; Gómez-Baggethun and Barton, 2013; La Rosa et al., 2016). Also, GIS mapping using network analysis in order to take into account existing barriers and access ways, statistics (EKLIPSE)
Strengths and weaknesses	Strengths: Studies have shown the positive effects of urban green spaces on urban residents through psychological relaxation and stress relief (Roe et al., 2013; Ward Thompson et al., 2012) and enhanced opportunities for physical activity (Sugiyama and Ward Thompson, 2007). Studies have also identified positive health associations between distance to urban green spaces and potential health benefits, suggesting that being in proximity to urban green spaces (Maas et al., 2006) and viewing greenery (Dravigne et al., 2008; Ulrich, 1984; Ulrich, 2002) have positive health effects. Additional benefits include reduced depression (Bratman et al., 2015a) and improved mental health (Hartig et al., 2014; van den Berg et al., 2015; Vries et al., 2003); reduced cardiovascular morbidity and mortality (Gascon et al., 2016; Tamosiunas et al., 2014); improved pregnancy outcomes (Dadvand et al., 2012); and reduced obesity (Kim et al., 2014) and diabetes (Maas et al., 2009). Urban green space also provides opportunities for exploratory behaviour in children and improved functioning of the immune system (Kuo, 2015; Lynch et al., 2014) Weaknesses: allergic reactions, or vector-borne diseases, because of increased exposure to allergenic pollen or increased disease vectors in urban green environments (Bai et al., 2013; Calaza-Martinez and Iglesias-Díaz, 2016; Cariñanos and Casares-Porcel, 2011).
Data requirements	
Expected data source	Local city or district authority
Expected availability	Good
Collection interval	Good
Expected reliability	Good
Expected accessibility	Good
References (Elmqvist et al., 2015), (Claus and Rousseau, 2012) (Gómez-Baggethun and Barton, 2013), (Badiu et al., 2016), (Badiu et al., 2016; Gómez-Baggethun and Barton, 2013; La Rosa et al., 2016), (Madureira et al., 2011; Niemelä, 2014), (Kaźmierczak, 2013), (Krasny et al., 2013), (Carrus et al., 2015), (Tamosiunas et al., 2014), (Roe et al., 2013; Ward Thompson et al., 2012), (Sugiyama and Ward Thompson, 2007), (Maas et al., 2006), (Dravigne et al., 2008; Ulrich, 1984; Ulrich, 2002), (Bratman et al., 2015a), (Hartig et al., 2014; van den Berg et al., 2015; Vries et al., 2003, (Gascon et al., 2016; Tamosiunas et al., 2014), (Dadvand et al., 2012), (Kim et al., 2014), (Maas et al., 2009), (Bai et al., 2013; Calaza-Martinez and Iglesias-Díaz, 2016; Cariñanos and Casares-Porcel, 2011)	

Increased connectivity	Built Environment, Transport
Description incl. justification	Enhanced connectivity and multifunctionality of urban green infrastructure emphasizes the fact that these areas can be used to ameliorate the deficit of green space in major urban areas (Iojă et al., 2014).
Definition	Changes in the pattern of structural and functional connectivity (Iojă et al., 2014) Ecological connectivity (Pino and Marull, 2012)
Calculation	Comparing the overall linkage between NBS sites and the status of NBS implementation (Botzat et al., 2016) Questionnaires applied to the population for the recreational and cultural benefits of green spaces (Kabisch and Haase, 2014) Mapping of user values attached to green/blue areas (Raymond et al., 2016b; Vierikko and Niemelä, 2016; Wang et al., 2015a) Ecological and connectivity modelling for biodiversity benefits (Pino and Marull, 2012; Pirnat and Hladnik, 2016) Field surveys of (random) located plots, which are regularly resurveyed
Strengths and weaknesses	Strengths: Increasing opportunities for the citizen's to access green spaces at their own convenience, improved city aesthetics, provision of habitats for biodiversity Weaknesses: it takes time to change habits relating to exercise and thus derive the health benefits or build up attachments to places
Data requirements	
Expected data source	Local city or district authorities: to know changes previously done or those that will be done in the future, questionnaires for people to know their opinions
Expected availability	Good
Collection interval	Yearly
Expected reliability	Good
Expected accessibility	Good
References	
(Iojă et al., 2014) Ecological connectivity (Pino and Marull, 2012), (Botzat et al., 2016), (Kabisch and Haase, 2014), (Raymond et al., 2016b; Vierikko and Niemelä, 2016; Wang et al., 2015a), (Pino and Marull, 2012; Pirnat and Hladnik, 2016)	

Atmospheric pollutant flux	Built environment, Transport
Description incl. justification	Air quality is a major concern worldwide, particularly in urban areas, due to its direct consequences on human health. Vegetation affects air quality mainly through the removal of air pollutants (PM10, NO2, O3, CO, SO2) through dry deposition, although certain species can also emit biogenic volatile organic compounds (BVOC), which are ozone precursors. However, vegetation can also reduce the air temperature, which reduces the emission of BVOCs and slows down the creation of secondary pollutants such as ozone (Wang et al., 2015b; Calfapietra et al. 2013). Despite their limited contribution compared to the overall production of pollutants and GHG emissions at the city level, measures to tackle air quality by enhancing green infrastructure can be considered a good investment due to the number of co-benefits that they produce and their contribution to amenity value over time (Baró et al., 2015). A study by Manes et al. 82016) confirmed that the structural characteristics and functional diversity of forest types are the features that respectively affect the removal of PM10 and O3 most.
Definition	Flux of relevant atmospheric pollutants (PM10, PM2.5, NOx, etc.) per area per year (Manes et al., 2016; Tallis et al., 2011)
Calculation	Spatially-explicit models consider the differences in both urban forest structure and pollution concentrations in the different areas (Escobedo and Nowak, 2009). Manes et al. (2016) proposed a method based on the pollution flux approach to map air purification using spatially-explicit data on ecosystem types and characteristics (particularly leaf area index, LAI), and pollution distribution. i-Tree Eco can also be run in a spatially-explicit domain, in order to obtain spatial measures of air purification (Bottalico et al., 2016). Models to calculate deposition and capture of pollutants usually adopt hourly meteorological and pollution concentration data. Tallis et al. (2011) proposed and tested a useful approach that uses seasonal data instead Other (complex) numerical methods describe the interactions between vegetation and pollutants at the micro scale (Joshi and Ghosh, 2014) or simulate the emission and deposition processes based on trajectory and dispersion models, e.g. the atmospheric transport FRAME (Fine Resolution Atmospheric Multi-species Exchange) model (Bealey et al., 2007).
Strengths and weaknesses	Strengths: Weaknesses: NBS must be coupled with mitigation policies aimed at reducing emissions inside and outside urban areas to achieve a greater positive effect in air quality
Data requirements	
Expected data source	Air quality modeling systems widely used in air quality regulatory interventions and policies at the national level (Manes et al., 2016; Tallis et al., 2011), national forest ecosystem mapping system
Expected availability	Good
Collection interval	Yearly
Expected reliability	Fair - greatly depends on the frequency and accuracy of update
Expected accessibility	Good
References (Wang et al., 2015b; Calfapietra et al. 2013), (Baró et al., 2015), (Manes et al., 2016; Tallis et al., 2011), (Bottalico et al., 2016),	

Subsidies or tax deductions for NBS	Built Environment, ICT, Transport
Description incl. justification	Availability of incentives increases the probability of the measures to be put forward and resolve the challenges addressed by the city or state
Definition	Number of subsidies or tax reductions applied for (private) NBS measures (Meulen et al., 2013)
Calculation	Total number of available subsidies or tax reductions for the citizens
Strengths and weaknesses	Strengths: Increased willingness to invest as more of the co-benefits accrue to the initiator, increased competitive advantage for cities applying NBS measures (OECD, 2008) and creation of additional jobs in the green sector fuelled by new green investments Weaknesses:
Data requirements	
Expected data source	To be derived from municipalities, planning departments and interviews with residents
Expected availability	Data must be gathered and analysed to understand the extent of implementation and benefits gained
Collection interval	Before and after the implemention of NBS measures
Expected reliability	Unless the NBS measures are implemented by a large number of residents, the benefits gained from subsidies and tax deductions are difficult to assess
Expected accessibility	Information can be easily gathered from the authorities
References (Meulen et al., 2013) (OECD, 2008)	

Change in property value	Built Environment
Description incl. justification	In order to support decisions and choices between different options for NBS or alternative investments, the costs and benefits of each option need to be aggregated. The most common approach to this aggregation is based on economic (monetary) assessment methods which aggregate all monetary costs and expected benefits of the investment
Definition	Change in mean or median land and property prices (Forestry Commission, 2005) measured as a % or €.
Calculation	Change in trends for properties located closest to the NBS implementation site
Strengths and weaknesses	Strengths: Allowing for the general trend in property values, the calculation gives an direct indication of the usefulness of the NBS Weaknesses: Information may need to be gathered over a period months to gain a full understanding of the change in value
Data requirements	
Expected data source	To be derived from municipality departments and real estate offices
Expected availability	Data concerning previous years will need to be gathered and analysed to study the past trends
Collection interval	Before and after the NBS implementation
Expected reliability	Good, although several areas in the city will need to be studied
Expected accessibility	Good, information can be easily gathered from city office and real estate agencies
References (Forestry Commission, 2005)	

Job creation	
Description incl. justification	Research shows that increasing the green areas in the urban environment has considerable co-benefits. While contributing to meeting direct challenges, NBS generate co-benefits (Pearce et al., 2002) that can save money at household and government level and create economic opportunities for "Green businesses" (OECD, 2013). Furthermore, the introduction of NBS offers an opportunity for the creation of "Green-Collar Jobs", from low-skill, entry-level positions to high skill, higher-paid jobs (Apollo Alliance, 2008; Falxa-Raymond et al., 2013).
Definition	Number of jobs created (Forestry Commission, 2005) Gross value added (€/capita) (Forestry Commission, 2005)
Calculation	Number of jobs created from public employment records, number of jobs in specific sectors Creation of green jobs relating to construction and maintenance of NBS (Saraev, 2012)
Strengths and weaknesses	Strengths: Directly relates to socio-economic prosperity of the city Weaknesses:
Data requirements	
Expected data source	To be derived from municipalities and interviews with the residents
Expected availability	Good, data should be gathered for several areas to get a full insight
Collection interval	Before and after the NBS implementation
Expected reliability	Good, all job sectors must be taken into account
Expected accessibility	Good
References (Saraev, 2012) (Forestry Commission, 2005)	

Ground floor usage OR Increased use of ground floors	Built Environment
Description incl. justification	Making use of ground floors for commercial and public purposes can increase the liveability and atmosphere of a neighbourhood (Arlington, 2014). One can think of a variety of uses suitable for the ground floor, dependent on the location, including retail, personal and business services, retail equivalents such as educational and conferencing facilities, and arts and cultural resources. The potential for increasing the use for ground floor space lies mostly within residential and office buildings.
Definition	Percentage of ground floor surface of buildings that is used for commercial or public purposes as percentage of total ground floor surface OR Increase in ground floor space for commercial or public use due to the project as percentage of total ground floor surface (% of m2)
Calculation	(extra ground floor space used commercially/publically created by the project (in m2)/current total ground floor space (in m2) *100%
Strengths and weaknesses	Strengths: Absolute and objective value for ground floor usage. Weaknesses: Data are scattered. Definitions of public and commercial spaces can vary between cities.
Data requirements	
Expected data source	To be derived from design plans, building management, interviews with the project leader and with the department for urban planning within the local government
Expected availability	Good, data about ground floors can be easily be gathered
Collection interval	After project completion, or to be used ex-ante to evaluate plans
Expected reliability	Because of the subjectivity that cannot be excluded, this indicator is not 100% reliable.
Expected accessibility	Information on ground floor usage is specified in development plans
References Arlington County - Arlington Economic Development (2014). Ground Floor Retail & Commerce: Policy Guidelines and Action Plan for Arlington's Urban Villages	

9.2 City-level NBS performance and impact indicators

	Indicator - PEOPLE	Unit of measure	Metric	Source
1	Access to public open space	Likert scale	The extent to which public open space is available within 500 m	Adapted from CITYkeys
2		%	Average share of the built-up area of cities that is open space for public use for all, by sex, age and persons with disabilities. Identify population served by distance or travel time from public open space, overlying service area with socio-demographic data. Population with access to public open space (in %): $= 100 \times \frac{population\ with\ convenient\ access}{City\ population}$	SDG11 indicator 11.7.1
3		time or distance	Average journey time for residents/employees by foot or average distance to sports centre, recreation area, or green space	EKLIPSE
4	Access to public transport	Likert scale	The extent to which public transport is available within 500 m	CITYkeys
5			Public transport links: walking distance to nearest facilities	EKLIPSE
6	Public green space	km^2, % or km^2/hab	Quantification of public green spaces in the city, either direct value (area), percentage of area or area per inhabitant. Sum of the areas of public green spaces, Total area of green spaces divided by the total city area, Total area of green spaces divided by the number of inhabitants. Need land use data with specification of public green spaces. We could also calculate the total number of green spaces (public or not), including green roofs. Level of aggregation: city or neighbourhood.	Rizwan et al. 2008
7	Nature-based recreational opportunities	Number or %	Accessibility to public parks, gardens and playgrounds (more than 50 ha) (inhabitants within 10 km from a park)	MAES-urban
8		Number or %	Accessibility to public parks, gardens and playgrounds (between 10 and 50 ha) (inhabitants within 1 km from a park)	MAES-urban
9		Number or %	Accessibility to public parks, gardens and playgrounds (between 2,5 and 10 ha) (inhabitants within 10 km 500 m from a park)	MAES-urban
10		Number or %	Accessibility to public parks, gardens and playgrounds (between 0,75 and 2,5 ha, or smaller but important green spaces) (inhabitants within 250 m from a park)	MAES-urban
11			Weighted recreation opportunities provided by urban green infrastructure (Derkzen et al. 2015)	MAES-urban
12		Dimensionless	Nature based recreation opportunities (includes Natura 2000; includes bathing water quality) (dimensionless) (Zulian et al. 2013)	MAES-urban

13		km	Proximity of green infrastructure to green travel routes (km)	MAES-urban
14		Dimensionless	Green related social services provided to population (dimensionless) (Secco and Zulian 2008)	MAES-urban
15			Regression models on geo-referenced data (i.e. pictures or geo-tagged locations) (Tenerelli et al., 2016)	MAES-urban
16	Quality of public transport	Likert scale	The perception of users on the quality of the public transport service	CITYkeys
17	Access to vehicle sharing solutions for city travel	Number / 100 000	Number of vehicles available for sharing per 100 000 inhabitants	CITYkeys
18	Access to public amenities	Likert scale	The extent to which public amenities are available within 500 m	CITYkeys
19	Encouraging a healthy lifestyle	Likert scale	The extent to which policy efforts are undertaken to encourage a healthy lifestyle	CITYkeys
20	Improved human health and well-being	Multiple	Physical and mental health (increase in number of people engaged in sports, decrease in respiratory disease and obesity, decline in premature death during heat waves). Level of aggregation: city.	EKLIPSE, Kabisch et al. 2016
21	Crime rate	Number / 100 000	Number of violent incidents, annoyances and crimes per 100 000 population	CITYkeys
22	Public safety		Level of devices contributing to the safety of users in the neighbourhood: lighting of common areas, access control, presence of technical, or specialized staff, etc.	EKLIPSE
23			Bodily integrity: being able to move freely from place to place; to be secure against violent assault, including indicators of crime by time of day (Felson and Poulsen, 2003).	EKLIPSE
24			Proportion of persons victim of physical or sexual harassment, by sex, age, disability status and place of occurrence, in the previous 12 months	SDG11 indicator 11.7.2
25	Cybersecurity	Likert scale	The level of cybersecurity of the cities' systems	CITYkeys
26	Data privacy	Likert scale	The level of data protection by the city	CITYkeys
27	Length of bike route network	% in km	% of bicycle paths and lanes in relation to the length of streets (excluding motorways)	CITYkeys
28	Land devoted to roads	%	Percentage of city surface occupied by roads	EKLIPSE
29	Road density	km / ha	Length of the road network per area	MAES-urban
30	Leapfrog development index	km	Leapfrog development relates to land development in a manner that requires the extension of public facilities. Calculate as minimum distance of new development to pre-existing ones, based on land use data. Level of aggregation: city.	Pozoukidou and Ntriankos (2017)

31	Linearity development index	km	Quantify the extent to which new development follow existing roads. Minimum distances of new development to major road axis based on land use data. Level of aggregation: city.	Pozoukidou and Ntriankos (2017)
32	Area for pedestrians	%	Proportion of land dedicated to pedestrians as a percentage of the road network	EKLIPSE
33	Access to public amenities	% of people	Share of population with access to at least one type of public amenity within 500 m	CITYkeys
34	Environmental education	% of schools	The percentage of schools with environmental education programs	CITYkeys
35	Nature-based education	Number	Accessibility of parks from schools (number of public parks and gardens within a defined distance from a school)	MAES-urban
36	Perceptions of urban nature		Perceptions of citizens on urban nature (Buchel and Frantzeskaki, 2015; Colding and Barthel, 2013; Gerstenberg and Hofmann, 2016; Scholte et al., 2015; Vierikko and Niemelä, 2016)	EKLIPSE
37	Social values for urban ecosystems and biodiversity		Social values for urban ecosystems and biodiversity (Brown and Fagerholm, 2014; Kenter et al., 2015; Polat and Akay, 2015; Raymond et al., 2014, 2009; Scholte et al., 2015)	EKLIPSE
38	Social justice		The availability and distribution of different types of parks and/or ecosystem services with respect to specific individual or household socioeconomic profiles and landscape design (Cohen et al., 2012; Ernstson, 2013; Ibes, 2015; Kabisch and Haase, 2014; Raymond et al., 2016b; Shanahan et al., 2014)	EKLIPSE
39	Senses, imagination and thought		Ability to use the senses, to imagine, think, and reason about the environment, informed by indicators of levels of literacy, mathematics and science knowledge (Chen and Luoh, 2010; Elliott et al., 2001)	EKLIPSE
40	Emotions		Ability to have attachments to things and people outside ourselves; to love those who love and care for us, including indicators of place attachment, empathy and love (Lawrence et al., 2004; Manzo and Devine-Wright, 2014; Perkins et al., 2010; Raymond et al., 2010)	EKLIPSE
41	Social cohesion		Structural aspects: indicators of family and friendship ties; participation in organised associations; integration into the wider community (Cozens and Love, 2015; Stafford et al., 2003).	EKLIPSE
42			Cognitive aspects: indicators of trust, attachment to neighbourhood, practical help, tolerance and respect (Mihaylov and Perkins, 2014; Uzzell et al., 2002).	EKLIPSE
43	Access to housing		Housing affordability and choice	EKLIPSE
44	Diversity of housing	Simpson Diversity Index / Social Housing	Simpson Diversity Index of total housing stock in the project area OR Percentage of social dwellings as share of total housing stock in the project area	CITYkeys
45	Affluence		Access to financial resources, including indicators of income per capita in a given neighbourhood, or urban area (Klasen, 2008)	EKLIPSE

46	Preservation of cultural heritage	Likert scale	The extent to which preservation of cultural heritage of the city is considered in urban planning	CITYkeys
47	Protection of cultural heritage	Number or % per unit area	Cultural or natural heritage sites (e.g. UNESCO world heritage sites)	MAES-urban
48	Access to cultural facilities	time or distance	Average journey time for residents on foot or average distance to cultural centre	EKLIPSE
49	Ground floor usage	% of m2	Percentage of ground floor surface of buildings that is used for commercial or public purposes as percentage of total ground floor surface	CITYkeys
50	Public outdoor recreation space	m2 / capita	Square meters of public outdoor recreation space per capita	CITYkeys
51	Green space	hectares / 100 000	Green area (hectares) per 100 000 population	CITYkeys
52	Blue space	%, hectares, or ha/100 000	Urban area covered by blue spaces (ponds, rivers, lakes). Level of aggregation: city or neighbourhood.	CITYkeys
53	Green space to built form ratio	Number	Ratio of urban open space to built form	EKLIPSE
54	Flood risk - urban infrastructure	Probability	Inundation risk for critical urban infrastructure (Pregnolato et al., 2016)	EKLIPSE
55	Flood risk - material damage	€	Stage-damage curves relating depth and velocity of water to material damage (de Moel et al., 2015)	EKLIPSE
56	Recreational value	Number / 100 000	Number of visitors, or number of recreational activities (Kabisch and Haase, 2014)	EKLIPSE
57	Cultural value	Number/ 100 000	Number of cultural events, people involved, or children in educational activities (Kabisch and Haase, 2014)	EKLIPSE
	Indicator - PLANET	Unit of measure	Metric	Source
58	Annual final energy consumption	MWh/capita/year	Annual final energy consumption for all uses and forms of energy. Quantify the changes in energy consumption that can come from increased cooling, increased heating in individual dwellings or any other changes. Can be separated in categories (e.g. buildings, transport, ICT energy consumption). Level of aggregation: city or neighbourhood.	CITYkeys
59	CO2 emissions	t CO2/capita/year	CO2 emissions in tonnes per capita per year	CITYkeys
60		t CO2/capita/year	Resource efficiency in the urban system (CO2 emissions per capita, CO2 emissions for transportation per capita, etc.) (OECD, 2013)	EKLIPSE

61	Carbon stored	t/ha/y	Tonnes of carbon removed or stored per unit area (hectare) per unit time (year) (Zheng et al., 2013)	EKLIPSE
62		tonnes	Total amount of carbon (tonnes) stored in vegetation (Davies et al., 2011)	EKLIPSE
63		tonnes	Total carbon storage calculated using allometric forest models of carbon sequestration, developed using proxy data obtained from Lidar data (Giannico et al., 2016)	EKLIPSE
64		tonnes	Total carbon storage calculated using growth rates derived from Forest Inventory Analysis (Zheng et al., 2013)	EKLIPSE
65		t C / ha	Carbon storage in soil	MAES-urban
66		t / ha / y	Carbon sequestration	MAES-urban
67	Stormwater runoff	mm / %	Run-off coefficient in relation to precipitation quantities (Armson et al., 2013; Getter et al., 2007; Iacob et al., 2014; Scharf et al., 2012)	EKLIPSE
68	NBS stormwater retention capacity	m3	Absorption capacity of green surfaces, bioretention structures and single trees (Armson et al., 2013; Davis et al., 2009)	EKLIPSE
69	Flood protection by appropriate land coverage	%	Share of green areas in zones of danger from floods	MAES-urban
70		% / area	Population exposed to flood risk	MAES-urban
71		ha	Areas exposed to flooding	MAES-urban
72	Evapotranspiration		Evapotranspiration measured/modelled (Litvak and Pataki, 2016)	EKLIPSE
73	Water flow regulation and run-off mitigation	mm	Soil water storage capacity	MAES-urban
74		cm	Soil water infiltration capacity	MAES-urban
75		t / km2	Water retention capacity by vegetation and soil	MAES-urban
76		m3 / y	Intercepted rainfall	MAES-urban
77		mm	Surface runoff	MAES-urban
78	Water consumption	litres/capita/year	Total water consumption per capita per day	CITYkeys
79	Grey water and rainwater use	% of houses	Percentage of houses equipped to reuse grey water and rainwater	CITYkeys
80	Nutrient pollution of water	kg / y	Total nutrient load within all water discharged to local waterbodies	EKLIPSE
81	Metal pollution of water	g / y	Total metal load within all water discharged to local waterbodies	EKLIPSE
82	Wastewater treatment	%	Proportion of wastewater safely treated	SDG11 indicator 6.3.1
83	Drought risk	Probability	Drought risk (probability)	EKLIPSE

84	Groundwater quality	%	Proportion of groundwater resources contaminated by nutrients, metals/metalloids, organic compounds or other pollutants.	
85	Groundwater availability	metres	Depth to groundwater (Feyen and Gorelick, 2004)	EKLIPSE
86	Water Exploitation Index	% of m3	Annual total water abstraction as a percentage of available long-term freshwater resources in the geographically relevant area (basin) from which the city gets its water	CITYkeys
87	Surface water / groundwater for drinking	m3 / ha / y	Drinking water provision	MAES-urban
88		m3 / y	Drinking water consumption	MAES-urban
89	Surface water / groundwater for non-potable use	m3 / ha / y	Water provision	MAES-urban
90		m3 / y	Water consumption per sector	MAES-urban
91	Population density	Number / km2	Number of people per km2	CITYkeys
92		Number / ha	Number of inhabitants per ha	MAES-urban
93	Local food production	% of tonnes	Share of food consumption produced within a radius of 100 km	CITYkeys
94	Cultivated crops	t / ha / y	Vegetables produced by urban allotments and in the commuting zone	MAES-urban
95		ha	Surface of community gardens / small agricultural plots for self-consumption	MAES-urban
96	Pollination	Dimensionless	Capacity of ecosystems to sustain insect pollinator activity (Zulian et al. 2013)	MAES-urban
97		Number / area	Relative abundance of insect pollinators	MAES-urban
98	Urban sprawl	%	Percent of built-up area	MAES-urban
99		open space / built form	Ratio of urban open space to built form. Open spaces are spaces undeveloped and accessible to the public (EPA). Area of open space divided by built area. Level of aggregation: city or neighbourhood.	EKLIPSE
100		Number	Ratio of land consumption rate to population growth rate	SDG11 indicator 11.3.1
101		Number	Decentralisation. Proportion of the population living outside the city core. Calculate as (PopR - PopC)/PopC, where PopC = population living in the core of the city and PopR = population living outside city core, using census data. Level of aggregation: city.	Arribas-Bel (2011)
102	Contiguity	%	Measure of the closeness of urban patches (has been shown to have an impact on urban heating). Measure with the spatial metric PLADJ (percentage of like adjencies of urban patches) with the FRAGSTATS software. Need land use data with information on urban patches. Level of aggregation: city.	Debbage and Shepherd (2015)
103		m2 / person	Artificial area per inhabitant	MAES-urban

104	Land use and land use intensity	m2 / person	Land annually taken up for built-up areas per person	MAES-urban
105		Number / km2	Residential density: population density in residential area. Number of residents divided by their residential area based upon population (census) and land use data. Level of aggregation: residential area.	EEA (2006), Kasanko (2006), Sidentop and Fina (2010)
106		%	Proportion of urban green space	MAES-urban
107		%	Proportion of impervious surface area. Indicator for flooding (reduced water infiltration), urban sprawl (relates to change in land use) and urban heating (impervious surfaces increase the surface temperatures, especially asphalt). Area of impervious surfaces divided by the total urban area based on land use data. Level of aggregation: city or neighbourhood.	MAES-urban; Yuan & Bauer
108		%	Percent of built-up area to describe urban sprawl pattern. Built up area divided by total urban area, based on land use data. Level of aggregation: city of neighbourhood.	EEA (2006)
109		%	Share of low/dense residential areas. Describe the residential patterns of the area: Low density areas are areas with less than 80% of built-up areas (buildings, roads and other structures). Calculate as Dense (low density) area / Total residential areas using land use data with dense and low density areas specified. Level of aggregation: city.	EEA (2006)
110		Patches/km^2, patches/ inhabitants	Scattering Index. Differentiate urban sprawl from compact urban expansion: characterize how are urban patches dispersed in the landscape. Patches = urban areas laying less than 200m apart. Measure as Number of patches / Total area or Number of patches / number of inhabitants using land use data with the urban patches delimited. Level of aggregation: city.	Arribas-Bel (2011)
111		%	Proportion of natural area	MAES-urban
112		%	Proportion of protected area	MAES-urban
113		km2 or ha	Loss of environmentally fragile land: environmentally fragile land lost due to urban sprawl, based on land use data. In the context of NBS it can be rather a "gain" in environmental fragile lands, since new ecological spaces will be added to the landscape. Level of aggregation: city or neighbourhood.	MAES-urban, Johnson (2001)
114		%	Proportion of agricultural area	MAES-urban
115		%	Proportion of abandoned area	MAES-urban
116	Land use mix	Number (0-1)	Simpson's index : $\frac{1-\sum_1^m p_i}{1-1/m}$where pi is the proportion of the category i in the sample, and m the total quantity of classed of land use. Calculate based on land use data. Level of aggregation: city or neighbourhood.	Arribas-Bel (2011)
117	Brownfield use	% of km2	Share of brownfield area that has been redeveloped in the past period as percentage of total brownfield area	CITYkeys

118	Urban forest pattern	ha	Canopy coverage	MAES-urban
119	Urban tree health		Foliage damage crown dieback; measurements based on visual inspection of trees	MAES-urban
120	Climate resilience strategy	Likert scale	The extent to which the city has developed and implemented a climate resilience strategy	CITYkeys
121	Temperature and human comfort	°C	Mean or peak daytime local temperatures (°C) (Demuzere et al., 2014)	EKLIPSE
122		Comfort Index	Measures of human comfort e.g. ENVIMET PET — Personal Equivalent Temperature, or PMV — Predicted Mean Vote	EKLIPSE
123		Number	Number of combined tropical nights (>20°C) and hot days (>35°C) (Fischer, Schär, 2010, cited by Baró et al. 2015)	EKLIPSE
124		Index	Leaf Area Index	MAES-urban
125		°C / m2	Temperature decrease as a function of tree cover	MAES-urban
126			Cooling capacity of urban green infrastructure (Derkzen et al., 2015; Grêt-Regamey et al., 2014; Zardo et al.)	MAES-urban
127		% / area	Population exposed to high temperatures	MAES-urban
128	Albedo	Number (0-1)	Reflecting power of urban surfaces. Calculated using satellite imagery or modelling data: average albedo or an area. Need information about surface materials and their corresponding albedo. Level of aggregation: building, neighbourhood or city.	Rizwan et al (2008)
129	Energy demand for cooling	MWh/capita/year	Annual final energy consumption for cooling (Demuzere et al., 2014)	EKLIPSE
130	Urban Heat Island	°C UHImax	Maximum difference in air temperature within the city compared to the countryside during the summer months	CITYkeys
131	Nitrogen oxide emissions (NOx)	g / capita	Annual nitrogen oxide emissions (NO and NO2) per capita	CITYkeys
132	Fine particulate matter emissions (PM2.5)	g / capita	Annual particulate matter emissions (PM2.5) per capita	CITYkeys
133	Air quality index	Index	Annual concentration of relevant atmospheric pollutants	CITYkeys
134	Atmospheric pollutant flux	g / m2 / year	Flux of relevant atmospheric pollutants per area (m2) per year (Manes et al., 2016; Tallis et al., 2011)	EKLIPSE
135	Air pollution	µg / m3	Concentration of NO2, PM10, PM2.5, O3	MAES-urban
136		Number	Number of annual occurrences of maximum daily 8-hour mean of O3 >120 µg/m3	MAES-urban
137		Number	Number of annual occurrences of 24-hour mean of PM10 >50 µg/m3	MAES-urban
138		Number	Number of annual occurrences of hourly mean of NO2 >200 µg/m3	MAES-urban

139	Regulation of air quality by urban trees and forests	kg / ha / y	Pollutants removed by vegetation (in leaves, stems, and roots)	MAES-urban
140		mm / s	Dry deposition rate	MAES-urban
141		% on surface area	Population exposed to high concentrations of atmospheric pollutants	MAES-urban
142	Share of green and water spaces	% in km2	Share of green and water surface area as percentage of total land area	CITYkeys
143	Noise mitigation by urban vegetation	m	Leaf Area Index + distance to roads (m)	MAES-urban
144		dB(A) / m2	Noise reduction rates applied to urban green infrastructure within a defined road buffer dB(A) per m2 vegetation unit (Derkzen et al. 2015)	MAES-urban
145	Sky View factor	Number (0-1)	Portion of the sky visible from the ground. Calculate using digital models as the RayMan Model or SOLWEIG. Data needed: Digital Elevation Model or Fish Eye Photographs. Level of aggregation: individual site(s)/location(s) within the city.	Hämmerle et al (2011)
146	Connectivity of urban green infrastructure	%	Connectivity of green infrastructure	MAES-urban
147		Mesh density per pixel	Fragmentation of green infrastructure	MAES-urban
148		Mesh density per pixel	Fragmentation by artificial areas	MAES-urban
149	Ecological connectivity	Number	Dispersion of natural patches that influence the movement of species between habitats, useful for comparison. Calculate using the Proximity index (PROX) of the FRAGSTATS software. Need land use data with natural patches delimited.	EKLIPSE, Ioja et al (2014)
150	Urban continuity	Yes/No	State if an urban area is continuous or not according to European standards. If there is more than 80% of built-up area --> Yes, else No. Level of aggregation: city of neighbourhood.	EEA (2006)
151	Number of native species	Number	Number of native species	CITYkeys
152	Species diversity	Number / ha	Number and abundance of bird species	MAES-urban
153		Number	Number of different (e.g. lichen) species	MAES-urban
154	Conservation	Number / ha	Number and abundance of species of conservation interest	MAES-urban
155	Introductions	Number	Number of alien species	MAES-urban
	Indicator - PROSPERITY	Unit of measure	Metric	Source
156	Stormwater treatment cost	€ / 100 000	Cost of stormwater treatment in public sewerage system (€) per 100 000 city inhabitants (Deng et al., 2013; Soares et al., 2011; Xiao and McPherson, 2002)	EKLIPSE
157	Unemployment rate	% of people	Percentage of the labour force unemployed	CITYkeys

158	Youth unemployment rate	% of people	Percentage of youth labour force unemployed	CITYkeys
159	Affordability of housing	% of people	% of population living in affordable housing	CITYkeys
160	Share of certified 'green' companies	% of companies	Share of companies based in the city holding an ISO 14001 certificate	CITYkeys
161	Share of Green Public Procurement	% in €	Percentage annual procurement using environmental criteria as share of total annual procurement of the city administration	CITYkeys
162	Green jobs	% of jobs	Share of jobs related to environmental service activities that contribute substantially to preserving or restoring environmental quality	CITYkeys
163	Freight movement	# of movements	Freight movement is defined as the number of freight vehicles moving into an area (e.g. the city)	CITYkeys
164	Gross Domestic Product	€ / capita	City's gross domestic product per capita	CITYkeys
165	New business registered	Number / 100 000	Number of new businesses per 100,000 population	CITYkeys
166	Median disposable income	€ / household	Median disposable annual household income	CITYkeys
167	Creative industry	% of people	Share of people working in creative industries	CITYkeys
168	Innovation hubs in the city	Number / 100 000	Number of innovation hubs in the city, whether private or public, per 100 000 inhabitants	CITYkeys
169	Accessibility of open data sets	Number of stars	The extent to which the open city data are easy to use	City Protocol
170	Research intensity	% in euros	R&D expenditure as percentage of city's GDP	CITYkeys
171	Open data	Number / 100 000	Number of open government datasets per 100 000 inhabitants	CITYkeys
172	Congestion	% in hours	Increase in overall travel times when compared to free flow situation (uncongested situation)	CITYkeys
173	Net migration	Number / 1000	Rate of population change due to migration per 1000 inhabitants	CITYkeys
174	Population Dependency Ratio	Number / 100	Number of economically dependent persons (net consumers) per 100 economically active persons (net producers)	CITYkeys
175	International Events Held	Number / 100 000	The number of international events per 100 000 inhabitants	CITYkeys
176	Tourism intensity	Number / 100 000	Number of tourist nights per year per 100 000 inhabitants	CITYkeys
	Indicator - GOVERNANCE	Unit of measure	Metric	Source

177	Cross-departmental integration	Likert scale	The extent to which administrative departments contribute to NBS initiatives and management	Adapted from CITYkeys
178	Establishment within the administration	Likert scale	The extent to which the city's NBS strategy has been assigned to one department/director and staff resources have been allocated	Adapted from CITYkeys
179	Monitoring and evaluation	Likert scale	The extent to which the progress towards a climate-resilient city and compliance with requirements is being monitored and reported	Adapted from CITYkeys
180	Availability of government data	Likert scale	The extent to which government information is published	CITYkeys
181	Legitimacy of knowledge in participatory processes		Legitimacy of knowledge in participatory processes (Frantzeskaki and Kabisch, 2016; Luyet et al., 2012).	EKLIPSE
182	Participation in political choices		Ability of citizens to participate effectively in political choices that govern one's life, including indicators on level and quality of public participation in environmental management (Reed, 2008; Reed et al., 2009).	EKLIPSE
183	Direct participation structure of civil society in urban planning and management that operate regularly and democratically	Likert scale	A questionnaire with 5-point Likert scale (1-very low, 2-low, 3-moderate, 4-high and 5-very high) is used to test the level of participation from objective viewpoint: 1. Level of citizen involvement in urban income and expenditure agreements, 2. Supervision and criticism on the performance of urban management, 3. Membership in social foundations and organizations, 4. Level and diversity of cooperation in city planning/budgeting/ procurements 5. Participation in urban planning designs and agreements.	Adapted from SDG11 indicator 11.3.2
184	Citizen participation	% of projects	The number of projects in which citizens actively participated as a percentage of the total projects executed	CITYkeys
185	Openness of participatory processes		Openness of participatory processes (Frantzeskaki and Kabisch, 2016; Luyet et al., 2012; Uittenbroek et al., 2013)	EKLIPSE
186	Open public participation	Number / 100 000	Number of public participation processes per 100 000 per year	CITYkeys
187	Voter participation	% of people	% of people that voted in the last municipal election as share of total population eligible to vote	CITYkeys
188	City climate change adaptation policy	Likert	The extent to which the city has a supportive climate change adaptation city policy	Adapted from CITYkeys
189	Expenditures by the municipality for a transition	€ / capita	Annual expenditures by the municipality for a transition towards a climate change-resilient city	Adapted from CITYkeys

	towards a climate-resilient city			
190	Protection of cultural and natural heritage	% of annual budget	Total expenditure (public and private) per capita spent on the preservation, protection and conservation of all cultural and natural heritage, by type of heritage (cultural, natural, mixed and World Heritage Centre designation), level of government (national, regional and local/municipal), type of expenditure (operating expenditure/investment) and type of private funding (donations in kind, private non-profit sector and sponsorship).	SDG 11 indicator 11.4.1
191	Multilevel government	Likert scale	The extent to which the city cooperates with other authorities from different levels	CITYkeys
192	Regional development planning	Likert scale	Degree to which urban and regional development plans integrate population projections and resource needs, by size of city. Qualifying criteria: -Responds to population dynamics -Ensures balanced regional and territorial development -Increases local fiscal space	SDG11 indicator 11.a.1
193	Municipal support for greening	%	City budget (% of budget allocated to green space planning, implementation and maintenance)	Kabisch et al., 2016

9.3 Specific project-level NBS performance and impact indicators

	Indicator - PEOPLE	Unit of measure	Metric	Source
194	Encouraging a healthy lifestyle	Likert scale	The extent to which the project encourages a healthy lifestyle	CITYkeys
195		Number	Number and share of people being physically active (min. 30 min 3 times per week).	EKLIPSE
196		%	Reduced percentage of obese people and children	EKLIPSE
197		%	Reduced overall mortality and	EKLIPSE
198		% or number	Increased lifespan	EKLIPSE
199		Number	Reduced number of cardiovascular morbidity and mortality events (Tamosiunas et al., 2014).	EKLIPSE
200	Improved health due to provision of ecosystem services	%	Reduced autoimmune diseases and allergies (potentially) (Kuo, 2015).	EKLIPSE
201	Increased social justice		The availability and distribution of different types of parks and/or ecosystem services with respect to specific individual or household socioeconomic profiles and landscape design (Cohen et al., 2012; Ernstson, 2013; Ibes, 2015; Kabisch and Haase, 2014; Raymond et al., 2016b; Shanahan et al., 2014)	EKLIPSE
202	Reduction in premature deaths	Number or %	Reduction in the number or % of premature deaths due to air pollution per year (Tiwary et al., 2009)	EKLIPSE
203	Reduction in number of hospital admissions	Number or %	Reduction in the number or % of hospital admissions due to air pollution per year (Tiwary et al., 2009)	EKLIPSE
204	Stress reduction		Reduction in chronic stress and stress-related diseases measured through repeated salivary cortisol sampling (Roe et al., 2013; Ward Thompson et al., 2012) and hair cortisol (Honold et al., 2016); use cortisol slope and average cortisol levels as an indicator of chronic stress.	EKLIPSE
205	Improved cognitive and social development in children		Indicators related to improvement in behavioural development and symptoms of attention deficit/hyperactivity disorder (ADHD) related to green space use; questionnaire indicators on sociodemographic and household characteristics, the time spent playing in green and blue spaces, ADHD symptom criteria, such as emotional symptoms, inattention, conduct problems, hyperactivity/inattention, and peer relationship problems; and a strengths subscale for prosocial behaviour (Amoly et al., 2014)	EKLIPSE
206	Improved mental health	Likert scale	Mental health changes measured through Mental Well-being scales asking participants how they have felt over the previous four weeks in relation to a number of items (e.g., feeling relaxed, feeling	EKLIPSE

			useful), with responses rated on a 5-point scale from “none of the time” to “all of the time” (Roe et al., 2013).	
207	Improved human health and well-being	multiple	Physical and mental health (increase in number of people engaged in sports, decrease in respiratory disease and obesity, decline in premature death during heat waves)	Kabisch et al., 2016
208		multiple	Impact on quality of life, happiness and employment	Kabisch et al., 2016
209	Reduction in number of hospital admissions	People/year	Reduction in number of hospital admissions due to high temperatures during extreme heat events (heat stroke, dehydration). Need access to health statistics data. Level of aggregation: city.	EKLIPSE, Le Tertre et al (2006)
210	Reduction in crime rate	% of crimes	Percentage reduction in number of violent incidents, annoyances and crimes due to the project	CITYkeys
211	Improved cybersecurity	Likert scale	The extent to which the project ensures cybersecurity	CITYkeys
212	Improved data privacy	Likert scale	The extent to which data collected by the project is protected	CITYkeys
213	Extending the bike route network	% in km	Percentage increase of the length of cycling roads	CITYkeys
214	Increased area for pedestrians	%	Increase in the proportion of land dedicated to pedestrians: percentage of road network	EKLIPSE
215	Increase in online government services	Likert scale	The extent to which access to online services provided by the city was improved by the project	CITYkeys
216	Improved access to educational resources	Likert scale	The extent to which the project improves accessibility to educational resources	CITYkeys
217	Increased environmental awareness	Likert scale	The extent to which the project has used opportunities for increasing environmental awareness and educating about sustainability and the environment	CITYkeys
218	People reached	% of people	Percentage of people in the target group that have been reached and/or are activated by the project	CITYkeys
219			Involvement in green implementation projects (% of citizens involved)	Kabisch et al., 2016
220	Increased consciousness of citizenship	Likert scale	The extent to which the project has contributed in increasing consciousness of citizenship	CITYkeys
221	Green space ‘ownership’	%	Ownership and responsibility (% of people owning or maintaining green spaces)	Kabisch et al., 2016

222	Improved perceptions of urban nature		Perceptions of citizens on urban nature (Buchel and Frantzeskaki, 2015; Colding and Barthel, 2013; Gerstenberg and Hofmann, 2016; Scholte et al., 2015; Vierikko and Niemelä, 2016)	EKLIPSE
223	Increased social valuation of urban ecosystems and biodiversity		Social values for urban ecosystems and biodiversity (Brown and Fagerholm, 2014; Kenter et al., 2015; Polat and Akay, 2015; Raymond et al., 2014, 2009; Scholte et al., 2015)	EKLIPSE
224	Increased participation of vulnerable groups	Likert scale	The extent to which project has led to an increased participation of groups that are not well represented in the society	CITYkeys
225	Diversity of housing	Simpson Diversity Index / Social Housing	Simpson Diversity Index of total housing stock in the project area OR Percentage of social dwellings as share of total housing stock in the project area	CITYkeys
226	Connection to the existing cultural heritage	Likert scale	The extent to which making a connection to the existing cultural heritage was considered in the design of the project	CITYkeys
227	Conservation of built heritage	%	Percentage of built form retained for culture	EKLIPSE
228	Design for a sense of place	Likert scale	The extent to which a 'sense of place' was included in the design of the project	CITYkeys
229	Increased use of ground floors	% in m^2	Increase in ground floor space for commercial or public use due to the project as percentage of total ground floor surface	CITYkeys
230	Increased access to urban public outdoor recreation space	m^2	Increase in public outdoor recreation space (m^2) within 500 m	CITYkeys
231	Increased access to green space	m^2	Increase in green space (m^2) within 500 m	CITYkeys
232	Increased access to all forms of public open space	% or Likert scale	The increase in extent to which public open space is available within 500 m	Adapted from CITYkeys
233		%	Increase in proportion of population that has convenient access to a public open space. Can be disaggregated by sex, age and persons with disabilities. Identify population served by distance or travel time from public open space, overlying service area with socio-demographic data. Population with access to public open space (in %): $= 100 \times \frac{population\ with\ convenient\ access}{City\ population}$	Adapted from SDG 11.2
234		% or time or distance	Reduction in average journey time for residents/employees by foot or average distance to sports centre, recreation area, or green space	EKLIPSE

235	Accessibility of urban green space OR public open space	%	(Increase in) urban green space OR public open space within 500 m. Public open spaces are spaces undeveloped and accessible to the public (EPA). Open space within 500m or (open space within 500 after the project divided by open space within 500 before the project)*100. A proxy could be the area of residential area within a buffer of 500 m around open spaces. Level of aggregation: city of neighbourhood.	Adapted from CITYkeys
236		%	Increase in the proportion of population that has convenient access to a public green space / blue-green space. Can be disaggregated by sex, age and persons with disabilities. Identify population served by distance or travel time from public green space / blue-green space, overlying service area with socio-demographic data. Population with access to public green space / blue-green space (in %): $= 100 \times \frac{population\ with\ convenient\ access}{City\ population}$	SDG 11 indicator 11.2.1
237	Improved access to public transport	% or Likert scale	Increase in the extent to which public transport is available within 500 m	CITYkeys
238		%	Increase in public transport links: walking distance to nearest facilities	EKLIPSE
239	Improved quality of public transport	Likert scale	The perception of users on the quality of the public transport service	CITYkeys
240	Improved access to vehicle sharing solutions	Likert scale	Improved accessibility to vehicle sharing solutions	CITYkeys
241	Better access to public amenities	Likert scale	The extent to which public amenities are available within 500 m	CITYkeys
242	Reduced flood risk - urban infrastructure	Probability	Reduction of inundation risk for critical urban infrastructure (probability) based on hydraulic modelling and GIS assessment (Pregnolato et al., 2016)	EKLIPSE
243	Reduced flood risk - city area	Probability	Number and extent of flooded areas, spatial analysis, GIS-based spatial analysis and modelling (Cohen- Shacham et al., 2016; Langemeyer et al., 2016; Liu et al., 2014)	EKLIPSE
244	Reduced flood risk - material damage	€	Reduced value of material damage as determined using stage-damage curves relating depth and velocity of water to material damage (de Moel et al., 2015)	EKLIPSE
245	Increased recreational value	% or Number / 100 000	Change in the number of visitors, or number of recreational activities in the area affected by NBS project (Kabisch and Haase, 2014)	EKLIPSE
246	Increased cultural value	% or Number/ 100 000	Change in the number of cultural events, people involved, or children in educational activities in the area affected by NBS project (Kabisch and Haase, 2014)	EKLIPSE
247	Increased affluence		Access to financial resources, including indicators of income per capita in a given neighbourhood, or urban area (Klasen, 2008)	EKLIPSE

248	Gentrification		There is a potential trade-off between NBS implementation/introductions in urban environments and environmental justice, particularly concerning issues of gentrification (Checker, 2011; Dooling, 2009; Wolch et al., 2014). Such a trade-off requires effective identification	EKLIPSE
	Indicator - PLANET	Unit of measure	Metric	Source
249	Reduction in annual final energy consumption	% in kWh	Percentage change in annual final energy consumption due to the project for all uses and forms of energy	CITYkeys, EKLIPSE
250	Reduction in lifecycle energy use	% in kWh	Reduction in life cycle energy use achieved by the project (%)	CITYkeys
251	Cooling degree days	°C·day	Used to quantify the buildings' energy demand due to cooling or heating. Sum of the times (in day) when the mean outside temperature was above a threshold multiplied by the difference between the temperature and the threshold. Need temperature data. Both a proxy of energy consumption due to cooling and Temperature comfort from the EKLIPSE framework ("number of combined tropical nights (>20°C) and hot days"). Level of aggregation: city or neighbourhood.	Santamouris (2017)
252	Anthropogenic heat	W/m^2	Heat produced by human activity. Different models are possible (see Sailor 2010), and the output can be mapped, need energy consumption of building, traffic data, etc. to compute models. Level of aggregation: city or neighbourhood.	Sailor (2011)
253	Reduction of embodied energy of products and services used in the project	Likert scale	The extent to which measures have been taken to reduce the embodied energy of products used in the project	CITYkeys
254	Increase in local renewable energy production	% in kWh	Percentage increase in the share of local renewable energy due to the project	CITYkeys
255	CO_2 emission reduction	% in tonnes	Percentage reduction in direct (operational) CO_2 emissions achieved by the project	CITYkeys
256		t C/y saved	Reduction in carbon emissions from reduced building energy consumption	EKLIPSE
257	Reduction in lifecycle CO_2 emissions	% in tonnes	Percentage reduction in lifecycle CO_2 emissions achieved by the project	CITYkeys
258	Net Primary Production	gC/m^2/ year	Accumulated organic matter by plants per unit area and time: measures Nature's productivity. Several models exist, the CASA one is one of the most used. Data needed: Landsat images, precipitation and temperature data. Level of aggregation: city of neighbourhood.	Wang et al (2016)
259	Increased carbon sequestration	%	Increase in tonnes of carbon removed or stored per unit area (hectare) per unit time (year) (Zheng et al., 2013)	EKLIPSE
260		%	Increase in total amount of carbon (tonnes) stored in vegetation (Davies et al., 2011)	EKLIPSE

261		%	Increase in total carbon storage calculated using allometric forest models of carbon sequestration, developed using proxy data obtained from Lidar data (Giannico et al., 2016)	EKLIPSE
262		%	Increase in total carbon storage calculated using growth rates derived from Forest Inventory Analysis (Zheng et al., 2013)	EKLIPSE
263	Value of carbon sequestration	€	Value of gross and net carbon sequestration of urban trees based on calculation of the biomass of each measured tree (i-Tree Eco model), translated into avoided social costs of CO_2 emissions (value/t carbon) (Baró et al., 2014)	EKLIPSE
264	Reduced stormwater runoff	%	Percent reduction of run-off coefficient in relation to precipitation quantities (Armson et al., 2013; Getter et al., 2007; Iacob et al., 2014; Scharf et al., 2012)	EKLIPSE
265	Maximum Hourly Deficit	MHDx	The maximum yearly value of how much the hourly local demand overrides the local renewable supply during one single hour	CITYkeys
266	Increased efficiency of resources consumption	% in tonnes	Percentage reduction in material consumption of the project	CITYkeys
267	Energy efficiency		Building materials/ construction methods based on points awarded according to energy efficiency checklist	EKLIPSE
268	Share of recycled input materials	% in tonnes	Share of recycled and reused materials used by the project	CITYkeys / EKLIPSE
269	Share of renewable materials	% in tonnes	Share of renewable materials used by the project	CITYkeys
270	Share of materials recyclable	% in tonnes	Share of materials used by the project that are practically retrievable for recycling after the life time	CITYkeys
271	Proportion of environmentally-designed buildings	%	Incorporation of environmental design: percentage of total building stock	EKLIPSE
272	Life time extension	Likert scale	The extent to which the project attempted to prolong the service lifetime of products	CITYkeys
273	Flood peak reduction	%	Reduction in absolute height of peak floodwaters (Iacob et al., 2014)	EKLIPSE
274	Flood peak delay	time	Increase in time to flood peak (Iacob et al., 2014)	EKLIPSE
275	Increased stormwater retention	m^3	Increased capacity for stormwater retention based on absorption or retention of stormwater by project NBS (Armson et al., 2013; Davis et al., 2009)	EKLIPSE
276	Increased evapotranspiration	%	Increased evapotranspiration measured/modelled (Litvak and Pataki, 2016)	EKLIPSE

277	Reduction in water consumption	% in m^3	Percentage reduction in water consumption brought about by the project	CITYkeys
278	Increase in water re-used	% in m^3	Increase in percentage of rain and grey water re-used to replace potable water	CITYkeys
279	Nutrient pollution abatement	%	Reduction in nutrient load in combined discharge to local waterbodies	EKLIPSE
280	Metal pollution abatement	%	Reduction in total metal/metalloid load in combined discharge to local waterbodies	EKLIPSE
281	Drought risk reduction	Probability	Reduction of drought risk (probability)	EKLIPSE
282	Increased groundwater availability	metres	Increasing ground water availability (reduction in depth to groundwater) (Feyen and Gorelick, 2004)	EKLIPSE
283	Groundwater quality improvement	%	Reduction in water pollutant content, i.e. nutrients, metals/metalloids, organic compounds	EKLIPSE
284	Self-sufficiency - Water	% in m^3	Increased share of local water resources	CITYkeys
285	Increase in compactness	% of people or workplaces	Percentage increase in the number of people or workplaces situated in the project area	CITYkeys
286	Self-sufficiency - Food	% in tonnes	Increase in the share of local food production due to the project	CITYkeys
287	Climate resilience measures	Likert scale	The extent to which adaptation options have been considered in the project	CITYkeys
288	Temperature reduction / increase in human comfort	°C	Decrease in mean or peak daytime local temperatures (°C) (Demuzere et al., 2014). Difference of the mean spatially averaged temperature for a study area (e.g: the project area) after and before the project implementation. Need spatial distribution of mean daytime temperatures or direct measurements.	EKLIPSE
289		Comfort Index	Measures of human comfort e.g. ENVIMET PET — Personal Equivalent Temperature, or PMV — Predicted Mean Vote	
290		Number or %	Decrease in number of combined tropical nights (>20°C) and hot days (>35°C) (Fischer, Schär, 2010, cited by Baró et al. 2015)	EKLIPSE
291	Reduction in Urban Heat Island effect	% or °C UHI_{max}	Percent or absolute change in maximum difference in air temperature within the city compared to the countryside during the summer months attributable to NBS project implementation	CITYkeys
292	Urban Heat Island intensity	°C	Maximum temperature differences between the city core and the surrounding urban areas. Maximum of the average temperature in urban areas minus average temperature in rural surroundings area, calculation to be specified once the available data is spotted. Level of aggregation: city.	CITYkeys
293	Urban Heat Island magnitude	°C	Intensity of the UHI at a given time. Calculate as difference between mean land surface temperature (LST) and maximum of LST. Need Land Surface Temperature data (usually from thermal satellite imagery). Level of aggregation: city.	Schwarz et al (2011)

294	Heat Island Area	km^2 or ha	All parts of the city that have a higher land surface temperature (LST) than the threshold, the threshold being the mean LST of all the urban area plus the standard deviation. Need Land Surface Temperature data (usually from thermal satellite imagery). Level of aggregation: city.	Ward et al (2016)
295	Latent and sensible heat flux	W/m^2	Quantification of the exchanges of heat between the urban areas and the atmosphere. With complex models used to assess different scenarios for a given project, interesting when comparing changes between a reference scenario and future potential scenario. Need heat flux data. Level of aggregation: city or neighbourhood.	Rafael (2017)
296	Decreased emissions of nitrogen oxides (NO_x)	% in tonnes	Percentage reduction in NO_x emissions (NO and NO_2) achieved by the project	CITYkeys
297	Decreased emissions of CO_2	%	Resource efficiency in the urban system (CO_2 emissions per capita, CO_2 emissions for transportation per capita, etc.) (OECD, 2013)	EKLIPSE
298	Decreased emissions of fine particulate matter ($PM_{2.5}$)	% in tonnes	Percentage reduction in $PM_{2.5}$ emissions achieved by the project	CITYkeys
299	Decreased emissions of coarse particulate matter (PM_{10})	% in tonnes	Percentage reduction in PM_{10} emissions achieved by the project	
300	Reclamation of contaminated land	%	Percentage of contaminated area reclaimed through implementation of NBS project	EKLIPSE
301		area %	Regeneration of derelict areas & brownfield sites	Kabisch et al., 2016
302	Pollutant capture by NBS vegetation	t / year	Annual amount of pollutants captured by vegetation (Bottalico et al., 2016)	EKLIPSE
303		%	Proportion of emissions (air pollutants) captured/sequestered by vegetation (Baró et al., 2014)	EKLIPSE
304	Air quality improvement	% in tonnes	Net air quality improvement (pollutants produced – pollutants captured + GHG emissions from maintenance activities) (Baró et al., 2014).	EKLIPSE
305	Value of improved air quality	€	Value of air pollution reduction by implemented NBS (Manes et al., 2016)	EKLIPSE
306	Reduced exposure to noise pollution	% in dB	Percentage reduction of noise level at night measured at the receiver	CITYkeys
307	Increase in green and blue space	% in m^2	Percentage increase of green and blue spaces due to the project	CITYkeys
308	Value of urban forests	€ / ha	Total monetary value of urban forests including air quality, run-off mitigation, energy savings, and increase in property values (Soares et al., 2011)	EKLIPSE
309	Land devoted to roads	%	Change in the percentage of NBS project area occupied by roads	EKLIPSE

310	Increased ecosystem quality and biodiversity	Likert scale	The extent to which ecosystem quality and biodiversity aspects have been taken into account	CITYkeys
311		multiple	Biodiversity (increase in species numbers, functional richness and vegetation cover)	Kabisch et al., 2016
312	Increase in number of native species	Number	Increase in the number of native species present within area affected by NBS project	CITYkeys
313	Increased biodiversity		Species richness and composition in respect to indigenous vegetation and local/national biodiversity targets (Cohen et al., 2012; Krasny et al., 2013)	EKLIPSE
314	Increased connectivity		Changes in the pattern of structural and functional connectivity (Iojă et al., 2014)	EKLIPSE
315			Ecological connectivity (Pino and Marull, 2012)	EKLIPSE
316	Enhanced ecosystem regulation	multiple	Ecosystem regulation (decrease in air pollution, reduction in temperature and CO_2 emissions, tons of carbon stored and carbon emission, % reduction in flood risk)	Kabisch et al., 2016
317	Increase in BVOC	%	Urban trees may also produce allergens and can contribute to air pollution through the emission of biogenic volatile organic compounds (BVOC), which can lead to the formation of secondary ozone, carbon monoxide and Biological Particulate Matter; thus a quantification of the "net" air quality improvement should take into consideration this ecosystem disservice (Baró et al., 2014; Calfapietra et al. 2013, Grote et al., 2017)	EKLIPSE
318	Increased pollen count	% or # pollen grains/m^3	Pollen count is the measurement of the number of grains of pollen in a cubic meter of air. High pollen counts can sometimes lead to increased rates of an allergic reaction for those with allergic disorders. Usually, the counts are announced for specific plants such as grass, ash, or olive.	
319	Ecosystem disservices	multiple	Ecosystem disservices (increased number of mosquitos, plants emitting allergic pollen)	Kabisch et al., 2016
	Indicator - PROSPERITY	Unit of measure	Metric	Source
320	Increased use of local workforce	% in €	Share in the total project costs that has been spent on local suppliers, contractors and service providers	CITYkeys
321	Local job creation	Number	Number of jobs created by the project	CITYkeys
322		Number	Number of jobs created (Forestry Commission, 2005)	EKLIPSE
323		€ / capita	Gross value added (Forestry Commission, 2005).	EKLIPSE
324			Net additional positive outcomes into employment (Tyler et al., 2013).	EKLIPSE
325			Net additional jobs (Tyler et al., 2013) in the green sector enabled by NBS projects.	EKLIPSE

326	Value of new green jobs		Gross value added per employees based on full-time equivalent jobs (Tyler et al., 2013) in the green sector.	EKLIPSE
327	Cost of job creation to public sector		Public-sector cost per net additional job (Tyler et al., 2013).	EKLIPSE
328	Production benefit		Earnings uplift arising from skills enhancement (Tyler et al., 2013) in the design and implementation of NBS	EKLIPSE
329	Cost of housing	% in €	The percentage of gross household income spent on housing	CITYkeys
330	Consumption benefits		Property betterment and visual amenity enhancement (Tyler et al., 2013) resulting from NBS.	EKLIPSE
331	Change in property value	% or €	Change in mean or median land and property prices (Forestry Commission, 2005).	EKLIPSE
332	Certified companies involved in the project	% of companies	Share of the companies involved in the project holding an ISO 14001 certificate	CITYkeys
333	Green public procurement	Likert scale	The extent to which GPP criteria were taken into account for the procurement processes related to the project	CITYkeys
334	CO_2 reduction cost efficiency	€ / ton CO_2 saved / year	Costs in euros per ton of CO_2 saved per year	CITYkeys
335	Financial benefit for the end-user	€ / household / year	Total cost savings in euros for end-users per household per year	CITYkeys
336	Net Present Value (NPV)	€	The Net Present Value of the project calculated over the lifetime	CITYkeys
337	Internal rate of return (IRR)	% (interest)	The interest rate at which the NPV of the investment is zero	CITYkeys
338	Payback Period	Years	The number of years at which the net present value of costs (negative cash flows) of the investment equals the net present value of the benefits (positive cash flows) of the investment	CITYkeys
339	Total cost vs. subsidies	% in €	The percentage of subsidies as share of total investment of the project	CITYkeys
340	Involvement of extraordinary professionals	Likert scale	The extent to which the project involved professionals normally not encountered in these type of projects	CITYkeys
341	Stimulating an innovative environment	Likert scale	The extent to which the project is part of or stimulates an innovative environment	CITYkeys
342	Quality of open data	Number of stars	The extent to which the quality of the open data produced by the project was increased	CITYkeys
343	New start-ups	Number of start-ups	The number of start-ups resulting from the project	CITYkeys
344	New businesses	Number	New businesses attracted (Eftec, 2013).	EKLIPSE

345		€ / capita	Additional business fees collected by the city (Eftec, 2013).	EKLIPSE
346	Improved interoperability	Likert scale	The extent to which the project has increased interoperability between systems	CITYkeys
	Indicator - GOVERNANCE	Unit of measure	Metric	Source
347	Leadership	Likert scale	The extent to which the leadership of the project is successful in creating support for the project	CITYkeys
348	Balanced project team	Likert scale	The extent to which the project team included all relevant experts and stakeholders from the start	CITYkeys
349	Involvement of the city administration	Likert scale	The extent to which the local authority is involved in the development of the project, other than financial, and how many departments are contributing	CITYkeys
350	Clear division of responsibility	Yes / No	Has the responsibility for achieving the social and sustainability targets been clearly assigned to (a) specific actor(s) in the project?	CITYkeys
351	Continued monitoring and reporting	Likert scale	The extent to which the progress towards project goals and compliance with requirements is being monitored and reported	CITYkeys
352	Market orientation	Likert scale	The extent to which the project was planned on the basis of a market analysis	CITYkeys
353	Professional stakeholder involvement	Likert scale	The extent to which professional stakeholders outside the project team have been involved in planning and execution	CITYkeys
354	Bottom-up or top-down initiative		Has the project idea originated from the local community?	CITYkeys
355	Legitimacy of knowledge in project participatory processes		Legitimacy of knowledge in NBS project participatory processes (Frantzeskaki and Kabisch, 2016; Luyet et al., 2012).	EKLIPSE
356	Local community involvement in planning phase	Likert scale	The extent to which residents/users have been involved in the planning process	CITYkeys
357	Local community involvement in implementation phase	Likert scale	The extent to which residents/users have been involved in the implementation process	CITYkeys
358	Openness of participatory processes		Openness of NBS project participatory processes (Frantzeskaki and Kabisch, 2016; Luyet et al., 2012; Uittenbroek et al., 2013)	EKLIPSE
359	Participatory governance	% of people	Share of population participating in online platforms	CITYkeys
360	Social learning		Social learning concerning urban ecosystems and their functions/services (Colding and Barthel, 2013)	EKLIPSE

361	Policy learning		Policy learning concerning adapting policies and strategic plans by integrating ecosystem services and possibly their valuation (Crowe et al., 2016; Uittenbroek et al., 2013; Vandergert et al., 2015)	EKLIPSE
362	City climate adaptation policy	Likert scale	The extent to which the project has benefitted from a governmental climate adaptation city policy	Adapted from CITYkeys
363	Urban greening policy		The extent to which the city's greening (or similar) policy enforces micro-scale and cross-scale interactions, considers urban hinterland and "distant landscapes" (*sensu* Andersson et al. 2014)	EKLIPSE
364	Municipal involvement - Financial support	Likert scale	The extent to which the local authority provides financial support to the project	CITYkeys
365	Integrated governance	Number / sector	Integrated governance (number of stakeholders involved in planning and implementation from different disciplines/ sectors)	Kabisch et al., 2016
366	Long-term monitoring	time	Long-tern viability of activity/ projects and monitoring (duration)	Kabisch et al., 2016
	Indicator - PROPAGATION	Unit of measure	Metric	Source
367	Social compatibility	Likert scale	The extent to which the project's solution (NBS) fits with people's 'frame of mind' and does not negatively challenge people's values or the ways they are used to doing things.	Adapted from CITYkeys
368	Technical compatibility	Likert scale	The extent to which the NBS fits with the current existing technological standards/infrastructures	Adapted from CITYkeys
369	Ease of use for end-users of the solution	Likert scale	The extent to which the NBS is perceived as difficult to understand and use for potential end-users	Adapted from CITYkeys
370	Ease of use for professional stakeholders	Likert scale	The extent to which the NBS innovation is perceived as difficult to understand, implement and use for professional users of the solution	Adapted from CITYkeys
371	Trialability	Likert scale	The extent to which the NBS can be experimented with on a limited basis in the local context before full implementation	CITYkeys
372	Advantages for end-users	Likert scale	The extent to which the project offers clear advantages for end users	CITYkeys
373	Advantages for stakeholders	Likert scale	The extent to which the project offers clear advantages for stakeholders	CITYkeys
374	Visibility of Results	Likert scale	The extent to which the results of the project are visible to external actors	CITYkeys
375	Subsidies or tax deductions for NBS	Number	Number of subsidies or tax reductions applied for (private) NBS measures (Meulen et al., 2013).	EKLIPSE
376	Solution(s) to development issues	Likert scale	The extent to which the project offers a solution to problems which are common to European cities	CITYkeys

377	Market demand	Likert scale	The extent to which there is a general market demand for the solution	CITYkeys
378	Changing professional norms	Likert scale	The extent to which the project changes the professional ‘state of the art’	CITYkeys
379	Changing societal norms	Likert scale	The extent to which the project changes the norms and values of the society	CITYkeys
380	Diffusion to other locations	Likert scale	The extent to which the project is copied in other cities and regions	CITYkeys
381	Diffusion to other actors	Likert scale	The extent to which the project is copied by other parties	CITYkeys
382	Change in rules and regulations	Likert scale	The extent to which the project has contributed to, or inspired, changes in rules and regulations	CITYkeys
383	Change in public procurement	Likert scale	The extent to which the project has contributed to, or inspired, new forms of public procurement procedures	CITYkeys
384	New forms of financing	Likert scale	The extent to which the project has contributed to, or inspired, the development of new forms of financing	CITYkeys
385	NBS project visitors	Number of visitors	The number of visitors to the physical project site (ULL) or to the website hosting the NBS project	Adapted from CITYkeys
386	Citizen uptake		Sharing and adopting NBS in community (use of new media such as Facebook - number of "likes")	Kabisch et al., 2016
387	Transferability		Transfer of actions (number of actions/ projects/ results transferred into practice or teaching)	Kabisch et al., 2016

10. Appendix III: Macroinvertebrate Sampling - Examples

Volunteer Field Data Sheet

Sample ID___________ **Stream Name**____

(Sub)Catchment____

SiteName/Road Crossing____

Date______________

Person(s) collecting samples____

1. Weather (circle all that apply):

Today:	Clear	Partly Cloudy	Overcast	Light rain	Steady rain	Snow
Past 48 h:	Clear	Partly Cloudy	Overcast	Light rain	Steady rain	Snow

2. Establish 100 m Stream Sampling Reach:

Measure approximately 10 m from culvert, bridge, road crossing, or other stable landmark to start of sampling reach.

- Identity of landmark: ____
- Distance and direction from landmark to start point:______________________________

Mark start of sampling reach and measure 100 m from this point.

3. Instream Habitat Proportions:

Habitat	Percentage	Number of Jabs
Hard bottom (riffle/run/pool/cobble/boulder)		
Aquatic Plants (submerged/emergent vegetation)		
Undercut Banks (undercut banks/overhanging vegetation)		
Snags (snags/rootwads)		
Leaf Packs		
	100	***Total = 10***

4. Habitat Assessment

Bottom Composition (%)**:**

Bedrock	Boulder	Cobble	Gravel	Sand	Silt	Organic

% Embedded: *(estimate % of large rocks or particles covered with silt)*

0%______ 0-25%______ 25-50%______ >50%_______

Flow: _____% *(estimate % of stream bottom currently filled with water)*

Overhead Canopy_____% **Algal Growth (circle one):** None Little A lot

Water Odour (circle all that apply)**:**

None Fish Organic Sewage Oil Other__________

Left Bank Description: (*facing upstream, estimate % of each cover type out of 100*)

Shrubs	Grass/forbs	Conifer	Deciduous	Clear	Erosion

Right Bank Description: (*facing upstream, estimate % of each cover type out of 100*)

Shrubs	Grass/forbs	Conifer	Deciduous	Clear	Erosion

5. Estimation of Flow

Depth: Select a spot typical of the sampling site and measure depth in 20-30 cm intervals:

1.	___________	6.	___________	11.	___________	16.	___________	21.	___________
2.	___________	7.	___________	12.	___________	17.	___________	22.	___________
3.	___________	8.	___________	13.	___________	18.	___________	23.	___________
4.	___________	9.	___________	14.	___________	19.	___________	24.	___________
5.	___________	10.	___________	15.	___________	20.	___________	25.	___________

6. Current Velocity:

Velocity = 3 m/no. of seconds **Wetted Width (m):** _______

Fast 1: _____ seconds velocity: _____ m/second

Fast 2: _____ seconds velocity: _____ m/second

Slow 1: _____ seconds velocity: _____ m/second

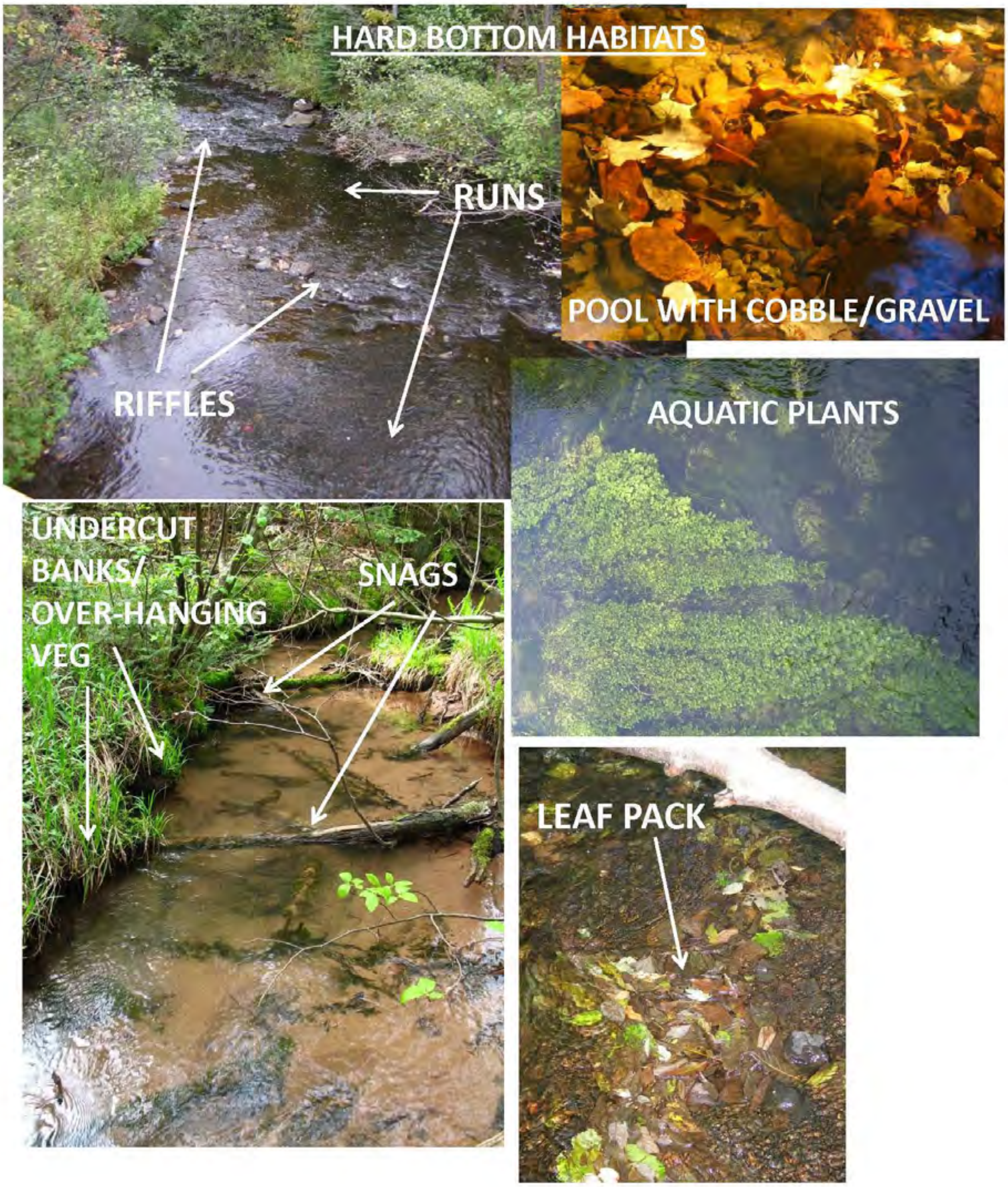
Slow 2: _____ seconds velocity: _____ m/second

Average site velocity: Total _____/4 = ________ feet/second

7. Site Sketch

Sketch major features and mark areas from which samples were taken in the stream reach.

Examples of Macroinvertebrate Habitats



Descriptions of macroinvertebrate habitat types

The multi-habitat method of macroinvertebrate sampling involves collecting a composite sample from up to five different habitat types, including:

- **Hard bottom (riffle/run/pool/cobble/boulder)** – category intended to cover all hard, rocky substrates, not only riffles. Runs and wadable pools often have hard substrates and should be included in sampling. The surfaces of large boulders and areas of flat, exposed rock are generally unproductive. When this is the case (exposed rock or boulder surfaces are not productive macroinvertebrate habitat in a particular stream), avoid including these large boulders and areas of flat, exposed rock in the sampling area when possible.
- **Aquatic plants (submerged/emergent vegetation)** – any vegetation at or below the water surface is in this category. Emergent vegetation, which extends above the water surface, is included here because all emergent plants have stems that extend below the water surface and serve as suitable substrate for macroinvertebrates. Do not sample the emergent parts of any plant.
- **Undercut banks (undercut banks/overhanging vegetation)** – areas often found where the main streamflow runs along the stream bank and erodes away the bank. This action produces a cavity that is well-shaded, frequently has overhanging stream bank vegetation, and is typically somewhat protected from high water velocities.
- **Snags (snags/roots)** – snags include any piece of large woody material found in the stream channel. Logs, tree trunks, entire trees, tree branches, large pieces of tree bark, and dense accumulations of twigs are considered snags. Roots of streamside vegetation may form masses, or “rootwads”, where roots extend from the stream bank.
- **Leaf packs** – dense accumulations of leaves, typically present in the early spring and late autumn. Leaf packs are found in deposition zones, generally near stream banks, around logjams or in current breaks behind large boulders.

Substrate Embeddedness

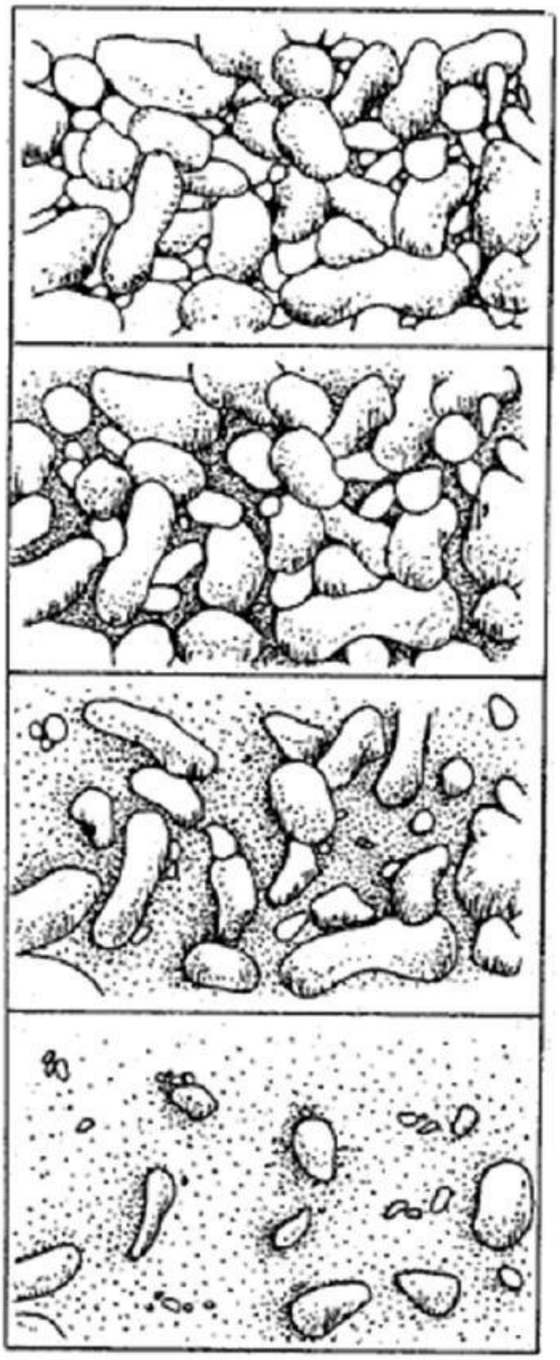
Embeddedness of substrate refers to the extent to which the rocks in the stream bed (gravel, cobble and boulders) are surrounded by, covered, or sunken within sand, silt or mud of the stream substrate. In general, a greater degree of embeddedness means that less habitat is available for macroinvertebrates. To estimate embeddedness, observe the amount of sand, silt or mud overlying and surrounding rocks in the stream bed.

0% embeddedness

0-25% embeddedness

25-50% embeddedness

>50% embeddedness



http://watermonitoring.uwex.edu/pdf/level1/riverkey.pdf