Asset Management of Green Infrastructure

Mahdi Bahrami

Supervisors:
Marius Møller Rokstad (NTNU)
Franz Tscheikner-Gratl (NTNU)
Tone Merete Muthanna (NTNU)

04.10.2024

Rain garden in Trondheim, (https://climatescan.org/)

NTNU

Introduction

- Traditional vs. Modern Urban Drainage
- Asset Management of Grey and Green Infrastructure

Our research:

- Performance assessment of Green Infrastructure
- Failure analysis of Green Infrastructure
- Inspection of Green Roofs

Traditional vs. Modern Urban Drainage

- The management of urban drainage and the urban water cycle has seen significant change over the past decades (Fletcher et al. (2015))

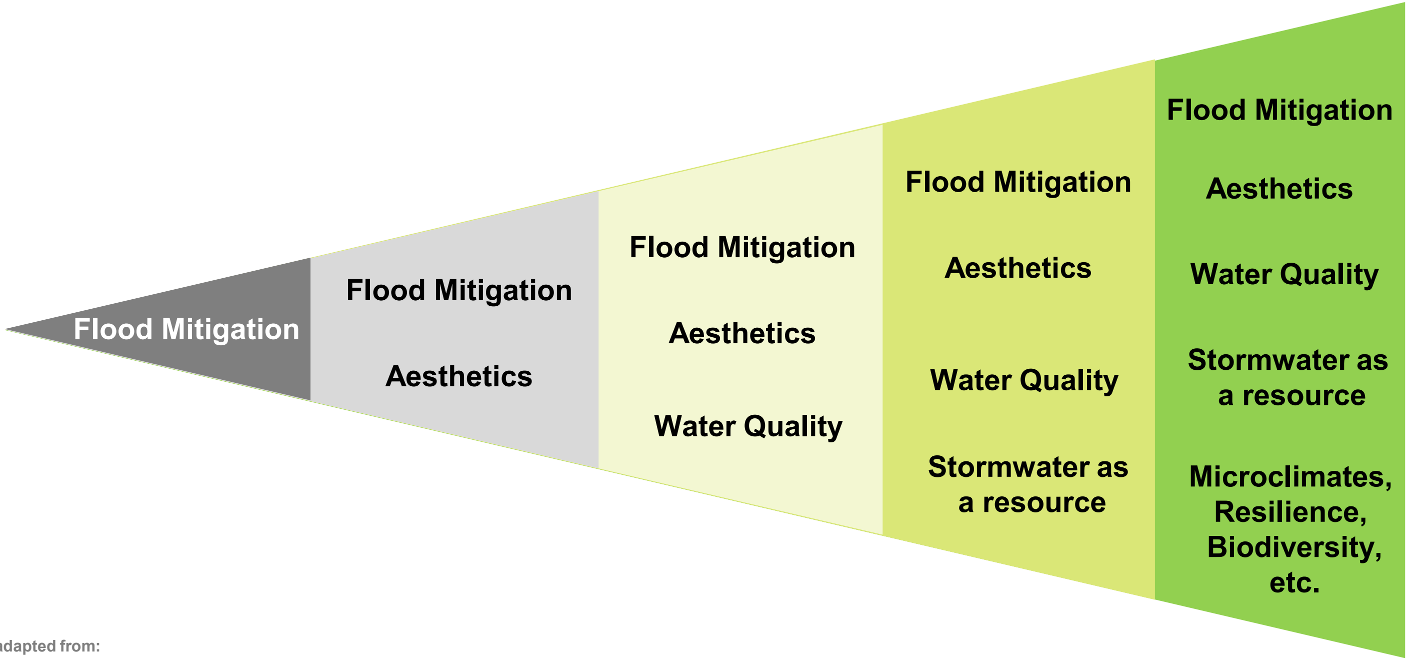


Figure adapted from:

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D., & Viklander, M. (2014). SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. Urban Water Journal, 12(7), 525-542. https://doi.org/10.1080/1573062x.2014.916314

Traditional vs. Modern Urban Drainage

- Structural
- Immediate effect of rehabilitation
- Similar components
- Managed by one department

- Mix of structural and natural elements
- Natural elements are time-dependent
- Variety between types and components
- Require collaborative management

Grey Infrastructure

Green Infrastructure (GI)

Pictures are from:

Toronto and Region Conservation Authority (TRCA). (2016). Low Impact Development Stormwater Management Practice Inspection and Maintenance Guide. Prepared by the Sustainable Technologies Evaluation Program. Vaughan, Ontario.

Green Infrastructure (GI)

Green infrastructure uses filtration, infiltration, and evapotranspiration to treat and soak up rainwater where it falls. It can deliver multiple environmental, social, and economic benefits beyond stormwater management alone.

(https://www.epa.gov/green-infrastructure/about-green-infrastructure)

Bioswales

Rain Gardens

Green Roofs

Pictures are from:

Toronto and Region Conservation Authority (TRCA). (2016). Low Impact Development Stormwater Management Practice Inspection and Maintenance Guide. Prepared by the Sustainable Technologies Evaluation Program. Vaughan, Ontario.

Asset Management

Asset Management:

Optimal use of infrastructure during their *optimal* service lifetime *(ISO 31000)*

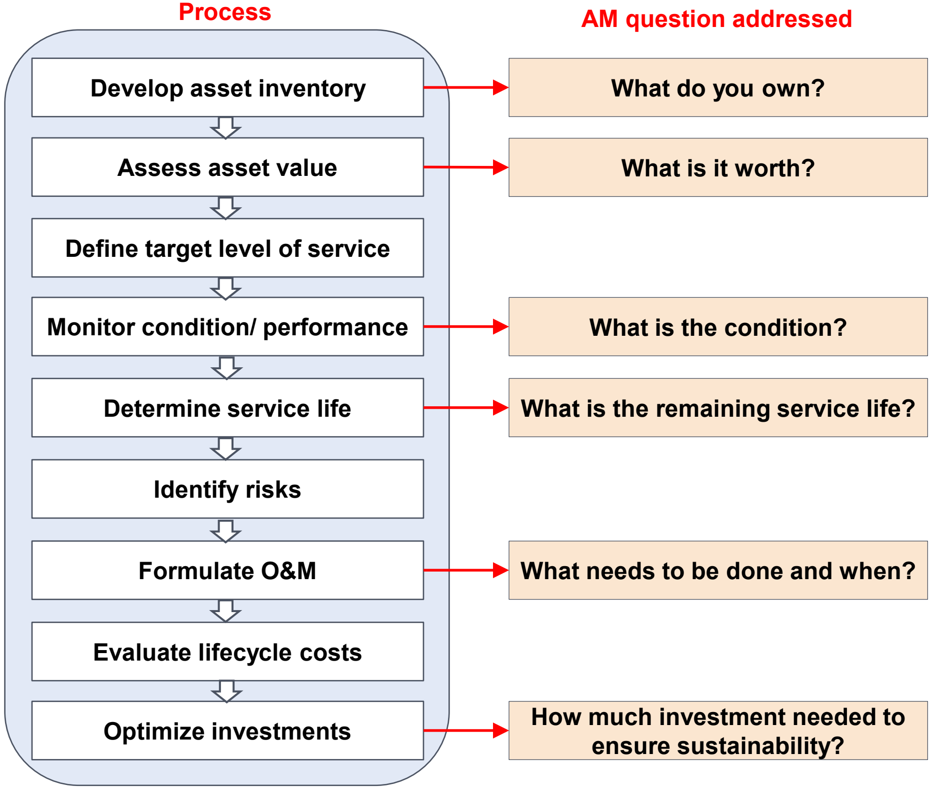


Figure adapted from:

- Yang, Y., Ng, S. T., Xu, F. J., & Skitmore, M. (2018). Towards sustainable and resilient high density cities through better integration of infrastructure networks. Sustainable cities and society, https://doi.org/10.1016/j.scs.2018.07.013

Asset Management of Grey and Green Infrastructure

Asset management for blue-green infrastructures: a scoping review

Jeroen G. Langeveld[a,*], Frédéric Cherqui[b], Franz Tscheikner-Gratl[c], Tone Merete Muthanna[c], Marina Fernandez-Delgado Juarez[c], Joao P. Leitão[d], Bardia Roghani[c], Karsten Kerres[e], Maria do Céu Almeida[f], Caty Werey[g] and Bénédicte Rulleau[h]

- ✓ Asset Management is widely applied
- ✓ Widely accepted operation and maintenance techniques
- ✓ Proactive and predictive maintenance based on deterioration modeling and risk analysis supported by years of data

- χ Only the critically important GIs are monitored
- χ The variety of types and compositions makes them difficult to manage
- χ Neglected, lack of financial support, lack of data, etc.

Studies on the long-term performance of GIs

- Variations in hydraulic performance and infiltration rates
- GIs can be a source of stormwater pollution
- Concerns about GI's long-term financial and operational sustainability

GIs need dedicated Asset Management methods to ensure their continued performance

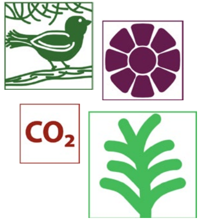
Image from:

Toronto and Region Conservation Authority (TRCA). (2016). Low Impact Development Stormwater Management Practice Inspection and Maintenance Guide. Prepared by the Sustainable Technologies Evaluation Program. Vaughan, Ontario.

How to define performance?

Function

Indicators



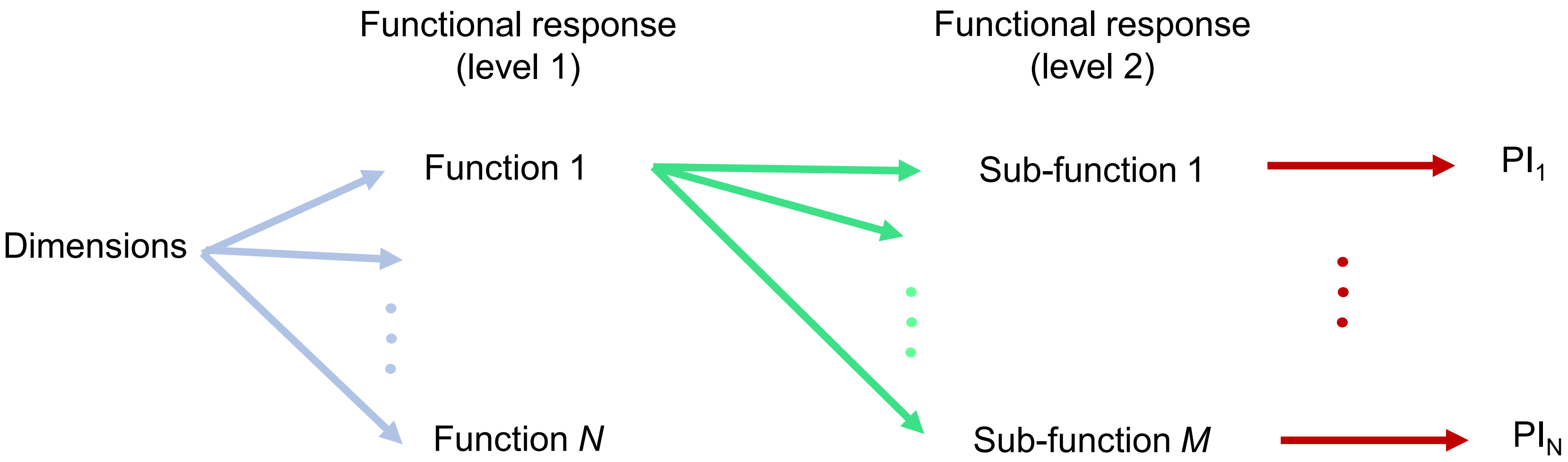
To date, assessing the holistic performance of GIs through a composite indicator-based model remains a major challenge (Langeveld et al., 2022).

Figure downloaded from:

https://www.stormwatershepherds.org.au/articles/green-infrastructure-naturalised-solutions-to-stormwater-treatment/

A review of GI functions

GI functions and co-benefits were gathered from publicly available literature:

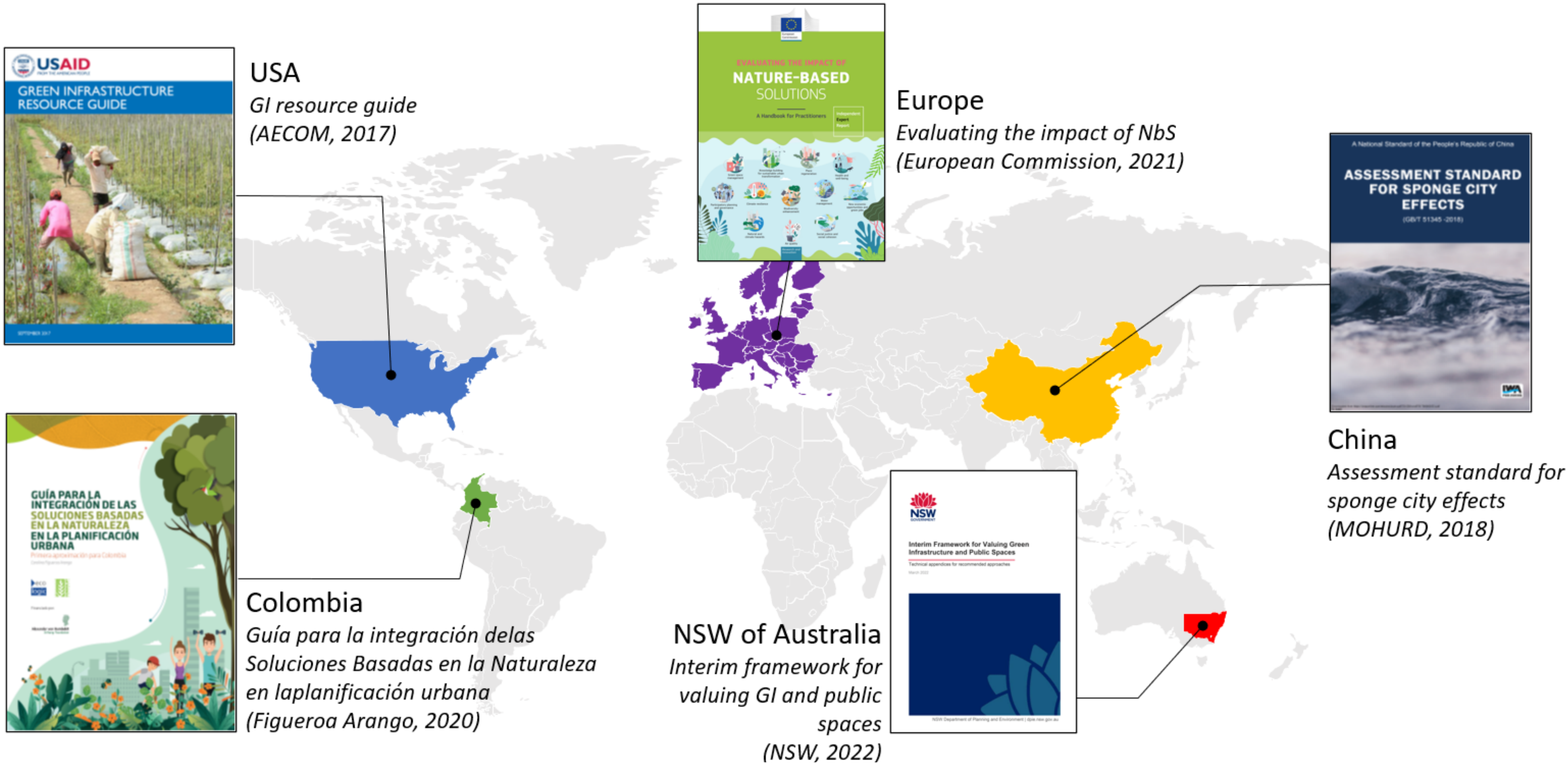


Performance indicators **(PIs)** are:

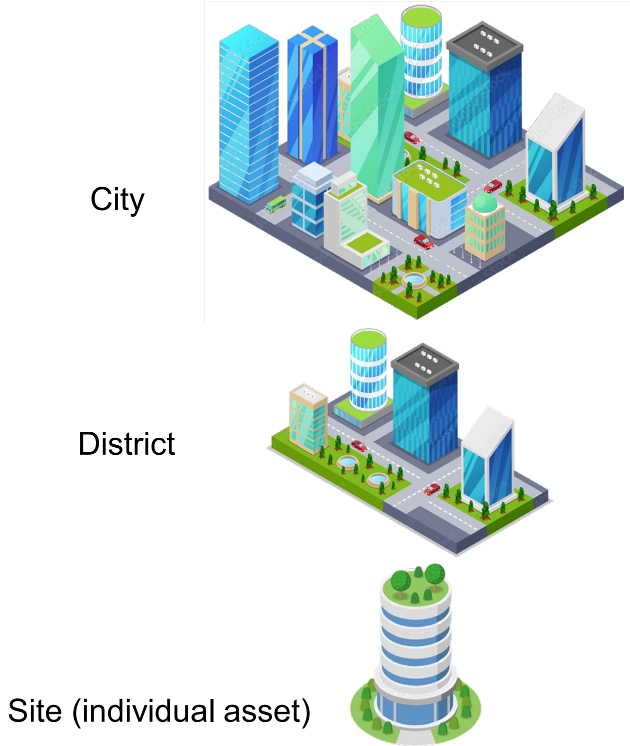
- A measure of advantages provided by GI
- Track the performance of the system

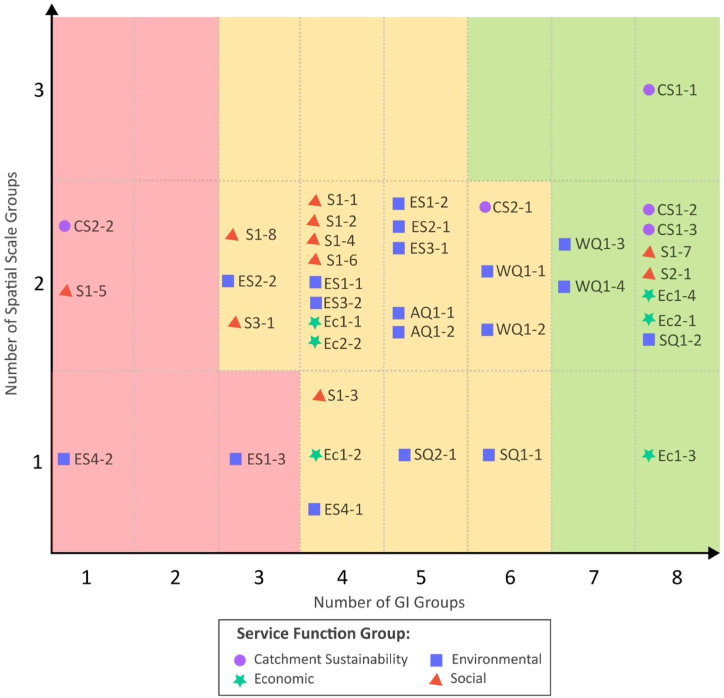
How to define performance?

- How can we **evaluate** GI performance for the desired functions?
- Which **GI type** is suitable for a desired function? On what **scale** assessing the performance is meaningful?
- What **resources** are needed to measure and evaluate GI performance?


USA
GI resource guide
(AECOM, 2017)
USAID
GREEN INFRASTRUCTURE RESOURCE GUIDE
Europe
Evaluating the impact of NbS
(European Commission, 2021)
EVALUATING THE IMPACT OF NATURE-BASED SOLUTIONS
A Handbook for Practitioners
China
Assessment standard for sponge city effects
(MOHURD, 2018)
A National Standard of the People's Republic of China
ASSESSMENT STANDARD FOR SPONGE CITY EFFECTS
Colombia
Guía para la integración delas Soluciones Basadas en la Naturaleza en laplanificación urbana
(Figueroa Arango, 2020)
GUÍA PARA LA INTEGRACIÓN DE LAS SOLUCIONES BASADAS EN LA NATURALEZA EN LA PLANIFICACIÓN URBANA
NSW of Australia
Interim framework for valuing GI and public spaces
(NSW, 2022)
Interim Framework for Valuing Green Infrastructure and Public Spaces

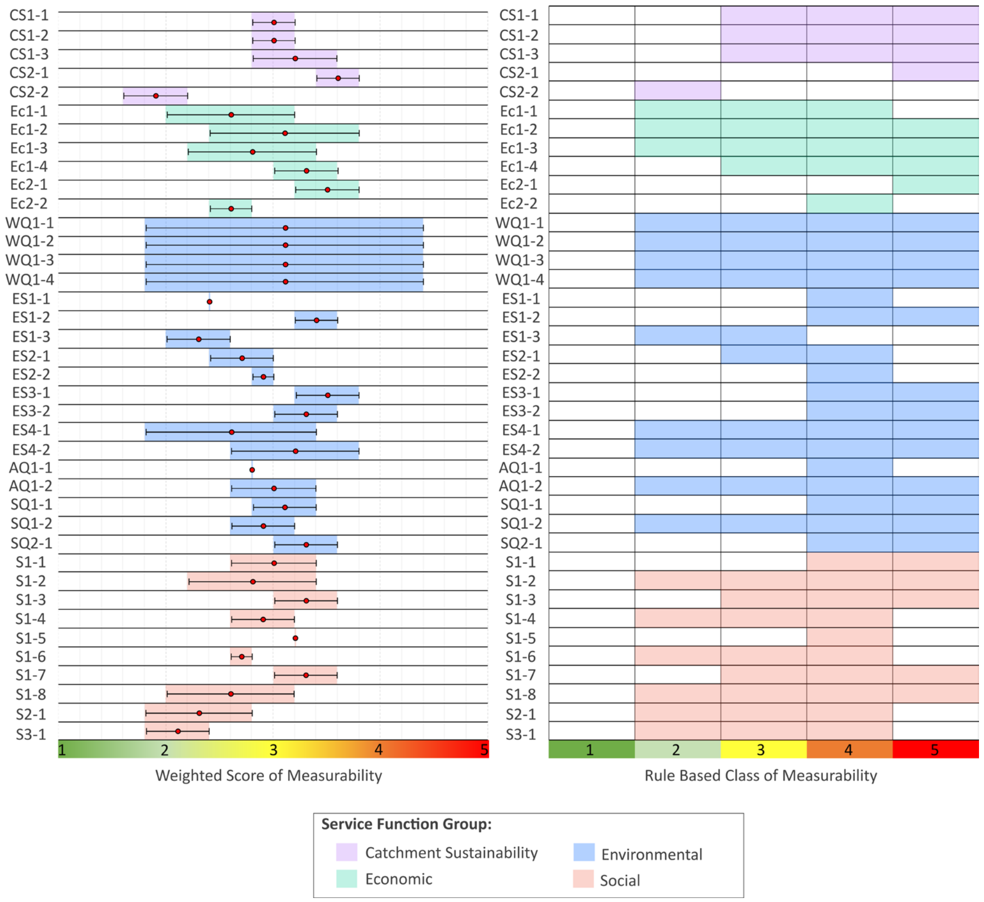
Which GI type is suitable for a desired function? On what scale assessing the performance is meaningful?





What resources are needed to measure and evaluate GI performance?

	Measurability of a PI			
Score	Data collection frequency	Level of expertise required	Data collection methods	Data collectors
1	Annually or every few years	Very low	Automatic Data Collection	Individual Data Collection
2	Monthly or several times per year	Low		
3	Weekly	Intermediate	Hybrid Data Collection (Combining Automatic and Manual)	Team-Based Data Collection
4	Daily	High		
5	Real-time	Very high	Manual Data Collection	Large-Scale Data Collection



RESEARCH ARTICLE | MAY 31 2024

A comparative analysis of international guidelines for green infrastructure performance assessment

Bardia Roghani; Mahdi Bahrami; Franz Tscheikner-Gratl; Frédéric Cherqui; Tone Merete Muthanna; Marius Møller Rokstad

Blue-Green Systems (2024) 6 (1): 133–152.

Preprint

Exploring Key Characteristics of Performance Indicators for Green Infrastructure Assessment

January 2024
DOI: 10.2139/ssrn.4916713

Bardia Roghani · Mahdi Bahrami · Frédéric Cherqui · Show all 5 authors ·
Marius Møller Rokstad

Under Review

Modeling GI performance

Two barriers exist for modeling GI performance (*Langeveld et al., 2022*):

1. GIs are complex

- Mix of green and grey components

- Interacting with the city and its habitants

2. Each GI is unique

- Unique size, composition, form, and functions

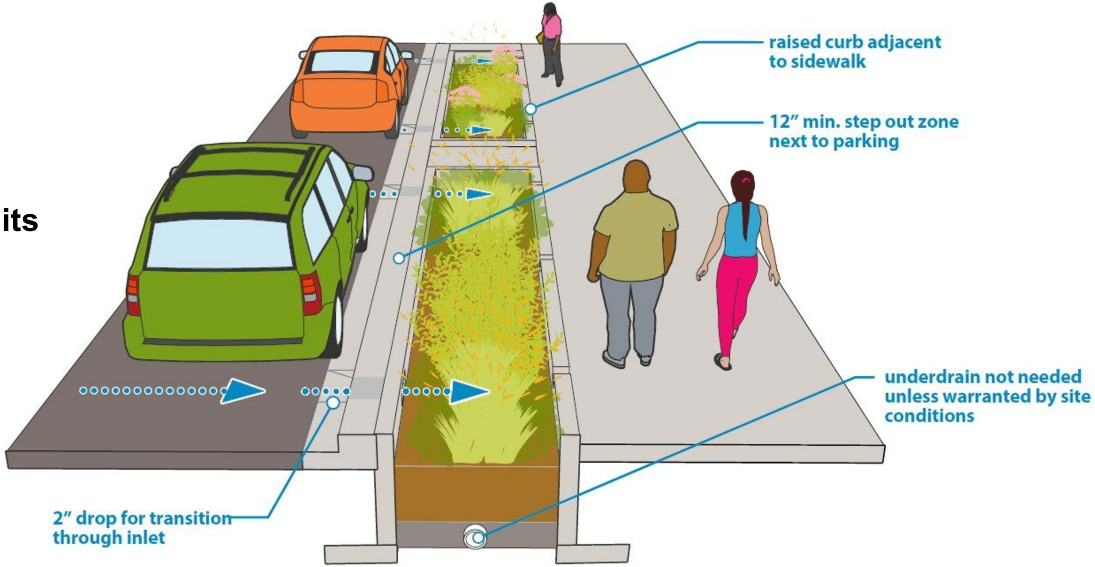


Figure downloaded from:
https://sdg.minneapolismn.gov/design-guidance/boulevards-and-furnishings/green-stormwater-infrastructure

Required data for different levels of Asset Management

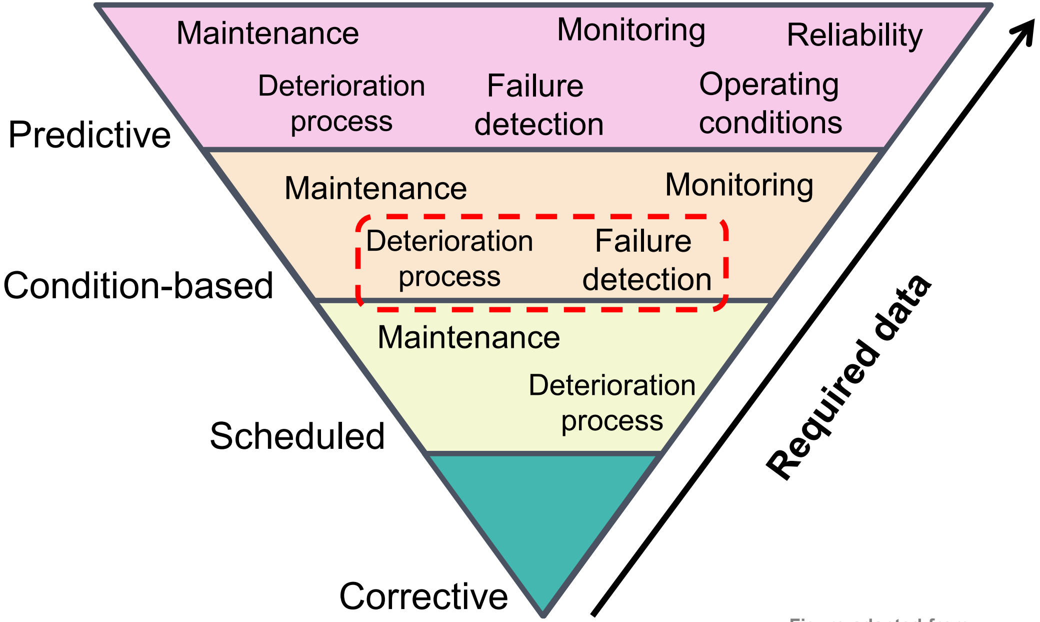


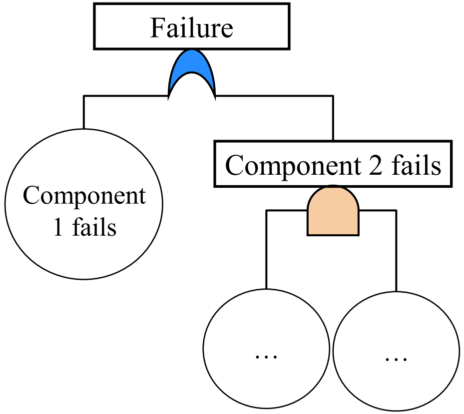
Figure adapted from:

Pinciroli, L., Baraldi, P., & Zio, E. (2023). Maintenance optimization in industry 4.0. Reliability Engineering & System Safety, 234. https://doi.org/10.1016/j.ress.2023.109204

Failure Analysis

In short:

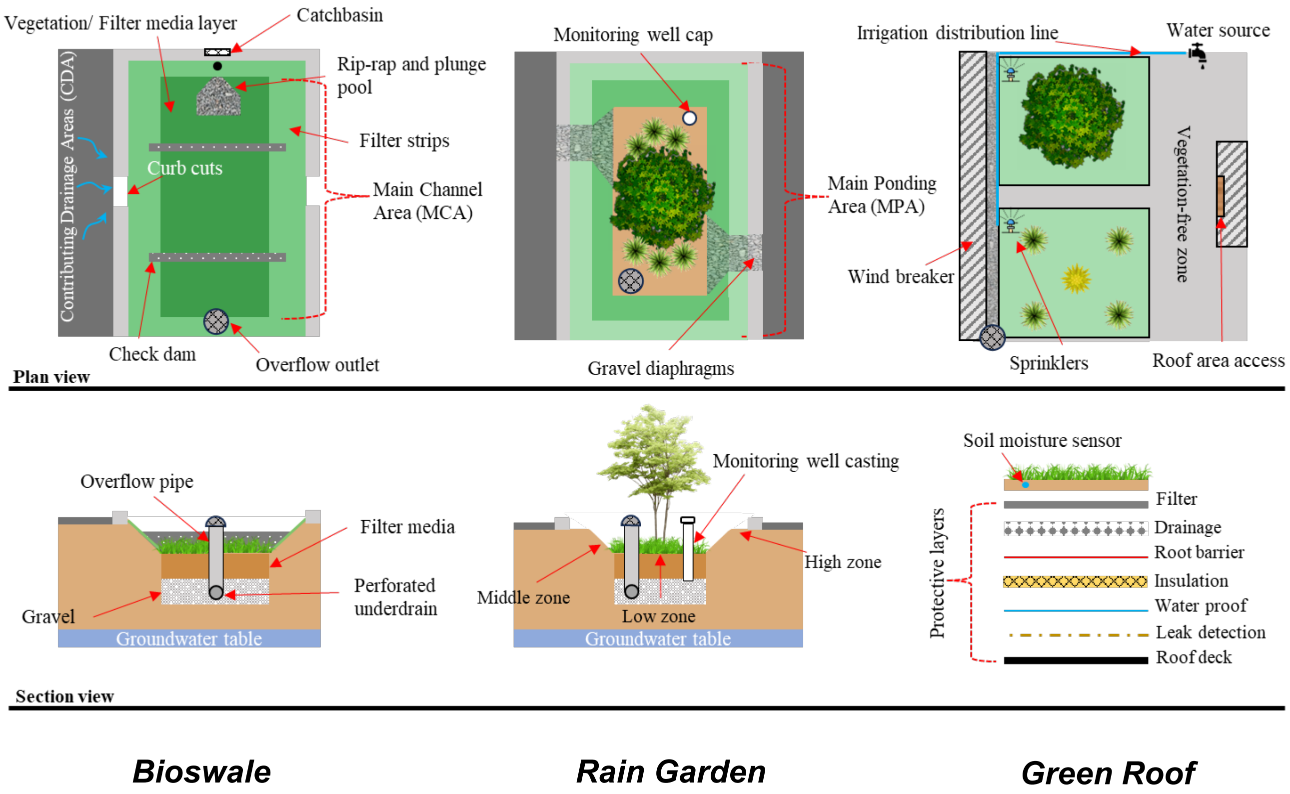
1. *We need to understand the interactions between GIs their components and their environment.*
2. *We need information (data) on their performance, conditions, deterioration process, failures, etc.*



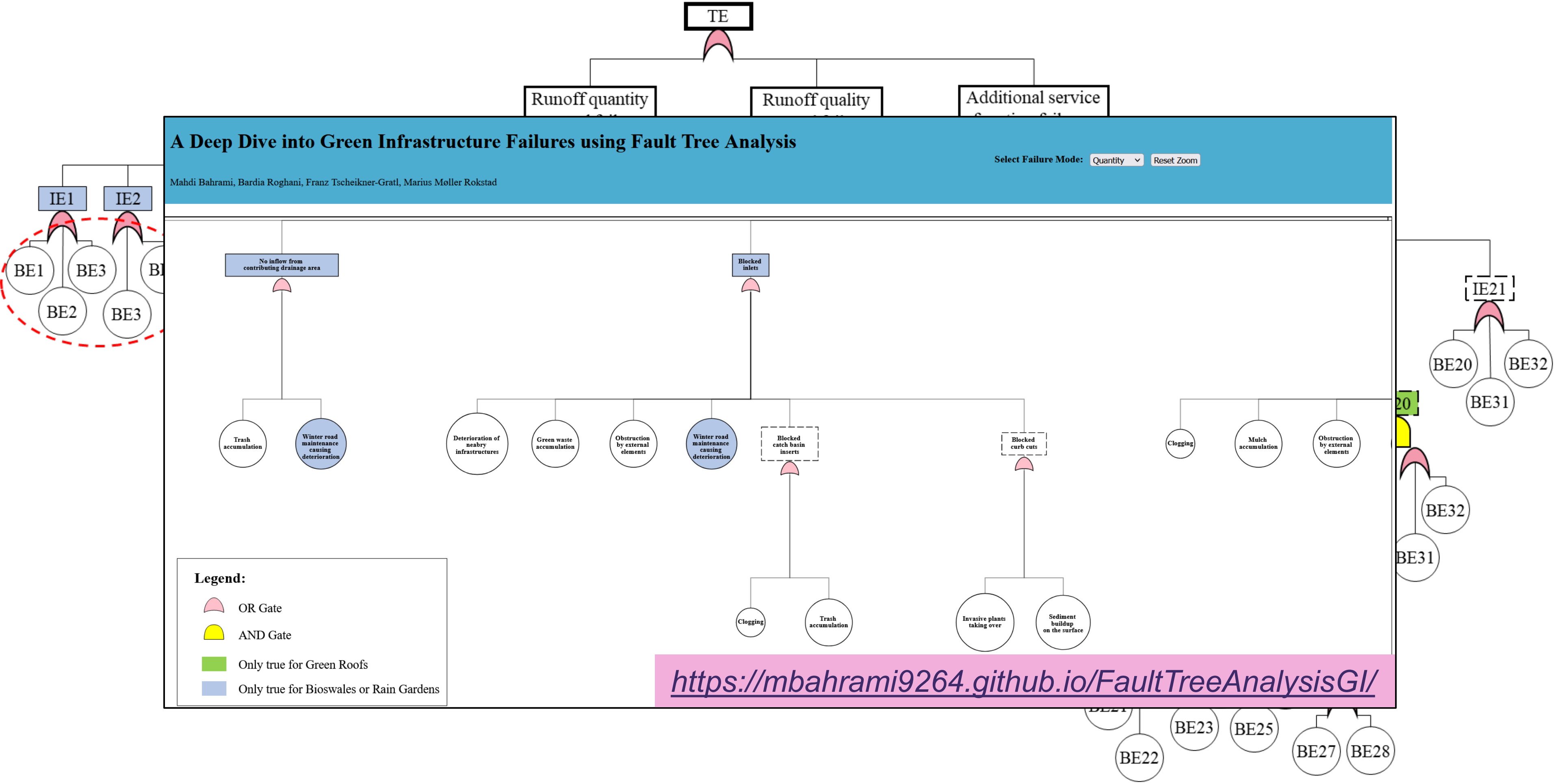
Fault Tree Analysis

1. *Simplicity and similarity to binary logic analysis*
2. *No requirement for mathematical equations*
3. *Could be a practical method even if it's just qualitative*

Common components



NTNU


TE
Runoff quantity
Runoff quality
Additional service
A Deep Dive into Green Infrastructure Failures using Fault Tree Analysis
Select Failure Mode: Quantity
Reset Zoom
Mahdi Bahrami, Bardia Roghani, Franz Tscheikner-Gratl, Marius Møller Rokstad
IE1
IE2
BE1
BE3
BE2
BE3
No inflow from contributing drainage area
Blocked inlets
Trash accumulation
Winter road maintenance causing deterioration
Deterioration of neabry infrastructures
Green waste accumulation
Obstruction by external elements
Winter road maintenance causing deterioration
Blocked catch basin inserts
Blocked curb cuts
Clogging
Mulch accumulation
Obstruction by external elements
Clogging
Trash accumulation
Invasive plants taking over
Sediment buildup on the surface
Legend:
OR Gate
AND Gate
Only true for Green Roofs
Only true for Bioswales or Rain Gardens
https://mbahrami9264.github.io/FaultTreeAnalysisGI/
IE21
BE20
BE32
BE31
BE32
BE31
BE23
BE25
BE22
BE27
BE28

ELSEVIER

Water Research
Volume 257, 15 June 2024, 121676

A deep dive into green infrastructure failures using fault tree analysis

Mahdi Bahrami, Bardia Roghani, Franz Tscheikner-Gratl, Marius Møller Rokstad

NTNU

Inspection guidelines for GIs

Louise Horn Buøen

Evaluating the Condition of Green Roofs: Development and Application of Inspection Checklist

Master's thesis in Civil and Environmental Engineering
Supervisor: Marius Møller Rokstad
Co-supervisor: Franz Tscheikner-Gratl
June 2024

Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

(a) Green roof Trondheim Spektrum (Photo: Adressa.no)

(b) Green roof at Frode Rinnans veg Student Village (Photo: SIT.no)

(c) Roof gardens at St. Olavs Hospital (Photo: Arkitektskaperverdi.no)

(d) Green roof at Lade Skole (Photo: Eggen Arkitekter)

Figure 4: Green roof case studies in Trondheim.

NTNU

Inspection of Green Roofs in Trondheim

Component	Condition state	Comment
Accessibility/safety		
How easily can the facility be accessed for inspection purposes?	4 3 **(2)** 1 NA	Access through authorized people only.
Are there safety measures in place to ensure inspections on the roof are safe?	4 **(3)** 2 1 NA	To climb the sedum roof at the GC harness was required. Therefore, observations were done from the ground.
Perimeter		
Is there a vegetation-free zone of at least 500 mm around roof penetrations (vents, drains, etc.)?	**(4)** 3 2 1 NA	Inspection chamber around outlet
Is there a vegetation-free zone of at least 500 mm along the perimeter of the roof?	4 **(3)** 2 1 NA	Gravel perimeter at the GC, the moss should not be present here.
Vegetation		
Is the roof completely covered in vegetation?	**(4)** 3 2 1 NA	Excellent vegetation coverage at sedum roof at the GC.
How is the overall plant health? Any signs of wilting, discoloration, bare stems?	4 **(3)** 2 1 NA	Some signs of weeds on the sedum roof at the GC.
Growing medium		
Are there any visible areas of bare soil?	**(4)** 3 2 1 NA	No areas of bare soil
Are there any signs of uplift?	**(4)** 3 2 1 NA	No
Protective layers (filter layer, drainage layer, root barrier, waterproofing membrane)		
Is there enough overlap of the layers?	**(4)** 3 2 1 NA	
Do the layers run up all edges?	**(4)** 3 2 1 NA	
Overflow outlets		
Are the overflow outlets clear of blockages from sediments, debris, or trash?	**(4)** 3 2 1 NA	
Are the gutters clear of blockages from sediments, debris, or trash?	**(4)** 3 2 1 NA	
Are the components free from damage (corrosion, deterioration)?	4 3 **(2)** 1 NA	Signs of corrosion on overflow outlets.
Irrigation systems		
Is the irrigation system protected against frost?	4 3 2 1 **(NA)**	
Are the components free from damage and corrosion?	4 3 2 1 **(NA)**	

Inspection guidelines for GI

Table 8: Conditions state levels in case studies.

Layer	Visual indicators	Case studies			
		GR1	GR2	GR3	GR4
Perimeter	Vegetation free zone around roof penetrations				
	Inspection path				
Vegetation	Vegetation coverage				
	Invasive species present				
Growing medium	Signs of bare soil				
	Signs of uplift				
Protective layers	Enough overlapping				
	Run up all edges				
Overflow outlets	Debris and trash in outlets				
	Debris and trash in gutters				
	Damage and corrosion on components				
Irrigation system	Protected against frost				
	Damage and corrosion				

❹ Excellent, ❸ Good, ❷ Fair, ❶ Poor, ● Not applicable.

Condition	4 (Excellent)	3 (Good)	2 (Fair)	1 (Poor)
Perimeter	 Vegetation free zone around outlets (Photo: Vegetal ID).	 Vegetation-free zones along roof edges, lacking inspection paths in central roof area (Photo: Daniel Filippi).	 Vegetation within the vegetation-free zone.	 Vegetation damaged from foot traffic to the ladder.
Vegetation	 Sedum is thriving and looking healthy.	 Weeds present on large areas of roof.	 Areas of roof that are not covered in vegetation.	 Vegetation is not atteched to the substrate.
Growing medium	 Vegetation coverage is dense and uniform indicating growing medium with ideal drainage and nutrient content.	 Texture is fairly consistent, and there are no major signs of erosion.	 The sedum is not attached to the growing medium, possibly due to inadequate properties.	 The growing medium is completely eroded in this part of the roof.

NTNU

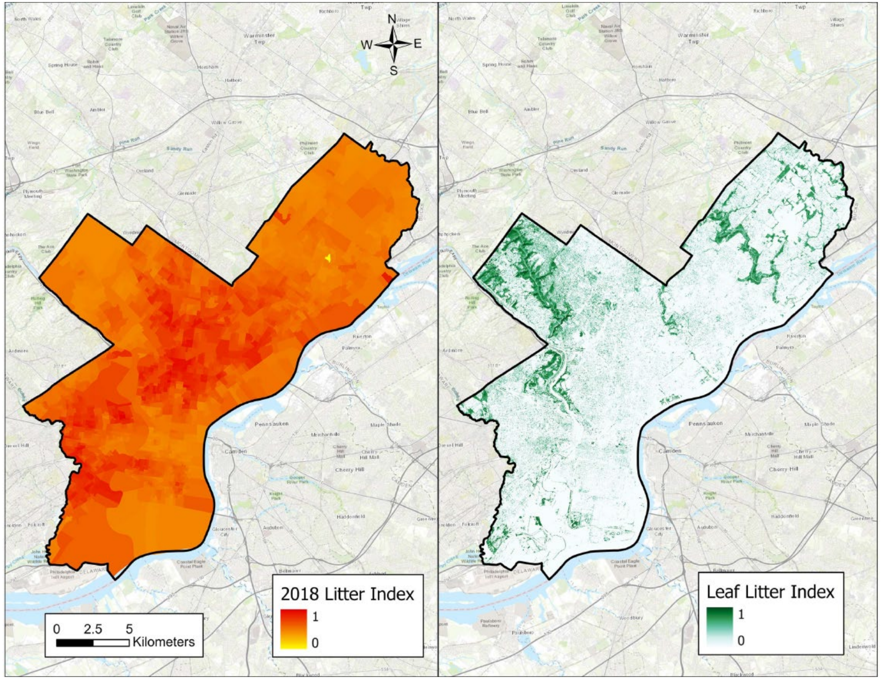
The next step

1. Identifying the types of data required for modeling the impact of external activities

   - such as winter road maintenance, construction activities, deterioration of nearby infrastructure

2. Develop a risk based assessment method for maintenance needs of GIs

   - GIS method for developing risk maps



Homet, K., Kremer, P., Smith, V., Ampomah, R., & Strader, S. M. (2022). Mapping Predicted Areas of Common Maintenance Impacts to Green Stormwater Infrastructure in Philadelphia, Pennsylvania. *Journal of Sustainable Water in the Built Environment*, *8*(3). https://doi.org/10.1061/jswbay.0000986

NTNU

Key takeaways

GIs are part of the sustainable urban water management, and in order to have multifunctional systems, we need GIs to perform as intended

> GIs need their dedicated asset management

GIs need holistic guidelines that provide decision makers with tools to assess their performance, and measure their effectiveness.

- **How to evaluate GI performance?**
- **What resources are needed for performance evaluation?**

GIs lack maintenance guidelines that provide operators with detailed information based on local context.

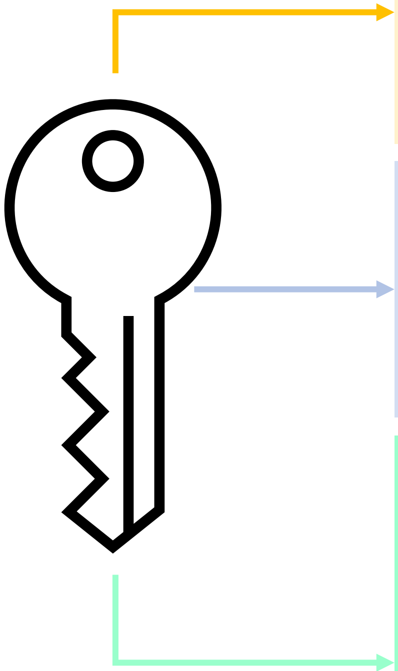
> GI Monitoring data should be collected (such as failures, deterioration processes, and maintenance activities should be collected)

Contact Info

THANK YOU!

Mahdi Bahrami
PhD candidate
NTNU, Norway
mahdi.bahrami@ntnu.no

Key takeaways Performance Indicators



- EU and USA proposed indicators for a wider range of GIs’ benefits
- China, Colombia, and NSW of Australia focused on some specific aspects

Differences may come from:

- ✓ Philosophies regarding GIs applications
- ✓ Guideline perspective: "Federal (e.g EU or USA)", "National (e.g. Colombia or China)", and "State (e.g. NSW)"

Important common shortcomings:

- Instructions on evaluation and interpretation of measured PIs are not provided

- The scale of applicability of PIs

- Resources required for measurement and evaluation

Key takeaways Fault Tree Analysis

Some events were identified as **recurring causes of failure** in different components of all three types of GI:

- Clogging from sediment accumulation, Trash accumulation, Overly dense vegetation

Human activities near GIs, like winter road maintenance or construction, can cause failures especially to the vegetation or filtration layers.

Such events can also disrupt higher number of GI functions

Component failures can spread and affect other parts of the GI, so it's important to focus on those key areas for inspections and repairs

- Vegetation
- Filter media
- Irrigation components