Down in the Flood: Mapping the Impact of External Factors and Flood Paths on Green Infrastructure Maintenance

A la croisée des chemins : Cartographie de l'impact des facteurs externes et des chemins d'écoulement sur l'entretien des solutions fondées sur la nature

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RÉSUMÉ

Les solutions fondées sur la nature (SfN) sont de plus en plus mobilisées pour la gestion des eaux pluviales urbaines, mais les communes disposent de peu d'outils pour localiser les facteurs externes susceptibles d'affecter leurs performances à long terme. Cette étude développe un cadre opérationnel pour la maintenance des SfN basé sur des proxys pour trois facteurs externes – feuilles mortes (LL), sédiments issus de surfaces non revêtues (SU) et accumulation de déchets (TA) – et les combine avec la cartographie de chemins de ruissellement de surface pour 139 GI à Trondheim (Norvège). Des cartes de points critiques ont été produites à partir de jeux de données disponibles, tandis que les chemins de ruissellement (0,5–5 ha de surface contributive) servent à classer les SfN selon leur proximité aux couloirs d'écoulement. Les résultats montrent des interactions complexes entre les LL, SU et TA, indiquant que chaque SfN est soumise à une combinaison spécifique de pressions. Seule une minorité de SfN se trouve à moins de 5 m des principaux chemins de ruissellement, ce qui en fait des ouvrages hydrauliquement stratégiques. L'analyse de quatre SfN distinctes montre comment la combinaison des cartes de facteurs externes et de ruissellement peut guider la planification saisonnière des inspections et des opérations de maintenance à l'échelle de la ville.

ABSTRACT

Green Infrastructure (GI) is increasingly used for urban stormwater management, yet municipalities lack systematic tools to assess where external stressors may compromise long-term performance. This study operationalizes a proxy-based framework for external stressors and combines it with overland flood-path mapping for 139 GIs in Trondheim, Norway. Stressor indices for leaf litter (LL), sediments from unsealed surfaces (SU) and trash accumulation (TA) were derived from available datasets to create hotspot maps. Overland flood paths were obtained for contributing areas between 0.5 and 5 ha and were used to classify GIs according to their proximity to flood corridors. Results show distinct spatial patterns for LL, SU and TA, implying that different GIs are dominated by different stressor combinations. Only a small subset of GIs lies within 5 m of the main 5 ha and 2.5 ha flood paths, making these hydraulically strategic assets. Four contrasting GIs are examined in detail to illustrate how combined stressor–flood mapping can guide inspection and maintenance activities. The approach supports GI asset management by linking spatial stressor information with flood-path exposure at city scale.

KEYWORDS

Asset management, Flood paths, Monitoring & inspection, Proxy indicators, Stormwater

1 INTRODUCTION

In recent decades, Green Infrastructure (GI) has been adapted across the world to mitigate the environmental impacts of urbanization. While GI systems are increasingly recognized for their role in flood mitigation and climate adaptation, municipalities continue to face challenges in ensuring their sustained performance (Bahrami et al., 2024). GI are exposed to a variety of external stressors - ranging from environmental and hydrological conditions to human activities - that can accelerate deterioration and reduce performance over time. Long-term studies show widespread under-maintenance of GI, leading to reduced performance or failures, decline in infiltration capacities, and pollution accumulation (Blecken et al., 2015; Bahrami et al., 2024).

While these stressors are increasingly acknowledged, systematic methods to quantify and map them remain scarce (Langeveld et al., 2022). In many urban contexts, long-term monitoring data on these factors is either unavailable or too limited to provide a reliable basis for assessment. This data gap makes it challenging to evaluate GI vulnerability and hinders proactive maintenance planning (Langeveld et al., 2022). In this regard, proxy data can function as an alternative for estimating the spatial distribution and intensity of external stressors. By linking external stressors to spatially available indicators, municipalities can approximate where GI are likely to experience higher maintenance needs (Bahrami et al. 2025). Such maps can also support early design decisions about optimized GIs placement, and during operation, help prioritize inspections, or targeted maintenance activities. Bahrami et al. (2025) recently proposed a framework that identifies external stressors relevant for bioretentions, selects suitable proxies, and specified the datasets required to estimate them in cold climate like Norway. Building on that work, this study operationalizes the proposed framework and integrates it with high-resolution overland flow paths as another impotant influential factor.

2 MAPPING THE IMPACT OF EXTERNAL STRESSORS ON GREEN INFRASTRUCTURE

Bahrami et al. (2025) identified twelve external stressor categories and screened candidate proxy indicators based on conceptual relevance and data suitability. only four stressor groups have been included due to data availability. These four stressors form the basis for spatial mapping in this paper (Table 1).

Table 1. List of identified proxies with available datasets for the case study of Norway (Bahrami et al. 2025)

External stressor	Proxy	Factor represented by proxy data	Data sources needed for calculation of proxy
LL: Leaf Litter	Changes in Normalized difference vegetation index (NDVI)	Changes in the value as a proxy for changes in leaf coverage	High resolution multispectral satellite imagery (3x3m) and information on location of trees in the urban areas
SU: Sediments (unsealed surfaces)	Unsealed surfaces area, Slope length and steepness (LS factor from RUSLE)	More erosion from unsealed roads or surfaces situated at higher slopes	Parcel maps, Digital Elevation Maps (DEM)
TA: Trash accumulation	Distance to trash receptacle, Permanent population, Proximity to industrial areas, Presence of Points of Interest (POIs)	Higher rates of littering in areas with higher activities and high distance from trash receptacles	Location of trash receptacles, 250x250m population distribution data, district population data, Land use maps, Locations of restaurants, shopping malls, retail stores, and entertainment centers
FP: Flood Paths	Proximity to overland flow paths at multiple contributing-area thresholds (0.5–5 ha)	Exposure of GI to high surface flows and potential delivery of upstream stressors along mapped flood corridors	Flood path network from SCALGO Live (minimum contributing areas of 0.5, 1, 2.5 and 5 ha)

The methodology is demonstrated for Trondheim, a coastal city in central Norway with a cold climate and frequent precipitation. The analysis covers the urban settlement area. National and municipal datasets were combined with high-resolution satellite imagery and land-use information to derive the proxy layers. For LL, SU, and TA, each proxy was converted to a raster layer, normalized to [0,1], and combined into a stressor index using an equal-weighted average. These three stressor categories were then averaged into an aggregated maintenance needs index at grid scale and classified into five ordinal classes (Minimal–Severe) using equal intervals. All the analysis was performed in QGIS version 3.40. The method for constructing each proxy layer varies. For LL, we assumed that maintenance needs increase with the presence of deciduous vegetation and seasonal canopy change. NDVI values were compared between spring (28 April) and early summer (15 June) of 2024 to estimate the seasonal change in leaf coverage.

The grid layer was calculated using Equation 1. The values fall between 0 (no leaf litter) to 1 (high leaf litter). In the next step, the shapefile for trees in Trondheim was used to extract the changes in areas with tree canopy:

$$LL^{(grid)} = \frac{(NDVI_{July} - NDVI_{April})}{|NDVI_{July}|} \qquad \text{Equation 1}$$

For SU, the slope length and steepness (LS) factor was calculated using the DEM as the input. Parcel data was used to create a grid using information on the area of unsealed roads and surfaces in each parcel. For TA, we assumed that littering risk increases with human activity and decreases with access to trash receptacles. For the grid-based map, the population grid was normalized and rasterized. A POI heatmap was created with a 100 m radius. An analogous 100 m influence zone was defined around trash receptacles, but with inverted values to represent reduced littering potential near bins. In addition, a land-use raster was created where Industrial and Urbanized areas, which can have a higher rate of littering, were assigned a value of 1 and all other classes 0 (Bahrami et al., 2025). For PF, overland flood paths were obtained from the Digital Elevation Model (DEM) (1m*1m) embedded in the web application of SCALGO Live platform. In this study, we use the mapped flood paths as a representation of the major stormwater system. Flood paths were exported for a range of flow network detail values (minimum contributing areas of 0.5, 1, 2.5, and 5 ha) as vector layers. Exposure to overland flow was then defined by the spatial relationship between each GI point and the flow networks: GIs intersecting or located within 5 m of any mapped flow path in a given network were labelled as *on flood path* for that contributing-area class. The 5 m value is illustrative and could be refined in future applications, for example by using 2D hydraulic model results to approximate the actual width of overland flow.

In the final step, bioretentions across Trondheim were graded based on both their external stressor indices (LL, SU, TA) and their floodway exposure classes. From these, a small number were selected and mapped in detail to illustrate how the proposed mapping approach can be used to support targeted maintenance of GI assets.

3 RESULTS AND DISCUSSION

Figure 1 presents grid-based hotspot maps for three external stressors in Trondheim, along with the flood paths for the 5-ha flow network. Each map provides a relative rather than absolute indication of where GIs are likely to experience higher external pressure. The maps therefore highlight comparative spatial patterns of exposure that can guide where different types of maintenance may be most critical.Together, the LL, TA and SU maps reveal that different external stressors follow distinct spatial patterns, implying that GIs will face different dominant pressures across the city. This differentiation is useful for practice: LL hotspots call for seasonal inspection and autumn cleaning, TA pressure suggests more frequent visits and bin placement along activity corridors, and SU prone areas highlight the need for pretreatment, erosion control and inlet protection. An analysis of 139 GI locations in Trondheim based on the FP map showed that only 4 GIs are located in a 5 meter radius from a 5 ha flood paths, 5 GIs were located on the 2.5 ha, 9 on the 1 ha and 11 on the 0.5 ha flood path network, while the remaining assets are located more than 5 m from any mapped flow path. This means that only a small subset of GIs are directly integrated into the main overland flood corridors, whereas most facilities are primarily exposed to local stressors rather than concentrated flood routing. From a maintenance-planning perspective, GIs on 5 ha and 2.5 ha paths can be seen as hydraulically strategic assets, where failure or clogging may have wider consequences for surrounding streets and properties, while GIs on 1 ha and 0.5 ha paths mainly interact with more local flood dynamics.

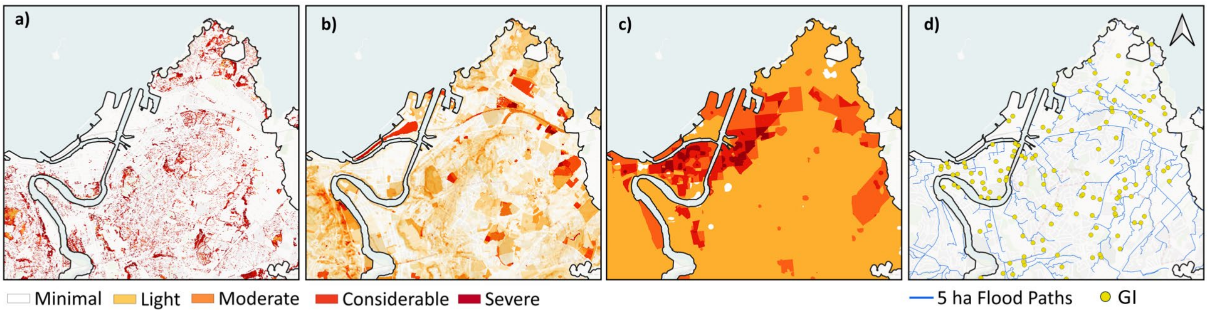

Figure 1. Hotspot maps for external stressors in Trondheim: a) LL, b) TA, c) SU, and d) FP for 5 ha

To further explore the implications of the method, four GI examples were selected from different parts of Trondheim and are shown on Figure 2. The first GI (Figure 2.1) is a bioretention which is not located on a mapped flood path but shows a moderate TA index while LL and SU remain low. This indicates that the main pressure is local human activity rather than runoff transport. For this asset, maintenance can prioritize regular litter removal and checking for clogging at inlets after busy periods, while structural inspections and sediment removal can be scheduled less frequently.The second GI (Figure 2.2) is a detention pond that, like the first GI, is not intersected by any incoming flood path; instead, the mapped flow path represents the outflow leaving the GI. At the same time, this site shows severe LL and moderate TA intensity, reflecting dense tree canopy in and around the facility. This combination suggests that the GI itself is a potential point for flooding and a source of debris to the downstream system if outlets clog or bypass occur. Maintenance and inspection should therefore prioritize keeping the inlet and outlet structures clear of leaves, with targeted cleaning in autumn and after major storms to ensure that flows can safely pass through the facility without causing local overflow or exporting large debris loads.

The third GI (Figure 2.3) is a multi-functional football field located directly on a primary 5 ha floodway, where overland flow is intentionally routed so that water can spread, be temporarily stored and infiltrate into the soil. This site combines severe LL intensity with moderate TA, reflecting both dense tree cover around the pitch and intensive recreational use. If design checks indicate that larger events are likely to exceed this capacity several times per year, it may be more realistic to accept occasional surface flooding and instead design the GI so that these exceedances have limited consequences for nearby streets and properties. In parallel, maintenance and inspection should focus on keeping the surface relatively free of leaves and litter, both to reduce damage to the turf and to limit the export of organic debris and trash in outflowing water. Seasonal leaf removal, monitoring low points after major storms and regular clean-ups after periods of heavy use can help ensure that the pitch continues to function as a safe recreational area while still providing reliable temporary storage and reasonably clean outflows as part of the wider flood-management system.

The fourth GI is a bioretention located along a 1 ha flood path, i.e. a smaller overland corridor than the main 5 ha routes. The hydraulic capacity of such a facility is primarily assessed during the design phase, but simple hydrological analysis can also be used in operation to estimate how often this flood path is activated. This frequency gives an indication of how often the GI is likely to receive concentrated inflows, which in turn governs how often litter and sediments will accumulate and therefore when inspections should be prioritised. At the same time, this GI lies in the city-centre area and shows high TA, making the site a candidate for litter management, for example by adding bins and scheduling frequent clean-ups around the contributing streets.

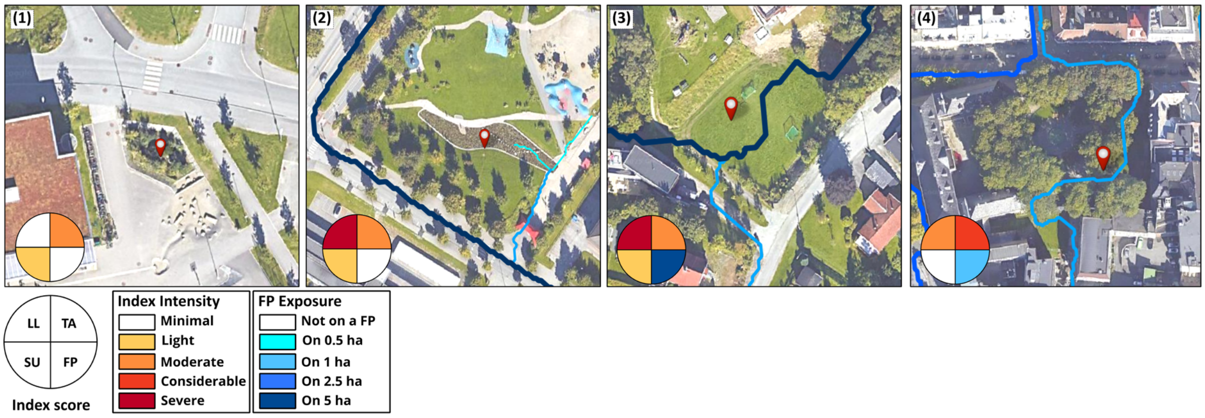

Figure 2. Comparison of index intensities for four different GIs in Trondheim.

Future work should extend the mapping framework to additional external stressors, such as pollutants from roads to better capture other risks to GI. Floodpath information could then be used not only to assess hydraulic exposure, but also to trace potential transfer of pollutants from upstream areas with high stressor indices into individual GIs. Combining such source–pathway mapping with information on the frequency, seasonality and magnitude of flood events would enable more refined maintenance planning, for example by aligning inspections with periods of likely pollutant delivery and could inform the design and placement of GI elements that are robust to both hydraulic and water quality pressures.

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