

Establishing an Extreme Weather Exposure and Resilience Index for Nature-based Stormwater Infrastructure in Urban Environments Using a Multi-Method Approach

Établissement d'un indice d'exposition et de résilience aux phénomènes météorologiques extrêmes pour les infrastructures urbaines de gestion des eaux pluviales fondées sur la nature à l'aide d'une approche multiméthode

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RÉSUMÉ

Les phénomènes météorologiques extrêmes, tels que les vagues de chaleur, les vagues de froid, les sécheresses et les pluies intenses, s'intensifient à l'échelle mondiale et en Corée du Sud, exerçant une pression considérable sur les infrastructures vertes urbaines (UGI). Cette étude a développé un indice d'exposition aux événements météorologiques extrêmes fondé sur une approche multiméthode pour les revêtements perméables et les toitures végétalisées, en utilisant des projections CMIP6 corrigées des biais (2015–2100) et six indicateurs clés (TXx, TNn, HWD, CWD, CDD, Rx1day/R20mm). Les poids des indicateurs ont été déterminés au moyen de l'Analyse Hiérarchique des Procès (AHP), de l'Analyse en Composantes Principales (ACP) et de la méthode de l'entropie, révélant une dominance constante de la chaleur et de la sécheresse selon AHP/ACP ($\rho = 0,74-0,93$) ainsi qu'une influence plus marquée des extrêmes de froid selon l'entropie. Malgré les différences méthodologiques, l'ensemble des indices a identifié Daegu, Gwangju et Séoul comme des villes fortement exposées. Le cadre proposé fournit des scores d'exposition exploitables et fondés sur des scénarios climatiques, permettant de soutenir la conception d'UGI adaptées au climat, la priorisation des zones vulnérables et la planification de la résilience à long terme.

ABSTRACT

Extreme weather events phenomena such as heat waves, cold surges, droughts, and heavy rainfall, are intensifying globally and in South Korea, creating significant stress for urban green infrastructure (UGI). This study developed a multi-method extreme weather exposure index for permeable pavements and green roofs using bias-corrected CMIP6 projections (2015--2100) and six key indicators (TXx, TNn, HWD, CWD, CDD, Rx1day/R20mm). Indicator weights were derived using Analytical Hierarchy Process (AHP), Principal Component Analysis (PCA), and entropy methods, revealing consistent dominance of heat and drought under AHP/PCA ($\rho = 0.74-0.93$) and higher influence of cold extremes under entropy. Despite methodological differences, all indices identified the cities Daegu, Gwangju, and Seoul as high-exposure cities. The framework provides actionable, scenario-based exposure scores that support climate-adaptive UGI design, prioritization of vulnerable cities, and long-term resilience planning.

KEYWORDS

Climate change adaptation, exposure index, extreme weather, nature-based solutions, urban green infrastructure

1 INTRODUCTION

The intensification of extreme weather phenomena has become a major global concern, particularly in urbanized environments. Projections suggest a temperature increase of about +2 °C by mid-century, with serious implications for urban systems under climatic and human pressures (Vargas Zeppetello et al., 2022). In South Korea, recent decades have shown greater variability in both high and low temperature extremes, indicating shifting climatic conditions (Kim & Lee, 2019). Urbanization has worsened these impacts by increasing impervious surfaces and reducing natural cooling, thereby heightening risks of flooding and overheating. Nature-based stormwater management technologies in urban areas, also referred to as urban green infrastructure (UGI), have been implemented to mitigate such risks. However, their resilience under prolonged climate stress remains uncertain, as previous studies have focused mainly on precipitation extremes while neglecting droughts, heat waves, and cold events.

This study introduces an extreme weather exposure index for UGI using multi-method indicator weighting and climate modelling. Three techniques, particularly Analytic Hierarchy Process (AHP), Principal Component Analysis (PCA), and entropy weighting, were applied with bias-corrected CMIP6 projections under SSP1-2.6 and SSP5-8.5 scenarios to assess exposure in permeable pavements and green roofs across major South Korean cities. The framework offers a structured approach for quantifying climate exposure and guiding adaptation planning.

2 METHODOLOGICAL APPROACH

A framework (Figure 1) was developed to construct an extreme weather exposure index for nature-based stormwater management technologies. The process involved six steps, including selection of study areas, indicator identification, weighting, climate modelling, index computation, and ranking comparison. Two UGI types, permeable pavements and green roofs, were analyzed across eight South Korean cities classified as humid continental (Dfa) or humid subtropical (Cfa). Seven indicators representing thermal, drought, and rainfall extremes were used, particularly annual temperature extremes (TXx, TNn), maximum yearly number of heat wave and cold wave days, yearly rainfall extremes (Rx1day, R20mm), and maximum yearly number of consecutive dry days. Historical data were obtained from the Korea Meteorological Administration, and CMIP6 projections (EC-Earth3, KACE-1-0-G, MIROC6) under SSP1-2.6 and SSP5-8.5 scenarios were bias-corrected using quantile mapping.

Indicator weighting employed three techniques: AHP for expert judgment, PCA for co-varying stressors, and entropy weighting for data variability. Normalized indicator values were combined with method-specific weights, and ranking stability was evaluated using mean rank, standard deviation, and Spearman’s correlation to assess consistency across weighting methods and climate scenarios.

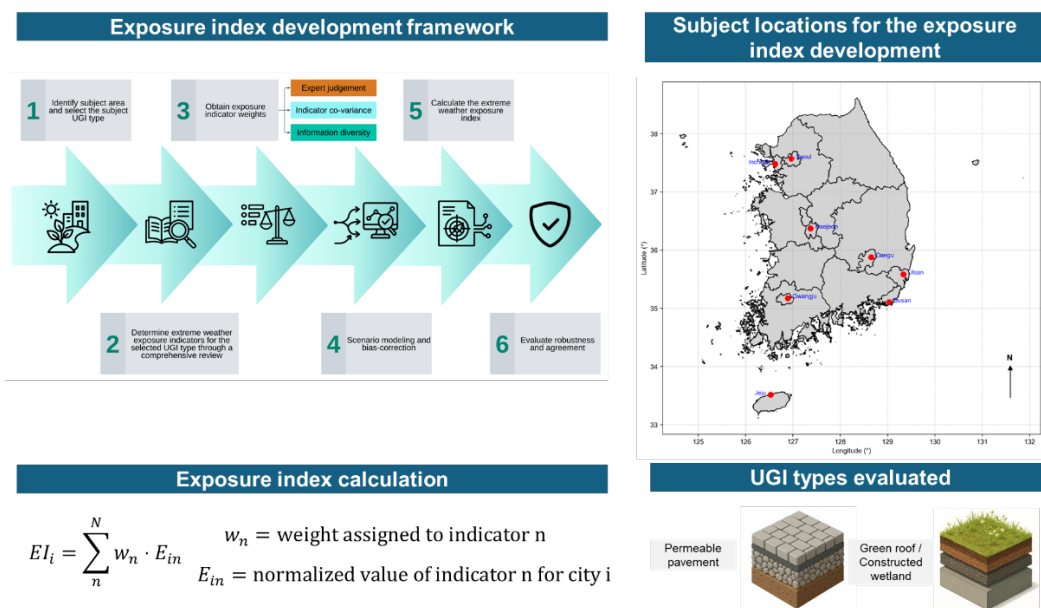


Figure 1 Summary of the exposure index development framework, subject locations for the index development, formula for

the exposure index, and the subject UGI types.

3 RESULTS AND DISCUSSION

The developed framework was applied to evaluate extreme weather exposure for permeable pavements and green roofs across eight South Korean cities under SSP1-2.6 and SSP5-8.5 scenarios. Bias-corrected CMIP6 projections indicated marked increases in temperature and drought extremes toward mid-century. The yearly maximum of daily maximum temperature (TXx) increased by 2.4–3.8 °C, and heat wave days (HWD) rose from 6–15 days yr⁻¹ to 20–45 days yr⁻¹, while consecutive dry days (CDD) increased by up to 12 days. In contrast, rainfall-related indicators such as maximum 1-day precipitation (Rx1day) and days with rainfall ≥ 20 mm (R20mm) exhibited relatively minor spatial variability.

Through the AHP, which results are shown in Table 1, Rx1day (0.220) and TXx (0.217) were identified as the dominant stressors for permeable pavements, followed by R20mm (0.179) and HWD (0.178). For green roofs, HWD (0.204), CDD (0.198), and R20mm (0.201) were most influential, reflecting vulnerability to thermal and hydrological extremes. PCA produced similar results, with the first component explaining 46–52 % of total variance and highlighting TXx and HWD as key co-varying indicators (Figure 2). Entropy weighting assigned greater importance to spatially variable parameters such as CDD (0.237–0.255) and CWD (0.255–0.348). Despite methodological differences, all weighting techniques consistently identified Daegu and Gwangju as the most exposed cities and Jeju as the least exposed (Figure 3). The strong correlations between AHP and PCA ($\rho = 0.74\text{--}0.93$) confirmed methodological robustness.

Table 1 List of indicators for the extreme weather exposure evaluation of permeable pavements and their corresponding weights obtained from the Analytical Hierarchy Process.

Code	Exposure indicator	Short name	Relative weight
A1	Yearly maximum of daily maximum temperature	TXx	0.217
A2	Yearly minimum of daily minimum temperature	TNn	0.124
A3	Yearly number of heat wave days	HWD	0.178
A4	Yearly number of cold wave days	CWD	0.083
A5	Yearly maximum of daily maximum precipitation	Rx1day	0.220
A6	Yearly precipitation on wet days	R20mm	0.179

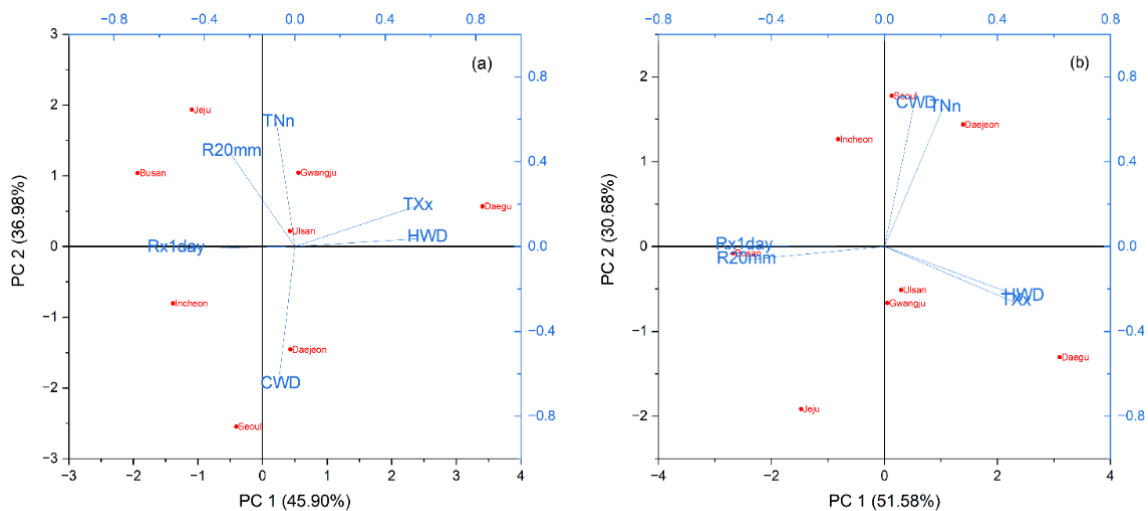


Figure 2 PCA biplots of the extreme weather exposure indicators for permeable pavements under (a) SSP1-2.6 and (b) SSP5-8.5.

The exposure indices developed using AHP, PCA, and entropy weighting revealed consistent spatial patterns of climate stress across the eight cities, with higher values clustering in inland regions. For permeable pavements, Daegu and Gwangju showed the highest exposure under SSP1–2.6, while under SSP5–8.5, Seoul reached the

highest composite score across all methods, driven by sharp increases in cold-wave variability emphasized in the entropy index. For green roofs, Daegu and Gwangju again emerged as the most exposed cities, with large contributions from heat wave days and drought conditions, indicators that intensified markedly under SSP5–8.5. Exposure index magnitudes increased across all cities in the high-emissions scenario, with several shifting from low/medium to high-exposure categories.

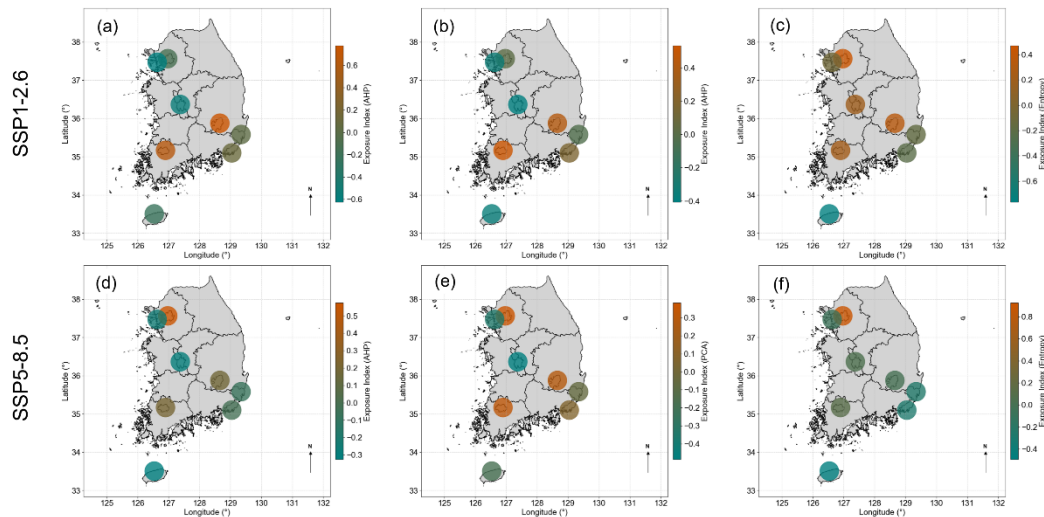


Figure 3 Exposure index for permeable pavements under SSP1-2.6 and SSP5-8.5 and spatial exposure distribution considering AHP (a, d), PCA (b, e), and entropy weighting (c, f). Panels (a) to (c) display the spatial exposure distribution under SSP1-2.6, while panels (d) to (f) show the results for SSP5-8.5.

4 CONCLUSIONS

This study shows that extreme weather exposure for urban green infrastructure is shaped by intensifying heat, drought, cold-wave variability, and high-intensity rainfall, with inland cities such as Daegu, Gwangju, and Seoul consistently emerging as the most vulnerable across scenarios. The triangulation of AHP, PCA, and entropy weighting confirms that heat-related indicators dominate in expert- and variance-driven approaches, while spatially variable drought and cold extremes gain prominence under entropy; yet all three methods converge in identifying high-exposure cities, supported by strong agreement between AHP and PCA ($\rho = 0.88\text{--}0.93$). By translating these stressor patterns into practical exposure scores for green roofs and permeable pavements, the framework provides a decision-ready basis for strengthening UGI resilience, informing climate-adaptive design choices, material and vegetation selection, targeted retrofits, and prioritization of at-risk cities. Ultimately, the developed indices offer an evidence-based foundation for ensuring that UGI remains functional and reliable under accelerating climate extremes.

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