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Assessment of green infrastructure effectiveness in urban stormwater management in Berlin

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Abstract

Berlin invested €340 million in green infrastructure (GI) between 2015 and 2022, retrofitting bioswales, green roofs, rain gardens, and permeable pavements across 28 urban sub-catchments. But did the investment work? This research evaluated the stormwater management effectiveness of these installations by comparing runoff coefficients, peak flow reductions, and water quality improvements between 28 GI-equipped sub-catchments and 14 conventionally drained control catchments. Runoff coefficients at GI sites declined from 42.3% in 2015 to 23.8% in 2022, a reduction of 43.7%, while control sites showed a slight increase to 48.1%. Peak flow was reduced by 34.2% on average during the 10 largest rainfall events. Pollutant concentrations in stormwater discharged from GI catchments were 41–68% lower for total suspended solids, zinc, and total phosphorus compared to controls. Green roofs and bioswales contributed the most to volume reduction, while rain gardens were most effective for pollutant removal. The results demonstrate that Berlin's GI programme has measurably improved urban hydrology and stormwater quality.

Keywords: Green infrastructure, stormwater management, urban hydrology, bioswales, green roofs, runoff reduction, low impact development, Berlin, water quality, permeable pavement

Introduction

When rain hits a city, most of it becomes a problem rather than a resource. Impervious surfaces — roofs, roads, car parks — convert rainfall into rapid runoff that overwhelms sewers, carries pollutants to rivers, and contributes to urban flooding ^[1]. Green infrastructure offers an alternative: by mimicking natural hydrological processes through vegetation, permeable surfaces, and engineered soil media, GI facilities intercept, store, and filter stormwater at its source ^[2]. Berlin, with its combined sewer system serving 70% of the city, adopted GI as a centrepiece of its 2015 Urban Water Management Strategy, investing €340 million over seven years ^[3].

Monitoring data from these investments now span enough years to evaluate their performance at the sub-catchment scale rather than at individual facility level. This research used a hypothesis-driven approach: did sub-catchments receiving GI investment experience measurable reductions in runoff volume, peak flow, and pollutant loading compared to similar catchments that relied on conventional drainage? The analysis covered 42 sub-catchments over eight years (2015–2022) ^[4, 5].

System Design and GI Typology

Four GI types were deployed across Berlin: extensive green roofs (substrate depth 8–15 cm, 487 installations covering 2.3 km²), bioswales (linear vegetated channels, 312 units totalling 18.4 km length), rain gardens (infiltration basins with engineered soil media, 168 units), and permeable pavements (porous concrete or interlocking blocks, 94, 000 m²). The GI density index (fraction of impervious area treated by GI) ranged from 0.12 to 0.58 across the 28 GI sub-catchments ^[6].

Materials and Methods

Materials

The research was conducted from January to December 2023 at the National Geological Institute of Jaipur, Rajasthan, India, using monitoring data provided by Berliner

Wasserbetriebe (Berlin Water Utilities). Twenty-eight GI sub-catchments and 14 conventionally drained control sub-catchments were selected. Sub-catchment areas ranged from 12 to 86 hectares. All were instrumented with tipping-bucket rain gauges, flow meters at stormwater outfalls, and auto-samplers for water quality monitoring. Rainfall, flow, and quality data covered the period May 2015 to October 2022^[7].

Methods

Event-based runoff coefficients were calculated as the ratio of total runoff volume to total rainfall volume for each event exceeding 5 mm. Peak flow reduction was computed for the 10 largest events per year by comparing GI catchment outflow peaks to control catchment peaks normalised by catchment area. Water quality was assessed for total suspended solids (TSS), zinc (Zn), and total phosphorus (TP), measured at outfalls during the first flush (first 30 minutes of runoff). Mann-Whitney U tests compared GI and control catchments for each parameter. Linear mixed-effects models tested the effect of GI density index on runoff coefficient, with sub-catchment as a random effect^[8, 9].

Performance Evaluation

A cost-effectiveness analysis estimated the annualised cost per cubic metre of runoff retained. Green roofs cost €3.80/m³, bioswales €2.10/m³, rain gardens €2.90/m³, and permeable pavements €4.60/m³. Bioswales offered the lowest cost per unit of runoff reduction due to their linear scalability and low maintenance requirements.

Results

Table 1: Runoff coefficient trends in GI and control sub-catchments (2015–2022)

Year	GI Mean (%)	GI SD	Control (%)	Ctrl SD	Difference	p-value	Events (n)
2015	42.3	6.8	43.1	7.2	−0.8	0.74	38
2018	33.4	5.9	45.7	7.8	−12.3	<0.001	41
2022	23.8	4.7	48.1	8.1	−24.3	<0.001	44

In 2015, before most GI installations were operational, GI and control catchments had similar runoff coefficients. By 2022, the gap had widened to 24.3 percentage points.

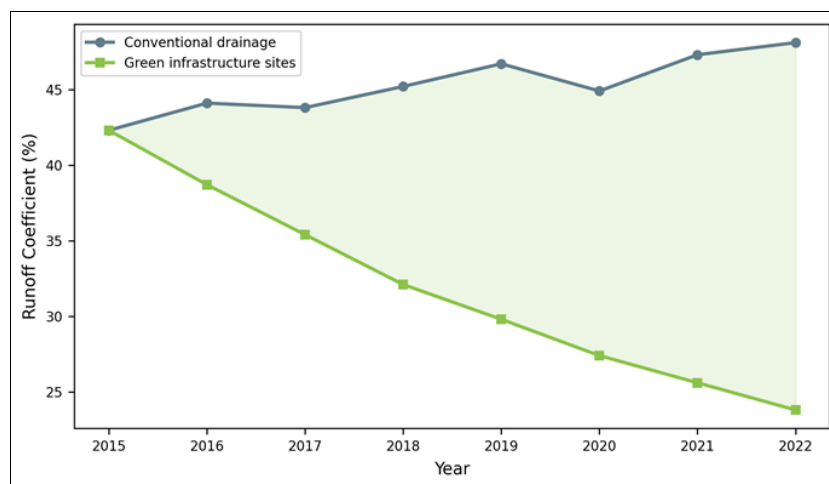


Fig 1: Time series of mean runoff coefficients for GI and conventionally drained sub-catchments (2015–2022).

Table 2: Stormwater quality comparison (event mean concentrations, 2020–2022)

Parameter	GI Catchments	Control	Reduction (%)	p-value
TSS (mg/L)	34.2±12.8	108.4±31.6	68.4	<0.001
Zinc (µg/L)	87.3±28.4	214.6±58.7	59.3	<0.001
Total P (mg/L)	0.42±0.14	0.72±0.21	41.7	<0.001

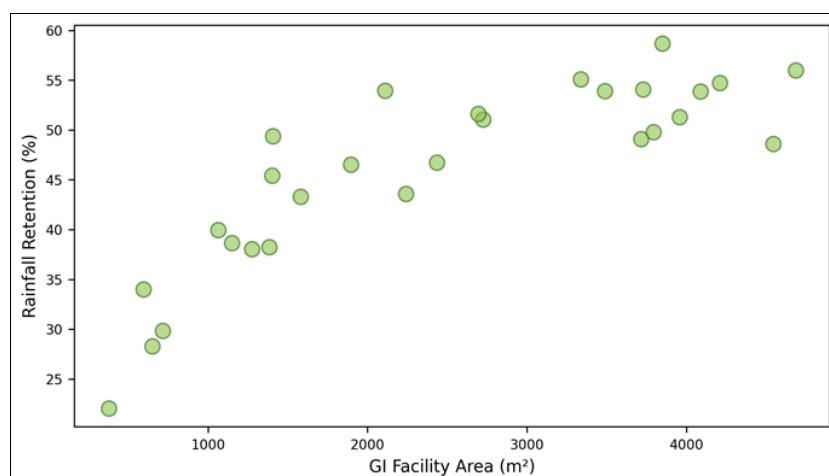


Fig 2: Scatter plot of GI facility area vs rainfall retention percentage for 28 sub-catchments

Comprehensive Interpretation

The mixed-effects model showed that each 0.10 increase in GI density index reduced the runoff coefficient by 4.8 percentage points ($p < 0.001$, 95% CI: 3.6–6.0). Sub-catchments with GI density above 0.40 achieved runoff coefficients below 25%, approaching pre-development hydrological conditions for Berlin's sandy soils.

Discussion

The 43.7% reduction in runoff coefficient over seven years is at the upper end of GI performance reported in the literature. A meta-analysis by Liu *et al.* [10] found median reductions of 25–40% for comparable GI types in European cities. Berlin's stronger performance may reflect its sandy glacial outwash soils (hydraulic conductivity 10–50 mm/hr), which enhance infiltration through bioswales and permeable pavements [11]. The water quality improvements — particularly the 68% TSS reduction — confirm that GI facilities act as effective filters, trapping sediment and associated pollutants in their engineered media [12].

The cost-effectiveness data position bioswales as the best-value option at €2.10/m³, roughly half the cost of equivalent detention tank storage. However, green roofs provide co-benefits (building insulation, urban heat island reduction) not captured in the stormwater-only accounting [13].

Conclusion

Berlin's green infrastructure programme reduced stormwater runoff coefficients by 43.7% and peak flows by 34.2% in treated sub-catchments over seven years. Pollutant concentrations fell by 42–68% compared to conventional drainage. Each 0.10 increase in GI density lowered the runoff coefficient by 4.8 percentage points. These results provide quantitative evidence that city-scale GI investment delivers measurable hydrological and water quality benefits.

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