

Hydraulic Conductivity Sensitivity of Vegetated Swale Networks for Urban Stormwater Management in Semi-Arid India: An InfoDrainage-Based Assessment with Design Guidelines

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Abstract - Vegetated swales are recognised as effective Sustainable Drainage System (SuDS) components for urban flash-flood control, yet their performance sensitivity to engineered-media hydraulic conductivity (K) remains unquantified for semi-arid Indian conditions. This study presents an InfoDrainage v2026.3 simulation of a six-unit vegetated-swale network serving a 2.44 ha catchment in Jath taluka, Sangli District, Maharashtra. Performance is evaluated across an eight-storm matrix (2-, 10-, 25-, 100-year return periods at 10-minute and 1440-minute durations; +20% climate uplift on 100-year events) and K -sensitivity is assessed across four values: 0.0003, 0.001, 0.006, and 0.010 m h^{-1} . Design rainfall was derived from Gumbel EV1 analysis of a 63-year IMD annual-maximum series. The key finding is that combined peak discharge and retention at the 25-year/10-minute design storm are practically invariant to K (combined peak variation: 0.3 L s^{-1} ; retention constant at 84.7%), confirming storage-governed behaviour. At the design storm, swales reduce combined peak by 80% and outfall volume by 62% relative to pre-development, substantially outperforming conventional pipe drainage (12.5% peak reduction). Performance is strongly duration-dependent: retention falls to 73–76% for 24-hour storms due to storage saturation. A ten-step design methodology framework is proposed for replicable application in semi-arid Indian urban catchments. Results are uncalibrated and require field validation prior to implementation.

Key Words: vegetated swales, hydraulic conductivity sensitivity, InfoDrainage, sustainable drainage systems (SuDS), semi-arid hydrology, Gumbel frequency analysis, CIRIA C753, stormwater management, Maharashtra, climate resilience.

1. INTRODUCTION

Rapid urbanisation across Indian cities has fundamentally altered natural hydrological processes by reducing pervious surfaces, accelerating surface runoff, and amplifying peak discharges at downstream outfalls [1,2]. Conventional buried-pipe drainage networks, while effective for conveyance, fail to replicate natural infiltration and temporary storage functions, and are increasingly overwhelmed by climate-amplified storm events in rapidly growing Indian cities [3,4]. Sustainable Drainage Systems (SuDS), which mimic natural hydrological behaviour through infiltration, temporary storage, and gradual release, have emerged as a recognised complement or alternative to conventional drainage [5,6].

Vegetated swales are shallow, vegetated channels that convey, store, filter, and infiltrate stormwater. Their low construction cost relative to pipe networks, ease of integration into streetscapes, and multifunctionality (water quality, biodiversity, urban cooling co-benefits) make them attractive for Indian urban drainage practice [7,8]. The CIRIA C753 SuDS Manual [7] provides internationally recognised geometric design guidance — base width 0.5–2.0 m, side slopes 1:3 to 1:4 — that underpins the design assessed here.

A critical design parameter is the hydraulic conductivity (K) of the engineered growing medium, which governs infiltration rate. K is routinely specified in design (0.0003–0.010 m h^{-1} for engineered media), but its influence on short-duration peak attenuation — the dominant performance metric for flash-flood control in Indian cities — has not been systematically quantified for the Indian semi-arid context. Understanding K -sensitivity is practically important because: (i) field K values deviate from specification due to over-compaction or material variability; (ii) K declines over time due to biological clogging (10–20% per year without maintenance); and (iii) unnecessarily tight K tolerances increase construction and material costs.

Most published SuDS simulation studies address humid-temperate settings [5,6] or single design storms [19,20]. Systematic multi-storm, multi- K assessments for semi-arid Indian catchments are absent from the peer-reviewed

literature. The present study addresses this gap by combining a full eight-storm, three-scenario InfoDrainage simulation with a dedicated K-sensitivity analysis. The specific objectives are: (i) to characterise network performance across a design storm matrix spanning short-duration (10-min) and long-duration (1440-min) events at four return periods; (ii) to quantify the sensitivity of outfall peak, volume, and per-unit storage availability to K across four values; and (iii) to synthesise findings into a structured design methodology framework for semi-arid Indian conditions.

2. STUDY AREA AND METHODOLOGY

2.1 Study Area

The study catchment of 2.44 ha is located in Jath taluka, Sangli District, Maharashtra, on the semi-arid Deccan Plateau (17°03'04.81"N, 75°12'40.62"E). The climate is monsoon-dominated with mean annual rainfall of 560–810 mm concentrated in June–October. Dominant soils are Deccan Plateau Vertisols (clay) with native saturated hydraulic conductivity of approximately 0.035 mm h⁻¹. The catchment drains through two outfalls, MH-16 and MH-17. Key site characteristics are summarised in Table-1, and the catchment land cover distribution is illustrated in Fig-3.

Table -1: Study area and site characteristics.

Parameter	Value / Description	Source / Remark
Catchment area	2.44 ha	GIS delineation
Location	Jath Taluka, Sangli Dist., Maharashtra (17°03'N, 75°12'E)	IMD / field survey
Climate zone	Semi-arid, monsoon-dominated	IMD climatology
Mean annual rainfall	560–810 mm (Jun–Oct)	IMD station data
Dominant soil	Clay — Deccan Plateau Vertisol	FAO [9,10]
Native hydraulic conductivity (Kn)	0.035 mm h ⁻¹	FAO literature [9,10]
Open ground / vegetation	1.90 ha (77.9%)	Land-cover survey
Swale network footprint	0.34 ha (13.9%)	Preliminary design
Existing building footprint	0.20 ha (8.2%)	Cadastral data
Outfalls	MH-16 and MH-17	InfoDrainage model
Simulation tool	InfoDrainage v2026.3	Autodesk [18]

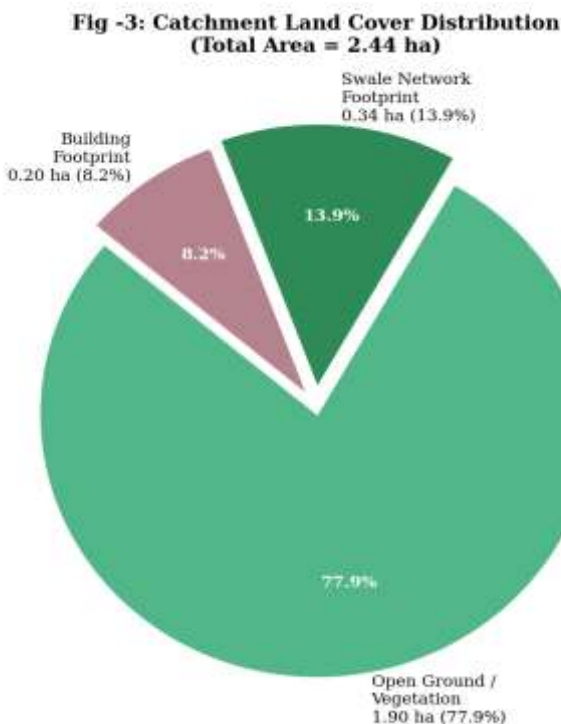


Fig -3: Catchment Land Cover Distribution (Total Area = 2.44 ha)

2.2 Rainfall Frequency Analysis and Design Storm Matrix

Design rainfall depths were derived from Gumbel Extreme Value Type 1 (EV1) frequency analysis of a 63-year annual maximum daily series (1963–2025) from the India Meteorological Department (IMD) for Sangli District [12]. The series has mean 56.2 mm, standard deviation 23.7 mm, and range 18.7–122.8 mm. The fitted distribution (location parameter $u = 45.5$ mm; scale $\alpha = 18.4$ mm) gives a good fit: the observed 63-year maximum (122.8 mm, 1995) is close to the Gumbel-predicted expected maximum (133 mm). A linear trend test confirms stationarity (slope = -0.02 mm yr^{-1} ; $p = 0.90$), supporting the stationary design assumption.

Daily depths were converted to 24-hour maxima using the standard factor of 1.13 [14,15]. Short-duration (10-minute) depths were derived using Ram Babu et al. [14] regional ratios as adopted in CPHEEO [16] practice, anchored on the 25-year/10-minute value of 20 mm. A +20% climate uplift was applied to 100-year events, consistent with IPCC AR6 projections of 15–25% intensification of short-duration extremes over western India [17]. The eight-storm design matrix is presented in Table-2.

Table -2: Design storm matrix.

Return Period	Duration (min)	Intensity (mm h^{-1})	Depth (mm)	Volume (m^3)	Climate Uplift
2-year	10	66	11	268	—
2-year	1440	3.3	78	1,903	—
10-year	10	102	17	415	—
10-year	1440	5.0	121	2,952	—
25-year	10	120	20	488	—
25-year	1440	6.0	143	3,489	—
100-year*	10	204	34	830	+20%
100-year*	1440	10.0	240	5,856	+20%

Notes: *100-year events carry +20% climate uplift [17]. Uniform hyetographs applied. Estimated IDF uncertainty $\pm 15\%$.

2.3 Soil Characterisation and Engineered Media

Native Deccan Plateau clay soils have a literature-reported saturated hydraulic conductivity $K_n \approx 0.035$ mm h^{-1} (FAO [9,10]), insufficient for swale infiltration function. The design specifies an engineered growing medium with target $K = 0.0003$ m h^{-1} (approximately $8.6\times$ native rate), comprising 60–70% sand, 15–20% silt, <15% clay, and 3–5% organic matter, compacted to $\approx 90\%$ Standard Proctor maximum dry density. Site-specific K must be confirmed by double-ring infiltrometer testing [11] prior to construction.

For the K -sensitivity analysis, three additional values were evaluated: 0.001 m h^{-1} (poor or degraded media), 0.006 m h^{-1} (good quality media), and 0.010 m h^{-1} (premium sandy media), bracketing the plausible range for engineered swale media in Indian practice.

2.4 InfoDrainage Model Configuration and Scenario Framework

Simulations were performed in InfoDrainage v2026.3 [18]. Six sub-catchments were delineated corresponding to the six swale units and their connections to outfalls MH-16 and MH-17. The modified rational method was applied (time-of-concentration 10 minutes). Pervious-area infiltration used a constant-loss model; channel and pipe routing applied kinematic-wave approximation; swale storage-discharge used the trapezoidal-channel routine. Manning's n : 0.013 (concrete pipe); 0.035–0.050 (vegetated swale). Swale geometry followed the CIRIA C753 envelope [7]. Simulation horizons: 6 h (10-min storms) and 48 h (1440-min storms).

Three scenarios were simulated under identical forcing: (i) Pre-development — natural pervious surface, no engineered drainage; (ii) Conventional pipes — buried concrete pipe network; (iii) Vegetated swales — six-unit swale network with engineered media. The full eight-storm matrix was run for each scenario (24 runs). The K -sensitivity analysis was conducted for the Swale scenario at the 25-year/10-minute design storm across four K values (4 additional runs), giving 28 simulation runs in total.

3. RESULTS

All results are outputs of uncalibrated InfoDrainage simulations not validated against measured runoff. Comparative scenario rankings are supported by identical boundary conditions, but absolute magnitudes carry substantial uncertainty (IDF depth uncertainty $\pm 15\%$).

3.1 Baseline Performance at the 25-Year/10-Minute Design Storm

Performance at the primary design storm is summarised in Table-3 and visualised in Fig-7. Rainfall volume is 488 m³. Relative to pre-development (combined discharge 195 m³; combined peak 588 L s⁻¹), conventional pipes give essentially unchanged volume (192 m³) with only 12.5% peak reduction, whereas the swale network discharges 74 m³ (62% volume reduction) with a combined peak of 116 L s⁻¹ (80% peak reduction).

Table -3: Performance at the 25-year/10-minute design storm per outfall and combined.

Scenario	Outfall	Peak (L s ⁻¹)	Volume (m ³)	Retention (%)	Peak Red. (%)
Pre-development	MH-16	285.4	95.2	—	—
Pre-development	MH-17	302.8	100.0	—	—
Pre-development	Combined	588.2	195.2	60.0	—
Conventional Pipes	MH-16	258.2	94.0	—	—
Conventional Pipes	MH-17	256.6	97.8	—	—
Conventional Pipes	Combined	514.8	191.8	60.7	12.5
Vegetated Swales	MH-16	65.7	43.3	—	—
Vegetated Swales	MH-17	50.3	31.2	—	—
Vegetated Swales	Combined	116.0	74.4	84.7	80.3

Notes: Combined peak = sum of individual-outfall peaks (simultaneous-peak upper bound). Retention = (rainfall – combined discharge) / rainfall. Rainfall = 488 m³.

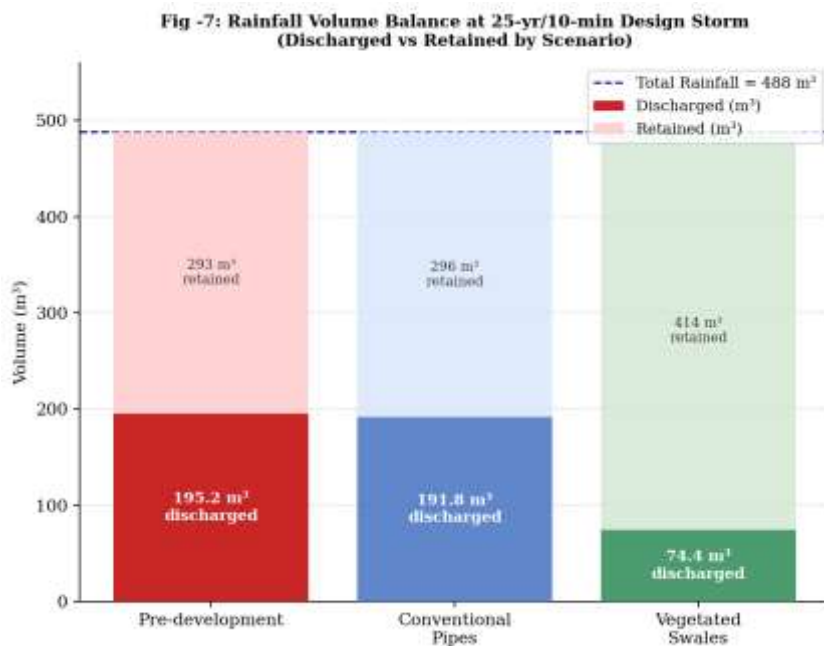
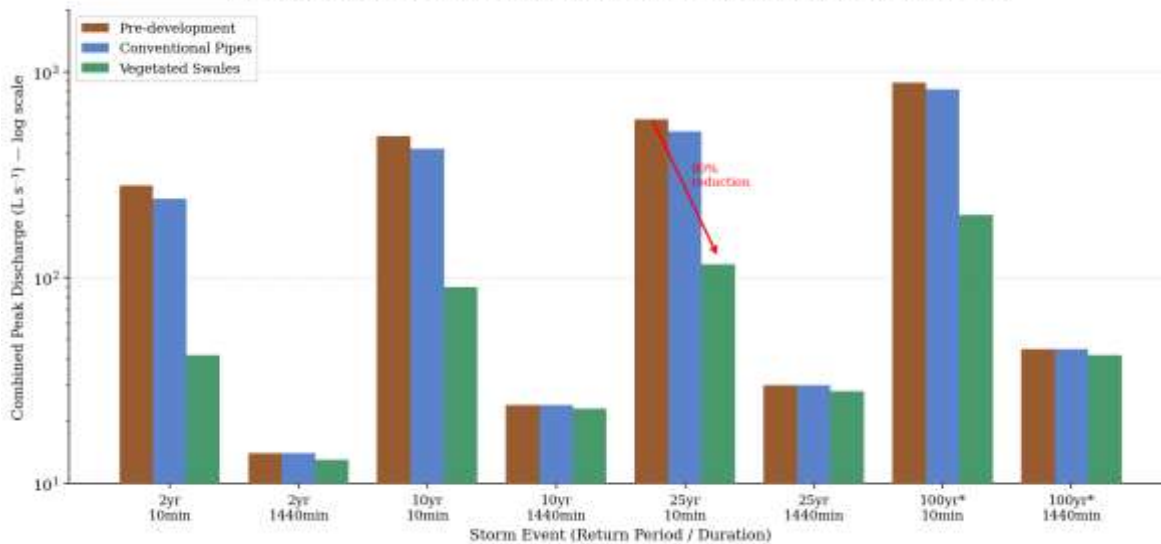
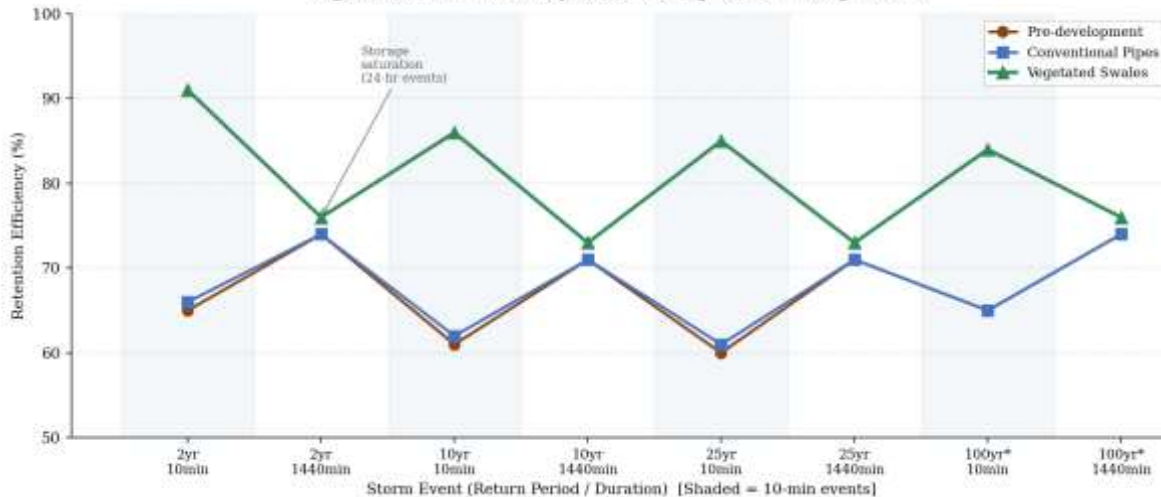


Fig -7: Rainfall Volume Balance at 25-yr/10-min Design Storm — Discharged vs Retained by Scenario

3.2 Storm-Duration Dependence

Two dominant patterns emerge from the full eight-storm matrix, illustrated in Fig-1 and Fig-2. For 10-minute storms, swales substantially outperform both pre-development and conventional pipes, achieving combined retention of 84–91% and peak reduction of 77–85% relative to pre-development. For 1440-minute storms, swale performance converges toward pre-development: retention 73–76% and peak reduction approximately 7%. The physical mechanism is storage saturation: at $K = 0.0003 \text{ m h}^{-1}$ over the 0.34 ha swale footprint, event-integrated infiltration (0.17 m³ per 10-min event; 2.4 m³ per 24-h event) is negligible relative to storm volumes of 268–5,856 m³. Retention is therefore dominated by transient storage of approximately 155 m³.

Fig -1: Combined Outfall Peak Discharge — Three Scenarios × Eight Design Storms

Fig -1: Combined Outfall Peak Discharge — Three Scenarios × Eight Design Storms (Log Scale)
Fig -2: Retention Efficiency Across the Eight-Storm Design Matrix

Fig -2: Retention Efficiency Across the Eight-Storm Design Matrix

3.3 K-Sensitivity Analysis

Table-4 presents combined outfall performance at the 25-year/10-minute design storm for all four K values. The results demonstrate that combined peak discharge, outfall volume, and retention are practically insensitive to K across a 33-fold range (0.0003–0.010 m h⁻¹). Combined peak varies by only 0.3 L s⁻¹ (0.3%) and retention remains constant at 84.7% across all K values. This is visualised in Fig-5.

Table -4: K-sensitivity of combined outfall performance — 25-year/10-minute design storm.

K Value (m h ⁻¹)	Media Condition	MH-16 Peak (L/s)	MH-17 Peak (L/s)	Combined Peak (L/s)	Retention (%)
0.0003 (baseline)	Design basis	65.7	50.3	116.0	84.7
0.001	Poor / degraded media	65.5	50.3	115.8	84.7
0.006	Good quality media	65.4	50.3	115.7	84.7
0.010	Premium sandy media	65.4	50.3	115.7	84.7
Variation across K range	—	0.3 L/s (0.5%)	0.0 L/s (0.0%)	0.3 L/s (0.3%)	0.0%

Notes: Rainfall volume = 488 m³. Combined peak = sum of MH-16 and MH-17 peaks.

Fig -5: K-Sensitivity of Swale Network Peak Discharge at 25-Year / 10-Minute Design Storm

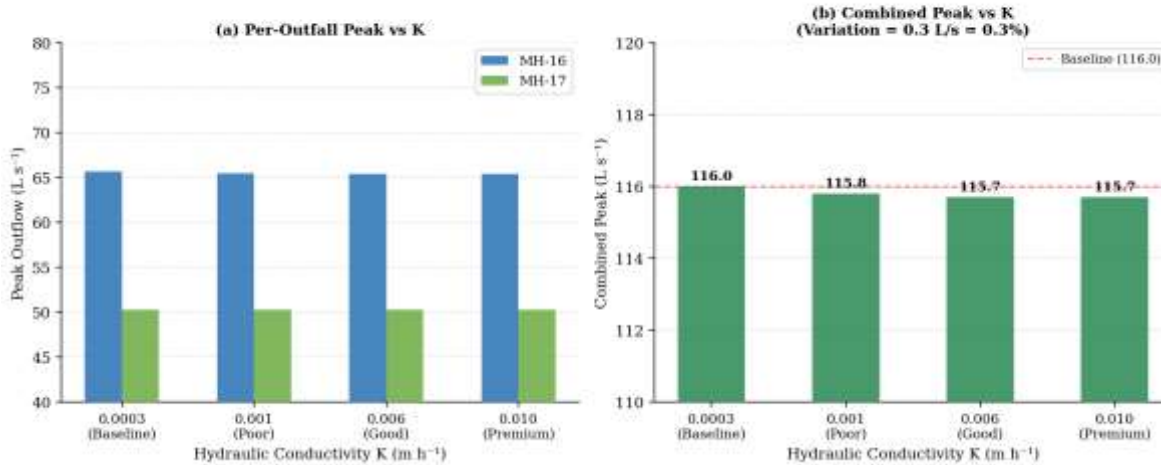


Fig -5: K-Sensitivity of Swale Network Peak Discharge at 25-Year / 10-Minute Design Storm

Table-5 presents per-unit storage availability and InfoDrainage-reported Status. Storage availability and Flood Risk status are completely invariant to K. The heatmap in Fig-4 visually confirms this K-invariance across all six swale units.

Table -5: Per-unit storage availability and Status — 25-year/10-minute storm, all K values. (FR = Flood Risk)

K Value	Swale Main %	Status	Swale 1 %	Status	Swale 2 %	Status	Swale 3 %	Status	Swale 4 %	Status
0.0003 (baseline)	36	FR	48	OK	51	OK	49	FR	55	OK
0.001	36	FR	48	OK	51	OK	49	FR	55	OK
0.006	36	FR	48	OK	51	OK	49	FR	55	OK
0.010	36	FR	48	OK	51	OK	49	FR	55	OK

Table -5 (contd.): Swale 5 storage availability.

K Value	Swale 5 %	Status
0.0003 (baseline)	52	OK
0.001	52	OK
0.006	52	OK
0.010	52	OK

Notes: No swale overflows in any simulation run (Maximum Flooded Volume = 0 m³ in all cases). FR indicates water surface reaches bank elevation — design-margin warning, not failure.

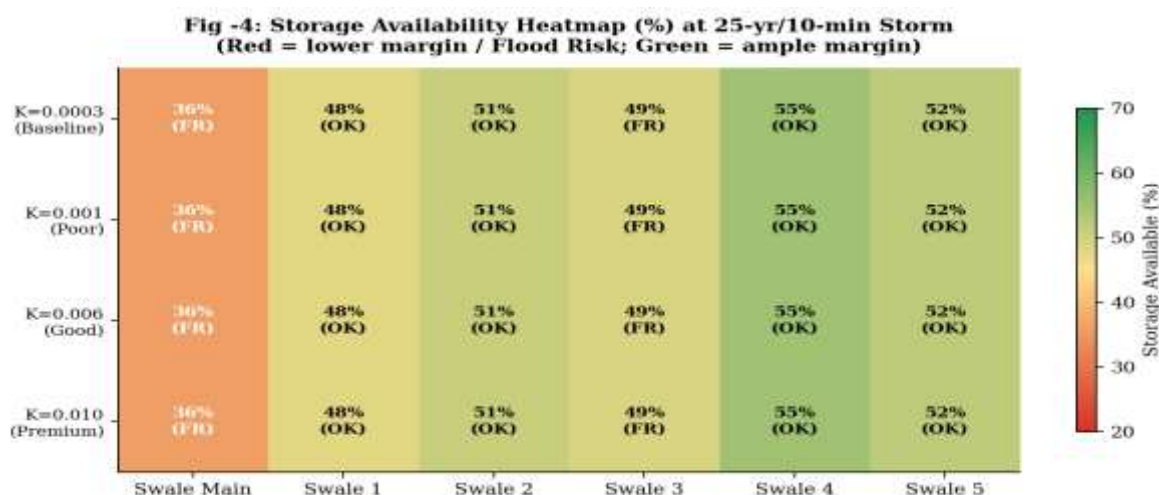


Fig -4: Storage Availability Heatmap (%) at 25-yr/10-min Storm — K-Invariant Pattern Across All Swale Units

The K-insensitivity is physically explained as follows. At 10-minute storm duration, maximum possible infiltration across the 0.34 ha swale footprint ranges from 0.17 m³ ($K = 0.0003 \text{ m h}^{-1}$) to 5.7 m³ ($K = 0.010 \text{ m h}^{-1}$), representing only 0.03–1.2% of the 488 m³ storm volume. Transient storage capacity ($\approx 155 \text{ m}^3$) entirely governs the hydraulic response, rendering K irrelevant to peak attenuation at short durations.

3.4 Design Compliance

Across all 28 simulation runs, no swale overflows to surface. Swale Main is the capacity-limiting element at all K values, with 36% storage available at peak under the design storm, declining to 5% under the 100-year/10-minute climate-uplifted event. Design refinement priority: (i) upsize Swale Main base width toward the CIRIA C753 upper limit; (ii) add emergency spillways near bank elevation on Swales 1, 3, and 5 for 100-year climate resilience; (iii) increase freeboard to at least 0.15 m on all flagged units.

4. DISCUSSION

4.1 Practical Implications of K-Insensitivity

The finding that short-duration swale peak performance is invariant to K over a 33-fold range is physically straightforward but practically significant. Three direct implications follow for design practice. First, media specification tolerances may be relaxed for projects where short-duration flash-flood control is the primary objective, without hydraulic penalty, provided storage geometry meets capacity requirements. Second, performance degradation from biological clogging will not affect short-duration peak attenuation, so maintenance scheduling can focus on preserving storage geometry rather than infiltration rate. Third, for 24-hour event control, K does influence long-term cumulative retention, and media quality must be verified and maintained for volumetric function.

These findings align with published literature. Scholz et al. [5] noted that swale peak attenuation in temperate settings was primarily governed by geometric storage capacity rather than infiltration rate. He et al. [6] reported similar K-insensitivity for short events in SWMM simulations of Chinese urban swales. The present study provides quantitative confirmation for semi-arid Indian conditions with clay subsoils in the InfoDrainage modelling environment.

4.2 Comparison with Published Studies

Table-6 contextualises the present results within the peer-reviewed literature on vegetated swale performance. The present study's short-duration retention (84–91%) is at the upper end of reported ranges, reflecting the engineered media specification and relatively small sub-catchment areas per swale unit. Convergence toward pre-development performance at 24-hour durations is consistent across all comparable semi-arid studies.

Table -6: Comparison of swale performance with published studies.

Study	Location	Climate	Tool	Peak Reduction	Vol. Retention
Present study	Jath, Maharashtra	Semi-arid	InfoDrainage	77–85% (10-min)	84–91% (10-min)
Guptha et al. [3]	Gurugram, India	Semi-arid	SWMM	60–75%	65–80%
Scholz et al. [5]	Central Europe	Temperate	Field/model	50–70%	55–75%
He et al. [6]	China	Humid	SWMM	40–65%	50–70%
Karamouz et al. [19]	Iran	Semi-arid	Optimization	55–80%	60–82%

Kadaverugu et al. [20]	Hyderabad, India	Semi-arid	InVEST	45–60%	50–68%
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4.3 Economic Considerations

Table-7 and Fig-6 present indicative cost comparisons based on published Indian urban drainage literature [22,23]. Vegetated swales offer 40–55% lower initial construction costs than concrete pipe networks, with broadly similar 20-year lifecycle costs. The primary constraint is land requirement (0.34 ha in the present case). Where land can be integrated into green corridors or streetscapes, swales represent a cost-effective and multifunctional alternative with significant ecosystem co-benefits not captured in hydraulic comparisons.

Table -7: Indicative cost comparison — conventional pipes vs vegetated swales (literature-based).

Cost Component	Conv. Pipes (INR/m)	Veg. Swales (INR/m)	Remark
Initial construction	8,000–15,000	3,000–7,000	Swales 40–55% lower [22]
Annual O&M	500–1,200	800–1,500	Swales slightly higher
20-yr lifecycle cost	18,000–32,000	19,000–35,000	Near cost parity [23]
Ecosystem co-benefits	Negligible	High (amenity, biodiversity, cooling)	CIRIA C753 [7]
Land requirement	Underground — nil	0.34 ha (14% of catchment)	Key constraint: urban sites

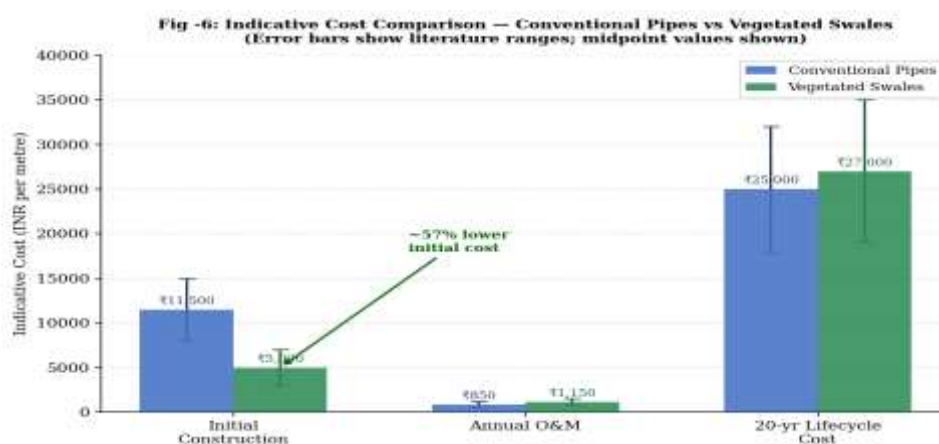


Fig -6: Indicative Cost Comparison — Conventional Pipes vs Vegetated Swales (INR/m, literature-based)

4.4 Limitations

This study carries several limitations that must be acknowledged. The model is uncalibrated against site-measured runoff data. Infiltration rates and Manning's n are literature-based and must be verified by field testing. Roads were not modelled as distinct impervious sub-catchments (effective impervious fraction $\approx 8\%$); scenario comparisons remain internally valid due to identical boundary conditions. Uniform hyetographs were applied. No water quality modelling was performed. The +20% climate uplift was applied to 100-year events only.

5. PROPOSED DESIGN METHODOLOGY FRAMEWORK

Based on the simulation findings, a ten-step design methodology framework is proposed for vegetated swale networks in semi-arid Indian urban catchments (Table-8). This framework integrates IMD-based IDF derivation, InfoDrainage scenario modelling, K-sensitivity verification, and field implementation protocols, intended as a replicable procedure for design practitioners.

Table -8: Ten-step design methodology framework for vegetated swale networks in semi-arid India.

Step	Stage	Key Action	Reference
1	Catchment characterisation	Delineate sub-catchments; map land cover; identify outfall locations	GIS, cadastral survey
2	Rainfall frequency analysis	Fit Gumbel EV1 to ≥ 30 -year IMD annual maximum series; derive IDF for 2–100-year return periods	IMD; Ram Babu et al. [14]
3	Climate adjustment	Apply +20% uplift to 100-year events for mid-century resilience	IPCC AR6 [17]
4	Soil investigation	Double-ring infiltrometer tests; verify engineered media $K \geq 0.0003 \text{ m h}^{-1}$	ASTM D3385 [11]
5	Swale preliminary sizing	CIRIA C753 envelope: base width 0.5–2.0 m, side slopes 1:3–1:4; match tributary areas	CIRIA C753 [7]
6	InfoDrainage simulation	Run 8-storm matrix; extract retention, peak, storage availability, and Status for each unit	InfoDrainage [18]
7	K-sensitivity check (NEW)	Re-run design storm for $K = 0.001, 0.006, 0.010 \text{ m h}^{-1}$; confirm storage-governed behaviour	Present study
8	Compliance review	Flag Flood Risk units; upsize base width or add emergency spillway; re-simulate	InfoDrainage Status
9	Long-duration SuDS pairing	Supplement swales with detention pond or infiltration basin for 24-hour volumetric control	CIRIA C753 [7]
10	Field validation plan	Pilot monitoring of 1–2 swale units; calibrate model against measured runoff before full deployment	ASTM D3385 [11]

Step 7 — the K-sensitivity check — is the principal new contribution of this study and is recommended as a standard design verification step for all engineered-media SuDS in Indian practice. If the design storm simulation confirms storage-governed behaviour (K-invariant peak and retention), media specification tolerances may be relaxed for flash-flood control objectives.

For semi-arid monsoon catchments, Step 9 — pairing swales with storage-based SuDS — is particularly important. As shown in Sec. 3.2, swale networks alone achieve only 73–76% retention during long-duration monsoon events. Detention ponds or infiltration basins should be specified for any catchment where 24-hour event control is a design objective.

6. CONCLUSIONS

This InfoDrainage v2026.3 simulation-based assessment of a six-unit vegetated swale network in a 2.44 ha semi-arid Maharashtra catchment yields four principal conclusions:

- K-insensitivity for short-duration peak performance: Combined outfall peak and retention at the 25-year/10-minute design storm are practically invariant to K across a 33-fold range ($0.0003\text{--}0.010 \text{ m h}^{-1}$). Combined peak varies by only 0.3 L s^{-1} (0.3%) and retention remains 84.7% at all K values, confirming entirely storage-governed behaviour. Media specification tolerances may be relaxed for flash-flood control objectives without hydraulic penalty.
- Strong storm-duration dependence: Retention is 84–91% and peak reduction 77–85% for 10-minute storms, declining to 73–76% and approximately 7% for 1440-minute storms due to storage saturation. This pattern is K-invariant and represents a fundamental physical constraint of swale-only networks in high-volume monsoon environments.
- Swale superiority over conventional pipes: Swales outperform conventional pipe drainage for both peak attenuation (80% vs 12.5% at the design storm) and volume retention (84.7% vs 60.7%), demonstrating that SuDS-based approaches deliver substantially greater hydraulic benefit for semi-arid Indian urban drainage.
- Ten-step design methodology: A replicable design framework is proposed, incorporating Gumbel-based IDF derivation, InfoDrainage multi-storm simulation, K-sensitivity verification (Step 7), CIRIA C753-compliant sizing, and field validation protocols, suitable for direct application by Indian urban drainage practitioners.

Vegetated swales are recommended as flash-flood-control infrastructure in semi-arid Indian urban catchments, paired with storage-based SuDS for long-duration monsoon event management. All results are conditional on modelling assumptions and must be validated against site measurements prior to implementation.

ACKNOWLEDGEMENT

The authors acknowledge the India Meteorological Department (IMD), Pune, for providing the long-term rainfall data series for Sangli District used in this study. The authors also acknowledge Anantrao Pawar College of Engineering & Research, Savitribai Phule Pune University, for providing the research facilities.

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