

Article

Evaluating Infiltration Ponds for Flood Mitigation and Aquifer Recharge in an Urban Area

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Abstract

Climate change and rapid urbanisation increasingly threaten urban water security and grey infrastructure, calling for adaptive stormwater strategies to mitigate hydroclimatic extremes. This study evaluates the hydrologic performance of decentralised infiltration ponds functioning as natural/small water retention measures in the regional recharge zone of the Nyírség region, Debrecen, Hungary. Using a sensor-calibrated Hydrus-1D model, we simulated a no-intervention baseline against three pond sizes across historical and mid-century regional climate model projections. While the baseline scenario yielded negligible deep percolation across all scenarios, the smallest infiltration pond resulted in increased vertical moisture flux. The infiltration pond simulation improved ET/PET ratios and increased root zone saturation, improving urban vegetation health and evaporative cooling. All the pond designs attenuated and stored runoff without overspilling. Emission pathway sensitivity showed different responses driven by regional climate scenarios; temperature-driven evaporative offsets dominated under moderate warming, whereas extreme precipitation intensity increased infiltration gains under higher emissions. These findings support infiltration ponds as resilient, dual-purpose measures for mitigating regional water table decline while providing local flood protection under changing climate futures.



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Keywords: soil water content; Hydrus-1D; infiltration pond; natural/small water retention measures; hydroclimatic risks; urban flooding

1. Introduction

Hydroclimatic swings between dry and wet extremes due to climate change have become increasingly apparent in recent decades [1,2]. These climate changes pose a significant threat to urban water resources management and infrastructure. Conventional, centralised, and rigid water management systems are even more vulnerable to these extreme events due

to the high proportion of impervious surfaces and increasing population density [3–5]. Traditional stormwater management systems were not originally designed to cope adequately with climate-induced extreme hydroclimatic events; as a result, they frequently underperform during high-intensity storms [6]. For example, urban stormwater drainage systems are increasingly unable to cope with intensified rainfall events, resulting in frequent overloads and localised urban flooding caused by undersized sewers designed using outdated methods [7]. Consequently, there is an urgent need to move towards sustainable, adaptive, and decentralised strategies that simultaneously support stormwater management, mitigate urban flooding, enhance infiltration, and conserve local water resources [8].

For urban areas such as Debrecen, this shift is imperative. Mid-century climate projections anticipate a 1–°C increase in annual temperatures and highly variable, intense precipitation [9]. These projected climate shifts threaten to accelerate pluvial flooding, groundwater depletion, and drive the expansion of drought-prone areas, particularly across the arid Great Hungarian Plain [9]. The dichotomous nature of climate change poses a challenge to traditional and uniform water management strategies, as they are not holistically equipped to address the dual threat of intensifying water deficits and flash flooding [10]. The EU Water Strategy, Hungary's Jenő Kvassay Plan, and regional research initiatives such as the National Laboratory for Water Science and Water Security create an enabling environment for sustainable water management [11–14]. Natural water retention and sustainable urban stormwater management thus serve as the principal strategies through which these policies address hydroclimatic extremes and secure long-term water resource sustainability.

Natural or Small Water Retention Measures (NSWRMs), such as infiltration ponds, embody these regulatory policies and are recognised as measures to buffer hydroclimatic extremes [15,16]. Infiltration ponds offer a decentralised means to improve local water storage, enhance infiltration, reduce runoff, and mitigate both drought and flood risks. These measures detain, slow down, and allow stormwater to infiltrate into the subsurface, supporting flood control and local groundwater recharge [17–20]. Such aquifer recharge interventions increase water availability within the vadose zone and improve river flow regimes [21,22].

The effectiveness of infiltration measures largely depends on the soil hydraulic properties, local climatic boundary conditions, and the magnitude and temporal distribution of rainfall inputs. NSWRMs are recommended as cost-effective climate adaptation strategies [17,18,23]; their long-term performance under projected climate change remains insufficiently explored, particularly regarding design layout optimisations where shifts in rainfall intensity and evaporative demand may alter infiltration efficiencies. This study aims to bridge this gap by conducting a pre-implementation scoping study using numerical modelling tools to optimise interventions.

The soil hydraulic properties of the subsurface primarily govern the effectiveness of NSWRM. However, characterising these properties is inherently complex, as subsurface fluid transport often exhibits significant non-linear features and dynamic instability. Recent studies using bifurcation dynamical analysis indicate that seepage stability can transition from steady states to complex periodic or chaotic oscillations depending on structural parameters and pressure gradients [24]. Furthermore, soil hydraulic properties are not static; external stressors such as extreme thermal cycling or high-intensity hydrological loading projected in climate projections can induce cumulative structural damage, fundamentally altering porosity and permeability over time [25]. Beyond these temporal evolutions, soil hydraulic properties show considerable spatial variability across landscapes due to heterogeneity in parent material, topography, and vegetation [26–28]. In particular, saturated hydraulic conductivity is highly variable spatially, which limits and complicates the application of hydrological models on larger scales [26].

Quantifying soil water content (SWC) dynamics is essential for evaluating the performance of infiltration ponds and optimising the design, planning, and implementation of these measures. SWC regulates the partitioning of rainfall into infiltration, evapotranspiration, runoff, and deep percolation [29,30]. Evaluating these transient, variably saturated flow processes requires numerical tools capable of resolving flow dynamics within the vadose zone. Hydrus-1D is widely used for this purpose, providing a physically based framework for simulating one-dimensional water movement using the Richards equation and soil hydraulic functions [29,31–33].

While the performance of infiltration systems has been studied globally [17–20], this research provides a novel contribution by evaluating decentralised infiltration ponds through a sensor-calibrated Hydrus-1D model of a disturbed urban soil profile. By integrating in situ soil moisture monitoring from an urban campus environment with mid-century regional climate model projections, the study addresses a critical gap in the existing literature regarding the long-term resilience of NSWRM in the Great Hungarian Plain. Furthermore, by evaluating the sensitivity of different pond sizes, this study provides the first numerical evidence for optimising decentralised retention measures to mitigate regional water table declines in Hungary's critical recharge zones.

This study addresses current gaps by modelling the long-term soil moisture response to infiltration ponds of different sizes under historical and projected climate conditions in Debrecen. Specifically, the study evaluates how pond area influences deep percolation and potential groundwater recharge using cumulative bottom flux, root-zone saturation, and evapotranspiration dynamics across a range of hydroclimatic scenarios. Combining high-quality soil data and soil hydraulic parameters derived from field and laboratory measurements has allowed this predictive modelling approach to provide a strong baseline evaluation of infiltration pond performance.

The current study aims to evaluate the effectiveness of infiltration ponds of different sizes in enhancing water retention and infiltration under historical and projected climate conditions. The specific objectives of this study were to: (1) set up and calibrate a Hydrus-1D model for a representative urban campus site in Debrecen; (2) simulate the long-term behaviour of infiltration ponds of different sizes (500 m², 750 m², 1000 m²); and (3) quantify the effectiveness of these ponds in enhancing deep percolation and improving soil moisture conditions under historical and projected climate scenarios. Through this approach, the study provides evidence-based insights for the optimisation of small water retention interventions. It aligns with the objectives of the National Laboratory for Water Science and Water Security project.

2. Materials and Methods

The study area, situated in the Nyírség region of the Great Hungarian Plain, represents a critical regional recharge zone characterised by downward vertical moisture flux and a persistent negative water balance (Figure 1). The reference soil profile is located in Debrecen. The terrain is defined by a gently undulating medium–high lowland topography, with elevations typically ranging between 85 and 175 m above sea level and a regional decline from the north-northeast toward the south-southwest [21,34]. This landscape consists of an alluvial fan plain shaped primarily by aeolian processes, which have created a surface of shifting sand and sandy loess punctuated by distinctive rim and parabolic dunes. These morphological features are horizontally divided by north-northeast to south-southwest-oriented valleys, which, alongside the elevated dunes, act as local topographic high points driving gravity-influenced groundwater infiltration [34]. In the upper 2–300 m of the subsurface, the vertical pressure gradient is smaller than hydrostatic, confirming a topography-driven downward moisture flux induced by the elevated hills of the Nyírség

to the north [34]. Because the infiltrating water moves away from these elevated regions toward deeper discharge areas to the south, the local water table is highly dependent on continuous recharge, resulting in a negative water balance.

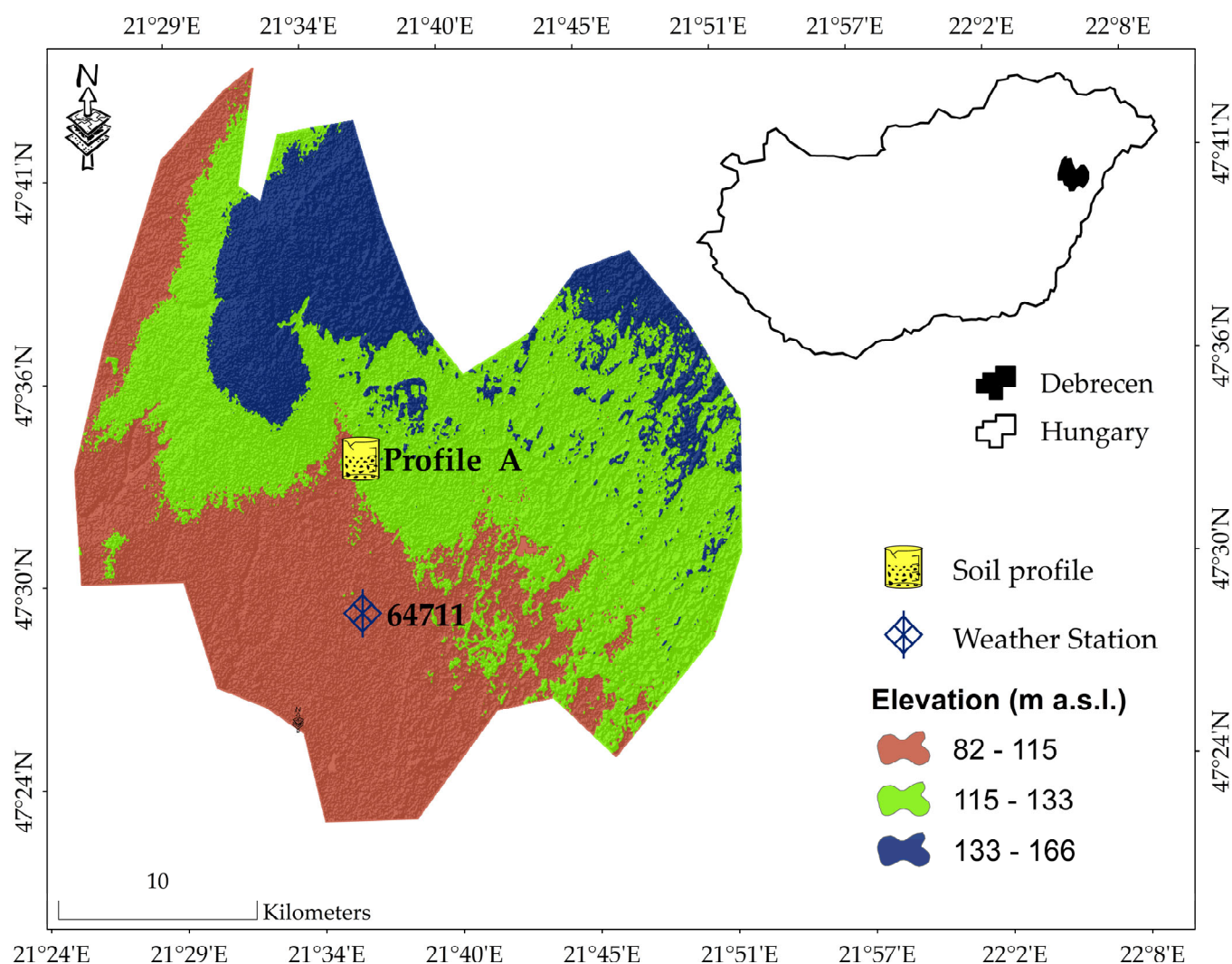


Figure 1. Location and topographic elevation of the study area in Debrecen, Hungary, showing the reference soil profile (Profile A) and the meteorological monitoring station (HMS ID: 64711) overlaid on the local digital elevation model (DEM) across the study area. The inset map indicates the location of the Debrecen municipality within Hungary.

The landscape of the study area is characterised by dominant soil textures including sand, sandy loam, loam, clay loam, clay, and peat [34]. In recent decades, the region has seen a significant groundwater deficit of 5–6 km³, driven by the dual stressors of climate change and anthropogenic activities such as intensive canalisation and urban water overexploitation around Debrecen [21]. These factors have led to a decline in the regional water table, which threatens to diminish local flow systems and has already resulted in the widespread desiccation of climate-vulnerable wetlands. The area is characterised by a humid continental climate with an average annual precipitation and temperature of 546 mm and 22.7 °C, respectively [34].

The reference profile (Soil Profile A) located within the University of Debrecen Campus was monitored for soil moisture and hydrologic modelling. The location map of the study area, in situ photographic documentation of the soil profile, and numerical represen-

tations detailing the vertical distribution of the soil hydraulic parameters are provided in Appendix A (Figure A1).

Soil profile surveys, soil sampling, and laboratory measurements were conducted for this site to determine soil physical and hydraulic properties. GroPoint time-domain transmission (TDT) soil moisture sensors (Riot Technology Corp, North Saanich, BC, Canada) were calibrated and installed at four depths within the profile to measure the continuous volumetric water content (cm^3/cm^3), as specified in Table 1. Soil Profile A is situated in an area that used to be an orchard, and currently, the vegetation is dominated by grasses, legumes, and various herbaceous species. Carbonate formations were observed in both the surface soil horizon and the deposition materials. The soil profile extends to a total depth of 150 cm with five horizons (A1, A2, B, BC, and C). The organic-rich humus layer extends to a depth of 70 cm, indicating significant organic matter accumulation. Physical and chemical properties for each horizon are detailed in Table 1.

Table 1. Physical and chemical properties of Soil Profile A at the University of Debrecen Campus.

Soil Horizon	Depth Range (cm)	Sensor Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture Class	pH	Humus (%)	EC (mS/cm)	CaCO ₃ (%)
A1	0–35	30	65.39	21.19	13.42	Sandy loam	7.53	1.275	0.229	0.9
A2	35–70	60	65.04	20.82	14.14	Sandy loam	7.63	1.183	0.22	1.07
B	70–90	80	52.93	26.39	20.68	Sandy clay loam	8.21	0.621	0.209	13.63
BC	90–130		45.08	31.94	22.98	Loam	8.28	0.531	0.22	22.59
C	130–150	140	31.96	46.17	21.87	Loam	8.39	0.218	0.257	23.41

The Hydrus-1D model is a physically based, process-driven tool used to describe water movement in variably saturated porous media [33,35,36]. It solves the one-dimensional vertical Richards equation for water movement:

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial x} \left[k(h) \left(\frac{\partial h}{\partial x} + 1 \right) \right] - S(h) \quad (1)$$

where $\theta(h)$ is the volumetric water content (cm^3/cm^3) at the matrix potential level h (cm); t is the time (day); x is the vertical spatial coordinate (cm); $k(h)$ is unsaturated hydraulic conductivity (cm/day); and $S(h)$ is the sink term (day^{-1}) applied to account for root water uptake.

The soil hydraulic functions were parameterised using the van Genuchten-Mualem formulation:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m}, & h < 0 \\ \theta_s, & h \geq 0 \end{cases} \quad (2)$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{\frac{1}{m}} \right)^m \right]^2 \quad (3)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (4)$$

where θ_r is the residual water content (cm^3/cm^3); θ_s is the saturated water content (cm^3/cm^3); α (cm^{-1}), n ($-$), $m = 1 - 1/n$, and l ($-$) are empirical van Genuchten parameters; K_s is the saturated hydraulic conductivity (cm/day); and S_e is the effective saturation.

The RETention Curve (RETC) program (Version 6.02) was used to estimate soil hydraulic parameters for each horizon based on in situ and laboratory-measured soil water

retention data derived from sampled physical cores. Within the RETC environment, the van Genuchten parameters were optimised and integrated into the Hydrus-1D model. While this model uses high-resolution parameters derived from site-specific field and laboratory measurements optimised via RETC, it is acknowledged that soil hydraulic parameters behave differently across the landscape [26]. To compare these local findings with heterogeneous porous media in future work, scaling techniques can be employed to coalesce multiple hydraulic equations into a single reference framework [37].

Hydrus-1D (Version 4.17) was set up with an atmospheric upper boundary that included precipitation and potential evapotranspiration fluxes, and a free-drainage lower boundary to simulate natural percolation. The model domain was extended to 300 cm to minimise the influence of the free-drainage lower boundary condition, adopted from Guram and Bashir [38], and to enable detailed vertical discretisation for accurate water budget modelling, as highlighted by Kozma et al. [31]. Extending the model domain below the deepest monitoring sensor (140 cm) and soil horizon (150 cm) eliminates artificial boundary reflections on simulated root zone dynamics. The Nyírség region's regional recharge setting places the groundwater table well below the modelled domain, justifying the use of a free drainage lower boundary in Hydrus-1D [21]. This setup not only prevents boundary effects on root zone dynamics but also reasonably simulates infiltration and deep percolation. Although short-term local groundwater fluctuations may occur, the approach captures main vadose zone water processes while balancing model complexity and computational efficiency given the hydrogeological data and the regional groundwater regime.

The model was simulated for 19 months, beginning with a four-month spin-up period to mitigate initial condition anomalies and capture antecedent moisture dynamics, followed by 15 months of calibration using observed data. Using the complete observational dataset for calibration was important for capturing the transient soil water dynamics and vertical moisture continuum across all four monitored horizon depths. Crucially, the dataset captures multiple high-intensity precipitation peaks as well as extended drought-induced drawdowns, providing an empirical basis for the reliable estimation of soil hydraulic parameters under contrasting hydroclimatic extremes.

A constant Leaf Area Index (LAI) of two was used throughout the simulation period. This was done to maintain a baseline constraint that isolates subsoil hydraulic performance and vertical drainage capacity from uncertainties arising from highly non-linear vegetative feedback [39]. In standard agronomic and hydrological frameworks, an active area dominated by herbaceous plants maintains an effective LAI within the 2.0–2.5 range, making a static value of two an established and generalised baseline for healthy ground cover [40].

The calibrated model was used to assess decentralised stormwater mitigation; an infiltration pond was conceptualised to receive runoff harvested from the rooftops of surrounding campus buildings. The rooftop catchment area, measuring 695 m², was mapped using the X120GO handheld laser scanner (Stonex, Milan, Italy) to derive the exact contributing geometry. To evaluate design sensitivities, three infiltration ponds were evaluated, including 1000 m² (S₁), 750 m² (S₂), and 500 m² (S₃), and contrasted against a baseline no-intervention scenario (S₀). The evaluated infiltration ponds were simulated as flat-bottomed with 0% bed slope, designed to receive concentrated runoff from a nearby 695 m² rooftop catchment. A uniform maximum ponding depth limit of 0.5 m was established across scenarios.

The daily combined volumetric water input Q_m (m³/day) was calculated as follows:

$$Q_m = \frac{(A_r + A_p) \cdot P}{100} \quad (5)$$

where A_r is the roof area (695 m²), A_p is the infiltration pond surface area (m²), and P is the precipitation (cm/day). The normalised daily hydraulic loading depth infiltrated into the soil domain (P_{sz} , cm/day) was calculated as follows:

$$P_{sz} = \frac{Q_m}{A_p} \cdot 100 \quad (6)$$

The output data were used as a time-variable atmospheric boundary condition in Hydrus-1D to simulate daily pond infiltration over multi-decadal periods. The approach assumes that all rooftop runoff was captured and redirected into the pond with negligible conveyance or evaporation losses. The current approach assumes direct transfer of rooftop runoff into the infiltration pond without accounting for open-water pond evaporation or additional surface runoff from adjacent non-roof catchment areas. While open-water evaporation during high-stage storage events may marginally lower net infiltration depths, uncaptured runoff would conversely increase total hydraulic loading. This scoping assumption was maintained to isolate subsoil infiltration performance under defined rooftop contributing areas. Still, full-scale engineering implementations should incorporate open-water pond water balances to account for seasonal evaporative losses. Clogging of the soil beneath the pond was also neglected.

The cumulative bottom flux was used as the indicator for potential deep percolation and groundwater recharge. Hydrus-1D calculated it through the temporal integration of the actual instantaneous water flux passing across the lower boundary of the 300-cm soil profile. Given the free drainage boundary condition used in this study, the bottom flux was determined based on a unit vertical hydraulic gradient, where the discharge rate matches the hydraulic conductivity of the bottom node [41]. Following the model's internal sign convention, downward drainage out of the domain is reported as negative.

The effects of climate variability and change on the performance of the infiltration pond were evaluated using multiple climate datasets. Climatic inputs included long-term historical point observations from the Hungarian Meteorological Service (HMS, Station 64711), historical gridded data from the FORESEE database (1991–2023), and six bias-corrected Regional Climate Model (RCM) combinations for the mid-century horizon (2021–2050) representing minimum (MPI_CCLM), moderate (CNRM_CCLM), and extreme (HadGEM2_CCLM) climate trajectories under both the RCP4.5 and RCP8.5 emission pathways [42]. Potential evapotranspiration (PET) was estimated using the Hargreaves–Samani approach [43].

3. Results

3.1. Model Calibration

The model was calibrated using the batched hydrologic runs algorithm by modifying parameters to determine the best fit between simulated and observed soil moisture at different depths. Saturated hydraulic conductivity and the parameters of the soil moisture retention curve were refined through this process. Model performance was evaluated using the Nash–Sutcliffe model efficiency coefficient (NSE) and the root mean square error (RMSE) between observed and simulated SWC.

The results show that observed and simulated values are closely related, a finding supported by excellent goodness-of-fit metrics, including an NSE of 0.705 and a low RMSE of 0.021 cm³/cm³ (Figure 2). However, when observing the response to individual storm events, it is evident that the model tends to slightly underestimate measured moisture content within the shallow 30 cm and 60 cm horizons during peak infiltration phases. Conversely, during extended dry spells, an opposite trend emerges where HYDRUS tends to overestimate the retained moisture content in the deeper soil horizons. Preferential flow

via decayed roots in shallow layers can increase soil water infiltration and supply [29]. Similarly, rainfall events can be pulsed or episodic, contrary to the slow-drip simulation by HYDRUS-1D in the daily time step [29].

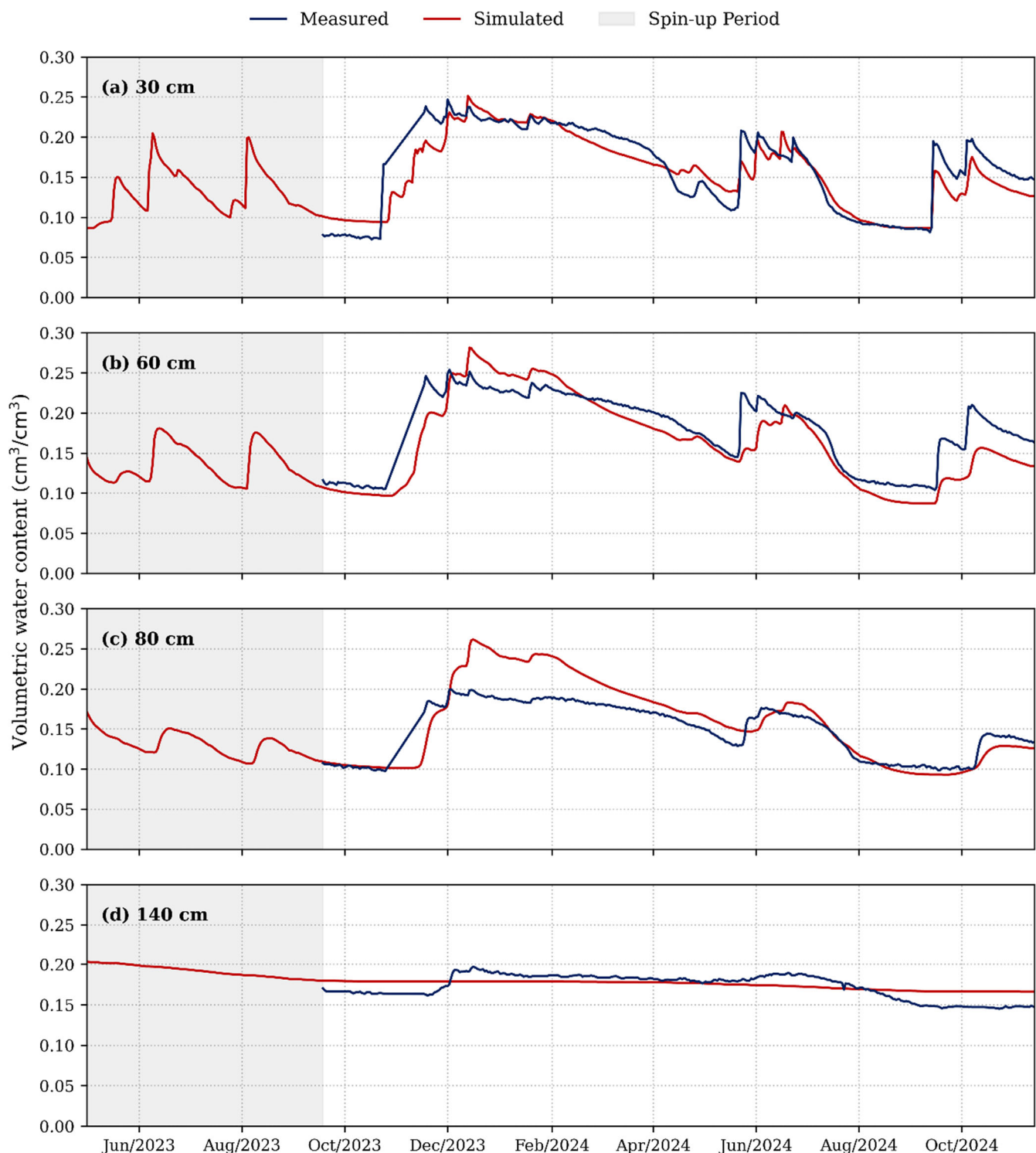


Figure 2. Observed and HYDRUS-1D simulated daily volumetric water content (cm³/cm³) across four monitored soil profile depths: (a) 30 cm, (b) 60 cm, (c) 80 cm, and (d) 140 cm at Soil Profile A (University of Debrecen Campus). Light grey shaded area indicates the initial model spin-up period (1 May to 18 September 2023) before model calibration. Continuous line segments represent measured sensor readings after linear temporal interpolation across minor logging gaps.

3.2. Long-Term Infiltration Performance and Inter-Scenario Balances

Different simulation scenarios were evaluated to determine the long-term effectiveness of the infiltration pond, as shown in Table 2. Baseline scenarios (S_0) yielded minimal deep percolation across all input datasets: 0.49 mm for local HMS data (2017–2023), 0.65 mm for FORESEE gridded data (2017–2023), and 18.06 mm for the long-term FORESEE data (1991–2023). These negligible percolation rates indicate that without decentralised intervention, nearly all input precipitation is partitioned between evapotranspiration, runoff, and shallow soil moisture storage, with minimal water bypassing the vadose zone.

Table 2. Simulated cumulative bottom flux, ET/PET ratio, and root zone saturation under historical and projected climate scenarios.

Source/Climate Model	Scenario	Cum. Bottom Flux (mm)	Avg. ET/PET Ratio (-)	Avg. Root Zone Saturation (%)
HMS (2017–2023)	S_0	−0.49	0.56	35
FORESEE (2017–2023)	S_0	−0.65	0.57	36
FORESEE (1991–2023)	S_0	−18.06	0.54	40
	S_1	−692.56	0.65	57
	S_2	−1023.53	0.66	60
	S_3	−1730.98	0.67	64
MPI_CCLM_RCP4.5	S_0	−1.31	0.53	35
	S_1	−393.57	0.68	55
	S_2	−645.53	0.68	58
	S_3	−1194.10	0.69	63
MPI_CCLM_RCP8.5	S_0	−1.04	0.51	33
	S_1	−303.96	0.69	53
	S_2	−526.85	0.69	57
	S_3	−1027.6	0.71	62
CNRM_CCLM_RCP4.5	S_0	−1.05	0.51	34
	S_1	−355.05	0.67	54
	S_2	−596.09	0.67	57
	S_3	−1127.2	0.68	61
CNRM_CCLM_RCP8.5	S_0	−1.75	0.56	36
	S_1	−500.76	0.69	57
	S_2	−782.52	0.69	60
	S_3	−1388.2	0.7	64
HadGEM2_CCLM_RCP4.5	S_0	−1.53	0.51	35
	S_1	−391.59	0.64	54
	S_2	−621.31	0.65	57
	S_3	−1127.7	0.66	61
HadGEM2_CCLM_RCP8.5	S_0	−1.17	0.47	34
	S_1	−311.2	0.61	51
	S_2	−516.14	0.62	54
	S_3	−973.29	0.63	58

On the other hand, introducing the decentralised infiltration pond increased downward vertical drainage fluxes. Under the 1991–2023 historical gridded data, the S_3 scenario resulted in 1730.98 mm of cumulative bottom flux (CBF), representing a significant increase over the baseline (Table 2, Figure A5). The cumulative fluxes for S_1 and S_2 were 692.56 mm and 1023.53 mm, respectively. This finding shows that smaller pond designs concentrate

inflow and provide less surface area for evaporative losses, thereby driving greater vertical drainage per unit area.

The ET/PET ratio compares ET to PET and indicates the degree to which atmospheric water demand is being met and ecosystem water availability, with values below 1 indicating water stress [44]. The results show that the ET/PET ratio increased with pond implementation across all climate projections, suggesting improved water availability for urban vegetation (Table 2). Current climate baselines demonstrated an ET/PET of 0.53–0.57, whereas S_3 scenarios reached 0.67–0.71, a mean increase of 0.14. Under the driest climate projection (HadGEM2_CCLM RCP8.5), ET/PET improved from 0.47 (S_0) to 0.63 (S_3), effectively restoring evaporative demand fulfilment to near-baseline levels (Table 2).

Average root zone saturation increased significantly from 33–40% in baseline scenarios to 58–64% in S_3 scenarios across all climate models. This increase indicates that surface infiltration ponds substantially enhance soil moisture storage, thereby reducing localised moisture deficits and strengthening urban vegetation resilience. Complete mitigation of surface stormwater runoff was achieved across all simulated scenarios without any overspilling, indicating that the soil column has adequate capacity to route incoming storm volumes under the designated scoping designs safely.

Across all simulated climate scenarios, the S_0 baseline produced negligible CBF, remaining near the zero-flux axis throughout the 2021–2050 period. This shows that projected climate variability alone is not enough to drive significant vadose zone percolation in the absence of intervention. Simulation of the infiltration pond fundamentally altered this response. Under the pessimistic HadGEM2_CCLM_RCP8.5 scenario, S_3 produced the highest cumulative bottom flux (~ -1000 mm), followed by S_2 (~ -520 mm) and S_1 (~ -320 mm), with the hierarchical ordering of pond designs remaining stable throughout the simulation period (Figure 3). The step-like morphology of the S_3 trajectory reflects the episodic character of deep percolation, driven by discrete high-intensity events rather than continuous seasonal drainage.

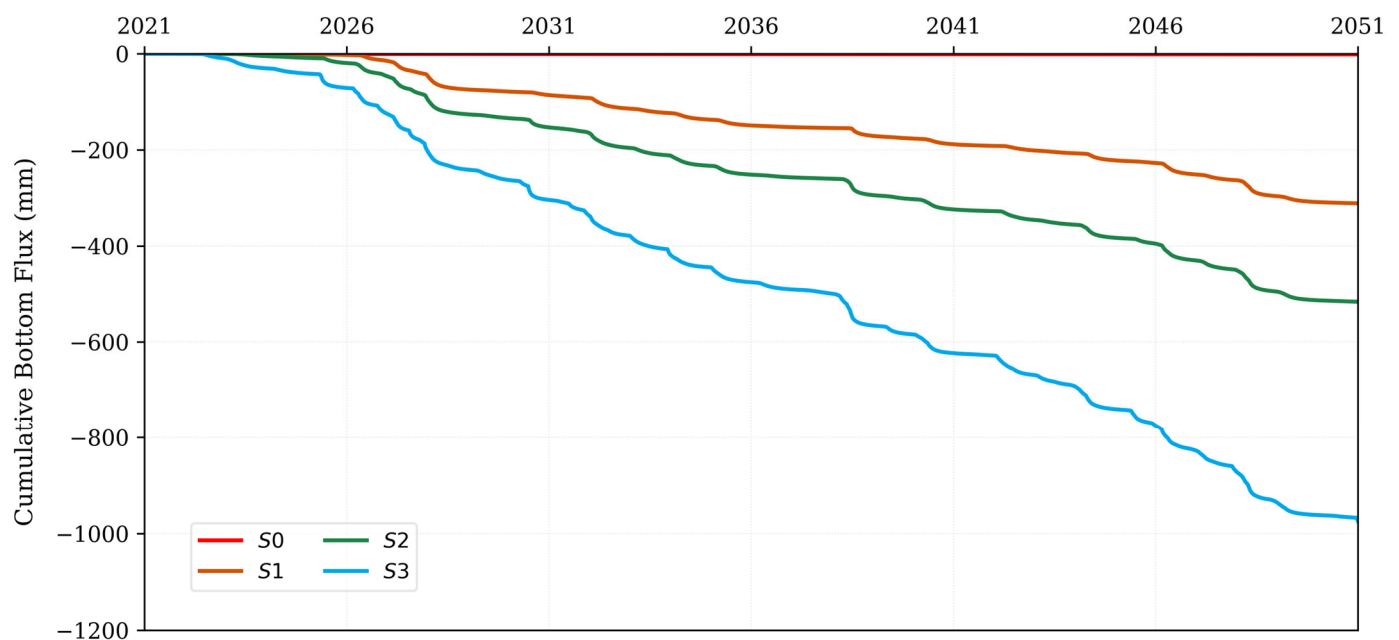


Figure 3. Effect of Infiltration Pond Size on Cumulative Bottom Flux Under a Pessimistic Climate Scenario (HadGEM2_CCLM_RCP8.5).

Evaluation of S_3 across the selected climate models yielded sustained negative fluxes under all six climate combinations, ranging from approximately -1000 mm

(HadGEM2_CCLM_RCP8.5 and MPI_CCLM_RCP8.5) to -1400 mm (CNRM_CCLM_RCP8.5) by 2050, demonstrating that pond performance is effective across the range of projected hydroclimatic conditions (Figure 4). Under the minimum warming trajectory (MPI_CCLM), RCP4.5 produced marginally greater cumulative flux than RCP8.5, suggesting that elevated evaporative demand under higher emissions partially offsets infiltration gains (Figures A6 and A7). On the contrary, CNRM_CCLM exhibited greater CBF values under RCP8.5 than RCP4.5, consistent with more intense and temporally concentrated precipitation events driving higher hydraulic loading under the moderate warming pathway (Figures A8 and A9).

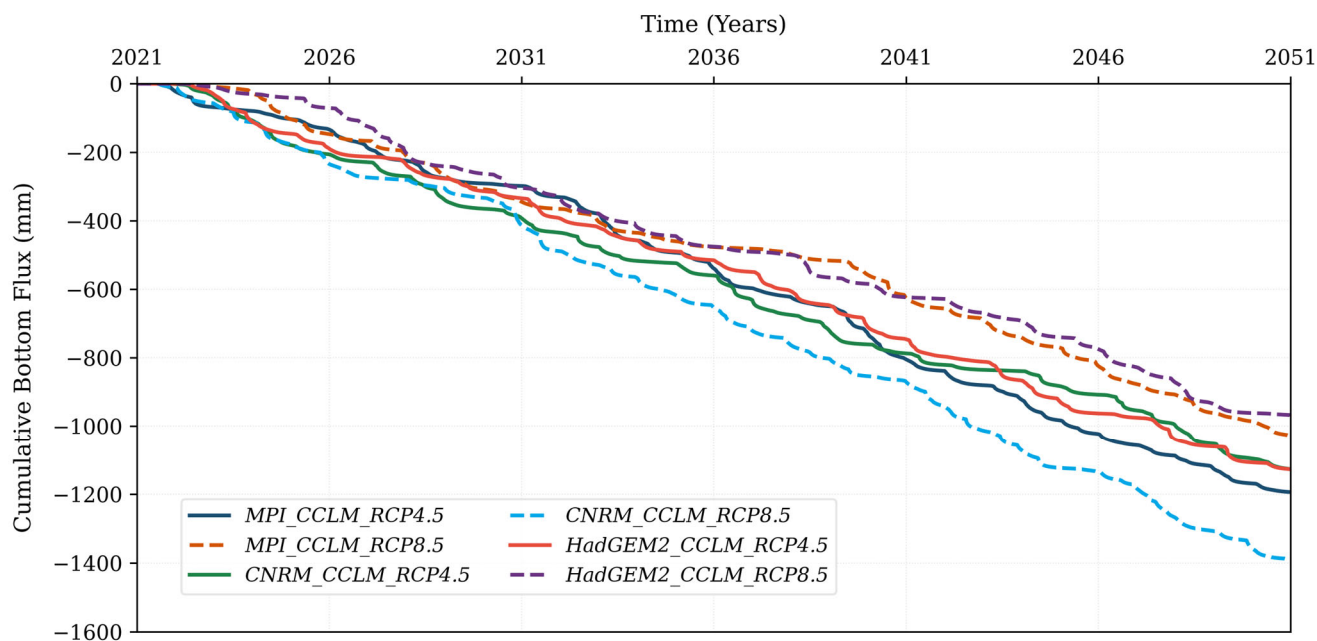


Figure 4. Cumulative bottom flux under different climate change scenarios for S3 (500 m^2).

All the intervention scenarios are well below the S_0 baseline (Figure 3) across the full RCM ensemble, providing quantitative evidence that climate-driven precipitation shifts alone will not compensate for the absence of managed retention infrastructure. The results show that decentralised infiltration ponds, also known as NSWRM, have the potential to enhance subsoil aquifer recharge across different projected hydroclimatic conditions. Therefore, supporting their role as adaptive water management interventions under climate change.

4. Discussion

The overall satisfactory performance of the model ($\text{NSE} = 0.705$; $\text{RMSE} = 0.021 \text{ cm}^3/\text{cm}^3$) aligns with the existing literature supporting the fact that Hydrus-1D provides reliable simulations of vertical moisture transport in layered soil environments when the vadose zone is accurately parameterised [31,33,36,39,45–51]. Observed systematic deviations, particularly the underestimation of soil water content (SWC) in shallow horizons during peak infiltration and the overestimation at depth during extended dry periods, are consistent with preferential flow dynamics through macropores and the inherent limitations of resolving episodic precipitation events at a daily time step [29,52,53].

The main hydraulic parameters, including saturated hydraulic conductivity, residual and saturated water contents, and van Genuchten curve-fitting constants, primarily drive these simulation sensitivities [31,54,55]. Inaccurate parameterisation of these variables is known to introduce systematic biases in gravity-dominated, deeper flow regimes; however, using in situ TDT sensor data for calibration helped minimise this uncertainty by grounding

the model in observed transient soil moisture dynamics. Furthermore, the progressive decoupling of surface and deep SWC over time reflects the contrasting dominance of rapid atmospheric forcing at the soil–atmosphere boundary and restricted capillary flow within the deeper horizons [53]. This pattern reinforces the importance of using site-specific field data to capture the complex rewetting and drying cycles that define urban infiltration systems. The use of high-resolution, sensor-calibrated data in this study ensures that the simulated vertical moisture flux is grounded in verified local conditions, providing a robust baseline that avoids the random and systematic errors often found in regional simulations [56]. Characterising soil hydraulic properties across broad landscapes is difficult and expensive, as saturated hydraulic conductivity is known to be overly spatially variable [26,56]. Studies in similar environments indicate that while site-specific, optimised parameters are highly representative within an immediate footprint of approximately 25 m [57], soil hydraulic properties can fluctuate by more than an order of magnitude across short distances due to variations in topography and depth [27,28].

The results show that decentralised infiltration ponds, functioning as natural/small water retention measures (NSWRMs), provide a dual-purpose hydrologic mechanism: the complete attenuation of surface stormwater runoff and the restoration of vertical percolation to support localised water balances. These findings directly corroborate prior research demonstrating that strategic water retention interventions effectively enhance groundwater recharge, increase irrigation water availability, and preserve downstream base-flow regimes in areas where urbanisation has historically disrupted the natural hydrologic cycle [17–19,21,22,58–60].

The negligible deep percolation (≤ 1.75 mm) observed in the S0 baseline across all climate scenarios corroborates the well-documented urban stream syndrome where land sealing and soil compaction fundamentally disrupt natural infiltration and groundwater recharge. These results align with findings by [17,29], who emphasise that traditional urban surfaces prioritise rapid runoff conveyance over vertical moisture flux, effectively decoupling the surface from the vadose zone.

The substantial increase in cumulative bottom flux (CBF) achieved by the S₃ configuration, which reaches 1730 mm historically and maintains up to 1388 mm under future projections, demonstrates the high efficiency of infiltration-based intervention in restoring vertical hydrologic connectivity [38,60]. Interestingly, S₃'s superior performance relative to larger pond areas suggests a threshold in the catchment-to-pond area ratio; larger ponds may face diminishing returns or increased evaporative losses without corresponding gains in infiltration capacity. This pattern is consistent with the literature, suggesting that decentralised, smaller-scale infiltration units can be more effective than centralised, oversized basins in maintaining moisture balances [60].

The observed improvements in the ET/PET ratio (0.63–0.71) and root zone saturation (58–64%) for S₃ identify these ponds as critical components for urban heat island mitigation through evaporative cooling [61–64]. This shift toward a more natural water balance corroborates the regional findings [21,31] regarding the importance of soil moisture for urban vegetation health in Debrecen. Furthermore, by restoring vertical percolation in the Nyírség region, the S₃ pond serves as the critical local water retention measure proposed by [21] to mitigate regional water table decline and protect the area's climate-vulnerable groundwater-dependent ecosystems. Therefore, runoff attenuation achieved in all pond scenarios confirms that these systems provide effective flood protection even under mid-century climate stressors.

The emission pathway sensitivity pattern, where MPI_CCLM showed RCP4.5 CBF values greater than RCP8.5 CBF, while CNRM_CCLM showed the reverse, can be attributed to the dynamic balance between projected precipitation intensity and actual evaporation. In

the MPI_CCLM model, the RCP8.5 scenario likely projects temperature increases that drive actual evaporation high enough to offset precipitation gains, thereby reducing net infiltration compared to the more moderate RCP4.5 [38]. Conversely, CNRM_CCLM under RCP8.5 likely predicts extreme precipitation intensities that override the increase in evaporative demand, leading to higher CBF.

This emission pathway sensitivity aligns with the projections of Staccione et al. (2021), who identified high variability in retention pond performance depending on the specific combination of climate scenarios used [22]. Furthermore, as noted by Jonoski et al. (2025), the hydrologic effectiveness of such nature-based measures is highly dependent on climate model scenarios, specifically how they represent the trade-off between short-duration, high-intensity events that drive infiltration and long-term temperature trends that escalate evaporative losses [18].

While our findings corroborate the general benefits of infiltration-based interventions identified by Baird et al. (2020), they diverge from some of the literature regarding the limitations of high-water tables; our results suggest that, provided the vadose zone is sufficiently thick (as in the Debrecen site), horizontal groundwater flow can actually enhance infiltration rates during peak stages [19]. The research has also shown that the S3 configuration provides a resilient solution for Debrecen, effectively bridging the gap between flood attenuation and groundwater replenishment under a range of future emission pathways.

5. Conclusions

This research provides a robust numerical evaluation of the potential for decentralised infiltration ponds to mitigate the urban stream syndrome and restore natural hydrologic cycles in regional recharge zones. The results of this investigation show that the S₃ configuration (500 m²) provides a highly efficient dual functional mechanism: the complete attenuation of surface stormwater runoff and the substantial restoration of vertical percolation to support localised water balances. By increasing cumulative bottom flux by over 1000 mm compared to the baseline, these ponds function as critical natural or small water retention measures capable of enhancing groundwater recharge in the climate-vulnerable Nyírség region.

The study highlights that the hydrologic effectiveness of such interventions is highly sensitive to the specific climate model representation of the trade-off between short-duration, high-intensity precipitation and long-term temperature-driven evaporative losses. Despite this, the proposed infiltration ponds remained effective in providing both flood protection and soil moisture content (58–64% saturation), which is essential for sustaining urban vegetation health and mitigating heat island effects.

While this study employs a process-driven Hydrus-1D model to simulate vertical moisture flux, advanced modelling in geohydrological engineering has increasingly utilised order-reduction techniques, such as coupled models and the truncated spectral method, to analyse the non-linear stability and bifurcation behaviour of subsurface seepage systems under critical conditions [24]. Implementing such low-dimensional modelling frameworks in future work would allow for a more efficient quantitative extraction of critical instability parameters, helping to identify tipping points where infiltration systems may lose stability under extreme hydraulic loading [24]. Additionally, future investigations should consider the long-term evolution of subsurface hydraulic properties resulting from cumulative environmental stress. Research into other geomaterials indicates that extreme environmental cycling such as the high-temperature and intense precipitation swings projected in RCP 8.5 scenarios can induce cumulative structural damage, fundamentally altering porosity and permeability over time [25]. Understanding how these stressors induce micropores,

preferential flow, and evolve fluid migration pathways will be essential for assessing the multi-decadal performance and structural integrity of decentralised retention infrastructure.

A limitation of the present modelling approach is the reliance on the 15-month continuous sensor dataset for model calibration without an independent validation period, constrained by the temporal availability of high-resolution field monitoring records. Using the available dataset for calibration ensured that the model effectively captured seasonal rewetting and drying cycles across all monitored depths; the absence of a separate validation phase means long-term simulations under projected RCM climate storylines should be interpreted as comparative scoping evaluations rather than exact deterministic forecasts.

To build upon these scoping findings, future work should prioritise: (1) constructing physical pilot-scale infiltration ponds equipped with multi-depth soil sensor networks and infiltrometers to perform empirical field validation under actual operational conditions; (2) incorporating dynamic clogging modules and open-water surface evaporation into multi-dimensional hydrological models such as HYDRUS-2D/3D or SWMM-HYDRUS coupling; (3) testing the transferability of this decentralised pond framework across diverse urban geomorphologies with shallow water tables or lower-permeability clay soils; and (4) integrating 3D landscape-scale soil hydraulic maps to assess parameter uncertainty propagation across broader urban catchments. Addressing these perspectives will advance the practical implementation of natural water retention measures for urban climate adaptation.

The findings of the current study are site-specific to Debrecen; however, they support the regional and international literature advocating for managed aquifer recharge as a primary adaptation strategy for water-scarce urban environments. We conclude that the strategic implementation and scaling of these decentralised infiltration ponds offer a resilient solution for flood mitigation, securing urban water assets, and replenishing depleted regional aquifers under a range of future emission pathways. In addition, to strengthen future regional upscaling of these decentralised interventions, scaling techniques can be applied to compare local findings with heterogeneous porous media. Integrating our results with high-resolution gridded hydraulic maps (e.g., 100-m resolution) would further allow the uncertainties propagated by this inherent landscape-scale soil variability to be quantified.

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Data Availability Statement: The historical meteorological records and simulated soil moisture datasets generated during the current study are available from the corresponding author upon reasonable academic request. Gridded climatic projections were sourced directly from the public FORESEE database (Historical Meteorological Records: https://odp.met.hu/climate/observations_hungary/daily/historical/, FORESEE Database: <https://meteordata.elte.hu/FORESEE/index.html> and <https://meteordata.elte.hu/FORESEE/DATA/>, accessed on 13 August 2026).

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Appendix A



Figure A1. Location of reference soil profile (Profile A), the HMS meteorological station (ID: 64711), and the proposed infiltration pond (blue circle on the map) and buildings in Debrecen. The inset map shows the scanned rooftop catchment in red (695 m²) and the proposed infiltration pond location near the building.

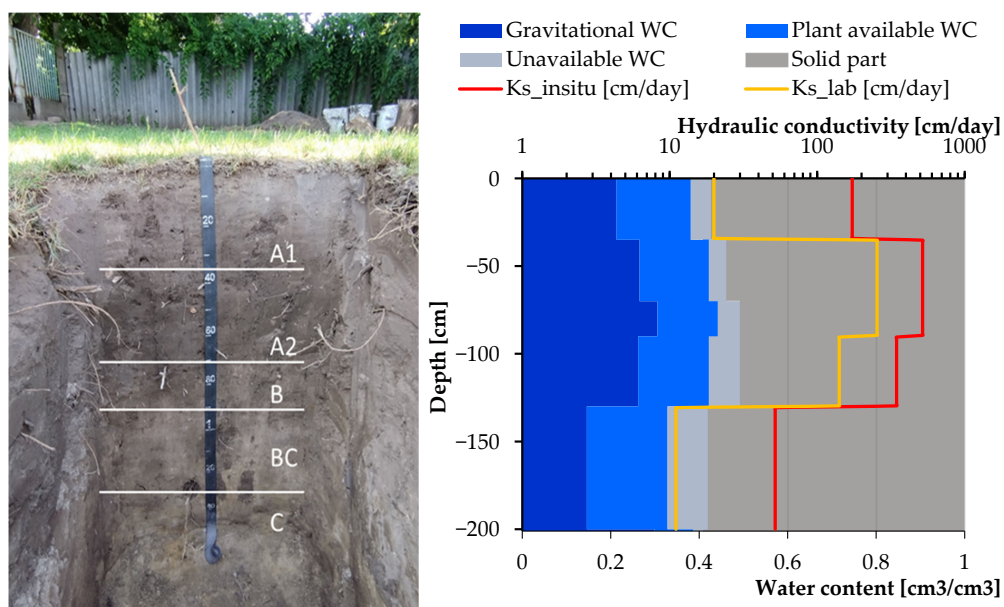


Figure A2. Reference soil profile at the University of Debrecen Campus: photo of the profile showing the soil horizons (left) and the numerical representation of the hydraulic properties applied in the Hydrus-1D model (right).

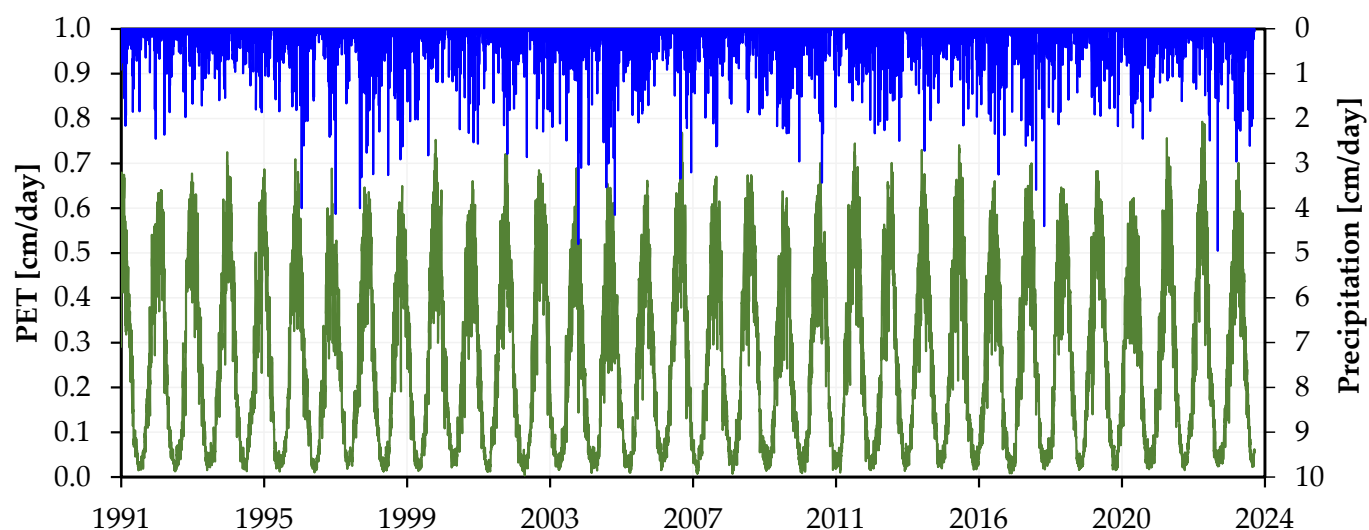


Figure A3. Daily Precipitation (**Blue**) and Potential Evapotranspiration (**Green**) from FORESEE Gridded Climate Data (1991–2023).

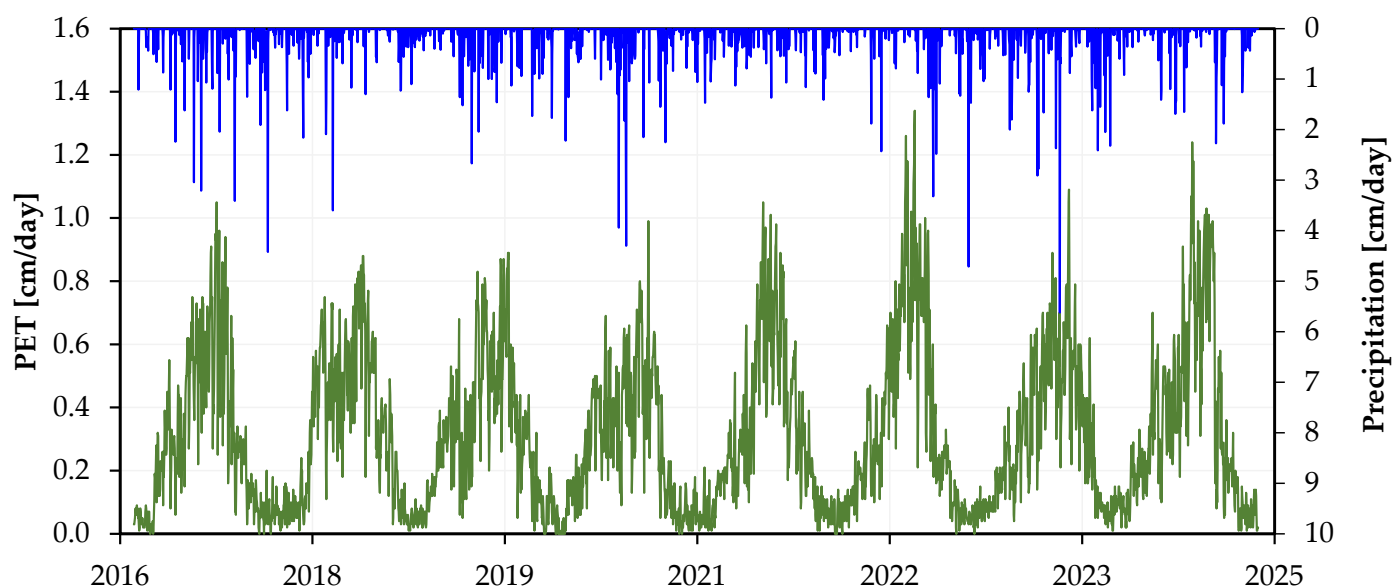


Figure A4. Daily Precipitation (**Blue**) and Potential Evapotranspiration (**Green**) from HMS Station Observations (2017–2023).

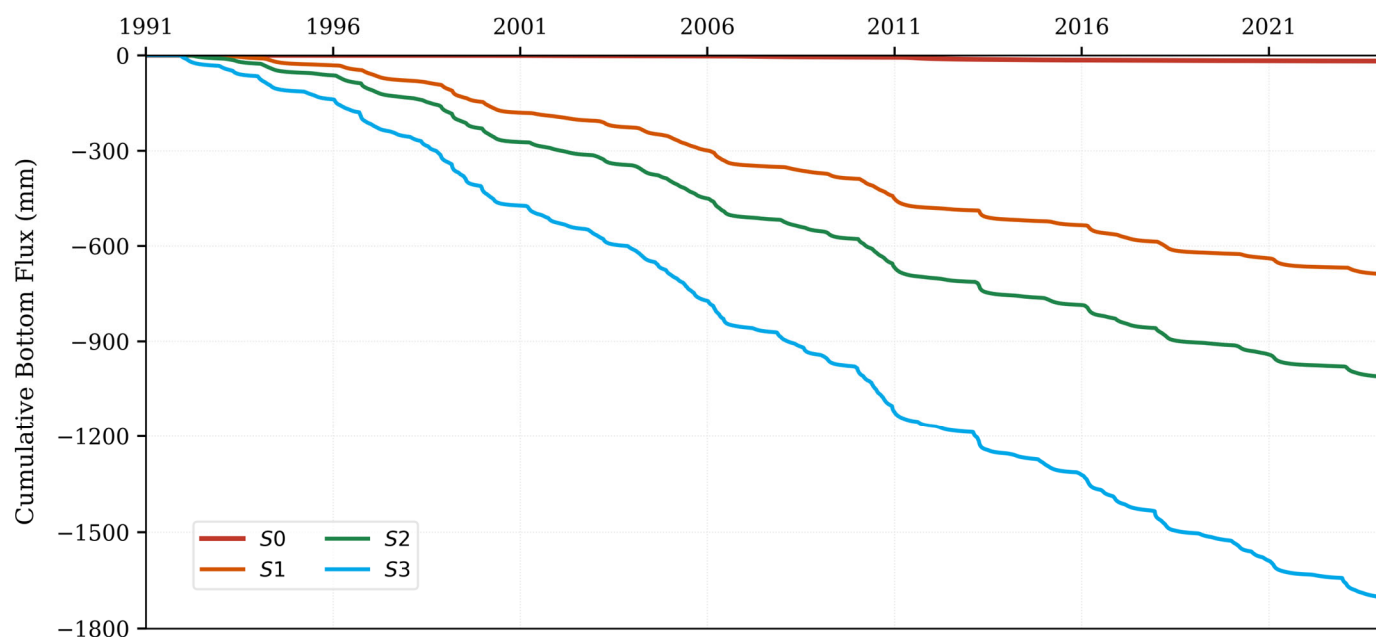


Figure A5. Simulated cumulative bottom flux under observed climate data (1991–2023) for four infiltration pond designs (S0–S3).

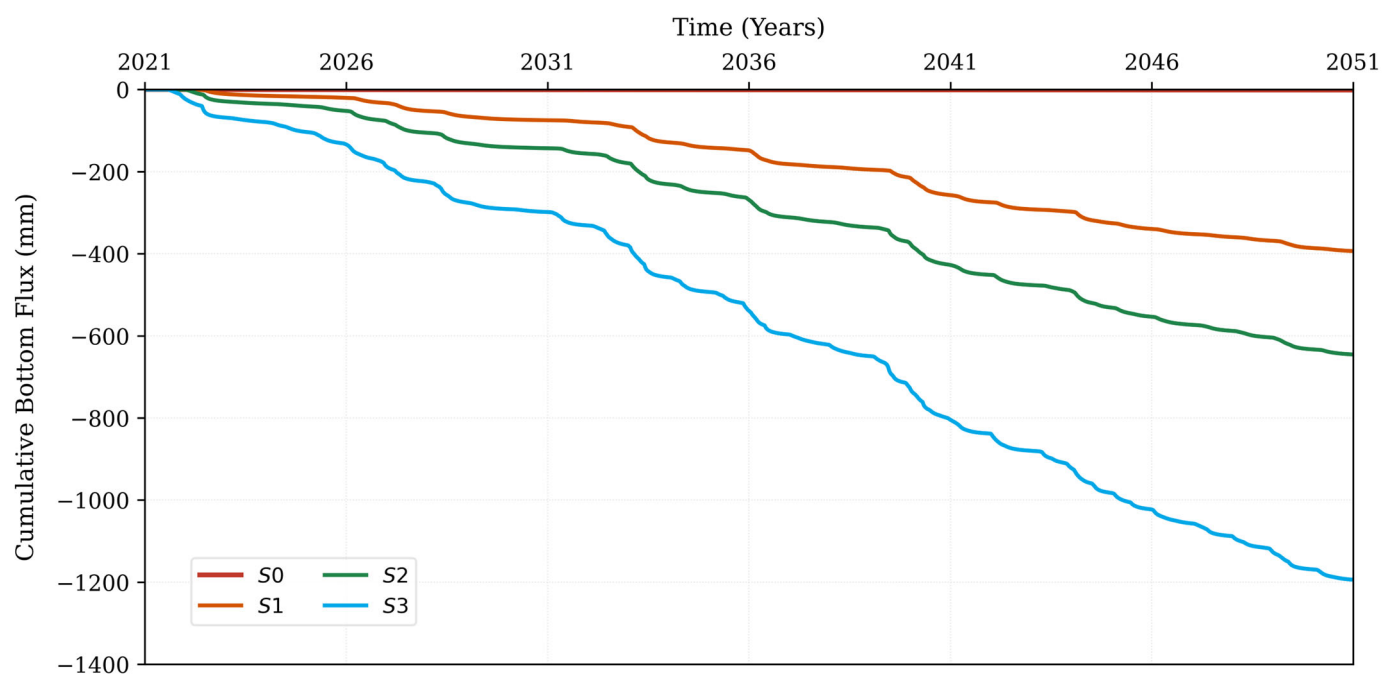


Figure A6. Cumulative bottom flux for infiltration pond scenarios S0–S3 under MPI_CCLM_RCP4.5 projected climate conditions (2021–2050).

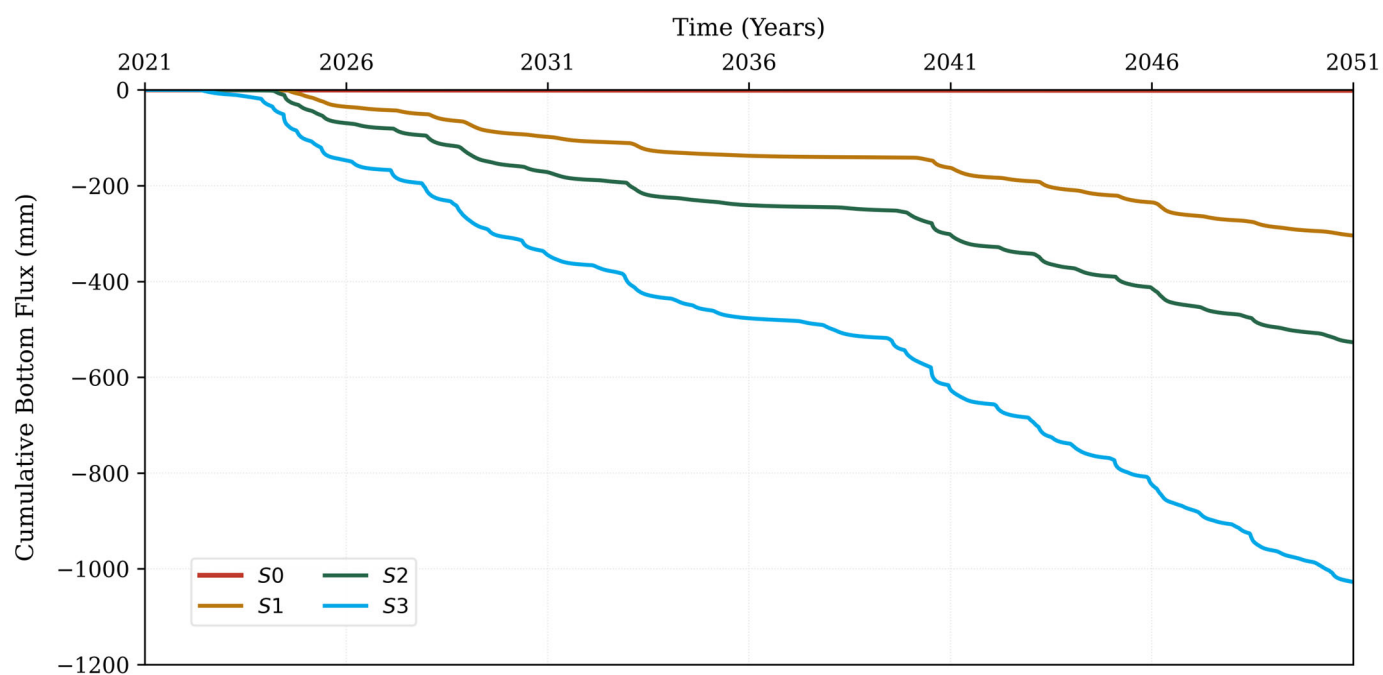


Figure A7. Cumulative bottom flux for infiltration pond scenarios S0–S3 under MPI_CCLM_RCP8.5 projected climate conditions (2021–2050).

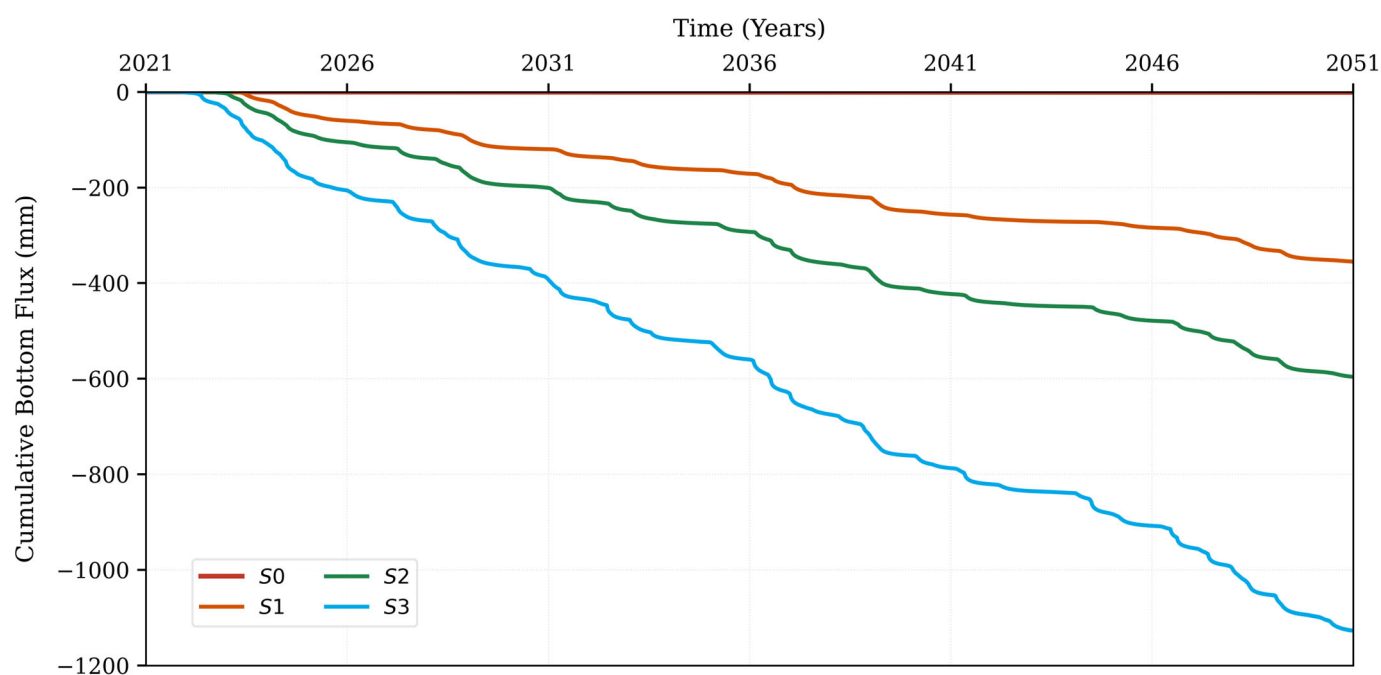


Figure A8. Cumulative bottom flux for infiltration pond designs S0–S3 under CNRM_CCLM_RCP4.5 mid-range climate projection (2021–2050).

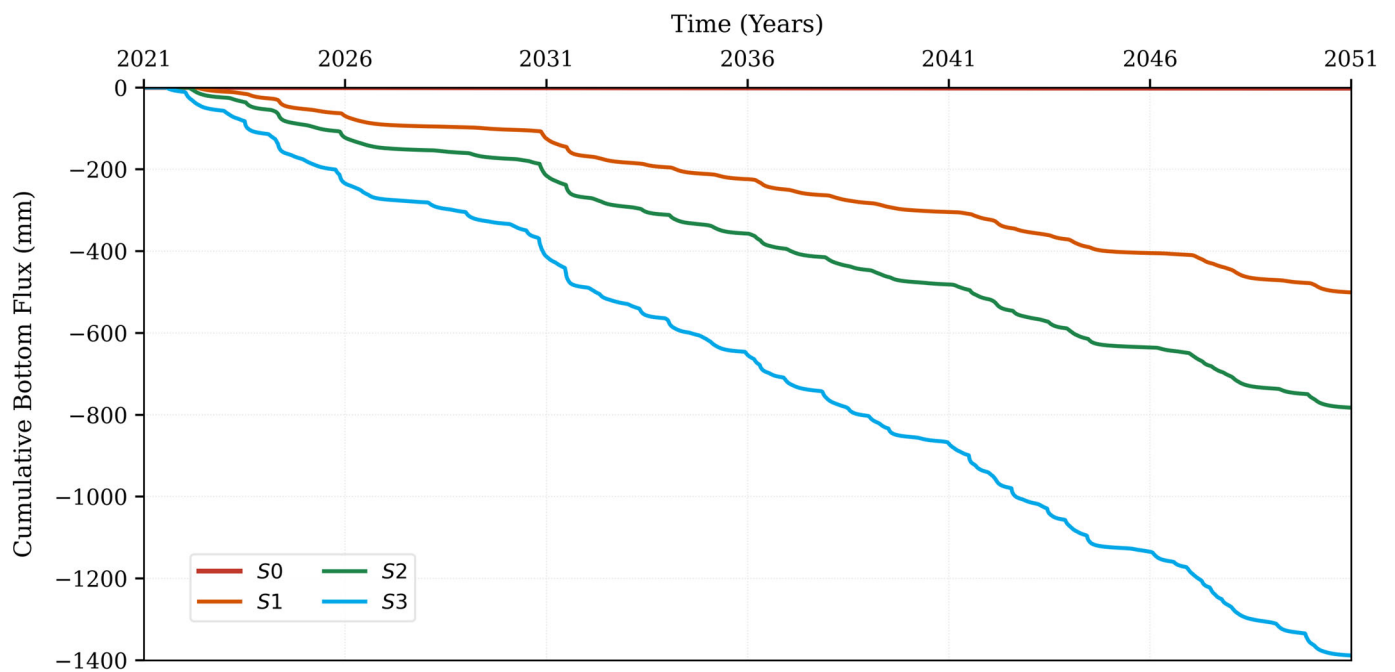


Figure A9. Influence of pond size on simulated bottom flux under the CNRM_CCLM_RCP8.5 emissions scenario (2021–2050).

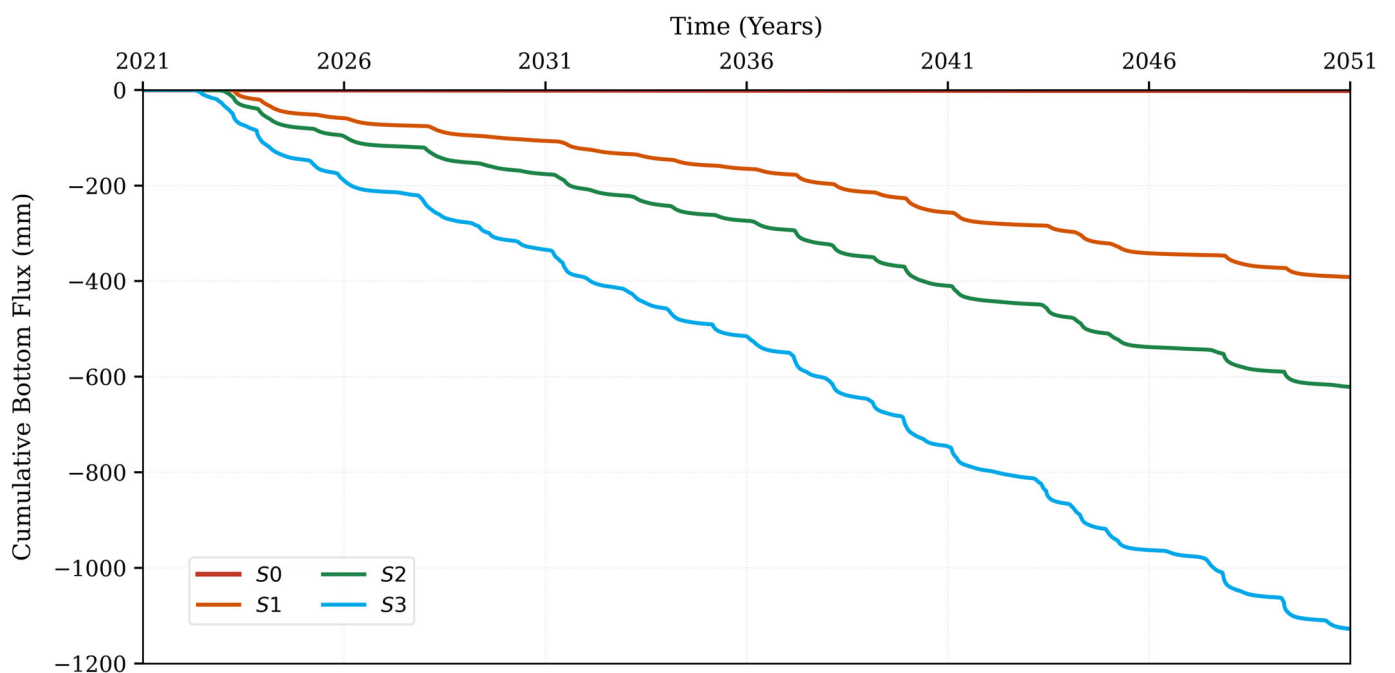


Figure A10. Cumulative bottom flux for infiltration pond scenarios S0–S3 under HadGEM2_RCP4.5 projected climate conditions (2021–2050).

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