Temporal dynamics of blue-green infrastructure at a catchment-wide spatial scale and their influence on combined sewer overflows

Dynamiques temporelles des infrastructures bleu-vert à l'échelle du bassin versant et leur influence sur les déversements d'eaux usées unitaires

Prabhat Joshi*, Max Maurer & João P. Leitão

Institute of Environmental Engineering (IfU), ETH Zürich
Department of Urban Water Management (SWW), Eawag
*Corresponding author email: prabhat.joshi@eawag.ch

RÉSUMÉ

Les infrastructures bleu-vert (BGI) — des dispositifs de gestion des eaux pluviales fondés sur la nature, tels que les toitures végétalisées et les noues de biorétention — sont de plus en plus utilisées pour atténuer les déversements d'eaux usées unitaires (CSO) à l'échelle du bassin versant. Cependant, leurs performances hydrologiques peuvent se dégrader au fil du temps en raison du colmatage, de l'accumulation de débris et du dépôt de sédiments. Cette étude examine comment cette dégradation temporelle des systèmes de biorétention influence les volumes de CSO à long terme. Nous avons développé un cadre de détérioration fondé sur des transitions discrètes d'états de condition, gouvernées par un processus semi-markovien et appliquées à un pas de temps journalier. Les transitions ont été paramétrées à l'aide de courbes de détérioration de type Weibull dérivées de réductions empiriques de la conductivité hydraulique, de la porosité, du taux d'infiltration et du rapport de vides de la couche de stockage. À l'aide d'un modèle SWMM calibré du bassin versant de Fehraltorf, nous avons simulé 53 sous-bassins entre 1987 et 2012 selon trois scénarios : performance stationnaire des BGIs, absence de BGIs et BGIs se détériorant dynamiquement. Les résultats montrent que la détérioration des BGIs entraîne une augmentation progressive des volumes de CSO, produisant environ 17 % de CSO cumulés supplémentaires à la fin de la période étudiée. Ces résultats soulignent l'importance du suivi et de l'entretien des BGIs pour préserver leurs performances hydrologiques. Ils fournissent également une base pour des analyses plus approfondies, notamment afin de déterminer si toutes les BGIs doivent être surveillées en continu ou si un sous-ensemble exerce une influence disproportionnée sur la dynamique des CSO à l'échelle du bassin versant.

ABSTRACT

Blue–green infrastructures (BGIs)—engineered, nature-based stormwater control measures such as green roofs and bioretention cells—are increasingly used to mitigate combined sewer overflows (CSOs) at catchment scale. However, their hydrological performance can deteriorate over time due to clogging, litter accumulation, and sediment deposition. This study investigates how such temporal degradation of bioretention systems can influence long-term CSO volumes. We developed a deterioration framework based on discrete condition-state transitions governed by a semi-Markov process, applied at a daily time step. Transitions were parameterised using Weibull-based deterioration curves derived from empirical reductions in hydraulic conductivity, porosity, seepage rate, and storage-layer void ratio. Using a calibrated SWMM model of a mid-sized Swiss urban drainage catchment, we simulated 53 sub-catchments from 1987 to 2012 under stationary, no-BGI, and dynamically deteriorating BGI scenarios. The results show that BGI deterioration leads to progressively higher CSO volumes, yielding approximately 17% greater cumulative CSO by the end of the study period. These preliminary results provide a basis and rationale for further analysis, such as whether all BGIs require continuous observation or whether a smaller subset disproportionately influences catchment-scale CSO dynamics.

KEYWORDS

Maintenance, EPA SWMM, infiltration, infrastructure management, urban drainage

1 INTRODUCTION

Blue-green infrastructure (BGI), decentralised stormwater interventions such as bioretention cells, green roofs, swales, and permeable pavements, are increasingly being implemented to mitigate combined sewer overflows (CSOs) (Liao et al., 2017; Moghanlo et al., 2025). By promoting infiltration, retention, and evapotranspiration, BGIs reduce peak runoff volumes and delay flow into the combined sewer systems. However, over time, BGIs can degrade due to clogging, sediment accumulation, compaction, and changes in vegetation dynamics. Our recent experimental study provided empirical evidence of such a degradation that affected the water detention and retention capabilities of BGI for short-term rainfall events from sand and leaf-litter deposition (Joshi et al., 2025). In the long term and at catchment-wide spatial scales, it is possible that such forms of physical deterioration progressively diminish the BGI's ability to retain and attenuate runoff, potentially reducing its effectiveness in mitigating CSOs. In this abstract, we present preliminary results of a modelling study that incorporated temporal deterioration dynamics of BGI at catchment-scale and their influence on CSOs.

2 METHODS

To model BGI deterioration over time, we developed a modelling approach in which discrete condition state (CS) transitions are informed by empirically derived deterioration curves. These curves offer a realistic simulation of performance decline in discrete steps. Such a discrete representation also enabled efficient computation to run long-term, multi-asset simulations across a catchment over numerous iterations.

2.1 Modelling the transition of BGI condition states using a semi-Markov chain

We used an ordinal condition class approach for describing the deterioration of the BGIs, going from CS1 (best) to CS5 (worst). We used the Markov process in discrete steps (called Markov "chain") for the transition of BGI from one CS to another. These CS are characterised in their substrate saturated hydraulic conductivity (K_S) and corresponding porosity ($\emptyset$) as well as the seepage rate (SR) and void ratio (VR) of the storage layer. We assumed the Markov chain to be unidirectional (i.e., only deterioration was modelled), also called "semi"-Markov chain.

The CS transition is dictated by a probability matrix comprising the probability of transition (deterioration) from one CS to another at a daily time step. We considered a two-parameter Weibull probability distribution function to model the transition probability.

2.2 Parameterising the Weibull function to model temporal deterioration

To determine the two parameters of the Weibull distribution function, we used a three-step approach. First, we simulated the annual degradation of K_S using the empirical equation proposed by Bergman et al. (2011). Second, we defined the five condition states (CS1 - CS5) based on the percentage reduction of K_S with respect to year 1987 (reference year). Third, we adapted the method suggested by Kleiner (2001) to compute the survival probabilities of BGI remaining in each CS (Fig. 1). For all five CS, the respective Ø values were also changed, corresponding to the change in the K_S, following Saxton and Rawls (2006). The deterioration of the SR and VR of the storage layers was also modelled similarly (Table 1).

Table 1: Bioretention cell parameter values used in this study for the five condition states (CS) in which the saturated hydraulic conductivity and porosity of the soil layer, and seepage and void ratio of the storage layer vary.

BGI layers and parameters	Units	CS1	Other CS
Soil			
Porosity ($\emptyset$)	[-]	0.67	CS 2: 0.51; 3: 0.48; 4: 0.44; 5: 0.40
Conductivity (K_S)	[mm·h^{-1}]	300.0	CS 2: 106.74; 3: 85.46; 4: 56.17; 5: 38
Storage			
Void ratio (VR)	[-]	0.39	CS 2: 0.20; 3: 0.20; 4: 0.19; 5: 0.19
Seepage rate (SR)	[mm·h^{-1}]	1.29	CS 2: 0.47; 3: 0.30; 4: 0.25; 5: 0.19

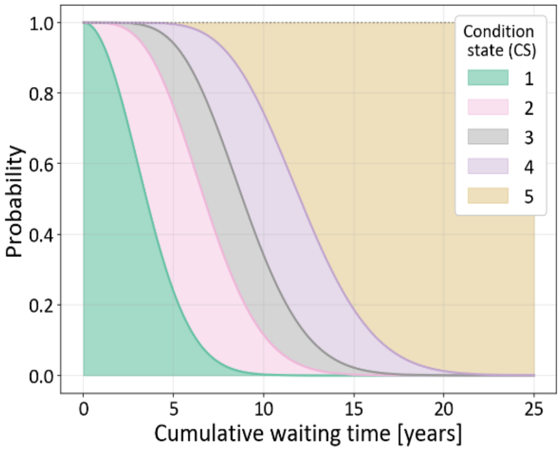

Fig. 1: Survival functions of cumulative sojourn times of the blue-green infrastructure (BGI) in various condition states.

2.3 Case study description

We used the EPA SWMM (v.5.2) model of the Fehraltorf catchment as our case study. Previous studies based on this catchment have calibrated the Fehraltorf SWMM model for optimal hydrologic-hydraulic parameters (Joshi et al., 2021; Rodriguez et al., 2024) and established the role of different types and combinations of BGIs to reduce CSOs (Cavadini et al., 2024; Joshi et al., 2021). To reduce computation time, we selected 53 sub-catchments to which we implemented bioretention cells as exemplary BGI. The bioretention cells received runoff from the entire non-BGI sections of the corresponding sub-catchments.

3 RESULTS AND DISCUSSION

Fig. 2 shows the annual combined sewer overflow (CSO) volumes for the period 1987–2012, comparing results from a stationary reference and no-BGI scenarios with those from a dynamic BGI performance scenario (mean ± standard error (SE)). The top panel shows the interannual variability in which the no-BGI case consistently produced the highest CSO volumes. On the other hand, the dynamic simulations showed varying degree of CSO volume mitigation, which reflects the influence of time and rate at which the CS of BGI changed. The bottom panel presents cumulative CSO volumes over time. The dynamic BGI simulations closely followed the stationary case initially but gradually diverged as performance declined. Eventually, the increase in CSO volume due to BGI deterioration was ~17% by the end of the modelling period.

These results provide a strong basis for deeper analysis of how BGI deterioration affects CSO volumes. In particular, it becomes relevant to examine whether all BGIs contribute equally to changes in CSO volumes or whether a smaller subset exerts a disproportionately large influence. Future works will also attempt to address an important operational question: over what monitoring duration can we confidently detect changes in BGI condition?

4 CONCLUSIONS

Our semi-Markov chain modelling approach provides an effective way to represent the temporal deterioration of BGIs across a catchment. The results show that we can create a realistic (based on literature data) and targeted decline of the system's CSO performance. These preliminary results establish a foundation for further analyses to optimise monitoring and maintenance. For the conference, we aim to investigate whether all BGIs require continuous monitoring or whether a smaller subset exerts a disproportionate influence on catchment-scale CSO outcomes. Such insights will be essential for designing efficient BGI monitoring strategies and prioritising maintenance interventions in order to ensure adequate BGI functionality over time.

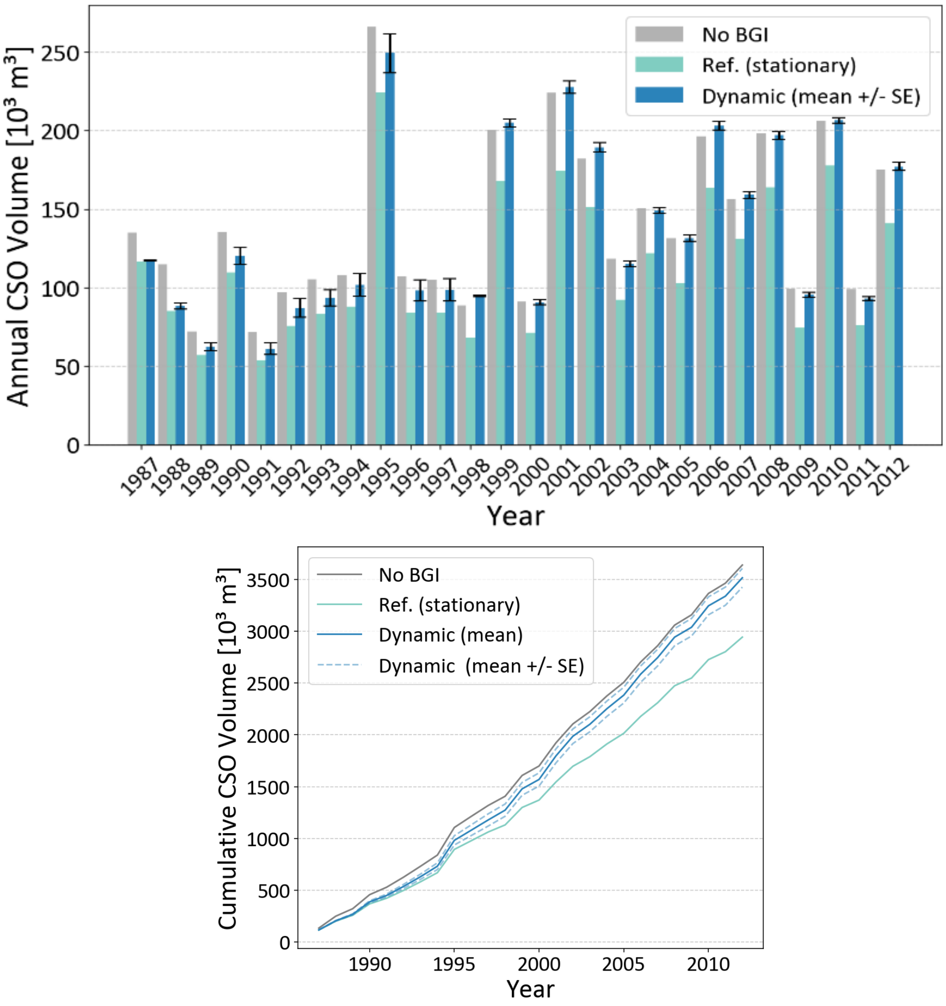

Fig. 2 : Comparison of no BGI, reference (stationary) and dynamic simulations of CSO volumes in Fehraltorf. Top: Annual CSO volumes show interannual variability with higher variability under dynamic simulations (mean ± standard error); Bottom: Cumulative CSO volumes for the different scenarios.

LIST OF REFERENCES

Bergman, M., M.R. Hedegaard, M.F. Petersen, P. Binning, … P.S. Mikkelsen, (2011). *Evaluation of two stormwater infiltration trenches in central Copenhagen after 15 years of operation*. Water Sci. Technol., 63(10), 2279–2286.

Cavadini, G.B., M. Rodriguez, L.M. Cook, (2024). *Connecting blue-green infrastructure elements to reduce combined sewer overflows*. J. Environ. Manage., 365, 121465.

Joshi, P., J.P. Leitão, M. Maurer, P.M. Bach, (2021). *Not all SuDS are created equal: Impact of different approaches on combined sewer overflows*. Water Res., 191, 116780.

Joshi, P., J. Naves, J. Anta, M. Maurer, J.P. Leitão, (2025). *Dataset on the impacts of sand and leaf litter on the hydrological performance of green roofs as surrogate for infiltration-based blue-green infrastructure (BGI)*. Data Br., 59, 111337.

Kleiner, Y., (2001). *Scheduling inspection and renewal of large infrastructure assets*. J. Infrastruct. Syst., 7(4), 136–143.

Liao, K.-H., S. Deng, P.Y. Tan, (2017). *Blue-green infrastructure: New frontier for sustainable urban stormwater management*. In: Tan, P.Y., C.Y. Jim (eds.), Greening Cities, Springer Singapore, Singapore, 203–226.

Moghanlo, S.J., A. Raimondi, (2025). *Impacts of blue-green infrastructures on combined sewer overflows*. Nat.-Based Solut., 7, 100208.

Rodriguez, M., G.B. Cavadini, L.M. Cook, (2024). *Do baseline assumptions alter the efficacy of green stormwater infrastructure to reduce combined sewer overflows?* Water Res., 253, 121284.

Saxton, K.E., W.J. Rawls, (2006). *Soil water characteristic estimates by texture and organic matter for hydrologic solutions*. Soil Science Soc of Amer J, 70(5), 1569–1578.

Scheidegger, A., T. Hug, J. Rieckermann, M. Maurer, (2011). *Network condition simulator for benchmarking sewer deterioration models*. Water Res., 45(16), 4983–4994.