Are we far from anticipating nature-based stormwater solutions maintenance needs?

Anticiper les besoins d'entretien des solutions fondées sur la nature de gestion des eaux pluviales : où en sommes-nous ?

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RÉSUMÉ

Les solutions fondées sur la nature de gestion des eaux pluviales (SFN GEP) sont devenues un élément essentiel de la gestion urbaine des eaux pluviales, offrant des bénéfices hydrologiques et des services écosystémiques. Toutefois, le manque de données sur leurs performances et leur entretien à long terme pose des défis pour une gestion durable de ces solutions. Cette étude présente un modèle à base agents basé sur la littérature scientifique et l'expertise métier pour combler ces lacunes en intégrant à la fois les dimensions hydrologiques et écologiques des SFN GEP. Le modèle conceptuel comprend des agents représentant les gestionnaires, les pratiques de maintenance, et les dysfonctionnements des composants des SGN GEP, tout en simulant leurs interactions au cours du temps. Les données mobilisées pour le modèle proviennent d'une analyse par arbre de défaillance (AAD), d'une enquête internationale menée auprès de gestionnaires de SFN GEP et de données issues d'inspections de terrains. Les résultats de la AAD et des inspections contribuent à identifier les défaillances des SFN GEP et à évaluer leurs effets sur les différents composants, tandis que les données d'enquête apportent un éclairage sur les pratiques de maintenance. La capacité des modèles à base agents à modéliser des comportements émergents et à simuler des stratégies de gestion offre une voie prometteuse pour optimiser la performance des SFN GEP, afin de préserver les bénéfices à long terme de ces aménagements essentiels.

ABSTRACT

Nature-based stormwater solutions (NBSS) have become a vital component of urban stormwater management, offering hydrological benefits and ecosystem services. However, incomplete data on their long-term performance, operation and maintenance poses challenges for their sustainable asset management. This study presents an agent-based model (ABM) to address these gaps by integrating Fault Tree Analysis (FTA), field inspection data, and stakeholders' opinions. Agents represent utilities, maintenance practices, failure events, and NBSS components, simulating their interactions over time. FTA and field inspection results help in identifying NBSS failures and their prevalence as well as assessing their effects on NBSS components, while survey data offers insights into maintenance practices and their frequency. ABM's capacity to model emergent behaviours and simulate management strategies offers a promising path toward optimizing NBSS performance. This study advances the understanding of the interplay between NBSS and their socio-ecological environment and supports the development of proactive, data-driven management frameworks to sustain the long-term benefits of these critical infrastructures.

KEYWORDS

Blue-green infrastructure, nature-based solutions, urban stormwater, agent-based modeling, asset management

1 INTRODUCTION

In recent decades, urban stormwater management has increasingly embraced nature-based stormwater solutions (NBSS) to complement traditional piped networks (Langeveld et al., 2022). In this article, NBSS refer to a variety of vegetated infiltration-based or retention-based solutions such as raingardens, swales and stormwater wetlands combining both (green) vegetated elements and (grey) built elements. This hybrid composition enables them to offer a wide range of services ranging from soil remediation to human well-being and flood control (Cook et al., 2024). However, research on their long-term performance suggests that, like any other infrastructure, they deteriorate over time, leading to failures in achieving desired performance (Bahrami et al., 2024). In comparison to traditional stormwater systems, NBSS lack dedicated asset management methods to ensure their long-term performance (Langeveld et al., 2022). Thus, current practices predominantly rely on reactive maintenance methods, addressing failures and issues after they occur. However, beyond the 'reactive' method, a fundamental requirement for any asset management approach is access to high-quality, relevant data, and predictive models to enable operators to proactively address common failures and other critical factors.

Asset management is a socio-technical process, where the interaction between social and technical systems directly impacts strategy development and the long-term evolution of the asset (Bush et al., 2014). To fully grasp the impact of the complex socio-hydro-ecological system (grey–green solution and its management) on NBSS performance, we have chosen to explore agent-based modelling (ABM). Agent-based models provide a comprehensive approach to modelling complex systems whose outcomes cannot be predicted by simply aggregating the behaviours of their individual components, because of the numerous interactions and feedback loops occurring within the system. In that sense, ABM is a suitable tool for exploring the impact of various factors influencing the deterioration of NBSS and evaluating the impact of different management strategies on the performance of their components. Accordingly, this abstract presents the foundation of the ABM conceptual model. Three methods aiming at gathering data needed for the model implementation are introduced: a Fault Tree Analysis (FTA), an international survey carried out among NBSS managers and results from field inspections. Finally, we discuss the imperative for a flexible, context-sensitive ABM framework to model multifunctional NBSS and support adaptive management strategies.

2 FROM A COMPLEX NBSS SYSTEM TO AN AGENT-BASED MODEL (ABM)

An ABM is defined by three components: (i) a set of agents, (ii) a set of relationships including the methods of interactions (how and with whom agents interact), and (iii) an environment (Macal & North, 2010). Each agent is defined by its species and specified by its attributes and its actions. An agent can represent a living or non-living, physical or abstract entity. The ABM is executed over a specified timeline over which agents repeatedly evaluate their behavioural rules, execute actions based on those rules, and update individual characteristics (attributes) (Berglund, 2015). The system we intend to model includes one NBSS made of multiple components and managed by multiple utility departments (e.g., green space, water, sewer, etc.). To simulate the deterioration of the NBSS overtime, its components are prone to dysfunction(s) as the result of a failure event. Failure events and maintenance practices impact, respectively negatively and positively, the performance of the components and consequently the overall performance of the NBSS. The performances considered are flood protection, ecosystem preservation, climate change adaptation, human health and well-being improvement. Each *maintenance practice* agent and *failure event* agent can impact one or several attributes of one or several NBSS components. Attributes define the performance of the agent at any time. Figure 1 illustrates interactions between the species of the ABM.

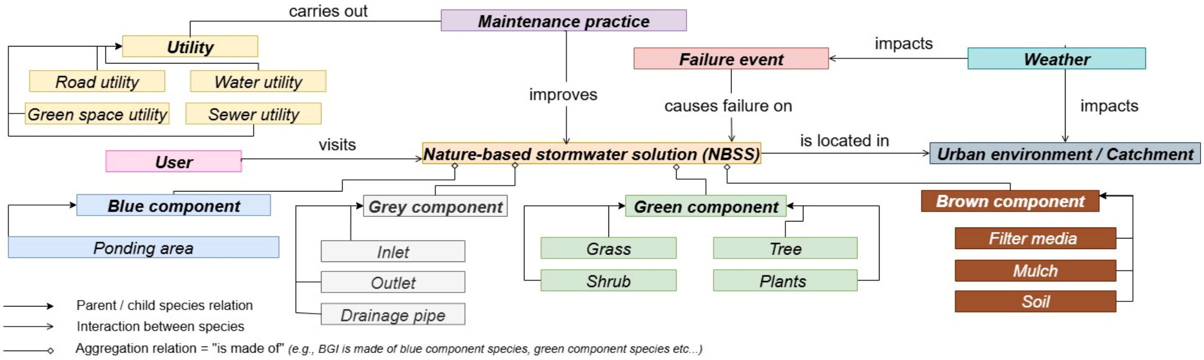

Figure 1. Conceptual diagram of the ABM simulating the asset management of BGI

3 GATHERING SCATTERED & FRAGMENTED INPUT DATA

The *maintenance practice* and *failure event* agents, which make it possible to account for the long-term performance of NBSS, require data for their characterization. As NBSS call for interdisciplinary and intersectoral management due to their complexity, such data is scattered and fragmented across various types of knowledge. Three complementary methods were considered to gather both scientific and operational data (see Figure 2).

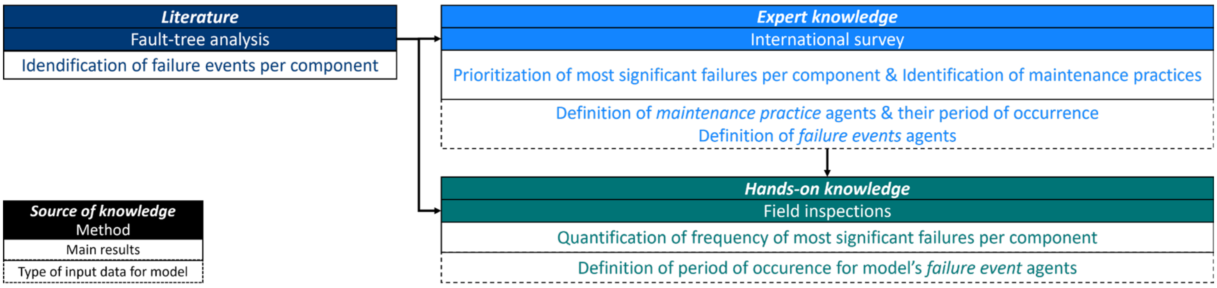

Figure 2. Data collection methods workflow and information considered in the agent-based model

3.1 Fault tree analysis (FTA)

FTA is a logical tool that models the combination of events that will lead to failures in the system, helping identify critical components and common causes of failure. The simplicity of the method makes it a suitable tool to model complex systems such as NBSS (Bahrami et al., 2024). To model the failure processes and interactions in NBSS, the FTA method developed by Bahrami et al. (2024) is utilized in this study. More detail on the methodology is available in the referenced study. FTA was applied to three types of NBSS: green roofs, bioswales, and raingardens. Based on the study, BGI failures were classified into three main categories: runoff quantity control failure, where NBSS inadequately manage stormwater runoff volumes; runoff quality control failure, where NBSS fail to remove pollutants or become a pollution source itself; and additional service function failure, relating to failures affecting co-benefits that are provided by NBSS. Figure 3 illustrates parts of a fault tree created by Bahrami et al. (2024) for runoff quantity control failure of BGI.

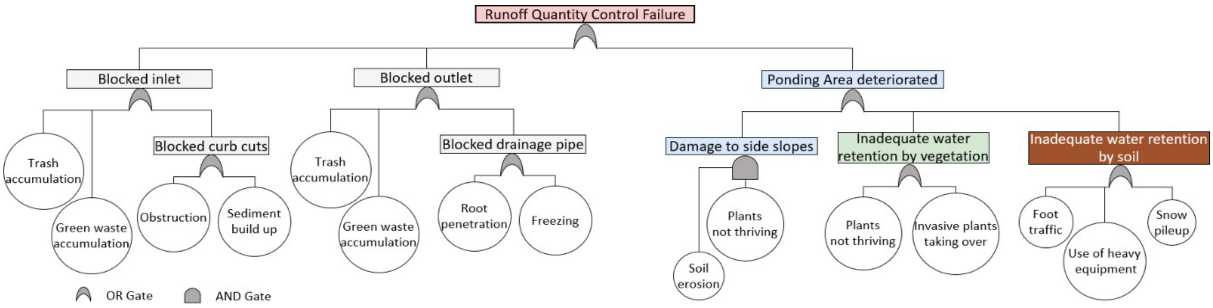

Figure 3. Parts of a basic fault tree for runoff quantity control failure in BGI

3.2 International survey

A survey involving researchers from 11 universities was translated in 13 languages in order to target NBSS managers in their own language to supplement and challenge the scientific findings achieved from the FTA with operational feedback. It was distributed from December 2024 to August 2025 and despite widespread dissemination, the survey had a low response rate - 22 responses out of 1116 online unique connections (2%). Its first aim was to identify most common maintenance practices and their frequency. The responses included dredging, cleaning inlets and outlets, vegetation maintenance and visual inspection. These practices help define an initial set of agents for the *maintenance practice* species. The frequency provided for these maintenance practices varied from less than once a year to more than four times a year, depending on the practice and within the same practice. This fluctuation opens a pathway for model exploration: by varying the frequency of a practice, we can identify the frequency that achieves the best performance for a specific NBSS. The second aim was to identify most occurrent and urgent failures according to the practitioners' responses to a list of proposed failures derived from the FTA (e.g., trash accumulation, plants not thriving). These results helped define an initial set of *failure event* agents to consider in the model.

3.3 Field inspections

A structured inspection form was developed to systematically document basic site information, construction characteristics, maintenance history, component condition, maintenance needs, surrounding environmental influences, prevailing weather conditions, and water-flow alignment. The inspection also evaluated design-related shortcomings, such as the existing of gully pot in front of an inlet. A mobile app embedding the inspection form has been developed to simplify on-site data collection and reporting. A comprehensive visual inspection campaign was carried out on 507 bioswales across five Dutch municipalities during spring 2024 and autumn 2025 (Figure 4). The purpose of the campaign was to identify bioswale components susceptible to failure, classify the types and frequencies of observed failures, and determine the underlying factors contributing to these failures. In particular, frequencies of observed failures will help define occurrences for *failure event* agents integrated in the model.

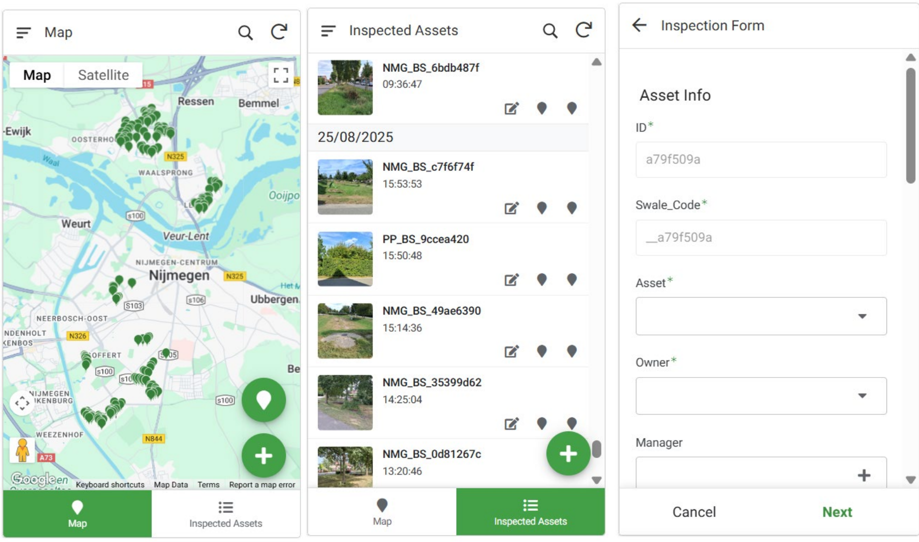

Figure 4. Enki Track app shows the inspected bioswales in Nijmegen municipality

4 CONCLUSION & PERSPECTIVE

The input data required for the model is distributed across multiple disciplines and sectors, reflecting the inherently multifunctional nature of NBSS. This dispersion underscores the need for a modelling framework capable of evolving as new data is acquired. Furthermore, because failures and performance are contingent upon specific local contexts in which NBSS are implemented, ABM's capacity to adjust to these contextual conditions shows its relevance. The conventional "predict-and-control" problem-solving paradigm inherited from piped-network management proves inadequate, as it privileges technological considerations while overlooking social and ecological dimensions that NBSS strongly embody. The main advantage of ABM lies in its ability to put into practice adaptive management. By defining targeted performance objectives, decision-makers can evaluate the potential future implications of their strategies through the model and learn from them. Our ongoing collaboration with the Greater Lyon Metropolis enables us to implement the model on a case study: results will be presented during the conference.

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