Modelling of Nature-Based Solutions on Surface Water Quality

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Global climate change and growing urbanization pose a threat to both natural and urban ecosystems. In these, one of the most impacted elements is water, which is responsible for a large variety of ecosystem services and benefits to society. Mathematical models can be used to simulate the implementation of Nature-Based Solutions (NBSs), thus helping to quantify their impacts on these issues in a practical and efficient manner.

Keywords: water quality ; nutrient ; sediment ; Nature-Based Solutions ; modelling

1. Introduction

It is expected that up to 68% of the world's population will be living in cities by the year 2050 [1]. This growing urbanization results in increased impermeable surface area, which leads to increased runoff, peak flow, and pollutant loads and concentrations [2][3]. The population is increasingly exposed to toxins resulting from industrial activities as well as traffic [4]. Urban non-point pollution is rising in urban environments, increasing concentrations of nitrogen, phosphorus, heavy metals, and organic carbon, among other pollutants, and is now a major case of concern for ecosystems in developed landscapes as well as human health [5][6][7].

With the growing recognition that hydrological resources must be carefully managed, water-related issues and potential ways to mitigate them have been a focus of study across several scientific areas, such as Environmental Science, Civil Engineering, and Hydrology. For this reason, the terminology used for solutions to urban water problems varies significantly in the literature, with terms employed such as 'Blue-Green Infrastructure' (BGI), 'Stormwater Control Measures' (SCM), 'Sustainable Urban Drainage Systems' (SUDS), 'Water Sensitive Urban Design' (WSUD), and 'Low Impact Development (LID) measures' often being used to refer to similar, or sometimes the same, applications. Despite the contextual differences in definition, these terms often overlap with the concept of 'Nature-Based Solutions'.

Nature-Based Solutions (NBSs) come in the form of natural or partly engineered measures that borrow from or incorporate nature in their usage as a means to mitigate societal issues. The International Union for Conservation of Nature (IUCN) defines NBS as "Actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" [8]. On the other hand, NBSs are defined by the European Commission [9] as "solutions inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience". The natural focus of the definition, as well as the added social and economic aspects of the measures, separate NBSs from SUDS or LID. Nevertheless, the concept is considered open and not well-defined by the scientific community [10].

The physical state of media (such as velocity, pressure, density, etc.) at every point in a specific domain can be predicted using numerical formulations, and models can solve the state of an entire system using sophisticated but well-understood numerical equation solvers [11]. Hydrological modelling, is described by Allaby and Allaby [12] as the characterization of real hydrological features and processes using small-scale physical models, mathematical analogues, or computer simulations. Thus, this type of modelling is used in the study of environmental phenomena concerning water excess or scarcity, as well as dissolved or solid material transport [13].

NBSs have been shown to be useful in the improvement of water quality [14]; their use in urban water management improves the quality of rainwater and runoff waters [15], and also helps create an approximation of the natural water cycle [16].

2. Modelling of Nature-Based Solutions on Surface Water Quality

Wetlands are by far the most frequently occurring NBS in water quality modelling studies, likely due to their extended use in wastewater treatment as well as stormwater control. Another interesting finding is that wetlands are most often the sole focus of the studies they appear in. Other solutions, however, appear often in groups, as is the case of green roofs that are always accompanied by more solutions. This is also the case for permeable pavements, reforestation, bioretention cells, retention ponds, and bioswales. The reason for this might be that these solutions (with the exception of bioretention cells) are more often used for air quality improvement and flood control, and less so for water treatment. In this way, the focus of studies may be on the modelling of NBS in sets or individually, but the focus may also be mixed. As an example, Dutta et al. [17] modelled the pollutant removal efficiency of bioretention cells, bioswales, and permeable pavements individually (in sets of two and sets of three), while Seyedashraf et al. [18] used model optimization to find the optimal scenario with multiple solutions, among which are permeable pavements, green roofs, rain gardens, bioswales, and other non-Nature-Based Solutions.

This study found that most of the literature on the topic of modelling NBS impacts on water quality is published in European countries; over 55% of publications came from Europe and, of those, over 33% originated from Italy. An important aspect to point out is that these results are highly biased towards European publications because of the usage of the term NBS, which is less common in other continents. Publications on the topic go as far back as 2018 due to the recency of the NBS term used and have been increasing since.

The most commonly recurring modelling software used was Stanford University's and Natural Capital Project's 'Integrated Valuation of Ecosystem Services and Tradeoffs' (InVEST) suite [19], an ecosystem service valuation and mapping tool employed by Di Grazia et al. [20], Zwadazka et al. [21], and Singh et al. [22]. The InVEST tool comes with a nutrient delivery ratio model that uses a mass balance approach [23] to model nutrient dynamics based on source mapping, transport capacity, and retention values of different land use and land cover conditions of an area, as well as the morphology of the catchment. The second most popular modelling tool used was the United States Environmental Protection Agency (EPA)'s 'Storm Water Management Model' (SWMM), a software solution for the design and analysis of stormwater runoff control strategies [24]. SWMM is reportedly the tool most commonly used by researchers to model NBSs and water quality [17], a trend that is not verified as InVEST is used in one more paper than SWMM. The tool comes with hydraulic modelling and pollutant load estimation capabilities, being employed by Dutta et al. [17] and Seyedashraf et al. [18]. Hamann et al. [25] chose to use two different modelling tools, the Dutch National Institute for Health and Environment's 'The Economics of Ecosystems and Biodiversity' (TEEB; [26]) and SusDrain's 'Benefits Estimation Tool' (B£ST; [27]). Both tools follow an ecosystem modelling approach as in InVEST, as opposed to the hydraulic modelling approach of SWMM. The scholars of the aforementioned paper modelled their water quality parameters using both tools, comparing the results after validation. Baustian et al. [28] used the Deltares Systems' Delft3D, the 3D modelling suite for hydrodynamic, sediment transport and water quality modelling, more precisely, the Integrated Biophysical Model [29]. Another similar approach was taken by Zhang et al. [30] with eWater's 'Model for Urban Stormwater Improvement Conceptualization' (MUSIC), which contains a wide range of functions to model stormwater runoff and contaminant removal resulting from treatment devices [31]. Lastly, Gallotti et al. [32] used NutSpaFHy, a tool that can model nutrient export from forest areas, in conjunction with Finnish Environment Institute's VEMALA, which calculates nutrient loads from the remaining land use and land cover categories [33][34]. Three of the aforementioned software suits (37.5%), SWMM, B£ST, and MUSIC, are advertised as directly supporting the modelling of NBS or analogue measures, suggesting that practitioners have access to varied options for these sorts of studies even before having to consider less-specific tools.

Nitrogen appears as the most commonly used element in the studies, which is to be expected as it is, along with Phosphorus, the most studied pollutant in the field of surface water quality. Indeed, Nitrogen levels in the form of Total Nitrogen (TN) are studied in over half of the selected papers. Results show that NBS can be beneficial to surface water quality by reducing the export of nutrient pollution (N, P) [20][21][22][35] as well as suspended solids [18][21], and by promoting nutrient removal services (N, P, BOD) [17][36][37]. Some scholars observed that NBS had "excellent performance" [36], while others saw only small improvements to water quality [25], with no particular performance trends associated with specific elements. It is also important to note that results from these studies should not be generalized, as the models are sensitive and require that calculations consider the local circumstances of each case study [21][25].

The water quality improvements obtained from NBS implementation can provide substantial benefits. The cost–benefit analysis-based studies highlight the economic feasibility of these solutions [38], deeming them well-justified considering their long-term benefits relative to the investment necessary [20]. The benefit assessment study also acknowledges the economic value of externalities from the water quality improvements of NBSs [35]. Finally, the cost-effectiveness approach studies do not mention economic viability but estimate that significant water quality improvements can be achieved by NBSs, with larger investment values often being associated with better performances [18][22].

While there is no significant pool of papers from which to extract conclusions on this topic, it is worth noting that Di Grazia et al. [20] found that NBSs can effectively reduce nutrient exports under RCP 4.5 conditions. Zhang et al. [30] found that NBS performed about the same under RCP 8.5 conditions as they do under current conditions, recommending larger systems in order to maintain water treatment effectiveness.

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