Simulating the impact of Nature-Based Solutions on runoff control by using i-Tree Hydro: a case study in Padua (Italy)

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Abstract

The progressive soil sealing in urbanized areas increases runoff due to surface imperviousness and leads the traditional drainage systems to a critical level, increasing flooding phenomena. The adoption of Nature-Based Solutions (NBS) can mitigate the risk of flood and increase territorial resilience to climate change. As part of the preparation of the Green Plan of the municipality of Padua (Italy), a simulation of the hydrological balance was carried out using i-Tree Hydro software to assess the effect of the increase of permeability due to the inclusion of NBS. The potential for improving the infiltration capacity relative only to urbanized surfaces was estimated considering three types of NBS: rain garden, green roof, and permeable pavement. The amount and the surfaces potentially improved with NBS have been calculated through the application of i-Tree Canopy. The simulation covered the years from 2014 to 2019. More precise analyses for an exceptional event that occurred in May of 2018 and an intense event that occurred in May of 2019 were conducted. The analysis demonstrated positive effects of the implementation of NBS on the management of rainwater runoff volumes, more accentuated in areas with a higher degree of urbanization. From the tested NBS, rain gardens were more effective in reducing runoff (about 34-41% on average) than permeable pavements and green roofs (about 25-35% and 15-26% on average, respectively), while the higher values were observed for the intense event. Permeable pavements, better accompanied by the presence of vegetation, could be used to maximize the benefits of a NBS urban design.

Keywords: resilience, flooding, green infrastructures, sponge city.

INTRODUCTION

The high rate of urbanization has led to a severe increase in soil sealing, which has reached very high percentages of the urban areas. Impervious surfaces reduce the infiltration of precipitation into the soil by increasing runoff in terms of both peak flow and volume (Jennings and Jarnagin, 2002; Dietz and Clausen, 2008). Rainwater is quickly directed into the urban drainage systems, creating serious problems with heavy rainfall events, such as local floods, river inundations, etc., but also reducing the availability of water for different uses and compromising its quality (Deletic and Maksumovic, 1998). It is known that the progressive soil sealing increases runoff and brings the traditional drainage systems of urbanized areas to a critical level (Lee et al., 2016).

In Veneto Region (north-eastern Italy), urbanization and industrial expansion have continued over the years (Fabian, 2012; Munafò and Congedo, 2017) and the increase in floods in this region is partly attributed to these soil transformation processes, which led to a decrease in drainage and water storage capacity and to a reduction in peak flow lamination, typical of natural and agricultural soils (Cazorzi et al., 2013; Pijl et al., 2018). Furthermore, climate change is causing the intensification and concentration of rain events, exacerbating the problem

(Bronstert et al., 2002). Sofia et al. (2017) have clearly highlighted the increase in the intensity of precipitation events that occurred in Veneto between 1910 and 2010 and how this was accompanied by an expansion of the dry periods. At the same time, there was an increase in the frequency of heavy rains (short-term events 3, 6, 12 hours), especially in the plain areas (Sartori, 2012).

The awareness of problems related to the progressive surface concreting and the climate change effects have led to a radical review of the rainwater management in urbanised areas by proposing new approaches for a more sustainable urban development, able to better manage runoff (Lloyd, 2001; Prince George's County, 2007; Woods-Ballard et al., 2007). To the various names and acronyms still in use such as LID (Low Impact Development), SUDS (Sustainable Urban Drainage Systems), Blue-Green Infrastructures (Dietz, 2007; Fletcher et al., 2015), the wider term Nature-based Solutions (NBS) is currently preferred by the European Commission. NBS is used to define the set of alternative solutions to conserve, manage in a sustainable way and preserve the functionality of natural ecosystems, or restore it in ecosystems altered by man, in order to increase human well-being and biodiversity, food and water security, the risks of disasters, social and economic development (Cohen-Shacham et al., 2016; Maes and Jacobs, 2017). The concept of *sponge city* (He et al., 2019) is also very effective to describe this form of sustainable drainage system on an urban scale.

Numerous studies have highlighted the positive effects of NBS interventions for runoff control to reduce flooding risks (see, for example, Zölch et al., 2017; Ruangpan et al., 2020; Alemaw et al., 2020). A multi-year study conducted in Veneto (Bortolini and Zanin, 2018) has shown that a bioretention area with ornamental herbaceous plants (rain garden) with a surface equal to 10% of a drainage area (a building roof) can manage more than 95% of the total runoff, throughout infiltration and evapotranspiration, effectively avoiding also irrigation request during the summer periods. In another study conducted in the same area, Bortolini et al. (2021) highlighted the positive effect on runoff reduction of various extensive green roof solutions. Depending on the stratigraphy and the type of vegetation, the reduction in runoff can exceed on average over 60% in the year, even if the effectiveness is less during the most intense rainy events, especially in periods characterized by lower temperatures in which the evapotranspiration phenomena are reduced (from November to February).

During the preparation of the Green Plan of the municipality of Padua (Veneto, Italy), a study on the runoff control by increasing permeability due to the adoption of NBS was carried out. i-Tree Hydro software was applied in order to evaluate the effects of NBS on the hydrological balance, aiming to promote a transition of Padua toward a sponge city.

MATERIAL AND METHODS

Padua is a city in the plain of the Veneto region, in North-Eastern Italy, with almost 210,000 inhabitants and an area of 92.85 km^2. For this analysis, the total area of the Municipality of Padova was subdivided in five homogeneous territorial areas (HTAs) (Figure 1).

The effect that a widespread realization of NBSs for the management of rainwater runoff could produce on the territory of the city of Padua was evaluated by determining the type of coverage present and, if impervious, this was susceptible to modification.

i-Tree Canopy, a software developed by the USDA Forest Service and available online (https://canopy.itreetools.org), was applied to accurately estimate the coverage of trees and other types of vegetation and not (sidewalks, roads, etc.), creating random points on an image extracted from Google Earth; each of these points has been assigned belonging to a given coverage class. For each HTA, 1000 points were considered to contain the standard error between 1 and 2% (Parmehr et al., 2016). In the analysis, the agricultural areas and the road network were not considered as improving. The percentage of area that can be improved for each HTA was then identified, i.e. those spaces in which the implementation of NBS can be assumed, as well as a classification of the coverage class (tree / shrub, grass / herbaceous, building, road, other impervious surface, cultivated / bare soil).

The NBSs, considered most feasible in the city of Padua for the management of rainwater runoffs, were the following three: rain gardens RG, permeable pavements PP and green roofs GR.

Using the permeable/impermeable surface data and the percentages of potentially feasible NBS interventions, i-Tree Hydro (USDA Forest Service, 2019) was applied, a statistically-distributed hydrology model simulating the effects of land cover on water quantity and quality by modelling vegetation processes (Wang et al., 2008). This tool allows to simulate the effects of changes in tree cover and impermeable surfaces on the hydrological cycle, resulting very interesting for comparative analyses of different land cover scenarios and their hydrological impacts at various scales including flow rates of rivers and water quality.

The simulations were carried out for each HTA of the Municipality of Padua by providing the three different types of NBS (rain gardens RG, permeable pavements PP and green roofs GR), comparing runoff values with those presumably generated at the current land cover, distinguishing between the effect produced considering the entire surface of each HTA or only the urbanized one (excluding agricultural areas).

The input data were:

- hourly meteorological data for the years 2014, 2015, 2016, 2017, 2018 and 2019 and with an interval of 10 minutes for an event classified as intense, with a return time within 2 years (4 May 2019) and for an exceptional event, with a return period exceeding 50 years (29 May 2018);
- digital elevation of the soil (DEM - Digital Elevation Model) of the entire surface of each HTA and of the urban area only (excluding agricultural areas);
- land cover, obtained from the elaboration of the Land Use Map of the Municipality of Padua.

RESULTS AND DISCUSSION

In Figure 1, obtained by elaborating Sentinel-2A MSI (ESA) satellite images, the impervious surfaces have been highlighted in a darker colour.

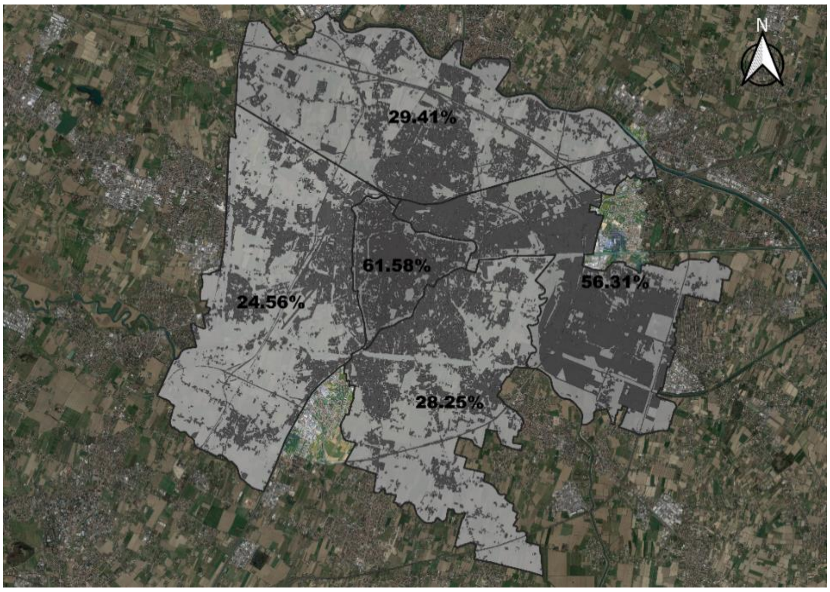

Fig. 1. Percentage of the impervious surfaces in the five homogeneous territorial areas (HTAs) of the Municipality of Padua (highlighted in a darker colour).

Currently, the surfaces made impervious by buildings, roads, sidewalks, etc. range from 24.56% in the West HTA to 61.58% in the HTA of the Historic centre, located in the “heart” of the city. Note also the high value of the East HTA (the industrial area) affected by the high presence of industrial and commercial buildings and parking lots.

By applying i-Tree Canopy, the percentage values of improvement in permeability were calculated, i.e. on which currently impervious surfaces the NBS solutions could be favourably implemented (Figure 2). It can be noted the high possibility of improvement (31.2%) that the East HTA potentially offers, a percentage that rises to 43.1% if the analysis is limited to the urbanized area only. However, in the other HTAs the percentages also increase, excluding the historic centre (without agricultural areas).

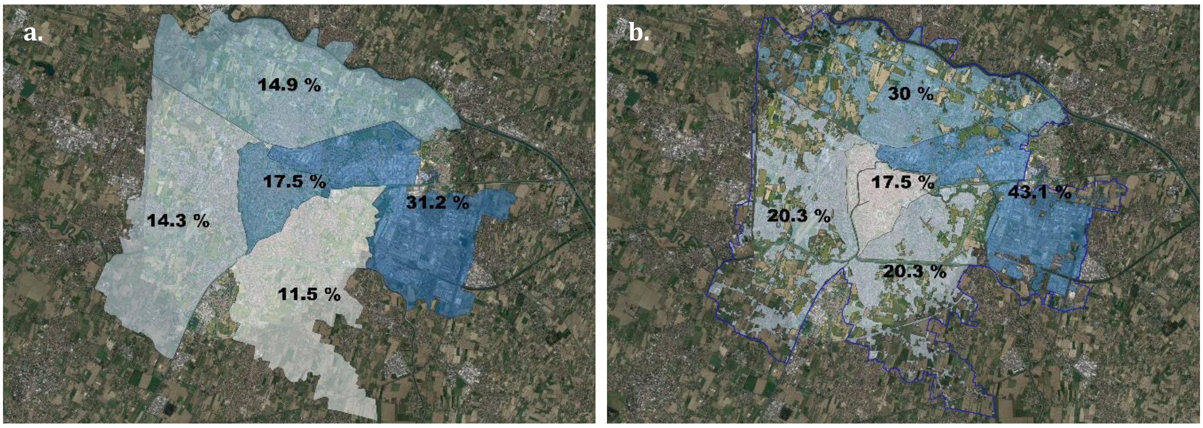

Fig. 2. Percentage of improvement in permeability with the application of NBS on the entire surface (a) and only on the urbanized surface (b) in each HTA of the area of the city of Padua.

From the photointerpretation of each of the 1000 points found with the application of i-Tree Canopy, the percentages of the three types of NBS that could be implemented in the each HTA were obtained (Table 1).

In the HTA of the historic centre, for example, on the 17.5% of potentially improvable area, 35% of rain gardens can be implemented, while the increase in permeability could derive from the use of permeable pavements in as many as 65%, considering above all sidewalks and cycle paths but also parking lots. As for the green roofs, excluding the historic centre characterized above all by the presence of historic buildings with roofs with tiles, the photointerpretation has shown a fair possibility of their installation in flat roof buildings, with the highest value in the East HTA that reaches the percentage of almost 27% if only the urbanized surface is considered (Table 1).

Table 1. Percentage of the three types of NBS interventions that could be implemented on the entire surface and only urbanized surface in the each HTA of the city of Padua.

HTA	Centre	North	East	South	West	Centre	North	East	South	West
	Entire surface (%)					Urbanized surface (%)				
Rain garden (RG)	35.43	39.86	35.58	41.74	38.46	35.43	51.67	24.13	23.15	26.11
Permeable pavements (PP)	64.57	45.95	46.15	40.87	47.69	64.57	37.33	48.96	62.07	60.59
Green roof (GR)	-	13.51	18.27	17.39	13.85	-	11.00	26.91	14.78	13.30

The results of the simulations carried out using i-Tree Hydro software were analysed. Results are related to the average values of the 2014-2019 period, an intense rainy event with a return time of fewer than 2 years (4 May 2019) and an exceptional event with a return time more than 50 years (May 29, 2018). The latter was characterized by 106.8 mm of precipitation in two hours starting at 12:40, with three peaks of intensity equal to 20 mm in 10 minutes. The return time defines an average time in which a given rain intensity value can be equalled or exceeded, i.e. the probability that a natural event will occur in that time interval. Besides, analysing the data, it was found that the average rainfall value of the period 2014-2019 is substantially equivalent to the average value of the rainfall time series 1992 -2018 (848 mm against 846 mm).

Runoff volumes produced in the various HTAs with the current land cover were compared with those that would arise following the implementation of NBS on the 100% potentially improvable surface, distinguishing between the effect produced considering the entire surface of each HTA or only the urbanized one (excluding agricultural areas). Figure 3a show the hypothesis of an implementation of 100% of NBS in the total potentially improvable. The more effective in reducing runoff are rain gardens (about 34% on average); however, a significant effect could be obtained also implementing permeable pavements and green roofs (about 25% and 15% on average, respectively).

The effect on the reduction of runoff volumes is more visible if only urbanized areas are considered, thus excluding agricultural ones, naturally characterized by high permeability (figure 3b). All the percentages rise reaching on average 45% (RG), 42% (PP) and 35% (GR) of runoff reduction. A high decrease can be observed in the North HTA, where the runoff control could have very positive effects on reducing the risk of flooding in those neighbourhoods where the current vulnerability is well known. In the East HTA with the industrial area, characterized by a high presence of flat roof buildings, the strongest reduction in runoff can be obtained, with percentages up to 55% if vegetated roofs were implemented in all roofs that could potentially be improved.

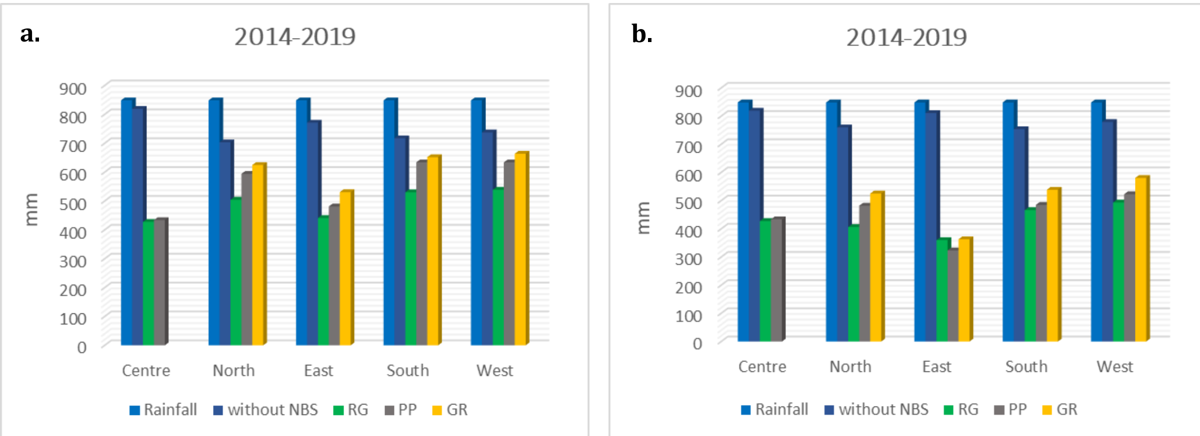

Fig. 3. Simulated runoffs with 100% application of NBS over the entire surface (a) and on the urbanized surface (b) of each HTA - average values (2014-2019).

The runoff control is certainly greater with moderate rainfall events. However, if we analyse the event of 4 May 2019, with a precipitation of 30.7 mm and classified as intense, the simulations conducted have shown high reduction on the runoff volumes in all HTAs and with all types of NBS. Surely, the values are affected by the period in which this event occurred. In fact, runoff volumes originated without NBS also show contained values in many HTAs (figure 4a e 4b). The percentages of runoff reduction vary on average from 41% of rain gardens to 26% of green roofs, while for permeable pavements the average value is 35%, but reaches peaks of almost 70% in the case of application on the urbanized area of the East HTA.

Very interesting is the analysis of the results of the extreme event of 29 May 2018, during which it rained 106.8 mm in two hours. Even in this case, the more effective in reducing runoff are rain gardens (about 35% on average), but a good runoff control could be also obtained with permeable pavements and green roofs (about 27% and 17% on average, respectively). In figure 5 it can be noted how the runoff reduction with NBS is more effective in the more urbanized HTAs (Centre and East). In the Centre HTA the 98 mm of runoff that would originate without NBS would be halved to about 50 mm both with rain gardens and with permeable pavements. In the East HTA, the highest reduction in runoff is guaranteed by the rain gardens, but it is the permeable pavements that allow for the greatest control of runoff volumes if only the urbanized area is considered. In fact, the reduction rises to 62%, a figure that would allow to mitigate the risks of flooding that frequently occur in the lower parts of the industrial area.

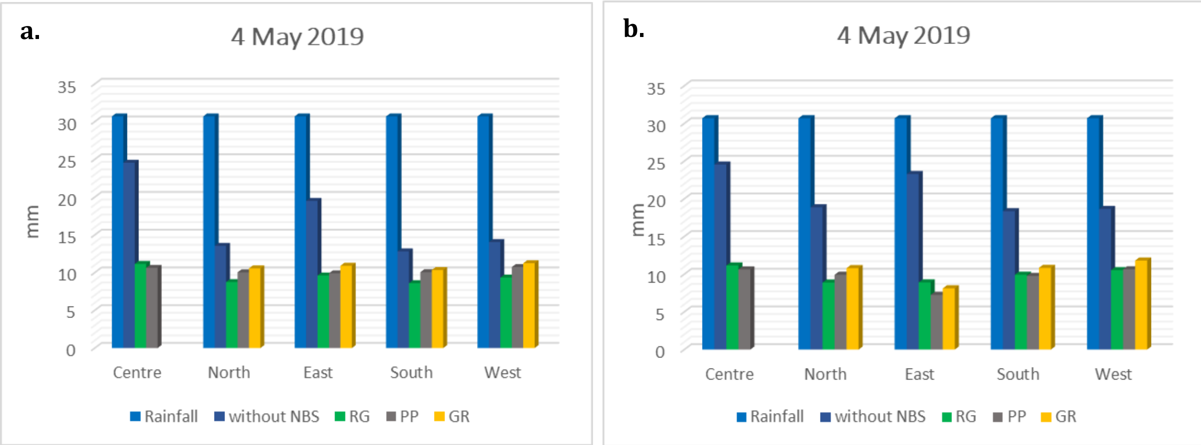

Fig. 4. Simulated runoffs with 100% application of NBS over the entire surface (a) and on the urbanized surface (b) of each HTA – intense rainy event (return time < 2 years).

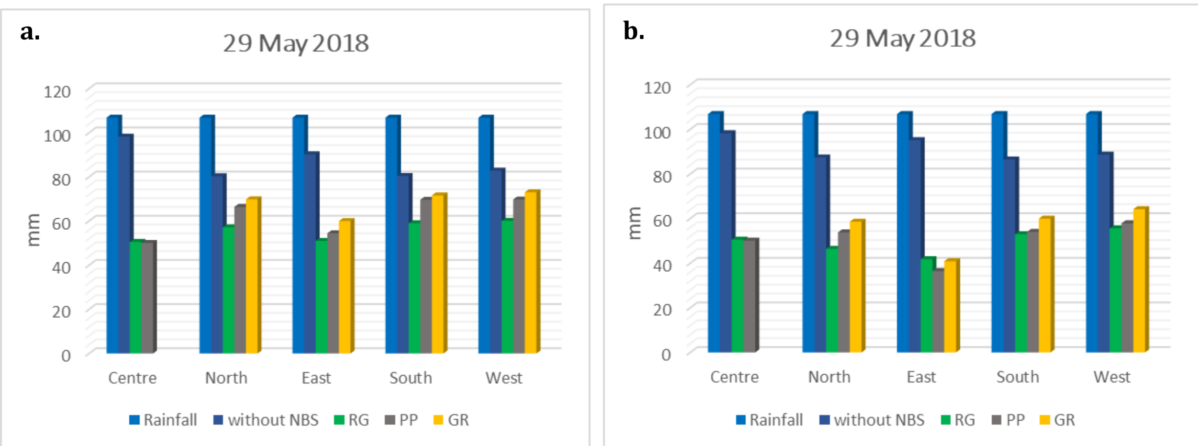

Fig. 5. Simulated runoffs with 100% application of NBS over the entire surface (a) and on the urbanized surface (b) of each HTA – exceptional rainy event (return time > 50 years).

i-Tree Hydro was also applied considering a more realistic application of 30% of NBS on the potentially improvable areas. Simulations provided very similar results, with runoff values on average slightly lower than those of the simulations with 100% application of NBS, attesting the high infiltration capacity of all these infrastructures. In particular, in the period 2014-2019 the values decrease on average to 31% (RG), 20% (PP) and 14% (GR) of runoff reduction, respectively.

The results show that on average the most effective in reducing runoff are rain gardens. The high effectiveness of rain gardens in managing rainfall runoff had already been demonstrated in previous experimental studies conducted at the same locations (Bortolini and Zanin, 2018).

Currently, there are still very limited applications of the i-Tree model to assess the impact of NBS on the reduction of runoff volumes. In an application carried out on four different types of urban green spaces (public park, protective green space, square green space, attached green space) Song et al. (2020) assessed a runoff avoiding efficiency of around 37%, with the highest values in the case of public parks (51.1%), probably due to the highest presence of vegetation. It should be pointed out that, where possible, it should be encouraged the presence of vegetation, even when the installation of permeable pavements is foreseen, that can further enhance runoff control. In fact, rainfall intercepted by leaves is directly evaporated or is gradually released on the ground through dripping, especially by large trees (Yang et al., 2019), increasing the reduction of runoff volumes to the urban drainage system. Kirnbauer et al. (2013) quantified the canopy interception and evaporation by the canopy of different tree species by applying i-Tree Hydro model. Their analysis demonstrated that the tree canopy layer was able to intercept up to 27% of the total rainfall depending on the leaf area per unit ground area of the species and the planting schemes. With regard to combining vegetation with permeable pavements, other studies have shown that the potential flooding risk, especially under a longer rainfall duration, could be well controlled by implementing a combination of green and grey infrastructures (Xie et al., 2017).

CONCLUSIONS

The analysis demonstrates the positive effects of the application of NBS on the management of rainwater runoff volumes, more accentuated in areas with a higher degree of urbanization. The decrease in the runoff volumes is accompanied by fewer contributions to the urban drainage system allowing a reduction in the risk of overloading. In this way, flooding due to the overflow from manholes placed in streets, parking lots, and squares is reduced. However, the widespread implementation of these infrastructures in the territory can produce positive effects in all areas at greatest risk of flooding, including those at lower elevations.

The great advantage of a sponge city is that the solutions are generally easy to implement and do not require large capital investments, but in order to keep their full functionality, maintenance must be careful and continuous. However, the higher maintenance costs can certainly be offset by the lower costs of damage caused by flooding.

Permeable pavements, while demonstrating high effectiveness in infiltrating runoffs, should possibly be accompanied by the presence of vegetation to maximize the environmental, aesthetic, and recreational values of a NBS urban design.

ACKNOWLEDGEMENTS

This research was funded by the Municipality of Padua.

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