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An Agent-Based Model for Greening the City of Ravenna and Reducing Flooding at a Cultural Heritage Site

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Abstract The paper presents an agent-based model exploring the impact of greening a city for groundwater flood risk reduction as a discussion tool to support urban planning decisions. The case study is an urban archaeological site in Ravenna, Italy. The model aimed to provide insights to generate discussion between researchers at the University of Bologna and the local authorities. The city map was divided into cells potentially suitable for modelled greening, combined with Ravenna precipitation and temperature data, and estimated scores for evapotranspiration and permeability. Generally, results indicate that more greening measures introduced correspond to a reduction in the volume of excess rainwater, with particular effectiveness in greened streets. Our results demonstrate the benefits of agent base modelling in the field of disaster risk management for testing measures prior to their implementation.

Introduction

Cultural and natural heritage sites constitute important testimonies of the past and their protection is of shared human concern [1]. Whilst historically surviving count- less hazardous events, human-induced climate change is posing increasing strain on heritage areas and their users. Heritage is a key component of resilience and efforts to encompass all its forms and typologies are increasingly common in disaster risk management frameworks [2, 3]. Climate change exacerbates the risks already faced by heritage sites, making them vulnerable in new ways which require novel solutions to protect them and ensure their conservation for the benefit of future generations. Urban areas experience particularly severe consequences of groundwater flooding during periods of heavy rainfall as impermeable ground surfaces lead to significant runoff [4]. The Church and archaeological area of Santa Croce in Ravenna, Emilia-Romagna region, Italy, is an urban heritage site at which groundwater flooding worsened by extreme rainfall events has begun to pose a serious threat [5].

The greening and de-sealing of urban areas is a solution for the reduction of urban flooding [6]. As well as having many side benefits including carbon sequestration, biodiversity improvement and temperature regulation, greening impermeable areas improves rainwater infiltration and reduce runoff on paved surfaces [7]. However, before any measures are implemented, the costs and potential benefits of a greening policy need to be quantified.

Agent-based modelling (ABM) provides a structured approach for examining disaster and post-disaster scenarios, as well as explore different measures to prevent impacts to quantify their benefits prior to the allocation of resources for their implementation [8]. The complexity of the multiple interacting parts of any heritage site includes stakeholders at different scales, visitors, residents, and future changes to the physical system itself amplified by climate change. The interplay between these factors often renders cultural and natural heritage sites unsuitable to traditional deterministic modelling methods. The ability of ABM to set behavioral rules and their interactions, and thereby speculate emerging factors into systems, is important for understanding this complexity and how it evolves over time. Moreover, studies have shown that ABM can address the different components of resilience including recovery, resistance, and variability, although their multidimensional study is still limited [9]. Its intuitive nature makes it an especially suitable tool for communication of results [10]. The outputs of ABM can therefore help to structure the discussion around what matters in terms of preparedness planning, by exploring options on how particular measures will help, Ravenna in this specific case, in a combined qualitative and quantitative manner, and thereby inform future policy decisions.

Through simulations of land surfaces as agents with surface type as a feature, the ABM developed aims to be an investigative resource for urban planners, particularly with regard to the impacts of urban flooding. The assessment of the effectiveness of certain measures is explorative rather than predictive. In fact, the impacts generated within the model rely on expert reasoning and literature, lacking empirical validation, although there is potential to incorporate this in forthcoming research.

Materials and Methods

Study Area

Throughout the 5th Century, Ravenna was the capital of the Western Roman Empire. As legacy of this period, the city now hosts the UNESCO designated Early Chris- tian Monuments serial site. The Church and archaeological site of Santa Croce, comprised in the UNESCO buffer zone, was chosen one case study of the H2020 SHELTER project. Due to past archaeological excavations, the area presents a basin- like configuration, bringing the remains more than two meters below the groundwater level, situation worsened by the anthropogenic subsidence which affected the territory in the second half of the last century [11]. This condition increases the risk of groundwater flooding exacerbated by increasingly heavy and unpredictable rainfall. The effect of subsidence combined with changes in rainfall patterns calls for a change in surface water drainage [12]. Constant presence of water contributes to the decay of heritage assets and an increase in precipitation resulting from climate change could lead to soil saturation and gutter overloading, as well as physical degradation of urban archaeological sites such as Santa Croce. Being located below ground level, flooding from excess rainfall is a persistent and serious issue in this area.

Designing a Model for Ravenna

The model idea was developed in close consultation with the University of Bologna who coordinates the Ravenna case study in the framework of the H2020 SHELTER project, to ensure that the resultant model fitted the city's needs. The overarching aim of the model was to provide interesting insights to facilitate a discussion between researchers and the local authorities in view of an improved safeguarding of heritage sites.

Model development was carried out using the Python library Mesa [13] and Mesa- geo [14], which was selected as the best software library to code the models in for three main reasons. Firstly, its use of a fully-fledged versatile programming language, Python, meant that any code produced would be universally usable. Secondly, its library extensions for geographic representations were found to be important for displaying visualization elements of the models. Finally, its batch runner capabilities allowed the running of many iterations of the model simultaneously and quickly.

The model attempts to determine volumes of prevented runoff with differing amounts of greening in the city, and how much runoff each scenario could prevent. The greening scenarios acknowledge that whilst greening could potentially be a useful tool, Ravenna is built over the ancient Roman town, and as such is subject to legal policies to protect the underground archaeological remains.

Greening policies, therefore, limit the planting of any deep-rooted vegetation which may be invasive to buried archaeological structures. This also places limitations on the areas where greening could occur, so a model will be helpful for determining whether greening to this smaller extent could be a useful policy.

Model Mechanics

The model consisted of three key components or modules, namely:

- Module for the weather and the physical drivers of rainfall: the first module relates to weather and the physical drivers of rainfall itself, important in determining the amount of water the city will need to adapt to in future and therefore how much greening is required. The input is current amounts of precipitation and evapotranspiration, which has the output of the amount of precipitation an area receives and thus how much will be excess runoff under current amounts of greening.
- Module for groundwater flooding and water retention capacity: the second module considered for this model relates to the water retention capacity of the ground surface, depending on the type of surface cover. When the maximum capacity is reached, rainwater becomes in excess and overflows, forming a pool.
- Module for ground surface properties and greening: this was simplified as either paved, or greened. The ground surface directly influences the amount of water able to be retained. If a ground surface is greened, less surface runoff results which is important for water capacity. Three types of paved ground surface were modelled as being eligible for greening; these were car parks, streets, and pedestrian areas.

Server Functionality and Technical Detail

From census data classification, the current model foresaw the partitioning of the Ravenna map into areas or “cells” of land surface which acted as agents. Each of these cells is characterized by its respective percentage of green spaces, streets, pedestrian areas, and parking lots. (Fig. 60.1). Depending on the user’s choice, a specific number of cells are randomly selected for greening in each model run.

Hourly data for average precipitation and temperature over a two-month period were gathered—from July 1 to August 31, 2018—when Ravenna experienced above- normal rainfall levels [15, 16]. This was selected on the basis that future rainfall is increasingly unpredictable and flooding issue arise during intense precipitation events; hence, it is logical to model a period of heavy rainfall. According to its land use, each cell is assigned a permeability score which enables it to absorb given amount of precipitation (Table 60.1).

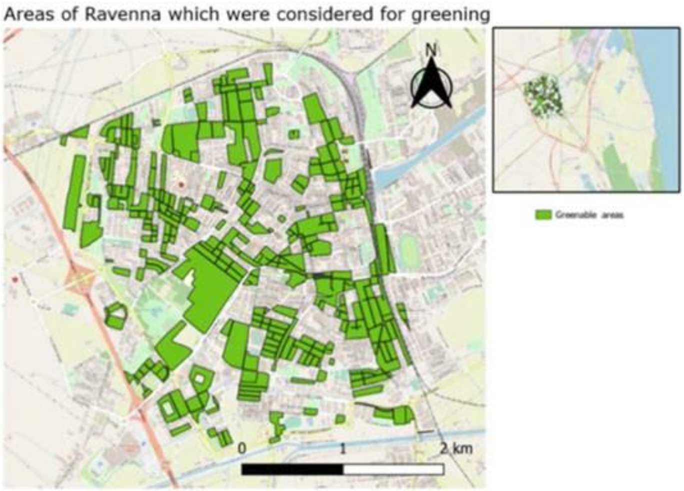

Fig. 60.1 Map with proposed cells for applying greening measures.

Table 60.1 Estimated permeability coefficient used when running the model, by the per cent of each cell covered by greened areas.

% of cells greened	> 80	70–79	60–69	50–59	40–49	30–39	20–29	10–19	< 9
Coefficient of permeability	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Any rainfall exceeding the capacity of each cell results in the formation of puddles or pools on the ground surface, which gradually diminish as a result of transpiration. The formula for excess rainfall was calculated as the rainfall volume received by each cell multiplied by its coefficient of permeability. To calculate the transpiration rates, a simplified coefficient was used within the transpiration equation:

$$\text{Transpiration} = m * \min\left(1.0, \frac{4.0}{\frac{(3.0*(\frac{e}{0.8}))}{0.4}}\right) * \text{PET}, \tag{60.1}$$

where *m* = transpiration coefficient (If the cell is over 70% greened then *m* = 0.3, if the cell is over 30% greened but less than 70% then *m* = 0.2 and if the cell is less than 30% greened then m = 0.01) *e* = excess rainfall/volume of pooling.

To be eligible for greening, a cell had to satisfy two criteria. Firstly, less than 70% of the cell had to have already been greened. Secondly, the cell must be covered by a minimum of 10% in either car parks or streets, or at least 5% in pedestrian areas, in order to model a justifiable level of greening. When a cell is selected for greening, both its permeability score and absorption capacity are adjusted accordingly.

In total, 294 out of the 664 cells were deemed eligible for greening simulations, of which 231 were streets, 42 car parks, and 21 pedestrianized zones (Fig. 60.1). Each cell was simulated as a ground block subject to both natural and static processes— area (m^2), initial percentage of greened land (%) and percentage of cell covered by car parks, streets and pedestrian areas (%)—as well as dynamic ones—overall percentage of greened land within each cell after greening the city (%), whether the cell experienced flooding (yes/no), and its permeability.

It is important to note that several factors were simplified within the model. Within the weather module, climate change scenarios impact precipitation and evapotranspiration by causing more extreme conditions. Therefore, runoff may be more severe when this is incorporated into the model; however, it is difficult to precisely quantify future precipitation patterns, and this was not considered within the scope of this work. Similarly, runoff absorption was estimated based on how much of the respective area could realistically be greened. In our modelling, the pedestrian areas were configured to have the potential to absorb 15% of runoff when greened, using solutions such as vegetation barriers at kerbsides and in the middle of paved areas. Car parks, on the other hand, could be greened in a similar manner but to a greater extent, allowing for an estimated absorption capacity of 30%. Given the narrowness of many streets in Ravenna and the limitations posed by archaeological risk considerations, intrusive greening methods were not applicable for streets, which could not be therefore greened in a typical sense. Instead, it was assumed that the most suitable intervention for street would be the use of permeable concrete or asphalt replacing traditional materials. This approach theoretically allowed the entire street area to be "greened", resulting in street absorption capacity of 80%.

The model was executed in batch mode with a series of variables and a set of consistent parameters. The latter included weather conditions and temperature, as well as the cells eligible for greening. Variable parameters encompassed the number of parking lots being greened (tested at values of 0, 10, 20, 30, 40), number of pedestrianized zones being greened (tested at values of 0, 5, 10, 15, 20), and number of streets being greened (tested at values of 0, 50, 100, 150, 200). The model was systematically run with every possible combination of these 15 variables, repeating each combination 100 times. This resulted in a total of 12,500 runs being conducted. For each of these model runs, various parameters were recorded, including the number of cells that underwent greening during the simulation, the total volume of excess flooding in the model, and the average runoff for cells with varying percentages of greened areas.

Results

The 12,500 runs of the model point to a strong correlation between the total volume of flooding in the model and the amount of greening measures introduced (Fig. 60.2). This is because, during heavy rainfall, urban surfaces are unable to drain sufficiently to prevent flooding. With an increase in greener surfaces on average, better drainage is facilitated, leading to reduced excess water accumulation and fewer pool formations. When the type of cells greened are compared, the trend of reduced flooding with increased greening still asserts itself. For greened streets, there is a strong trend between more of these measures being associated with less flooding, and whilst the trend repeats itself for car park and pedestrian area measures, this is much less pronounced (Fig. 60.3).

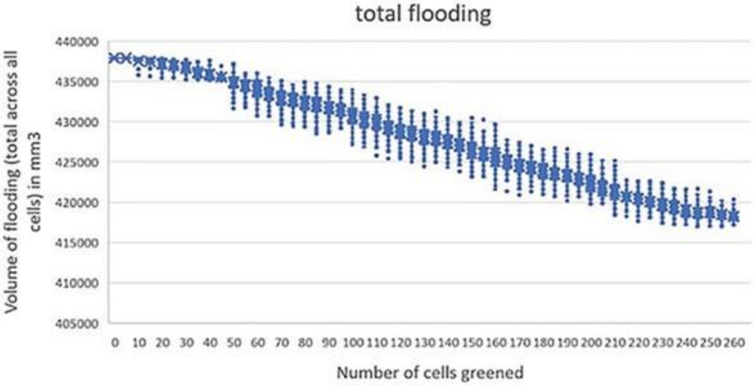

Fig. 60.2 Total volume of flooding across all cells against the number of greening measures applied to all cells. There is a clear trend of declining excess rainwater as more greening measures are implemented.

Fig. 60.3 Total volume of flooding across all cells by the number of greening measures applied, broken down by the type of greening measure implemented. Important to note is the different scale of each type of measure.

When flooding volume is separated by the amount of greening, each cell had individually rather than in general, trends vary according to how green each cell is. For areas which had 5% or less of their area greened there is a counter-intuitive negative relationship between flooding and the number of measures in place, meaning that these cells were more likely to flood. For other amounts of greening the trend mirrors the overall model's pattern by benefitting from less flooding, however the strength of this trend varies substantially depending on the category of greening.

When subjected to greening, the cells categorized as streets had the most substantial effect on reducing flooding (Fig. 60.3). Partly, this is due to the sheer abundance of these cells, and also because the de-sealing measures which were modelled for streets being the most effective flood reduction technique with an 80% absorption capacity.

Discussion

As a greater number of cells was interested by greening measures, the occurrence of excess runoff and rainwater pooling decreased proportionally. Indeed, as heavy rainfall occurs, urban surfaces are unable to drain water away quickly enough. As surfaces become on average greener, more drainage can occur which results in less flooding.

Cells with less than 5% green coverage are more prone to flooding, especially when neighboring cells have implemented a greater number of greening measures. Although at first seeming contradictory to the model mechanics, this increased flooding can be explained by cells elsewhere having a higher potential evaporative capacity and coefficient of water pooling as they are greened. Hence, as more rainfall is absorbed across other cells, in cells with little to no greening there is proportionally more water which cannot be absorbed. Where cells experienced a small amount of greening (10–20%), the trend of more flooding was reversed which can be explained by the small amount of greening causing a tangible difference to the cells' ability to absorb rainfall, thus resulting in less excess water. Cells that were 30–50% greened only slightly reflect the trend of reduced rainfall with increased greening, explained by the relatively fewer observations of cells falling into these categories, however important to note is the greatly reduced total of flood volume for cells in this cate- gory. Whilst the category for 60% greened cells seems anomalous, this can again be attributed to the lack of cells falling into this category, and the trend again returns for cells which were over 60% greened.

There were a much larger number of cells containing streets in the model compared with pedestrian areas or car parks, which partially explains why the greener streets seem to have a greater impact than other measures. Another contributing factor for this relative effectiveness is that the type of de-sealing modelled for streets was porous roads rather than typical greening, which enable a much greater proportion of the potentially greenable area than on other types of surfaces. Replacing roads of typical materials with porous material such as porous concrete is a very effective way to reduce pooling [17] but comes at a much greater financial cost than typical greening methods explored for other surface types less prevalent in Ravenna. Additionally, despite its ability to reduce flooding, this method will see fewer co-benefits associated with greening, including temperature regulation and biodiversity.

Uncertainties and Difficulties Encountered

Due to the technical complexity of many interacting systems which would have been present in a real-world version of the model, several assumptions and simplifications were made which could potentially be reduced in future iterations of the model. One key uncertainty of the model is that it did not account for the role played by sewage and drainage systems. This could increase the drainage potential of certain parts of the city, for both greened and paved areas. Another assumption made was that of uniformity in the spatial distribution of rainfall. However, it is realistic that some areas may have experienced more rainfall whilst others less.

Elevation was not considered in this model; however, some higher or sloped areas will drain into other areas which are flatter or more low-lying, and the water accumulation in lower areas will be greater. Another uncertainty of the model was the estimation of the greened factor for different types of land. This number is the proportion of the greenable area of a cell which was modelled as having had this greening fulfilled. It was modelled as 0.8 for streets, 0.3 for car parks and 0.15 for pedestrian areas, however it is realistic to expect that these numbers will vary greatly with different greening measures. The coefficient of permeability was also estimated, representing the proportion of the water pool able to be absorbed by different amounts of greening, and a more accurate number could have been achieved by carrying out water runoff experiments with different types of land to represent the numbers more accurately in this coefficient. The specific cells which were greened in each model run were randomly assigned. It appears probable that some of these may either be privately owned or pose logistical challenges that render greening in practice unfeasible. To narrow this uncertainty, it would be necessary to map the potentially greenable areas of Ravenna and calculate how much of their coverage could actually be greened. This would have to be done for each cell of data specified in the Ravenna map and then averaged for each type of land surface.

Despite several uncertainties that keep this model exploratory, it can potentially be used as a discussion tool for Ravenna authorities who, on one side, wish to encourage greening of privately owned land and, on the other, are in position to implement the greening in public areas. The model shows the positive impact greening can bring on flood reduction in Ravenna. It can be used to investigate the introduction of differing amounts of greening, and as such to see how many measures would be required to have a tangible difference in the challenge of groundwater flooding in Ravenna.

Conclusions and Next Steps

The protection of cultural and natural heritage is important for a site’s social, cultural, economic, and historical value. The cultural significance of historic areas is a non- renewable and unique resource that cannot be fully recovered after disasters. Thus, protecting important sites which are vulnerable is of paramount importance. ABM is a tool which has great potential to benefit the field of disaster risk management, particularly when dealing with new uncertainties such as climate change.

Our model investigates the interplay between rainfall, surface characteristics and flooding volume in Ravenna, Italy. Although various uncertainties restrict the immediate applicability of the final results for precise planning actions by the local authority, the model serves as a valuable tool for initiating discussion on land use planning. Furthermore, it holds significance for the research community in the context of risk reduction considerations. It demonstrates that, as more greening measures applied, the less excess runoff occurred. Similarly, a minimum of 10% greening within a cell is necessary to bring about a noticeable reduction in runoff. Other urban rainfall models include the SCS-CN model which have also observed a positive correlation between the expansion of urban green spaces and reduced runoff. Additionally, these models have noted that during heavy rainfall periods, green areas exhibit enhanced water retention [7]. It is to note that our study concentrated on monthly rainfall totals rather than individual rainfall events. This aspect should be considered in future iterations of the study. Whilst our model requires validation to quantify these results more reliably, it appears that public greening measures would be effective at reducing groundwater flooding in Ravenna.

If more detailed information, such as elevation, can be incorporated into future model iterations, the results could provide insight into where and how much impervious surfaces should be greened to reduce groundwater flooding in the Santa Croce church and archaeological area. Concluding, although the model is site-specific, European historic areas are rich of cultural heritage sites, and they may benefit from the results of this investigation and start participatory planning processes to promote the greening of public and private land.

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