An agent-based model of greening a city for reducing pluvial flooding at a cultural heritage site

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Abstract. We present an agent-based model which explores the impact of greening a city for pluvial flood risk reduction, to inform planning decisions in cities. In particular we focus on the location of an archaeological site lying 2 meters below ground level in the city centre of Ravenna, Italy, which is subject to pluvial flooding. A map of Ravenna was divided into cells which could be eligible for modelled greening if they contained a car park, a street or a pedestrianised area. The number and location of cells greened varied with each run of the model. This was combined with precipitation and temperature data from Ravenna, and subsequently estimated scores for evapotranspiration and permeability. In general, the greater number of greening measures introduced corresponded to a reduced volume of excess rainwater. There was a particular effectiveness of greened streets at reducing excess runoff compared to car parks and pedestrian areas. Our results demonstrate the usefulness of ABM in the field of disaster risk management.

Keywords: Agent-based, Pluvial, Cultural Heritage.

1 Background

Sites of cultural and natural heritage represent important records of the past [1]. Despite having historically survived numerous hazardous natural events, anthropogenic climate change is placing increasing stress on cultural heritage sites and their users. Agent-based modelling, or ABM, is useful in this context by enabling a structured exploration of disaster and post-disaster scenarios and different impact prevention measures, to quantify their benefits before resources are committed to their implementation [2].

The impact of pluvial flooding from precipitation is especially severe in urban areas of heritage due to impermeable ground surfaces causing high runoff [3]. The Santa Croce Church and archaeological site of Ravenna, Italy, is one such cultural heritage area at which pluvial flooding has become a problem [4],[5]. Since the 1990s the whole city of Ravenna and its surroundings have been subjected to the subsidence phenomenon. Moreover, due to being situated below both street and sea level, ground water levels are particularly high, meaning that water drains into these important areas from the above-ground street following heavy rainfall. Greening impermeable parts of the city can improve water infiltration and thus reduce surface runoff and flooding risk.

By simulating areas of the ground surface as agents with surface type as a characteristic, our agent-based model aims to be an explorative device to examine the usefulness of ABM as a tool for urban planners. Important to note is that this model is explorative since it is without empirical validation. The interpretation of which measures are most effective is based on deduction since the developed impacts in the models are based on expert logic and literature where available.

2 Methods

The model was built with the Python ABM libraries Mesa [6] and Mesa-geo [7]. In our model, a map of Ravenna was divided into areas or ‘cells’ of ground surface, determined by census data classifications, which here acted as the agents. Each one is characterised by its percentage of green land, streets, pedestrian areas and car parks. Depending on how many cells the user decides to green in each model run, a selection of cells are randomly chosen. Hourly totals of precipitation and means of temperature for a 2-month time series was taken in August 2018, when Ravenna saw greater than average rainfall. Each cell has a permeability score based on its land use, which enables it to absorb a given amount of rainfall. Rainfall in excess of this forms pools which remain on the ground surface and are slowly reduced by transpiration. If the cell is selected for greening, its permeability score changes and so does its absorption capacity. For a cell to be eligible for greening, it had to meet two criteria: Less than 70% of the cell had to have been already greened, and the cell must also be covered by at least 10% of either car park or street, or at least 5% of a pedestrianised zone, to model a justifiable amount of greening. In total 294 out of 664 cells were eligible for greening each run, broken down into 231 streets, 42 car parks and 21 pedestrian areas (fig 2). Each cell was simulated as a block of ground with natural processes and the following characteristics:

Static characteristics: Area (m^2), Amount of greened land in each cell (%), Amount of cell covered by car parks, by streets and by pedestrian areas (%).
Dynamic characteristics: Overall amount of greened land in each cell, after greening the city (%), Whether cell is flooded or not (yes/no), Permeability (a static coefficient which changes depending on the percent of green space in the model).

Important to note here is that the runoff absorption was estimated based on how much of the respective area could realistically be greened. This meant that pedestrian areas were modelled as being able to absorb 15% of runoff if greened, for example by installing vegetation barriers at kerbsides and in the middle of paved areas. It was assumed that car parks could be greened in a similar way but to a greater extent, leading to this value being estimated at a 30%. Due to the narrowness of many streets in Ravenna, however, it was assumed that these could not be greened in a typical sense and instead the more intrusive measure of installing permeable concrete or asphalt was assumed to be the most appropriate. This meant that the entire street area could in theory be ‘greened’ and as such streets were assumed to have an absorption capacity of 80%. The model was run as a batch with a series of variables. The consistent parameters included weather and temperature, and the variable parameters were as follows:

- Number of car parks being greened: Tested at values of 0, 10, 20, 30 and 40.
- Number of pedestrian areas being greened: Tested at values of 0, 5, 10, 15 and 20.
- Number of streets being greened: Tested at values of 0, 50, 100, 150 and 200.

These variables were each run for 5 values, with every combination between the three variables, 100 times. This resulted in **12,500 runs** of the model being carried out. For each of these model runs, 10 parameters were recorded. These were the number of cells which were greened during a model run, the total volume of excess flooding in the model, and the average runoff per cells with differing percentages of areas greened.

3 Results

The areas of Ravenna which were modelled as greenable can be seen in figure 2. Firstly, the more cells have greening measures applied to them, the less excess runoff occurred. This is because as heavy rainfall occurs, urban surfaces are unable to drain this water away quickly enough before more occurs. Thus, as surfaces become on average greener, more drainage can occur and hence less flooding (fig 1). Secondly, cells which have less than 5% of their area greened are more likely to flood with a higher number of greening measures applied to other cells. Similarly, cells which are over 10% greened benefit from less flooding as more greening measures are introduced.

The cells categorised as streets had the highest impact on flooding reduction when greened. This is partly attributable to the sheer quantity of these cells, and also because the streets were modelled as having a higher modelled runoff reduction per greened cell compared to pedestrian areas or car parks.

Finally, there is a greater impact from greening streets than other surfaces. This can be largely explained by the sheer quantity of streets compared to the other surfaces.

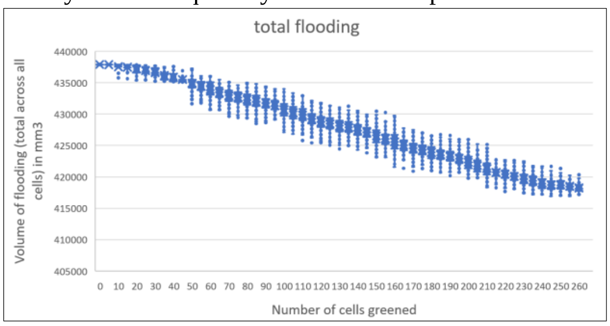

Fig. 1. Volume of flooding against number of greened cells in place.

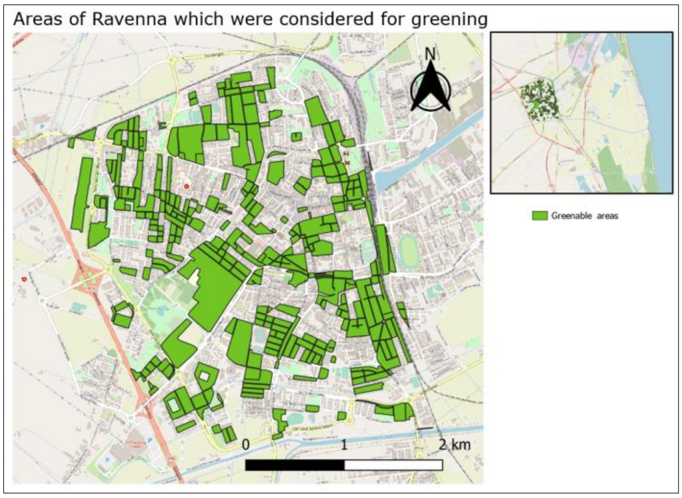

Fig. 2. Map with proposed cells for applying greening measures

4 Uncertainties and difficulties encountered

Several uncertainties must be considered alongside result interpretation. Firstly, rainfall parameters used were based on historic events, and thus do not account for climate change. Secondly, the role played by sewage systems was not accounted for. This may increase the drainage potential of certain parts of the city and worsen it in others due to Ravenna's generally high level of ground water. Neighbourhood interaction between cells was also not accounted for, but in reality greener cells are likely to influence the drainage of nearby cells. Thirdly, elevation and aspect were not considered. In reality, areas which are more sloped will drain into low-lying areas where water accumulation will be greater. This could be solved by incorporating digital elevation datasets. The greened factor for different types of land, as well as the coefficient of permeability, were also estimated. To improve this would require calculating how much of each greenable area could realistically be greened in practice. Finally, some cells will either be privately-owned or logistically impossible to green. A land survey could be carried out to determine which cells it would be feasible to green.

Despite several areas of proposed further development, our exploratory model demonstrates the usefulness of agent-based modelling to local decision-makers as well as to the research community for its exploration of city greening.

5 Conclusions and next steps

Our model explores the interaction between rainfall, surface type and flooding volume in Ravenna, Italy. Although several uncertainties limit the direct applicability of final results to justify specific planning actions on behalf of the local authority, our model is useful as a discussion tool for land use planning from a risk reduction perspective. The model's key conclusions include the relative effectiveness of greening streets compared with other surface types. Similarly, at least 10% of the cell must be greened to cause a tangible reduction on runoff. Other urban rainfall models include the SCS-CN model which similarly finds that increasing urban green space correlates with runoff reduction, and also finds that periods of heavy rainfall result in higher water retention by green spaces [8]. Our study did not consider individual rainfall events but rather focused on monthly totals, and this is worth considering in future iterations.

If more detailed information such as elevation can be incorporated into future model iterations, then the insights gained could allow an understanding of where and how many impervious surfaces should be greened to reduce pluvial flooding at the Santa Croce Church and archaeological area. The model can then be used as a discussion tool for organisations in Ravenna to incentivise the greening of public and private land.

The use of agent-based modelling as an explorative tool in disaster risk management was demonstrated for pluvial flooding, for the purpose of testing disaster management greening interventions. The value of using ABM in this way is the rapid testing of random behaviour of using different combinations of cells being greened each model run.

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