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Integrating raster and vector spatial representations with interaction graphs for multi-scale environmental simulations

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Abstract: Nowadays, developing tools for modelling complex system is a mandatory issue in environmental research. Environmental modelling implies taking into account processes at different scales of space and time. Ocelet is a domain specific environmental modelling language that uses graphs to describe how spatial entities in the system interact, with functions attached to the arcs of the graphs that are activated within scenarios to represent the dynamics of the system. The language has a strong focus on spatial interactions where the vector format is used for attributing geometries to entities, thus allowing a precise description of their shapes. However, the vector format is not appropriate for representing spatially continuous information for which the grid format is more efficient. In this paper, we describe how the grid format was formalized in Ocelet to allow a joint use with the vector format and interaction graphs, together with the key concepts and constraints for the combination of the two spatial formats. In this formalization, entities can be cells of different predefined shapes (square, beehive) and sizes. Processes can then be described with relations between cells that are handled as proper entities with their own properties as defined by the modeller. An example is given to illustrate this combination with a case study on water runoff modelling in a tropical insular environment subject to urban sprawl and soil sealing.

Keywords: Spatial dynamics, Domain specific language, Interaction graph, Raster

1 Introduction

The importance of a knowledge-driven approach to modelling in environmental studies has been highlighted in Villa et al. [2009]. Processes at different scales of space and time has to be taken into account in an integrated way including social, economic and environmental considerations (Laniak et al. [2013]). Most spatial modelling and simulation tools are however designed around one preferred internal representation of space: they either discretize continuous spatial information into a grid of regular cells, as in Netlogo, Tisue and Wilensky [2004] or they work with a set of vector geometries representing the shape of well delimited objects as shown in Gaucherel et al. [2006]. In many environmental modelling situations though, one could benefit from being capable of manipulating both forms in a seamlessly integrated modelling design.

The advantages of using a Domain Specific Language (DSL) when expressing environmental knowledge in a model are described in Athanasiadis and Villa [2013]. Ocelet is a DSL dedicated to spatio-temporal modelling and simulation that was designed independently of one specific internal representation of space (Degenne et al. [2009]). When modelling with Ocelet one manipulates explicit interaction graphs to represent relationships between the entities of a model. The different kinds of interactions present in a model are all described with one same formalism (interaction graphs), whether they express spatial, functional, hierarchical or social relationships. To be able to relate such interaction graphs with geographical information, the Ocelet language already provide appropriate features to import and export vector data formats, to store vector geometry attributes in entities and to build spatial relationship graphs from that information.

In this paper, we describe how the grid format was formalized and integrated into Ocelet to allow a joint use with the vector format and interaction graphs, together with the key concepts and constraints for the combination of the two spatial formats. The key concepts at the heart of the Ocelet language are presented first. Then we show how these concepts were used to integrate raster based geographical information into the Ocelet runtime. Finally, the new feature is experimented on a case application of water runoff modelling in a tropical insular environment that requires both vector and raster spatial representations of multi-scale processes.

2 Ocelet concepts and raster integration methods

2.1 Ocelet

Ocelet is a DSL designed to write spatially explicit models and to perform spatial dynamics simulations as shown in Degenne et al. [2010]. The language is meant to ease working with geographical data and information, and is kept generic enough to offer a wide range of possible applications when studying urban sprawl, land use change, coastal dynamics or species distribution in space and time.

In a rather classical approach, Ocelet is based on concepts such as (i) Entities that contain Properties reflecting their state, (ii) Relations that allow to describe what types of entities are expected to interact with each other and what exactly happen when they do interact and (iii) Scenarios where the sequence of operations and interactions are specified in order to simulate the evolution of the system. A fourth concept named Datafacer is provided to help reading and writing geographical or non-geographical data from different storage formats (such as Shapefile, PostGis database, CSV or KML files).

More original is the way spatial and non-spatial relationships are formalized in Ocelet. Explicit interaction graphs are used in all cases. An interaction graph is an instance of a Relation. It means for example that one can define a Relation between a Parcel entity and a Farmer entity, and the Relation can be instantiated as a bipartite graph where the vertices are either individual parcels or individual farmers, and the edges would link some parcels with some farmers. Another Relation could for example be defined between Parcel entities to create a spatial neighbourhood graph between parcels.

Within one relation definition, one can specify a series of interaction functions describing how the entities at both ends of an edge have their properties affected when those entities interact with each other. When one such interaction function is called during a simulation, it is applied simultaneously on all the edges of a graph. It is however possible to reduce the number of edges involved by defining and using graph filters.

Two more details must be given to enlighten the explanations of the next section:

- The entities can have properties of different common types like Integer, Boolean or String but Ocelet provides also vector geometry types such as Point, Line, Polygon, MultiPoint etc.

- When a Datafacer is used to read data from a file or a database, a series of individual entities are obtained with their properties already initialized from the data source. Those entities can then easily be used in interaction graphs when needed.

2.2 Raster integration

Studies on duality in spatial representation from grid or discrete objects are not recent, Couclelis [1992]. Previous studies present a conceptual approach leading to link these two formats, Goodchild et al. [2007]. These studies are more about the representation of space and time with geographical information system than for using them in simulations. However, these studies have suggested that the choice of a format often depends on the spatial scale. A related work concerned the reduction of scale sensitivity using vector data and a cellular automata as shown in Moreno et al. [2009]. Conceptually, two main aspects were taken into consideration when integrating raster (or regular grids) into the Ocelet language:

1. We want to be able to access every grid cell (or pixel of a raster image) and to relate these cells with properties inside entities of a model. We also need to be able to extract all cells within the boundaries of a Polygon or following a linear geometry so that we can link one geometry to a group of cells located in the same area.
2. A regular grid of triangular, square or hexagonal cells can be seen as a neighbourhood graph where the edges are implicitly deduced from the relative position of the cells. We then need to be able to define formal Relations between cell entities and write interaction functions completely consistent with the already existing interaction graphs.

More concretely that integration was realized in several steps:

- A new Cell type was added to the language that allows definition of property of type Cell in entities. A Cell is characterized by its location (x and y), a shape (square, hexagonal, triangular) and a size.
- A new type of Datafacer was developed to allow access to raster image data (like remote sensing images). Modellers have to define an entity with a Cell property as defined before. This is only a spatial representation; the values from different bands of the image are attributed to entity properties via the datafacer by matching the property to a band value. The datafacer automatically creates entities from the user definition and assign the corresponding property values. The entities are then ready to be used in the model and come associated in an interaction graph.
- New functions were added to the runtime to give access to all cells located in the same area of a point, line,(using the Bresenham [1965] algorithm) or surface geometry (using the scan line algorithm).
- The construction of two types of interaction graphs was provided. The first type relates entities with a vector geometry to entities with Cell geometries. Ocelet can then automatically create the edges of such graphs. The second type of graphs relates entities with Cell geometries with each other. In that case, the edges of the graph are not explicitly created because they can be deduced on demand due to the regular topology of the grid. Internally an iterator on the edges is provided that can be filtered like any other graph made with Ocelet. That second type of graph would for example allow to easily model cellular automata using Ocelet.

3 Results and discussions

3.1 Case application

We test the new feature on a test case that requires both vector and raster spatial representations of multi-scale processes. In a wider context of a project where a cartographic simulation tool is being developed for the agro-ecological evaluation of land use scenarios in a space constrained insular environment, we focus on the effect of soil sealing resulting from urban sprawl on runoff during cyclonic events. Reunion Island is located in south-western part of the Indian Ocean. It has a surface area of around 2500 km^2 and lies about 800 km to the east of Madagascar. The Saint Gilles catchment area is located in the drier north-western part of the island with an annual rainfall of 2 m. Slopes are high, with more than 2000 m altitude difference over a distance of about 18 km. Deep gorges called ravines lie along the catchment to collect water during rainfall events, but remain dry most of the time. Planned and unplanned urbanization (sprawl) results in soil sealing that accelerate water into the ravines, reducing concentration time and thus increasing risks of floods and landslides downstream. This process is often ignored in runoff models such as USACE-HEC [2008] whereas it is quite important in the present setup.

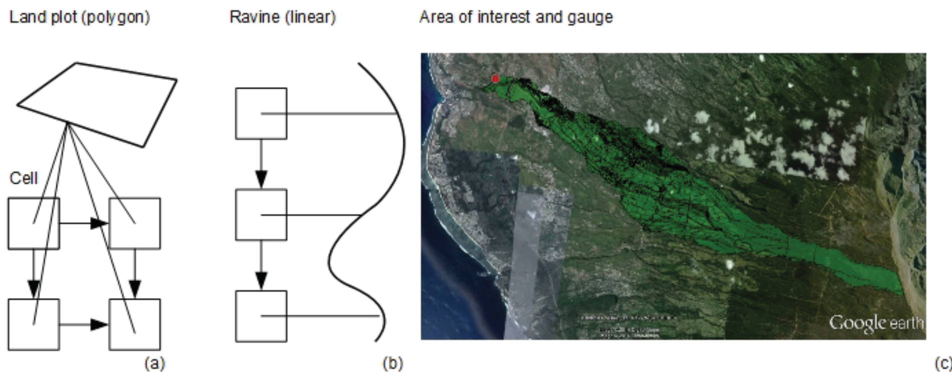

Figure 1. (a) Relation in cells for water flows and access to entity property (land cover) with a geometry. (b) Linear entity affected by water quantities contained in attached cells. (c) Geometrical view of a landscape and the gauge (red) where water flows are measured and computed.

We use Ocelet to model runoff in the Saint Gilles catchment where urban areas account to about 10 % of the area. In particular, we try to reproduce how water is collected around houses and transferred quickly to the ravines through the road network. We use the vector format to represent land parcels (polygons), the road network (line segments) and the ravine / river network (line segments). A 10 m resolution raster DEM gives the slope and the direction of flow within parcels and along the networks. We also use another raster (Spot 5 06/07/2002) to better estimate vegetated areas where infiltration is higher. The model describes how water is transferred between adjacent cells within parcels and into line segments of road and ravines networks. The basic raster spatial unit is the DEM cell. A simple water budget is computed for each cell with rainfall and output of adjacent cells as input, and infiltration and flows to adjacent cells as output. Infiltration depends on land cover, and is nil for artificial surfaces. Lateral flows depend on altitude differences. Cells and parcels in contact with the road and ravine will output their water into the network instead of nearby cells. The time step is 1 min and the simulation period of the Dina (2002) cyclonic event is of 4 days.

3.2 Discussion

Figure 2 shows that comparison between simulated water flows at Saint Gilles with measurements made in this area during the Dina cyclone in 2002. The order of magnitude of water flow is well reproduced, however, a first peak appear in the first steps of the simulation suggesting that the infiltration function is too simple, and could have been replaced by one with a threshold on water input (when water input is low, infiltration remains high until a saturation threshold is reached, after which runoff is predominant). The same effect may explain why the decrease after the peak value is not more rapid.

This modelling experiment shows that the interaction graph formalism is capable of combining raster and vector spatial representations, not only for display purposes but more so for modelling processes

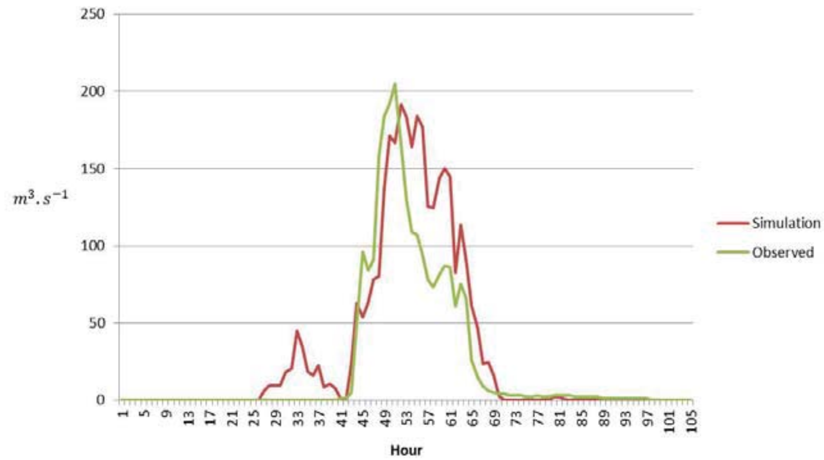

Figure 2. Restitution of the water flood and comparison between the observed and simulated values

at different spatial scales. Vector and raster model entities have been made to interact (here by exchanging water) when modelling a process which would otherwise be too difficult or impractical to model with either vector or raster representations alone, hence combining multiple processes in a system. This spatial data integration follows the semantics of the Ocelet´ s concepts in order to describe natural processes without being limited by spatial representation.

The simulated water flow at the outlet of the catchment does not fit well with the hourly observations, although the correct order of magnitude is obtained. Many reasons can be put forward to explain the discrepancies, including the spatial resolution of input data (one rain gauge for the whole catchment), the lack of appropriate parameterization and above all the simplicity of the transfer and infiltration functions used. However, the objective of the study was more to test a formalism combining raster and vector spatial representations than to build a new runoff model for cyclone events in steep catchments as found in Reunion Island. Having said that, we find that the results are encouraging enough either i) to use the multi-scale modelling, which is more relevant mainly on urbanized areas, to better parameterize existing models to better take into account soil sealing on runoff or ii) to develop a complete runoff model with the new formalism by integrating necessary processes and related functions appropriate for these types of catchments and rainfall regimes.

4 Conclusion

The Ocelet DSL was designed along the idea that it may be possible to provide a spatio-temporal modelling and simulation tool that would not impose a preferred form of representation of space. We showed how it was possible to improve the first version of Ocelet by seamlessly integrating raster and grid data forms into the language and its runtime, allowing mixing vector and raster in one same set of coherent concepts. The experimental case application showed encouraging results especially in demonstrating that this raster integration into Ocelet allows to create models that use both vector and raster data representing spatial dynamics at two different scales. Perspectives on this work may concern the optimisation in case of big data raster images and graph synchronization for multiple processes. Moreover we planned to integrate time series with such formalism in order to force or help model processes.

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