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Cellular Automata Approach for Medium Sized Cities

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1 ABSTRACT

We show how small to medium sized cities can make use of the Cellular Automata (CA) approach to integrate land use data and other GIS based data with inter-active long-term scenario evaluation. Our CA model illustrates the interdependency between transport infrastructure supply and population density. It can be used to generate maps of future land use patterns for potential future scenarios. It provides a fast and economical way to compare alternative strategic plans and development rules for a small to medium sized city. For our sample town, Austria's second largest city Graz, we develop three different long-term scenarios (fast population growth, slow population growth, and urban sprawl scenario in which population growth is concentrated in the suburban areas). The model output for each scenario can then be used as input for infrastructure planning procedures. We illustrate some examples: the graphic representation of the spatially differentiated structure of the population, ex-ante public transport infrastructure evaluation, evaluation of existing zoning rules, and the evaluation of infrastructure capacities by combining the model outcomes with capacity calculations for the public sewage system.

2 INTRODUCTION

The starting point of our Cellular Automata model is the Corine Land Cover (CLC) Project (2006) which is used to represent the current situation of land use within the city limits of Graz and also provides us with the cells of the dimension 100m x 100m that serve as the individual building blocks of our Cellular Automata model. Using this structure we develop a Cellular Automata model that illustrates settlement activity within the city limits of Graz for each year until 2050. This is done for three different scenarios which illustrate a broad spectrum of possible future developments of the city until 2050. We feed each of these alternative scenarios into the model, combine it with future population predictions, and let it run for 44 periods, where each period represents one year. The model output then illustrates settlement activity within the city limits of Graz until 2050 in the case this particular scenario occurred.

We choose a broad variety of different scenarios to illustrate the scope of our model's possibilities. The first two of these scenarios are based on extrapolations of current trends of population growth (one illustrating a fast growth scenario and the other one a slow growth scenario). The third scenario deals with the issue of urban sprawl.

The model output for each scenario can then be combined with a variety of infrastructure applications to estimate likely future needs and to check in which way capacities of the current (public) infrastructure would need to be expanded. For example we look at where new public transport routes would be necessary, we check whether the current sewage pipe system would be adequate for the city of Graz under each of the three scenarios. By comparing the model output with actual zoning rules we can pinpoint areas that experience too much population pressure as well as those areas that have free capacities for densification. By highlighting areas with potential for further improvement the model can help city planners to locate areas that would benefit from an improvement in public infrastructure (which in turn would increase their attractiveness for development in the model and in reality). The model could also be used to find the optimal future locations for kindergartens, schools, shopping facilities and other infrastructure needs.

In this paper we show how our CA model can be used by city planners to better understand the structure and dynamics of their city as well as its infrastructure limitations. This should be helpful for long term planning of zoning regulations, public infrastructure such as public transport services, the dimensions of sewage systems to name but a few.

3 MODEL

3.1 Model Structure

The basic structure of our model consists of four parts: the cells, their states, their neighbourhoods, and the transition rules that regulate how cells can change their state through influence of their neighbourhood.

We choose the model's cell structure to coincide with the grid structure of the Corine Land Cover Plan 2006 (European Environment Agency, 2010). This provides us with a two dimensional representation of Graz that consists of 12,762 grid cells with dimension 100 by 100 meters. The possible states of the model were defined by us and are based on the Corine land use classes which were combined with population data. The Corine Land Cover Project allocates to each cell one of potentially 42 different land cover classifications. 12 of these land cover types are represented within the city limits of Graz. The actual population data for Graz is available at census district level (“Zählsprengel”) of which there are 259 within the city limits of Graz. We define the neighbourhood of a cell as the 8 cells surrounding the cell itself. The transition rules are more complicated as they depend on more than one factor. We concentrate on the transition of unpopulated cells into populated ones. For an agriculturally classified cell to be converted into building land it has to be surrounded by at least 4 populated cells. The likelihood with which a cell attracts population is then dependent on two factors: one is the proximity to the city centre, the other is the distance to public transport stops.

The distance to the city centre is important as Graz is a traditional city that is structured in a way similar to the monocentric city model (Alonso (1960, 1964), Mills (1967) and Muth (1969)). Most jobs are located in the central part of Graz and there is a central transit place in the city center (“Jakominiplatz”) where all public transport routes of the city meet. To illustrate this situation we divide the city into three distinct areas by introducing two concentric circles around city centre (with a 1500m and 3000m radius). For the cells in these areas we assume different possibilities of development (transition probabilities). The levels of these relative probabilities are found by solving a linear optimization problem. A graphic illustration is given in Figure 1.

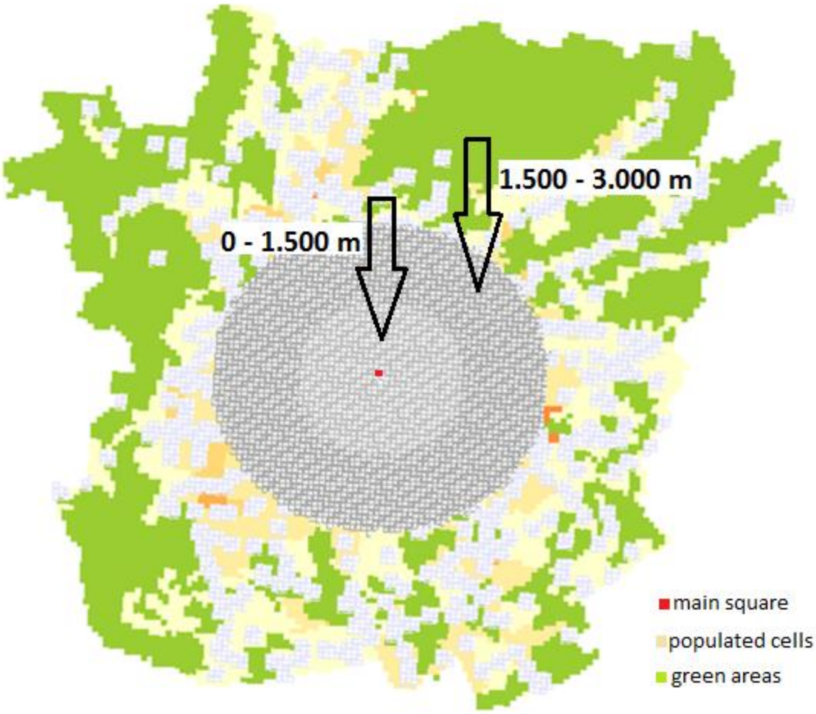

Fig. 1: Graz divided into three main areas.

3.2 Data

The following data inputs have been used in this model:

- Public transport stops (busses and trams) with GIS representation

- Coordinates of River Mur
- Distance of all cells to city centre (main square)
- All major roads out of the city centre with GIS representation
- Population density data comes from the 259 political “Zählsprengel” of the city of Graz 2006 – 2011 (Magristrat Graz, 2012). Apart from the number of people living in each census district this data set also contains age, citizenship, and whether the residency is used as a main or secondary residency (“Haupt/Nebenwohnsitz”). These population numbers are then divided up between all cells that lie within CLC classes 1 or 2 (urban fabric and discontinuous urban fabric respectively) within that “Zählsprengel” (census district). CLC class 1 (continuous urban fabric) receives four times as many people as CLC class 2 (discontinuous urban fabric).
- Corine Land Cover data from 2006 (version 13: 02/2010) with GIS representation

These data are presented in grid cells of 100m x 100m. We cut out the boundaries of the city of Graz from this data set. 12 of the 42 land cover types used in the Corine Land Cover data set occur within the city limits of Graz. Corine Land Cover class 1 and 2 are “town”, which are defined as continuous urban fabric and discontinuous urban fabric respectively. In our Graz data set we have 573 cells with CLC class 1 and 6,241 cells with CLC class 2. The total city area consists of 12,762 cells. Thus, according to the Corine Land Cover data 53 % of the area of the city is covered by populated “built-up” area.

3.3 Scenarios

One of the greatest advantages of modelling urban development with a CA model is the relative ease and economic efficiency with which different scenarios can be “played through”. To develop the individual scenarios we have focused on existing trends that are discussed in the local media as well as future infrastructure decisions that are currently discussed by the local municipality. These scenarios are sample inputs – we can easily combine the model with other statistics or incorporate other scenarios that city planners are interested in. We will illustrate three different scenarios here. Each scenario has its own probabilities of change associated with it. These probabilities were obtained by solving a linear optimization problem. Wherever possible we included past population trends in this optimization process.

The following scenarios have been considered so far:

Scenario 1	Fast population growth
Scenario 2	Slow population growth
Scenario 3	Population growth focused on suburban areas

Table 1: Characterisation of the three scenarios.

Scenario 1 assumes an extreme increase in population until 2050. In this scenario we take the predicted population numbers for “Greater Graz” area (Landesstatistik Steiermark, 2010) and allocate them all into the city area. The point of this excersise is to see how the city’s infrastructure would cope under this extreme scenario.

Scenario 2 is the most realistic scenario. It is based on a demographic study by ÖROK (2004) for the individual districts of Graz until the year 2031. For the period 2032 – 2050 we use our own extrapolations of these numbers.

Scenario 3 shares the population numbers with scenario 2 – but now we assume that because of socio-economic preference changes additional population is mainly locating in the outer areas of the city.

Figure 2 illustrates the starting situation of land use classes and cell level population density in 2006. Figure 3 shows the outputs of scenarios “fast growth” and “urban sprawl” for 2050 (after 44 model sequences).

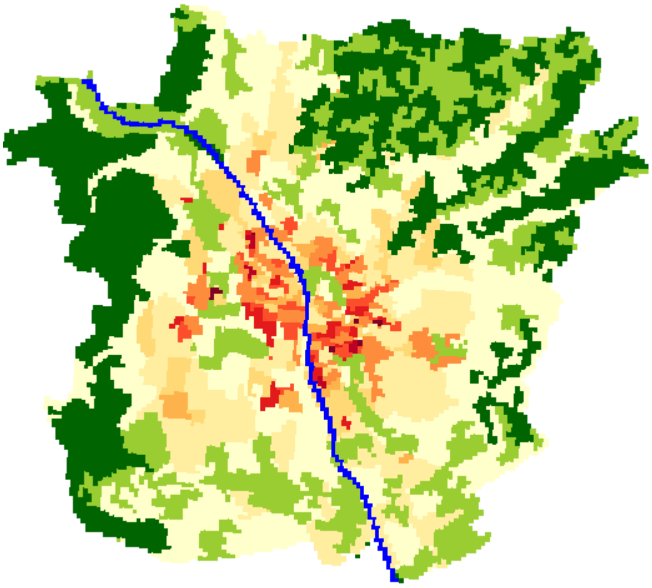

Fig. 2: Land use and population density at cell level in 2006.

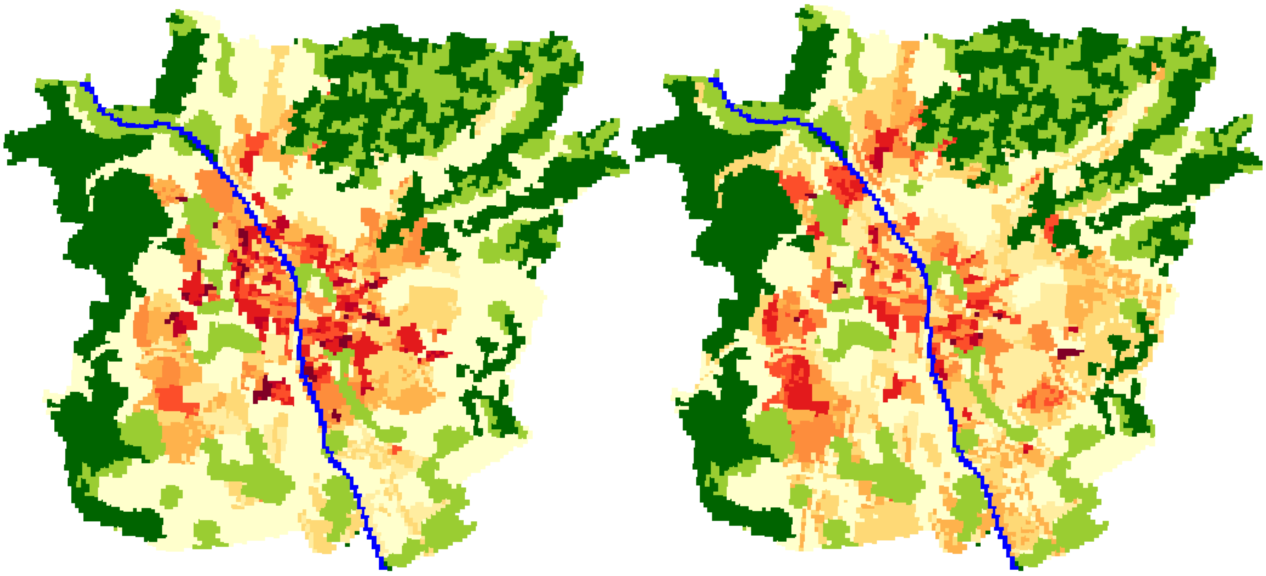

Fig. 3: Land use and population for the year 2050 for scenario "fast growth" (left) and scenario "urban sprawl" (right).

4 APPLICATIONS

4.1 Ex-post building density evaluation

The zoning plan is the main instrument with which the city's future shape and structure are influenced. The city of Graz has set maximum as well as minimum building densities per square meter building block via their zoning plan (see 3.0 Flächenwidmungsplan Graz, 2002). The official building densities differ quite substantially within the city of Graz. While the inner city area has building densities of up to 2.5 the outer areas generally have maximum building densities around 0.3 or 0.4 and a minimum building density of 0.2 (compare 3.0 Flächenwidmungsplan Graz, 2002). For example, a maximum building density of 0.4 implies that on a 1,000 square meter plot a building can have a maximum living space of 400 square meters. If a minimum building density of 0.2 applies to this plot, then the building needs to have at least 200 square meters of living space. Thus, the legal building densities are given as proportions to the actual land area. These legal requirements expressed in the zoning plan of the city of Graz is available in GIS format and can be incorporated into our model.

Ex-post we can compare how the various scenario predictions of the CA model correspond with these politically set boundaries for building density. The CA model can thus highlight "pressure point" areas where the model predicts a higher building density than the city currently allows. On the other hand it can also highlight those areas where the model predictions do not reach the minimum density levels. These areas are areas with potential for “densification”.

There are no legal restrictions on the population density per square meter. However, we know that the average living space per person in Austria is 42 m² (Lugger, 2002). We use this number to calculate the maximum average population density for each cell (per rata). If a cell consists of two or more zoning classes with different upper and lower building density limits we calculate the proportional average building density rules and use those.

With this information we calculate an average statistical “upper population boundary” per cell which can then be compared with the results of the various simulations of the CA model. This gives us an indication of whether there are population pressures in certain areas. However, the excess population of a cell does not per se mean that the building requirements are violated – as mentioned before a larger than the average number of people can live in one place. But it is an indication that more people want to live in that area than foreseen by the zoning plan.

In this situation city planners have two fundamental choices: They can keep the existing zoning regulations. In this case a cell once “full” will not take on any more buildings or population and the population that feels attracted by this cell will choose a cell with similar attributes. This movement of course illustrates the issue of “urban sprawl”. Another possible action plan of city planners in this situation is to loosen the building density restrictions. This will lead to more densely populated cells and a lower degree of urban sprawl as before. This situation illustrates how city planners can influence the future shape of a city through the design of the zoning rules. Both cases can easily be incorporated into our CA model and thus illustrate the long-term consequences of zoning regulations.

The red cells in Figure 4 mark the areas which would require an increase in building densities. On the other hand, the yellow cells in the graph below show those cells that do not reach the minimum building density if each person allocated to those cells uses 42 square meters of living space. Orange cells indicate those areas where the statistically average living space of the allocated people lie within the range set by the present zoning plan.

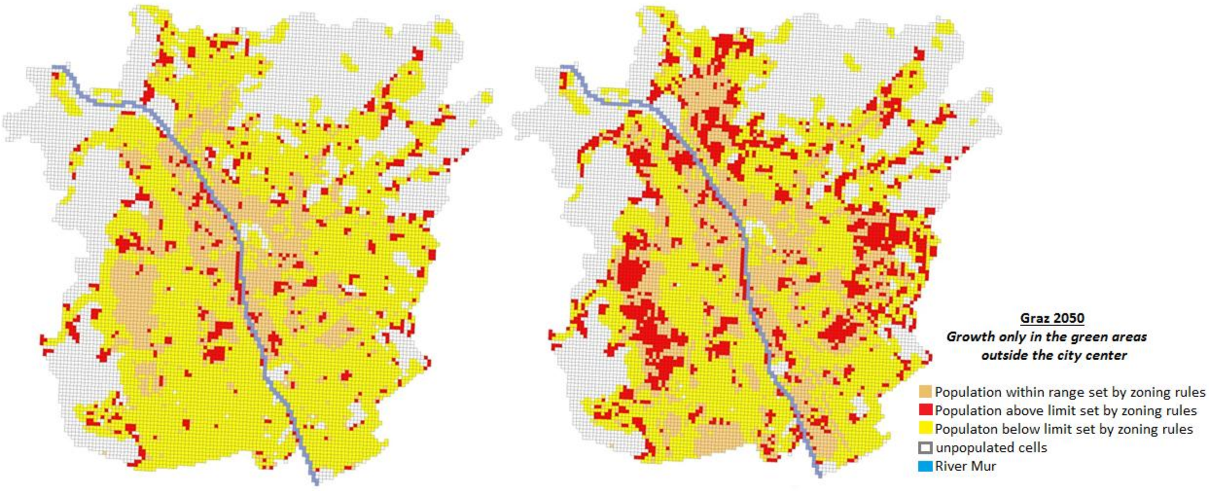

Fig. 4: Density and zoning rules 2006 (left) and 2050 – scenario “urban sprawl” (right).

We see that in 2006 there still is a lot of potential for densification in the outer areas of the city according to our calculations. If we contrast this picture with the figure of the sprawling scenario for 2050 we see that a large proportion of this potential has been used up by then.

4.2 Dynamic transport stops

An inherent question in urban economics is whether people move into an area because of good public infrastructure, or whether good infrastructure is provided wherever there is population that demands it. While our CA model cannot be used to address the causality issue per se, we can use the model to illustrate influences both ways.

If sufficient population grow exists in a particular area we can for example set new public transport stops. In the example below we stopped the model in certain time intervals and checked for the "need" of new transport stops. We followed the rule that a new public transport stop was created if considerable population growth existed within the area and the distance to the next public transport stop was larger than 375 meters. The arrows in Figure 5 indicate the new public transport stops that would be necessary to provide adequate access for the growing population. In this example the number of new stops was quite low however, because of the already very dense public transport net of the city of Graz. Of course, the additional transport stops will improve the attractiveness of the cells within this area, which will then change the probability of additional population being attracted into this area. Thus the model output for the year 2050 will be different to the original situation.

Because of the already very dense public transport system within the city limits, the population results do not differ very substantially from the original model. This example does however provide an illustration of how new public transport opportunities will attract new settlements. In a similar way entire new transit routes could be incorporated into the model to illustrate how these would influence future urban development.

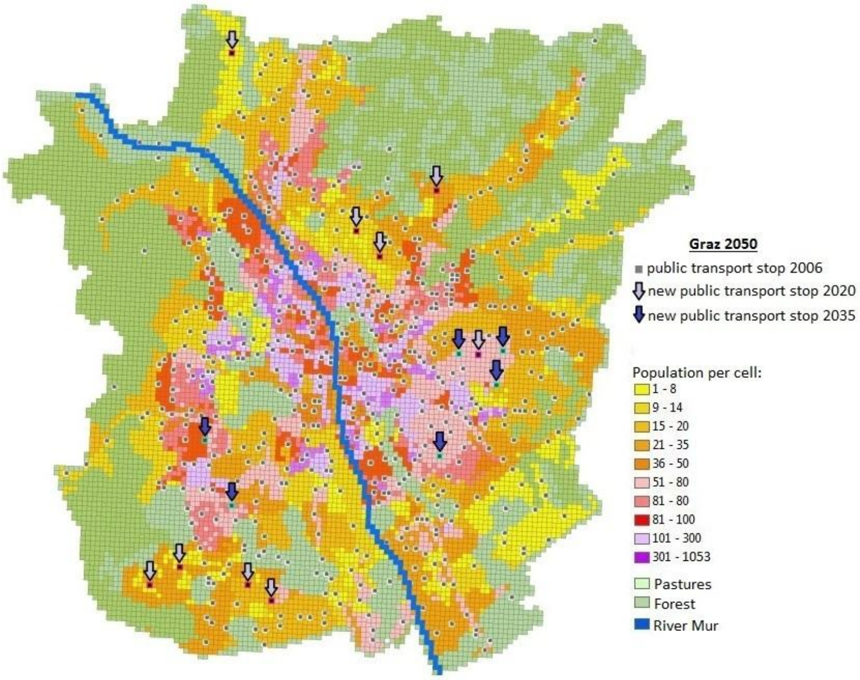

Fig. 5: Dynamically set transport stops 2050 – scenario "fast growth".

4.3 Sewage system checks

Figure 6 is an illustration how the scenario model output can be combined with the existing sewage system of a city. Again we illustrate how our model can be used as a tool to evaluate future needs. The intuitive graphic representation helps in the visualisation of potential problem areas. The GIS based output can also be incorporated into existing infrastructure systems.

For strategic points of interest for each of the three scenario outputs we can calculate whether the capacities of the sewage system are sufficient to meet potential future demands. These calculations can be useful to illustrate bottle-necks in the sewage system, to highlight needs for pipe expansion, or to illustrate the need to restrict future settlement by limiting additional population growth in certain areas via zoning rules.

For two reasons we concentrate on pipe diameters of more than 800mm. First, the bigger pipes illustrate the overall capacities of the sewage system which cannot be altered as easily as the more regional smaller pipes. Another reason is that the CA grid size of 100m x 100m is too coarse to allocate smaller pipes accurately. To illustrate our method we consider the scenario of "fast growth" and check how the existing pipes would handle the scenario needs for the year 2050.

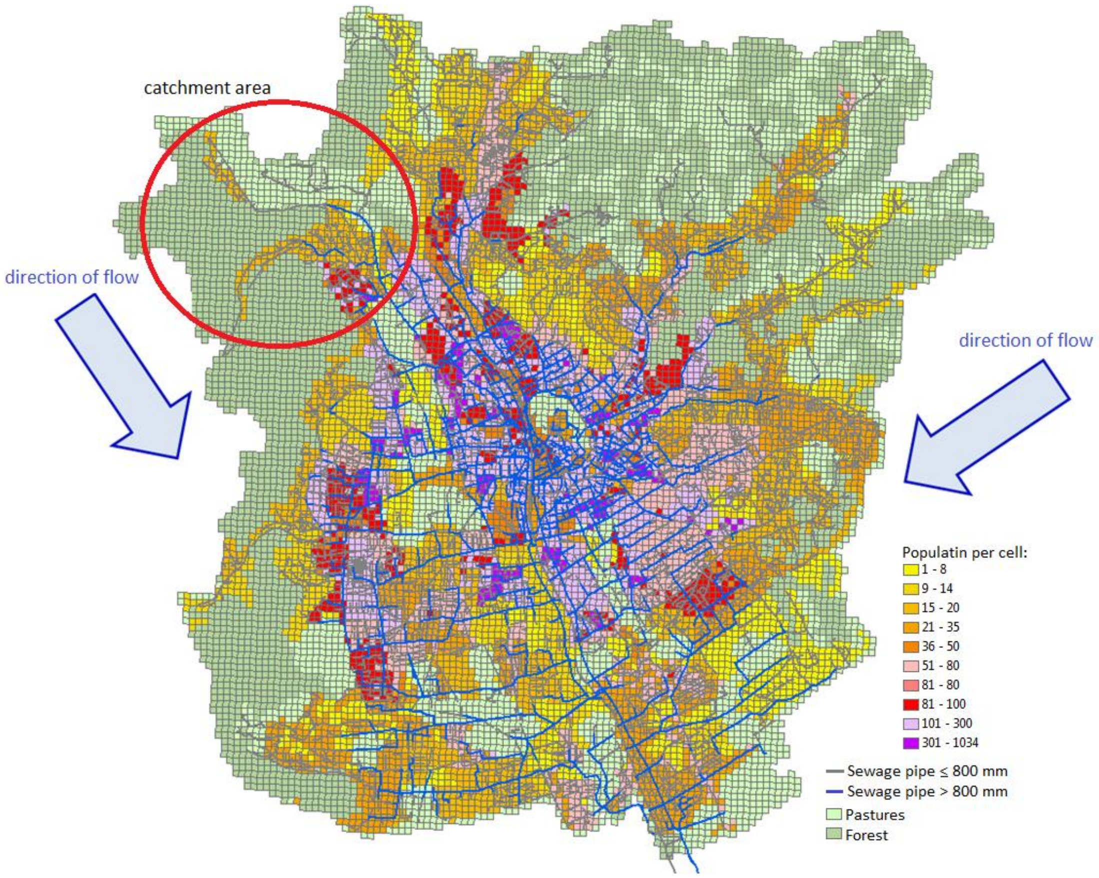

Fig. 6: Sewage system 2050 – scenario “fast growth”.

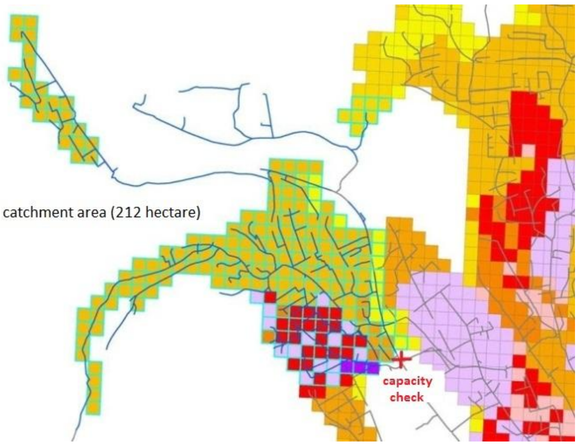

Fig. 7: North-West segment of sewage system 2050 – scenario “fast growth”.

We calculate the sewage output of the catchment area by multiplying the simulated population numbers of the cells in the catchment area with the per capita sewage assessment values for the city of Graz (details can be found at the webpage of Holding Graz, 2013). We calculate maximum pipe capacities with the help of the Hazen-Williams formula, which is often used for the design of pipe systems with larger diameters (Bobardelli und Garcia, 2003), the “90 % rule”, and the average European conversion factor (which lies at 0.849). For this specific area we find that the pipe diameters are large enough to handle all three of the scenario situations.

5 CONCLUSION

The last decade has seen a surge of GIS data sources becoming available to city planners. Because of its two dimensional model representation via grid cells, Cellular Automata models provide a natural framework within which GIS data can be represented. The CA model we develop in this paper is useful for city planners because it provides an intuitive, fast, and economical representation of alternative scenarios.

By comparing the outcome of the model with the zoning rules of the city of Graz we can highlight areas with potential for densification as well as areas with intense population pressure.

We have shown three different potentially possible scenarios for the future expansion and population structure of the city of Graz. Each of these scenarios is associated with different infrastructure needs. These infrastructure needs can then be assessed by integrating additional layers into the model or by exporting the model scenarios and assessing them with traditional methods.

There is a long list of potential extensions for the model. We have already made some progress in the inclusion of sewage systems and we will tackle the optimal allocation of elementary schools in a next step. The strategic setting of new commercial infrastructure locations (e.g. super market locations) is a further potential extension.

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