CELLULAR AUTOMATA FOR EARTH SURFACE FLOW SIMULATION

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Abstract

Cellular automata as a tool for modelling and simulation of processes taking place in the real world are now increasingly used, as evidenced by their use not only as a tool for creating simulations, but also by their use in areas of crisis management. Using GIS knowledge it is possible to create cellular automata, which can appropriately and authentically reflect the water flow on the Earth’s surface. The issue of the water flow simulation on the surface using cellular automata is a complex problem, into which a large number of external factors enter. Some of these factors are necessary to be generalized to a great extent; some must be included in the model itself. These factors may include, for example, liquid balance equation where it is necessary to determine the amount of liquid which is located in the cell, the amount of liquid which is absorbed into the terrain (infiltration) and that which is partially evaporated (evapotranspiration). Another factor is determination of the speed of distribution of liquid amongst the cells during each step of the simulation. The project is divided into several individual parts, amongst which the preparation of test data (input layers), the design of cellular automata interface, which eventually serves for communication with the user and the core are included. The most important part of the solution is to create the core of cellular automaton, which will deal with the computation for the liquid flow. The result is then stored as a sequence of raster images that were created in a certain chronological order.

Keywords: cellular automata, model, hydrology, simulation, liquid flow

INTRODUCTION

Water drainage in the terrain is not a simple process. It is a part of a far more complex, precipitation-drainage process. In short, it can be stated that the water falls from the atmosphere in the form of precipitation, part of precipitated water is trapped on the surface of plants and objects, another part supplements the volumes in lakes, reservoirs and ponds, and part is absorbed into the ground. Previous relationship demonstrations provide a very simplified view of the complex precipitation-drainage process, whose understanding sets the basis for each analysis connected with the simulation of water mass. The aim of this paper is not "just" an understanding of the distribution of water, or liquid in nature but also its conversion into a digital format in the form of cellular automata. In terms of cellular automata for the water distribution, the contribution of the paper lies in providing information on the possibilities of using cellular automata for the simulation of hydrological processes and their implementation, or their linking with GIS applications.

CURRENT STATE

The basics of cellular automata have been given in the 1950’s, inspired by the arrival of electronic computers, where some systems were equivalent to cellular automata. The cellular automata issue was first addressed by John von Neumann, who was trying to create an abstract model of self-reproduction in biology - the topic that he had to examine in cybernetics. However, the research on cellular automata began to recede due to the poor performance of computers and also due to the fact that the field of cellular automata was different from other sciences. John Horton Conway, who created a game called “Life”, brought revival into this area. The *"Life"* was based on a two-dimensional field, where the cells may have only two states and

8 cells define the environment. Two states, which the cells were able to reach, were either that of dead or alive. The Conway's *"Game of Life"* scored a great popularity in all age categories. (Wolfram, 1994).

In recent years, several types of cellular automata have been created, whose use found their justification in hydrology, or in the research of hydrological processes. The most development of such simulation programs occurs because of the repeated and more frequently occurring natural disasters. The creation of simulation models, which are useful as predictive tools, helps reduce or eliminate the impacts of natural disasters. The cellular automata can be used as a simulation tool, where by using simple rules as well as physical and mathematical equations it is possible to create a comprehensive system, showing the required processes.

The cellular automata (hereinafter referred to as the CA) represent the spatial processes of uneven terrains and simulate hydrologic and hydraulic behaviour (Pearson, 2007). The authors of the each paper use similar rules to those created by Conway in his game *"Life",* and the fact that the state of the cell is influenced by the state of the previous cell. Pearson has also addressed the CA dedicated to surface drainage. His model uses the layers of a digital terrain model, the infiltration and the friction layer. The advantage of the model is that the actual outcome also incorporates the time required for the move from one cell to another. The weakness of the model could perhaps be seen in the fact that the whole cellular automaton was created in the Java programming language and thus its implementation as the programme module into already existing GIS applications is not possible.

In addressing liquid flow in the terrain it is necessary to develop such a model in which the liquid will not be distributed only through one channel, namely from the higher situated point to the point below it, but it is necessary to create the so-called multi-flow direction (MDF), where a part of the liquid is converted into nearby cells, located near the main channel. A similar case, on a larger scale, has been dealt with by the model for the simulation of braided water flow. Braided water flows are characterized by high drainage activity without the characteristic valley, cohesive banks and vegetation. In this case, the classical cellular automata rules for the water distribution could not be used. See Fig. 1.

Fig. 1: The braided river

The accuracy of the inflow is restricted by several factors. If liquid is channelled into the following three cells, the flow direction is limited to a 45° angle. As a result, the meanders which are more than 45° cannot be further monitored. Secondly, if the routing algorithm does not take into account the relationship between water drainage and water column height (amount of liquid in the cell), the complete emptying of the cell may occur. It is this example, to simulate braided water flow, which well illustrates the need of water distribution into the neighbouring cells, next to the main channel (Thomas, Nicholas, 2002).

An interesting cellular automaton that uses multi-drainage and its deployment in crisis situations is the cellular automaton for mudflow distribution. This machine uses the Moor neighbourhood concept (8 neighbouring cells). An algorithm simulates the mudflow as the liquid drainage that uses data such as the height of all points and the mud volume shown in a given period. The algorithm also uses variable percentage of the neighbours and thus ensures a random direction of drainage (Busaki, 2009).

The form-based algorithm determines the estimated flow through the digital terrain model. As a result, the form-based algorithm was compared with the results provided by the ARC / INFO programme. The algorithm has turned to provide better results than the algorithm that is used by the ARC / INFO programme. The reason is that the form-based algorithm works and divides terrain into several categories. The result of the aforementioned comparison can be seen in Fig. 2 (Pilesjö, 1998).

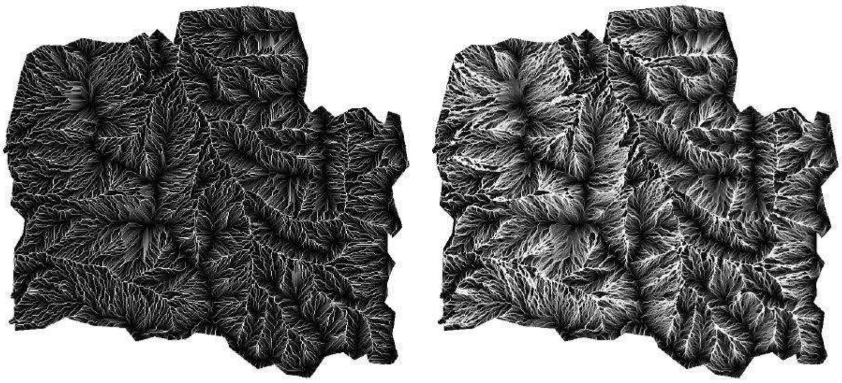

Fig. 2: Comparison between computed flow accumulation, left: flow accumulation estimated by ARC/INFO, right: flow accumulation by the form-based algorithm

WHAT IS CELLULAR AUTOMATON?

Models based on the CA principle stems from the principle of simple local interactions. The local interactions form the basis of the CA. Whether there is a change in the cell state is given by the transition rule, which is assessed using predefined neighbourhood of the cell. From this perspective the idea of using the CA to simulate liquid flow to the Earth surface is ideal. The raster data values are stored in a regular network, where both the shape and dimensions of each cell are identical. An important aspect that must be evaluated before the creation of CA is its own use in GIS.

General Principles

Cellular automata are divided into two categories, namely the CAs working with raster data, or matrix cells, which are always represented by one raster pixel, and the vector CAs (Shiyuan, 2004). In the vector CAs, the method and the work with neighbourhood is already more complex, which is so due to defining the transition rules.

The cellular automaton is a dynamic, discrete system, which works with a network of cells of the same type. Status and behaviour of the cell is determined by its current state, and the condition of the cells located in its immediate neighbourhood (Wolfram, 1984). Generally, two types of neighbourhood are used, namely the neighbourhood formed by the four closest cells (Neumann neighbourhood), see Fig. 3 (left), and the one formed by the eight cells (Moor neighbourhood), see Fig. 3 (right). An updated status of the central cell occurs during the convolution window movement, see Fig. 4, by the movement through the entire cell network. The state of the central cell varies according to defined rules, whose number is finite and the states of all cells are changing simultaneously in one instant of time. All cells use the same transition function. As a result, creating and applying the simple rules can obtain complex patterns.

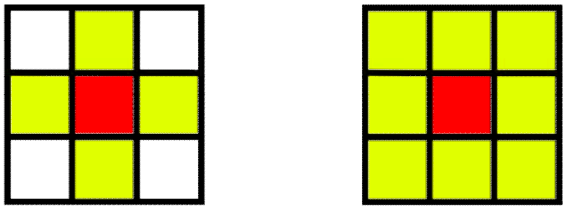

Fig. 3: The types of neighbourhood (left: Neumann´s neighbourhood, right: Moor´s neighbourhood)

The main features of cellular automata include:

- Parallelism (computations in all cells take place simultaneously, not serially)
- Location – state of the central cell depends on its current state and the state of its neighbourhood
- Homogeneity – the same rules apply to all the cells

Basic features of cellular automata are as defined below:

- Work in discrete time and space
- Formed by cells
- Each cell can have different states
- The value of the cell state is determined by the local transition function, which is the same for all cells and is defined by the rules
- Each cell has information not only about itself, but also about its neighbourhood (local information) and on this basis it makes decision what to do in the next cycle.

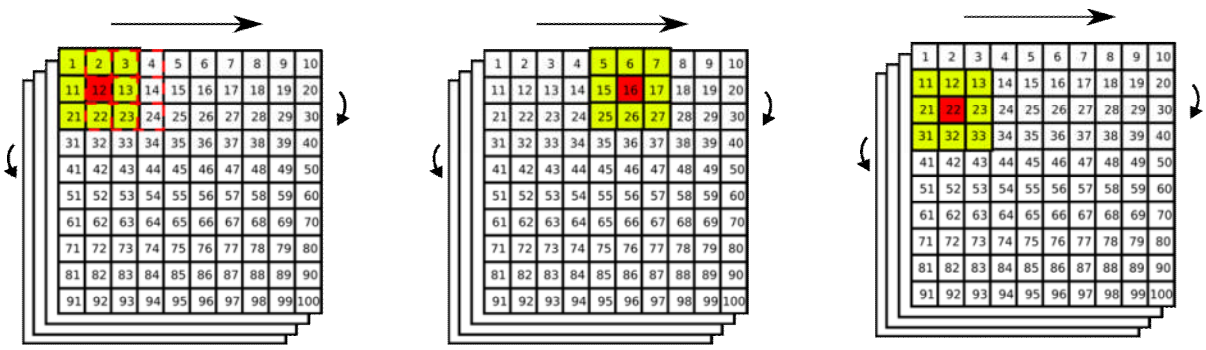

Fig. 4: Movement of convolution window

Hydrological Basis for Cellular Automata

For the simulation of hydrological processes such as the precipitation-drainage and hydrodynamic models both more and less complicated and complex simulation tools are used. These tools are used to simulate various types of spatial processes. For the model, in this case, the tool was used that is based on mathematics, whether it concerns analytical or numerical models. In the area of hydrology it generally considers complex mathematical models. These models require for its function spatial data, which must, before their use, undergo preparation (pre-processing). The data adjustment is performed by the GIS applications that are used in the final adjustment to the final data (post-processing). The GIS applications provide facilitation in the interpretation of the data with the possibility of their further use and thereby also increase their latent value.

Hydrological simulations allow us to not only study complex spatial processes that affect the water flow, but also to anticipate future situations based on the current status. Predicting hydrological processes such as directions of water spread through the terrain or an affected and contaminated area are the properties that can be used and deployed in the areas of crisis management. The issue concerning the flow of water on the Earth surface is a complex problem, into which a large number of external factors enter. Some of these factors are in the model itself necessary to be to a large extent generalized, others need to be included in the model itself. These factors may include, for example, hydrological balance equation, the amount of liquid, which is absorbed into the terrain (infiltration) and the amount, which is partially evaporated (evapotranspiration).

PROGRAMME AND DATA TOOLS

Selecting a suitable programming tool in which the cellular automaton will be created is very important. From the very beginning of the project the Python programme seemed a suitable candidate. Suitability of the Python language was confirmed by a number of reasons. First, it was the multi-platform. A script written in Python can be run in both OS Windows and Linux. For example, the Java language is also multi-platform. Another reason is that Python supports existing GIS applications. The largest representatives of the GIS software in the commercial sector include the ArcGIS programme that enables import of modules into its toolbox, developed in the Python language (Java language support is not provided). In a non-commercial area there are e.g., OpenJump, GRASS programmes that also provide a similar import.

The disadvantage of Python is a work with designing and creating a user-friendly environment. Using additional libraries solves this part. The existence of a considerable number of libraries and thus the expanding of other programming language skills are, on the other hand, again the benefits that Python provides. For working with a raster the gdal library is used. This library allows the direct download of the raster in a GeoTiff format. After downloading the raster the programme works with it as if it was a two-dimensional field (hereinafter referred to as the network of values).

The cellular automaton is programmed to be object-based. To calculate the individual elements the modules that are selected gradually and, if appropriate, are created. Modules were created gradually, as requirements and new rules for the CA have increased. The first created module was the liquid detector. It serves to detect the presence of liquid in the neighbouring cells of the matrix when the convolution window moves through the network of values. In the event of liquid detection the algorithm decides if the liquid is to be added or not to the central cell. Other models developed are as follows:

- Module for determining the outflow directions
- Module for calculating the terrain gradient
- Module for calculating the liquid distribution speed
- Module for calculating the liquid flow rate through the given cell
- Infiltration module
- Slowing of liquid movement due to ruggedness of the terrain
- Module providing an update of each network

However, the list of modules is not final and their number is with enhancement of other CA features likely to further increase.

With the development of modules there is a growing demand for storage of the calculation results. Those are recorded in the auxiliary networks. The base network is a digital terrain model and a network with the localization of liquid source. It is necessary to work on levels of several networks that are built above the base entry network. Auxiliary networks match the number created by the module, where each module stores the calculated values within its own network.

Area Studied

The base layer, which is used as a basis for simulation of the liquid flow, is in almost all analyses the digital model of terrain (DMT). DMT is most often used as a grid (in foreign literature is normally referred to as DEM). For the needs of cellular automaton generated in the following paper, a sufficient supporting input is the territory cut from DMT 25 (Digital Model of Territory). The selected territory falls within the northwestern part of Ostrava and is of the approximate area of 7.84 km^2. Selection of territories was purely accidental and not conditional by any determinants.

DMT 25 is part of the Military Information System and is generated in Toposlužba AVCR (VTOPÚ Dobruška). Information content essentially matches the 1: 25,000 topographic map (TM-25). The benefit of DMT 25 is a wider range of attachable attributes, especially in the area of communications and vegetation habitation and frequency. Some disadvantages of DMT are partial duplicity of some data and a slightly higher generalization of objects (mostly buildings and water areas).

CREATION OF CELLULAR AUTOMATON

Simulation of Liquid Flow

The base layer, which simulates the flow of liquid, is the layer of a digital model of terrain (DMT 25). Each raster cell is a carrier of information on the height. A new network of values, which contains directions of liquid distribution, is created above this layer. The values of flow directions are determined from the digital terrain model, where the central cell is assigned a value of the direction upon the movement of 3x3 convolution matrix. Directions are coded in binary manner between 1 and 128, see Fig. 5, where the following encrypted direction can be divided into liquid, if necessary, and more cells in Fig. 5. Before launching the determination of the flow and the spread of liquid it is necessary to know the location of the liquid source. Source of the liquid may be specified in either raster coordinates or information on the location can be transited through a new network of cells, which are formed above the layer of the digital model of terrain.

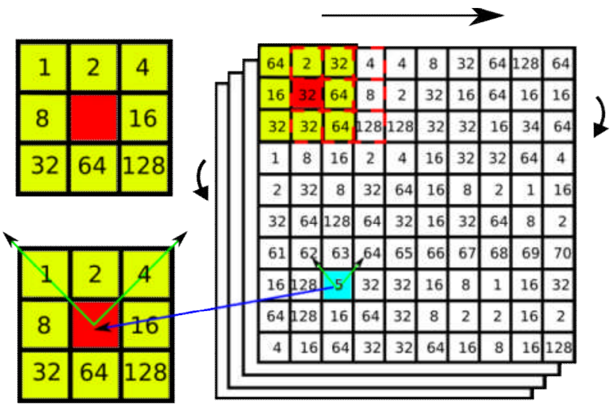

Fig. 5: Flow directions

Determination of the liquid distribution is speed calculated using the Manning roughness equation:

$$v = \frac{\sqrt[3]{depth.\sqrt{s}}}{n} \qquad (1)$$

where *depth* is the height of the water column value, which is located in the cell, *s* stands for the gradient or slant of the terrain, which is converted from the digital model of terrain, and *n* is the value of the friction coefficient for different types of cover. The value of friction coefficient can be expressed for the whole complex area of interest or based on the cover area the friction network can be created where each cell of the network contains the determined *n* value. Roughness values used for different types of cover are listed below.

Tab. 1: Manning *n* value

Surface Description	***n* Value**
Smooth surfaces (concrete, asphalt, gravel)	0.011
Uncultivated land	0.05
Agriculturally used land	
1. Cover less than 20%	0.06
2. Cover more than 20%	0.17
Grass	
3. Short grass (prairie type)	0.15
4. Dense grass	0.24
Pastures	0.13
Forest	
5. Brushes and Scrubs	0.40
6. Dense forest	0.80

The size of the liquid volume, which will be transferred to the next cell, is calculated as follows:

$$W = depth.width.v.t \qquad \textbf{(2)}$$

where W is the calculated volume of liquid in m^3, *depth* is the height of the water column, which appears in the cell, *width* is the pixel size, *v* is the calculated liquid distribution speed, and *t* is the time data in seconds.

After launching the cellular automaton, the user is prompted to enter time data, for a period for which output raster layers will be generated. Each iteration step corresponds to 1s. The 3x3 convolution matrix is moving through individual cells of the network. During the entered simulation period the movements of the convolution window in the network are continuously repeated, while after each movement of the network the information on elevation of terrain, outflow directions, terrain gradient and other values that are stored in the auxiliary networks must be updated. Upon exiting the simulation, the result is stored in the raster layers, which is consequently possible to simulate using a suitable software product. Simulation of raster images using the cellular automaton developed is not yet available. Fig. 6 shows the results of the simulation of the liquid distribution. The images show the results after application of cellular automaton where the input was the layer of digital model of terrain and the location of the liquid source. The value of the friction coefficient was set uniformly for the entire territory to be 0.05, which according to the table corresponds to the value of uncultivated land. After a selected time period, where one iteration corresponds to a time step of 1s there is a raster layer exported in the TIF format as an output. Each displayed image shows the result of the distribution after 5 minutes. The pixel resolution is 50x50 m. The liquid spreads from the source, which was set up as inexhaustible and still produces the same amount of liquid. The source was placed into a dry riverbed. While observing the distribution of the liquid from the source it is obvious that the liquid respects the riverbed. With an increasing amount of liquid the liquid rises in the riverbed and floods an increasing number of cells.

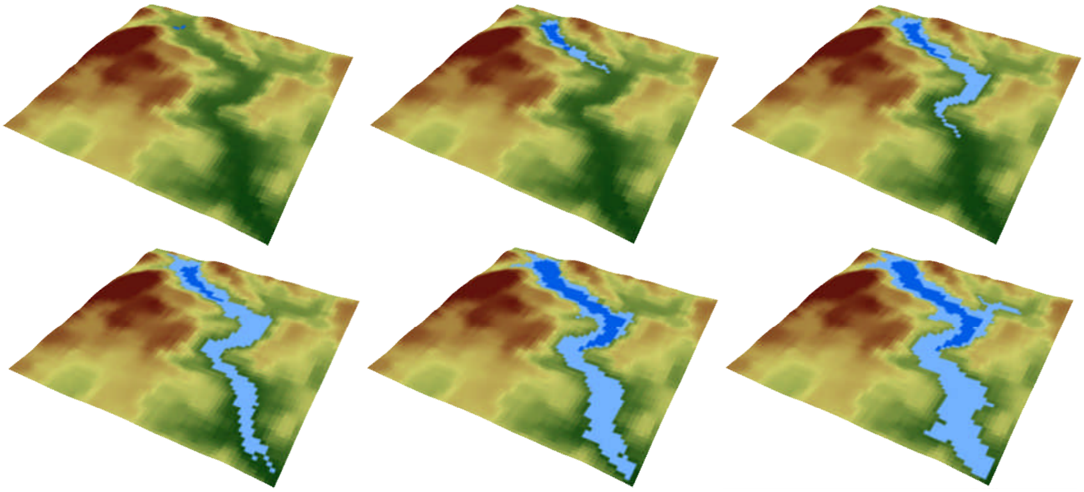

Fig. 6: Results of liquid flow simulations

CONCLUSION

To conclude, it can be stated that, although there has not been found much use for cellular automata in hydrological circles it is possible to deploy them as a tool for simulation of the liquid flow. By selecting the appropriate programming language the cellular automaton can be implemented in already existing GIS programme tools and thereby partially enhance their functionality. An important quality of the cellular automaton is in its individual approach and possibility to work independently on programme GIS applications. These arguments are already partially supported by the results obtained, which are presented at the end of the Flow Simulation chapter.

Further developments in the field of cellular automaton will be focused on the expansion of its computing parts, the capacity of the liquid infiltration as well as the possibility of entering different liquids with different densities. The results achieved will be compared and calibrated with already existing hydrodynamic models. The effort will be to get, as faithfully and accurately as possible, closer to the results obtained from comprehensive computational mechanisms that are used i.e. in hydrodynamic models.

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REFERENCES

Wolfram, S. (1984) Cellular automata as models of complexity, Nature. 311: 419-24.

Wolfram, S. (1994) Cellular automata and complexity: collected papers. Reading, MA: Addison – Wasley.

Thomas, R.; Nicholas, A.P. (2002) Simulation of braided river flow using a new cellular routing scheme, Geomorfology 43: 179-195.

Parson, J.; Fonstad, M. (2007) A cellular automata model of surface water flow, Hydrological Processes, 21.

Pilesjö, P. (1998), Estimating Flow Distribution over Digital Elevation Models Using a Form-Based Algorithm, Annals of GIS, 4.

Busaki, A.; Harson, T.; Arai. K. (2009) Modeling and Simulation of Hot Mudflow Movement Prediction Using Cellular Automata, Third Asia International Conference on Modelling & Simulation.

Shiyuan, H.;Deren, L. (2004) Vector Cellular Automata Based Geographical Entity, 12th Int. Conf. on Geoinformatics – Geospatial Information Research.