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Simulating rainfall, water evaporation and groundwater flow in three-dimensional satellite images with cellular automata

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A R T I C L E I N F O

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A B S T R A C T

Remote sensing has been used in numerous environmental simulations with the aim of solving and improving many different kinds of problems, e.g., meteorology applications, soil quality studies, water resource exploration, and environmental protection. Besides, cellular automata have been widely used in the field of remote sensing for simulating natural phenomena over two-dimensional satellite images. However, simulations on Digital Elevation Models (DEM), or three-dimensional (3D) satellite images, are scarce. This paper presents a study of modeling and simulation of the weather phenomena of rainfall, water evaporation and groundwater flow in 3D satellite images through a new algorithm, developed by the authors, named RACA (RAinfall with Cellular Automata). The purpose of RACA is to obtain, from the simulation, numerical and 3D results related to the total cumulative flow and maximum level of water that allow us to make decisions on important issues such as analyzing how climate change will affect the water level in a particular area, estimating the future water supply of a population, establishing future construction projects and urban planning away from locations with high probability of flooding, or preventing the destruction of property and human life from future natural disasters in urban areas with probability of flooding.

1. Introduction

This paper presents research applying the methodology of cellular automata to model and simulate the meteorological phenomena of rainfall, water evaporation, and groundwater flow to Digital Elevation Model (DEM) satellite images provided by NASA, showing hydrological results in numerical and three-dimensional formats of flow remaining water. Remote sensing [31] allows us to acquire information about the surface of the land and environmental information values [5] without having actual contact with the area being observed [11]. Examples of remotely-sensed applications include searching for water resources, ascertaining soil quality, addressing environmental protection, and creating meteorology simulations, among others [20].

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The weather phenomena have been extensively modeled and simulated by the worldwide scientific community. A deep investigation into the nature of these processes allows us to perceive and, above all, to predict the effects they have on the Earth's surface. Such predictions empower us to anticipate the effects of weather events in advance. For instance, at the present time we can foresee many consequences of climate change. Or, we can save lives by providing early warnings to the population before a hurricane hits.

One of the most studied and arguably the most important weather phenomenon is the process of rainfall. Its virtual modeling is a key factor in the estimation of various environmental changes caused by this phenomenon, e.g., variation of the amount of water remaining in a lake, formation of new rivers, or soil erosion process. The phenomenon of rainfall has been investigated from various scientific perspectives using diverse methods. The mathematical simulation of rainfall physical properties is a fairly complex process with many variables to consider.

Cellular automata [36] have been widely used in the last decades for environmental simulations such as modeling snow-cover dynamics [26] or snow avalanches [2], simulating land features dynamics [25] or multiple land use changes using GIS [27], modeling dynamic spatial in GIS [29], characterization of natural textures [24], modeling vegetation systems dynamics [3], detecting Vibrio cholerae by indirect measurement [28], modeling 3D clouds [23], simulating forest fire spread [21,30], understanding modular illumination systems [4], modeling lava flows [34], understanding of urban growth [9] and architectural design [8], modelling of vehicular traffic [1], classifying of satellite images [7,19], projecting population percentages infected by periodic plague [18], and simulating species competition and evolution [10].

This paper focuses on RACA (RAinfall with Cellular Automata), a new algorithm, developed by the authors, that simulates the complete rainfall process in the DEM satellite images. RACA has mainly been implemented to achieve the following four important objectives:

1. *Analysis of climate change evolution in a particular geographic region*. We can study the evolution of water level in a particular region as a result of climate change, taking into account various types of climates in order to consider possible alternatives in the future. Thus, we can analyze the influence of different types of climates on the total amount of accumulated water and the maximum water level reached in a particular geographic region, in order to predict future possible consequences.
2. *Estimation of future water supply of a population.* Taking into account the rainfall charts for the type of climate of a particular area, we can make very rough estimates of the approximate cumulative water flow in a region that has a constructed wetland. RACA also considers the initial amount of water that the lake could have (initial conditions before simulation). In addition, we can calculate the most appropriate areas for the construction of a dam to optimize the process of accumulation of water with a minimum wall built.
3. *Projection of future construction projects and urban planning.* We can identify safe regions for development around geographical areas at risk of flooding. Given all the graphs of rainfall recorded historically in a particular region, we can calculate the maximum height reached by the water at a given location in the 3D satellite image. Taking into account the results, we must avoid creating urban areas at altitudes lower than the height risk for certain areas with probability of flood in order to prevent further loss of life.
4. *Natural disaster prevention in urban areas with probability of flooding.* With the assistance of cellular automata, we can calculate the index ratio of flood disasters and streams in urban areas using the graphs of rainfall recorded historically in that region. In the visual results provided by the algorithm, we can clearly see which regions of the 3D satellite image will be covered by water after performing the corresponding simulations. Therefore, if an urbanized area appears to have a very high flood risk, the authorities can act to avoid future losses of life and property.

There exist several previous studies related to water process phenomenon simulation with cellular automata: a model for soil erosion by water [13], an algorithm for simulation of surface flows in large plains [32], algorithms for drainage network extraction and rainfall data assimilation [12], and developments of a flood inundation model based on the cellular automata approach [15]. All these research works obtained realistic results because they use a large number of states and rules in the cellular automata. However, they have the drawback that it is necessary to know a priori a large number of parameters to configure the performance of cellular automata, and therefore, it is necessary to perform a preliminary study of the simulation region. In many cases there is no such information to perform a simulation, or it is hard to get it in terms of time. However, RACA uses very few states and rules of cellular automata in order to simplify the simulation process, providing numerical and 3D quick view results on the final water level. Besides, RACA offers the possibility of making a preliminary field work of the study area in order to improve the basic results, adding water evaporation and groundwater flow to the simulation.

2. Cellular automata

A cellular automaton is a mathematical model which consists of a set of cells usually distributed in a matrix form [22]. In recent years, cellular automata have become a powerful tool applied in remote sensing especially to implement any kind of simulation processes in satellite images. From a mathematical point of view a cellular automaton is a set of six components, as shown in the following expression:

$$CA = (d, r, Q, \#, V, f) \tag{1}$$