# Simulation of Snow-cover Dynamics Using the Cellular Automata Approach

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## Abstract

The knowledge of snow-cover and its dynamics is an important factor to take into account when it is necessary to estimate the water content or to carry out hydrological studies in mountainous regions. The mathematical modelling of such a dynamics is not an easy task because of the many intervening variables and the difficulty which implies their measurements. On the other hand, during the last decades, the use of cellular automata (CA) techniques to simulate the behaviour of linear or non-linear systems is becoming of great interest. This fact is mainly due to the fact that this approach depends largely on local relations and a series of rules instead of precise mathematical formulae. This paper considers the use of the cellular automata (CA) to simulate the dynamics of the snow-cover in a mountainous terrain. The simulations of the snowed mountains, as well as the inclusion of important variables in the model, such as slope and insolation, offer enough flexibility to include in it the information provided by true digital elevation models (DEM) in future applications. While still in the early phases of development, the model provides promising results that encourage the continuation of further studies and experiences with this modern tool in order to obtain complementary and useful information.

KEYWORDS: Snow-cover, cellular automata, remote sensing

## 1. Introduction

The knowledge of snow-cover and its dynamics is an important factor to take into account when one needs to carry out hydrological studies in mountainous regions. The mathematical modelling of such a dynamics is not an easy task because of the many intervening variables and the difficulty which implies their measurements. During the last decade, the use of cellular automata (CA) techniques to simulate the behaviour of linear or non-linear systems is becoming of great interest. Furthermore, few applications to the field of remote sensing are known (Clarke, K. C. et al., 1994). This paper considers the use of that tool to simulate the dynamics of the snow-cover in a mountainous terrain under different conditions.

## 2. Cellular Automata, a brief introduction

Cellular automata (CA) were originally conceived by John von Neumann and Stanislaw Ulam in the 1940's to provide a formal framework for investigating the behaviour of complex systems (von Neumann, 1966). Cellular automata are dynamic systems which are discrete in space and time. A cellular automaton system consists of a regular grid of cells, each of which can be in one of a finite number of k possible states, updated synchronously in discrete time steps according to a local, identical interaction rule. Cellular automata (CA): is an array of "cells", which interact with one another. The arrays usually form either a 1-D string of cells, a 2-D grid, or a 3-D solid.

The essential features of a cellular automaton are:

- its state: is a variable that takes different values for each cell. The state can be either a number or a property
- its neighbourhood: is the set of cells that interact with the cell in question. In a grid these are normally the cells physically closest to it

A cell' state will change according to a set of transition rules that apply simultaneously to every cell in the space. These rules are based on both the current state of the cell under study and also the collective state of its neighbours.

Examples of neighbourhood used in cellular automata can be observed in Figure 1.

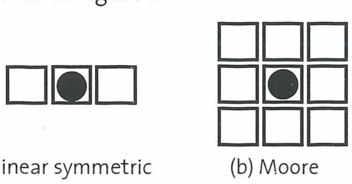
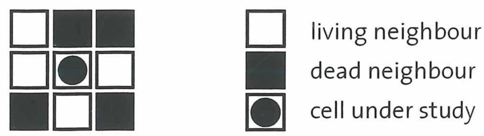



**Figure 1:** Different types of neighborhood used in cellular automata.

### 2.1. One example of system studied by using CA theory

The Game of Life: The first system extensively calculated on computers was the "Game of life" (Gardner, 1970). This "game", invented by John H. Conways, is based on cellular automata theory and uses a two-dimensional square space which is simply a matrix or grid. It was called "Life" because of its analogies with the rise, fall and alternations of a society of living organisms.

The Game of Life: Conways´s Rules




John Conway´s rules

- A living cell with 4 or more living neighbours, dies for overcrowding
- A living cell with only 0 or 1 living neighbour, dies for isolation
- A dead cell with exactly 3 living neighbour, becomes alive
- All other cells become alive

One particular example of "living system" is the so called "Glider" which dynamical behaviour after 2 steps is shown in Figure 2:

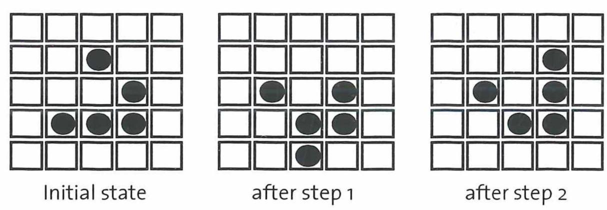



**Figure 2:** The "glider" figure after 2 steps of applying the Conway's rules. A square with a black circle inside is considered as an alive cell.

## 3. Generation of working data

To demonstrate the usefulness of the CA approach for the estimation of the snow-cover dynamics, a simulated mountainous terrain will be used. Furthermore, the assumption of a snowed region, the corresponding Digital Elevation Model (DEM), and an insolated situation will be taking into account in order to consider different conditions. Afterwards, the reduction of the snow-cover by smelting, during a given time duration and under different conditions, will be estimated

### 3.1. Generation of the synthetic mountain (DEM)

The synthetic mountain is generated by using 2-D sinusoidal functions. In Figure 3 we can see the mountain as seen from the top. The elevation is represented by different grey levels. The bar at the right side of the figure shows the elevation of the mountain is given in arbitrary elevation units. The whiter the colour, the higher the elevation. In fact, this figure is a DEM of the synthetic mountain. The altitude of the mountain goes from 0 up to 63 elevation units. A perspective view of the mountain can also be observed in Figure 4.

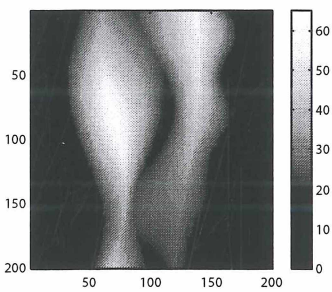



**Figure 3:** DEM of a synthetic mountain. The bar at right represents its elevation units.

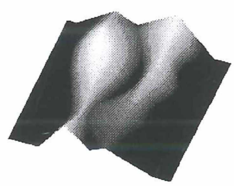


**Figure 4:** Perspective view of the mountain in Figure 5.

### 3.2. Generation of the snow cover

The snow cover is represented in Figure 5. We can observe the area covered by the snow supposing the snow-line is located at a uniform altitude of 35 elevation units. (in all the paper the elevation will be referred to that used in Figure 3). The snow-cover image is a binary image; i.e.: white=1 (snow), black=0 (no snow).

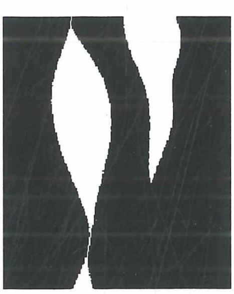


**Figure 5:** Area of snow covering the mountain of Figure 5 for an altitude equal or over 35 elevation units.

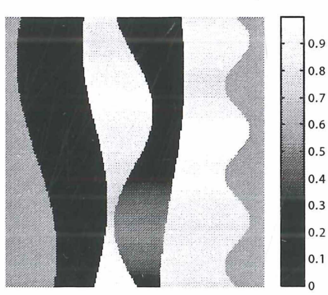



**Figure 6:** Normalized isolation values (0 to 1) for the mountain of image 5, assuming the sun is in the East and at an elevation of 50°.

### 3.3. Generation of the insolated region

The synthetic image shown in Figure 3 is supposed being illuminated from the East, with the sun located at an elevation angle of 50 degrees. The magnitude of insolation varies continuously from 0 to 1, depending on the exposition angle of the mountainous surface. The bar at the right of the figure represents the normalized levels of insolation.

## 4. Application of the CA theory to dynamic studies of snow-cover

In this section we present a CA approach to calculate the dynamics of the snow-cover during a given elapsed time. Starting from a given initial time and with a fixed snow region, such as that represented by the white colour in Figure 5, the snow-cover will suffer a reduction of its surface owing to different situations. In our case we will consider that the snow-cover reduction obeys to four different cases based on different situations of the snowed region. For all the cases we will consider the dynamics of the snow reduction after 20 time units.

### 4.1. Dynamic of the snow-cover in a flat surface by using a linear CA neighbourhood

In this case we suppose a snow-cover as a flat surface, assuming that the smelting of the snow comes from the borders of the snowed region. The CA neighbourhood is a linear block of cells (1x3), such as that showed in Figure 1.a.

The working image S is that of the snowed region (Figure 5). After applying the snow reduction process by means of the CA approach we obtain the output image R. The rule applied in this case is very simple:

Given a neighbourhood

$$N=[\, S(i,j-1)\;\; S(i,j)\;\; S(i,j+1)\,]$$

the rule is as follows:

$$\text{if } N=[1\,1\,1]\;\; R(i,j)=1, \;\; \text{else } R(i,j)=0$$

In Figure 7 we can observe: in (a) the remaining snowed area after 20 time units; in (b) the dynamics of the remaining area is shown.

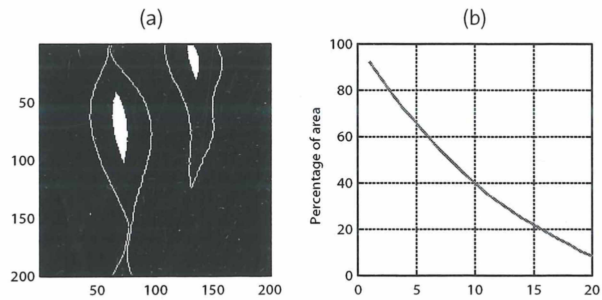



**Figure 7:** Snow cover on a flat surface and CA with neighborhood of Moore: (a) Remaining snow cover after 20 time units and T=6, (b) Dynamic behavior of the snow-cover.

## 4.2. Dynamic of the snow-cover in a flat surface by using a Moore CA neighbourhood

In this case, as in the first one, we suppose a snow-cover as a flat surface. The assumption that the smelting of the snow comes from the borders is also maintained. The CA neighbourhood is a Moor block of cells (3x3), such as that showed in Figure 1.b.

The working image S is that of the snowed region (Figure 7). After applying the snow reduction process by means of the CA approach we obtain the output image R which can be seen in Figure 8.a. The rule proposed in this case is very simple:

Given the neighbourhood

$$N=[\, S(i\text{-}1,j\text{-}1),\ S(i\text{-}1,j),\ S(i\text{-}1,j\text{+}1),\ S(i,j\text{-}1),\ S(i,j\text{+}1),\ S(i\text{+}1,j\text{-}1),\ S(i\text{+}1,j),\ S(i\text{+}1,j\text{+}1)]$$

the rule is as follows:

$$\text{if } \Sigma\,(N) \le T,\ R(i,j) = 0$$

where T is an arbitrary threshold : $2 < T < 8$

As we can observe, the threshold T allows the change of the dynamic rate in the snow reduction. This is possible thanks to the use of more pixels in the neighbourhood. Figure 11 shows the behaviour of snow reduction for different values of the threshold T; when higher the value of T more fast is the reduction of snow.

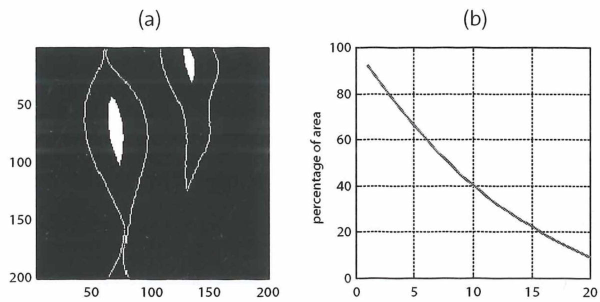



**Figure 8:** Snow cover on a flat surface and CA with neighborhood of Moore: (a) Remaining snow cover after 20 time units and T=6, (b) Dynamic behavior of the snow-cover.

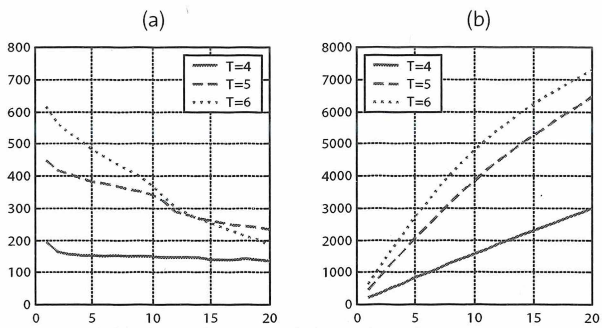



**Figure 9:** Behaviour of snow reduction for different values of the threshold T: (a) Extracted area per step for 3 values of T, (b) Corresponding accumulated areas extracted during 20 time units.

## 4.3. Dynamic of the snow-cover taking account of the DEM

In this case, the dynamics of the snow-cover reduction will be estimated taking into account the DEM of the synthetic mountain. The additional assumption is that at higher elevations the environmental temperature is lower than that at lower elevations; therefore, the snow reduction rate will be lower at higher altitudes compare to that occurring at lower altitudes. To that end the snow cover will be arbitrarily divided in 3 levels of altitude which are named region 1, region 2 and region 3 according to the diagram shown in Figure 10.

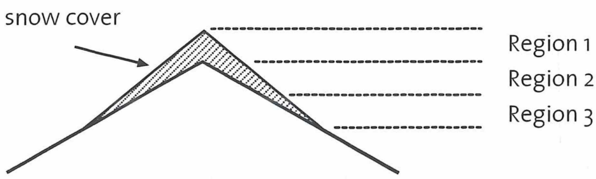



**Figure 10:** Different regions of snow-cover according to its elevation.

To taking into account this situation, the proposed rule is as follow:

Given the neighbourhood

$$N=[\, S(i\text{-}1,j\text{-}1),\ S(i\text{-}1,j),\ S(i\text{-}1,j\text{+}1),\ S(i,j\text{-}1),\ S(i,j\text{+}1),\ S(i\text{+}1,j\text{-}1),\ S(i\text{+}1,j),\ S(i\text{+}1,j\text{+}1)]$$

the rule states:

if $\Sigma\,(N) \neq 0$ it means that the analysed area is snowed; in that case:

if snow is in Region 1, T=5

if snow is in Region 2, T=4

if snow is in Region 3, T=3

then, if $\Sigma\,(N) \le T,\ R(i,j)=0$

The result of this operation can be seen in Figure 11, in (a) is the remaining area of snow after 20 time units. In (b) we have the behaviour of the snow reduction in percentage of the total area.

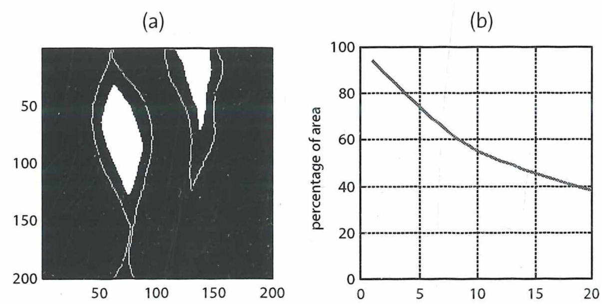



**Figure 11:** Snow cover reduction considering DEM and a Moore neighborhood: (a) Remaining area after 20 time units, (b) dynamic of the remaining area after 20 time units.

### 4.4. Dynamic of the snow-cover taking account the insolation

In this case, the dynamics of the snow-cover reduction will be estimated taking into account the information provide by the illuminated area (Figure 6). In that figure we assume that the insolation of the surface owes to the presence of the sun located at the moment of the observation, in the East (right side of the image), and at an elevation of 50 degrees. The result of the snow reduction estimation is shown in Figure 12, where the more insolated area suffers a remarkable reduction of snow. Figure 12 (b) shows the dynamic of that reduction during a period of 20 time units.

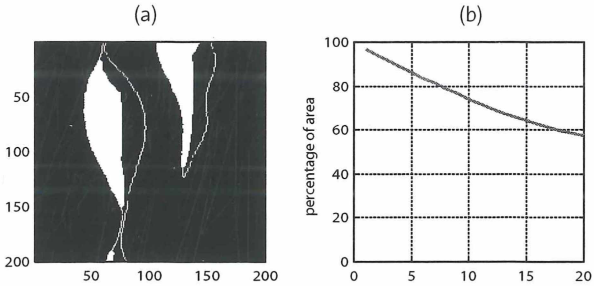



**Figure 12:** Snow cover reduction considering insolation and a CA Moore neighborhood: (a) Remaining area of snow-cover after 20 time units, (b) Percentage of reduction of the snow-cover during the elapsed time.

## 5. Conclusions

The present paper demonstrates the practical use of cellular automata (CA) to carry out studies of snow cover dynamics. This modern tool shows enough flexibility to simulate the snow cover in mountainous regions, with the inclusion of important information in the model, such as that provided by digital elevation models (DEMs) and insolation.

The proposed technique here presented is still in the early phase of development, therefore, the applications were carried on synthetic models of the terrain and idealized models of the snowed area. The results, however, are promising to continue further studies aiming at complementing those obtained by complicated and not always accurate mathematical models.

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