

## SOIL INFILTRATION EFFECT IN FLAT AREAS FLOODS SIMULATION

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**Key words:** Soil infiltration, floods simulation, shallow water equations, finite volume method

**Summary.** A enormous amount of literature exists in shallow water equations (SWE) application to model flood events. Several methods have been developed to improve the stability and accuracy in presence of wetting fronts. Some questions related to the real flooding phenomenon have been discarded compared to the pure numerical methods research. In this work the water infiltration is introduced as a new element to improve accuracy in the floods simulation. Several different phenomena are included as infiltration, for example soil retention or vegetation interception.

### 1 INTRODUCTION

The use of 2D-SWE models is usual in engineering works and the existing knowledge and applications are mature. Application of these models to flood fronts propagation over dry bed is one of the main employment areas, and, as a consequence, the research in this area is very active, in analytical area<sup>1</sup> as well as in numerical methods<sup>4</sup>. Most of the numerical advances have been carried out in the finite volume method (FVM) framework, in this work this is the selected numerical technique. The flooding wave modeling is improved using several methodologies to compute infiltration. Considering that floods occur over natural topographies, the effect of water loss, due infiltration or retention should be investigated. It's clear that is not possible to generalize the importance of infiltration in floods modeling, for the geologist is known that the spatial variability in geology, soils and land use is considerable, and these are the main variables in infiltration.

### 2 INCLUSION OF INFILTRATION TERM IN SWE

In this section the equation system will be described; knowledge related to SWE is general and included in multiple bibliographies<sup>12</sup>. The classical SWE are modified to include the infiltration, only one term is added to the continuity equation, it should be noted that in a rigorous way, also the momentum equations should be modified to include the momentum reduction due to mass loss, but supposing the infiltration rate as small compared to the remain terms, the effects on the momentum are neglected. The adopted SWE form is:

$$\left\{ \begin{array}{l} \frac{\partial h}{\partial t} + \frac{\partial hu_x}{\partial x} + \frac{\partial hu_y}{\partial y} - I = 0 \\ \frac{\partial hu_x}{\partial t} + \frac{\partial}{\partial x} \left( hu_x^2 + g \frac{h^2}{2} \right) + \frac{\partial hu_x u_y}{\partial y} = (S_0 - S_f)_x gh \\ \frac{\partial hu_y}{\partial t} + \frac{\partial hu_x u_y}{\partial x} + \frac{\partial}{\partial y} \left( hu_y^2 + g \frac{h^2}{2} \right) = (S_0 - S_f)_y gh \end{array} \right. \quad (1)$$

Where  $x, y$  are the spatial coordinates,  $t$  is the time,  $h$  is the water depth,  $u_x, u_y$  are the depth averaged velocities in the axes,  $g$  is the gravity,  $S_0, S_f$  are the terrain surface slope and the friction slope and  $I$  is the infiltration rate. The subindexes  $x, y$  indicate the projection in the spatial axes; the gravity term  $S_0$  and the friction term  $S_f$  are vectors, the gravity one in the steepest path direction, and the friction one in opposite direction to the velocity, so the projection term has sense. It's important to emphasize the fact that the infiltration rate  $I$  is in the same units as the depth change, this is important because in the infiltration models, the infiltration rate appears but should be corrected with the soil porosity  $n$ , to compare soil infiltration to runoff infiltration.

### 3 DISCRETE FORM

Several options exist to obtain the discrete version of the infiltration term; the mathematical classification of the modified SWE is variable. The mathematical behavior of the equations should be taken into account when selecting the numerical method, in order to skip the classification variability of the modified SWE, the infiltration process is split. First the classical SWE are solved and later the infiltration is computed to update the depth values, in a kind of operator splitting<sup>9</sup>. This method reduces accuracy but considering the minor influence of infiltration the error should be fitted.

### 4 INFILTRATION SIMULATION

The aim of this work is to test the effects of infiltration in flooding processes. In the hydraulic models, normally the infiltration is neglected. For flat areas the water levels are very low and maybe similar to the infiltration amount, the question is that to propagate correctly the flooding front perhaps is necessary to consider the infiltration effects over flat areas. An important question is related to the antecedent rainfall situation, the water infiltration will depend on the previous rain, if the area is saturated the effect over the flooding propagation will be completely different. In this work the terrain is considered to be almost dry, so in theory a flood is being calculated in an area where is not raining. The infiltration models and techniques that will be considered:

- a) Green & Ampt infiltration model
- b) SCS-CN infiltration model
- c) Depth threshold for flux
- d) Depth threshold with restoration

All these methods are used to try to evaluate the  $I$  term in the modified SWE, the physical origin of these different methods is wide but all of them have been used in the hydrology framework.

#### 4.1 Green and Ampt

In the development of the classical Green & Ampt model the surface water depth is neglected because is considered small, but in the present framework the water depths could be high, so could not be neglected in the equation development, the final adopted form for the equation is:

$$\frac{1}{n} \frac{\partial F}{\partial t} = \frac{1}{n} I = -K_s \left( (\Psi_f - h) \frac{\theta_s - \theta_i}{F} + 1 \right) \quad (2)$$

Where  $F$  is the total infiltration,  $I$  the surface infiltration rate,  $n$  is the porosity,  $\Psi_f$  is the dry suction, normally negative values,  $\theta_s, \theta_i$  are the saturated and initial soil moistures and  $K_s$  is the saturated hydraulic conductivity. As was commented previously, the infiltration rate should be corrected with the porosity to be compared to the runoff infiltration. The ODE is discretized using forward Euler to be in agreement with the Godunov method used in the SWE solution:

$$F_{ij}^{n+1} = F_{ij}^n + n\Delta t K_s \left( (h_{ij}^n - \Psi_f) \frac{(\theta_s - \theta_i)}{nF_{ij}^n} + 1 \right) \quad (3)$$

The subindexes  $i, j$  indicate the cell coordinate, superindex  $n$  indicate the time step, and  $\Delta t$  is the time increment, finally the depth is updated:

$$h_{ij}^{n+1} = h_{ij}^n - (F_{ij}^{n+1} - F_{ij}^n) \quad (4)$$

#### 4.2 SCS method

The SCS method it's considered as infiltration method <sup>2</sup>, and is based in the water balance equation:

$$P = I_a + F + Q \quad (5)$$

Where  $P$  is the total rainfall,  $I_a$  is the initial abstraction,  $F$  is cumulative infiltration excluding initial abstraction and  $Q$  is the direct runoff. To this basic equation a few hypothesis are added. An hypothesis relates the initial abstraction ( $I_a$ ) to the potential maximum retention ( $S$ ):

$$I_a = \lambda S \quad (6)$$

Being  $\lambda$  the proportionality factor, usually 0.2, combining all these elements the classical SCS-CN equation is obtained substituting the  $\lambda$  value:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad \text{or} \quad Q = \frac{(P - I_a)^2}{P + 4I_a} \quad (7)$$

As it's clear, a one parameter model is obtained, once this parameter is fixed, the total runoff only depends on the total rainfall amount. The time does not appear explicitly in the equation and therefore the rain intensity is missing in the model, so the cumulative infiltration  $F$  is independent of the storm duration. To compute the depth after infiltration in the last time step  $n$  the equation used is:

$$h_r^n = \frac{\left( \sum_{i=0}^n h^i - I_a \right)^2}{\sum_{i=0}^n h^i + 4I_a} - \sum_{i=0}^{n-1} h_r^i \quad (8)$$

Is straight to see that the problem with this model is the time lack, so, independently of the flooding water rising time, the infiltrated water amount is constant when a certain cumulated depth is reached. If the wetting front is formed by a sharp shock or a smooth wave, the depth abstraction is the same.

### 4.3 Runoff thresholds

Following the  $I_a$  (initial abstraction) concept existing in the SCS method, thresholds are proposed for depth before flow occurs. Two different methods dealing with these thresholds are proposed. The first method acts as a permanent water abstraction, so certain amount of water is removed in the cells until a limit is reached, then the flow starts. In the second method, once the limit is reached all the water flows, so there is not surface retention.

The existence of a depth threshold before the surface runoff initiation is explained using two different concepts. The first one comes from the original contribution of <sup>8</sup>, where the rain interception concept is introduced. The interception is related to the water capture by means of plants leafs and vegetation in general. Of course water flow and rain are essentially different processes, but the background idea considering the vegetation water storage is interesting for our purposes, the total amount could be between 0.25 and 1.5 mm <sup>5</sup>. The quantities should be adapted because the trees interception does not concern to flow process, grass, pastures and meadow effects should be considered instead.

The second concept to justify the depth threshold for runoff is the surface retention or depression storage <sup>11</sup>, several elements are included under this title, in general is referred to the water retained due to the existence of puddles, ditches among other natural or artificial depressions on the land, also the land use influence is a prime factor. There are some intuitive ideas belonging to this feature, for example as steep the slope is as smaller the retained volume is. As a reference values <sup>13</sup>, for lawn grass an 8 mm runoff threshold is recommended, and for open fields a 10.6 mm, for bluegrass turf a 5 mm value is recommended, for

agricultural soil a range between 0.6-7.5 mm is useful, similar values could be also found in <sup>3</sup>. There are more complex possibilities including the influence of different sizes of the surface depressions where the water is stored, for a complete review there are useful texts <sup>7</sup>.

## 5 TEST CASE

Several test cases were used, theoretical and real, due to space lack only the real test case is presented. The analytical test cases give information about the differences in the approaches. In this section, an application to a real event is shown. On October 13<sup>th</sup> 2005 an extreme rainfall occurs in the Catalonian Mediterranean coast. Several basins were affected by the floods; one of these streams called Calonge is selected to test the proposed infiltration methodologies.

### 5.1 Flooding event description

The Calonge basin is a 57 km<sup>2</sup> watershed located on the north coast of the Catalonia region, the so-called "Costa Brava" (Figure 1 left). The slopes are relatively steep (3,5 % mean slope) and concentration time short (4 hours aprox). Heavy rains in the upstream area of the basin generate an increase of water levels due to the flood wave propagation with very short response times (2 hours). The river crosses the town of Sant Antoni de Calonge (10.500 inhabitants) and the urban areas invade the downstream floodplains regardless the high risk of flooding. The constant urbanization pressure has reduced the width and hydraulic capacity of the original torrent, so on the October 13<sup>th</sup> 2005 event, important damages due to river flooding and river erosion occurred.

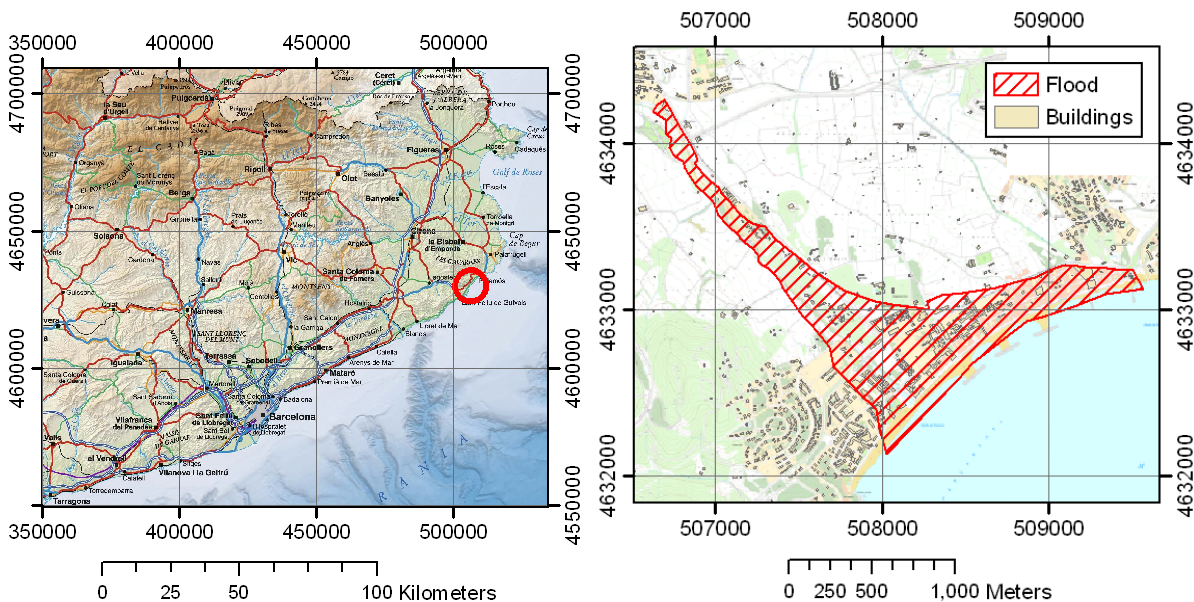


Figure 1: (Left) General view of Catalonia and in the red circle the "Sant Antoni de Calonge" village. (Right) Flooded area in the 2005 event in the Calonge river mouth.

A total precipitation amount of 350 mm was registered during the event on 12<sup>th</sup> -13<sup>th</sup> October 2005 with an approximately 48 hours rainfall duration, and a maximum rainfall intensity of 80 mm/hr. A 200 year Return Period rainfall is estimated for this event, so it has been classified as an extreme flash flood event. Hydrological modeling has been applied in the basin in order to simulate the runoff hydrographs in the downstream outlet (in the Sant Antoni de Calonge Section) due to the lack of flow gages in the Calonge river (ungaged basin). Two discharge peaks occurred in the river with 10 hours of delay, a maximum of 350 m<sup>3</sup>/s peak discharge was been estimated.

In consequence, the lower, left overbank area of the town was flooded and an old woman was drowned and died when getting out of her house. Later, a post-event field survey was conducted in order to delimitate the flooding extension (Figure 1 Right). The limits of the flooding have been used in the present study as a reference for the 2D hydraulic simulations.

## 5.2 Results

To simulate the floods, the bidimensional model FLATModel is used<sup>10</sup>. The structured grid size consists of 966x748 nodes and the cell size is 3 meters. The topography is constructed using 1 meter resolution LIDAR data. To compute the whole event a computational cluster is used, running the parallel version of the code over 16 nodes. The selected flooding area includes structures and buildings; in order to simulate the effect of these elements on the flow, the model includes cell blocking, as can be observed in a lot of existing literature about this topic<sup>6</sup>. The 30 hours of the hydrograph are simulated. The result without infiltration will be used as a reference.

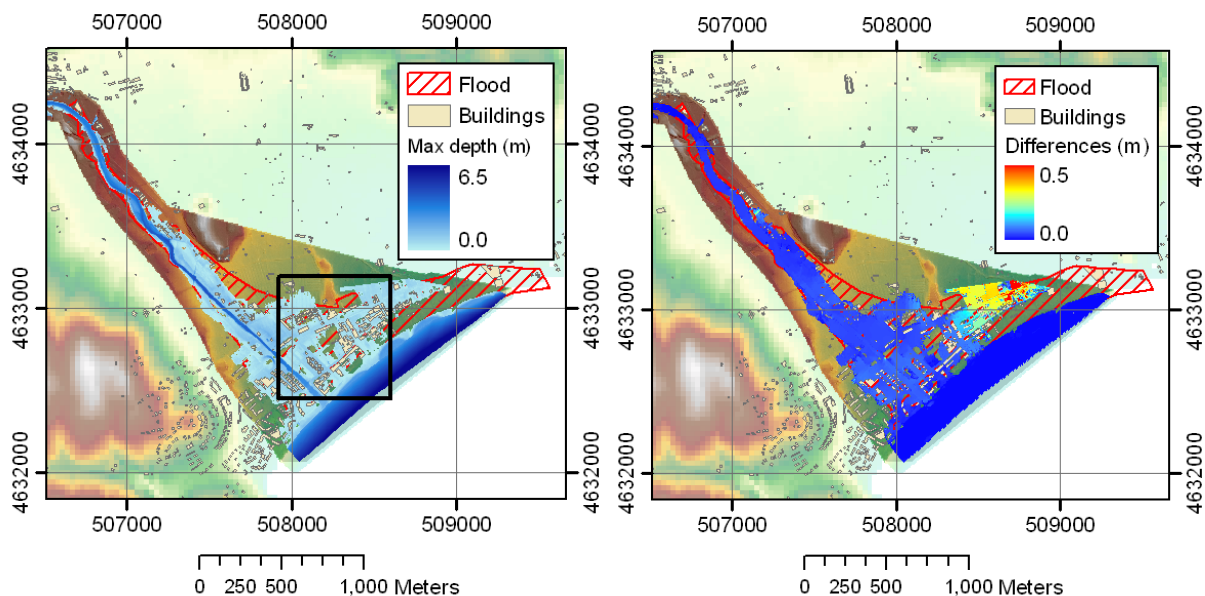


Figure 2: (Left) Maximum depth results obtained without infiltration, (Right) Differences in the maximum depth between the Green and Ampt infiltration algorithm and without infiltration.



The maximum depth along the simulation is shown In Figure 2, left. Due to the fact that the hydrograph is obtained through a hydrological modeling of an ungaged basin calibration should be required, anyway the preliminary results fitted quite well the flooded area. The main differences are due to the fact that the LIDAR topography (shown as picture background) does not cover all the flooded area, so the east corner of the flood is not included.

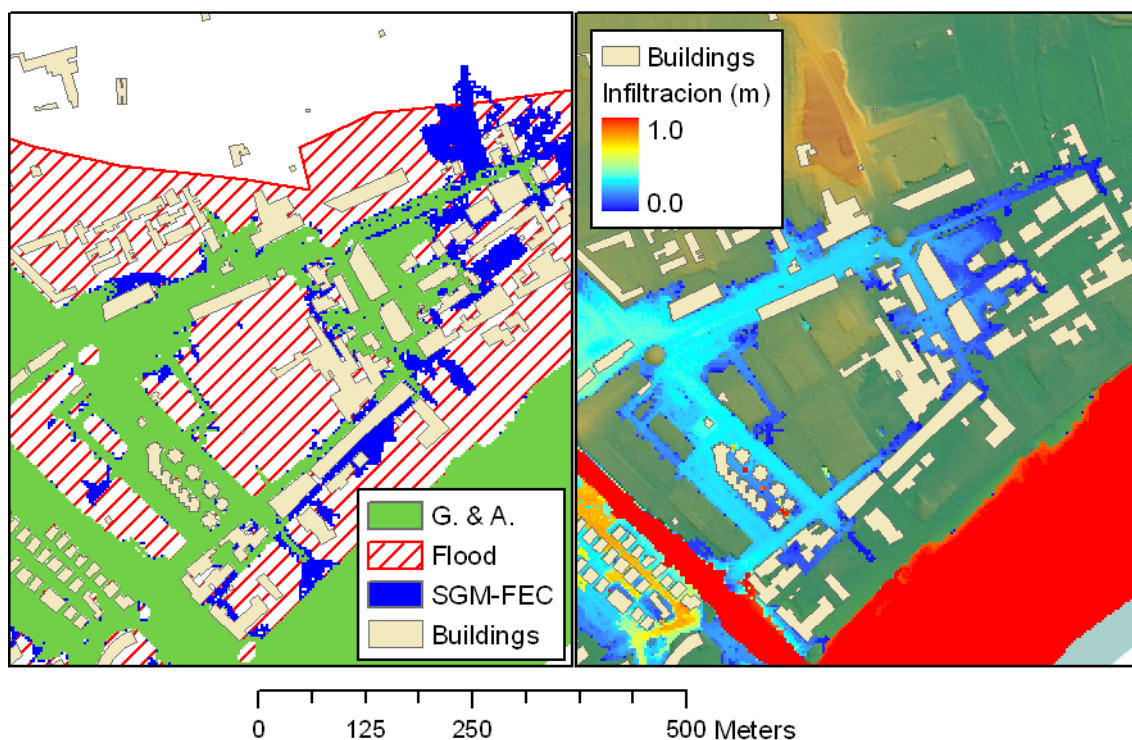


Figure 3: (Left) Maximum flooded area using the Green and Ampt infiltration (green color) and extra area flooded without infiltration (blue color). (Right) Infiltration value using Green an Ampt.

Only the comparison to Green and Ampt infiltration is presented in this short article ( $K_s = 0.00005 \text{ m/s}, \Psi_f = 0 \text{ m}, \theta_i = 0.0, \theta_s = 0.4$ ). The results presenting the influence in the flooded area extension with and without infiltration are presented in Figure 3, left. There are some flooded areas with the Green & Ampt method which were not flooded in the SCS-CN method and also the reverse situation could be found. The rule governing the differences is not clear but should be related to time, because infiltration in Green and Ampt depends strongly on it. The infiltration at  $t = 5 \text{ hr}$  is shown at the right side of Figure 3. The total amount of infiltration is greater than the previous results. This could be related to the selected parameters, but also the values are not homogeneous as those obtained with the previous methods. The areas wherein a permanent water depth is found (river bed and sea) have a large amount of infiltration, reaching more than a meter. Again a grid of hydraulic conductivities and initial moistures will improve the accuracy. The differences in the maximum depth are

shown in Figure 2, right. The values are large, more than half meter is found, probably due to the fact that the distant areas need more time to be flooded, so the infiltration process has more time to act reducing the flooding intensity. Again the area where the maximum depth is affected is the west end of the domain.

## 6 CONCLUSIONS

The role that plays infiltration in floods propagation models is not clear, an attempt to establish it is presented in this document using four different approaches. For every algorithm several references are introduced to justify the origin and the estimated values. A real case, of a flood occurred in Catalonia is presented and used to estimate the real effect of the different infiltration models. Analyzing the results, it seems that the different approaches are classified in two groups, the thresholds and the SCS-CN in the first group, and the Green & Ampt method in the second group. The time lack in the SCS-CN method approximates its behavior to the threshold methods. The Green & Ampt method results in a more realistic model but requires three different parameters, while the threshold methods are based just in one.

The choice should be between using a simplified method or a complex one. As simplified method, the threshold one could be an interesting option. If a complex infiltration model is preferable the Green & Ampt is a good option, but implies a parameter calibration process. In both cases the modification in maximum water level is not so evident, depends strongly on the particular characteristics of every area.

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