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A Computational Environment for Water Flow along Floodplains

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A numerical model for the computer simulation of large floodplain inundations is presented. The model is extremely simple in order to achieve efficient computations in regions greater than 1000 km^2. It is based on raster Digital Elevation Models (DEMs) and rules for water interchange between neighbor cells. The computer implementation, AQUA code, includes facilities for interpolation of precipitation data, graphics visualization and interactive DEM modification for simulation of alternative scenarios. The numerical performance was analyzed in some simple cases and the model was applied to a 1600 km^2 landscape corresponding to the region of Pehuajo in Argentina, which experiences frequent floodings.

Keywords: Floodplain inundations; Flooding; Large-scale simulation; DEM

1. INTRODUCTION

Simulations of surface flow in landscape models play an important driving role in floodplain management. In addition, surface water flow is a major transport mechanism in plain hydrology, either by delivering the elements to the biota or by removing the constituents in excess. Although considerable efforts have been put into creating adequate models for various landscapes, still there are no universal one that can be easily adapted for a wide range of applications. In Kouwen *et al.* (1993), Chen and Beschta (1999) and Kilsby *et al.* (1999) different models to address this problem can be seen. Substantial efforts are needed to tune existing models to the specifics on each landscape and the goals of the study. In general, hydrologic models are part of more complicated modeling structures, therefore requiring simple algorithms to run within the framework of the entire ecological scenario. Consequently, some details should be sacrifice in order to make the numerical calculation feasible. An important trade-off in hydrologic models is the coarser spatial and temporal resolution that should be employed (kilometers and days), in contrast to small scale flows (meters and seconds). The classical numerical methods, as finite differences or finite elements, hardly can be afforded in the former case.

The kinetic wave approximation of the St. Venant equations is a popular tool that have been applied to the simulation of linear flood routing in rivers (Ervine and MacCleod, 1999). In dealing with two-dimensional overland flows, explicit numerical schemes were used (Abbott *et al.*, 1986; Bates *et al.*, 1992). Explicit methods are appropriate when complex boundaries cannot be avoided, but they are stability dependent on the spatial and temporal resolution.

Current understanding of floodplain hydrology suggests that hillslope water levels play an important role in fluxes into and out of the alluvium. Previous numerical modeling of floodplain hydrology has ignored fluxes of water to and from surrounding hillslopes (Whiting and Pomeranets, 1997). Clear scope exists for a combined modeling and field monitoring of hydrological interactions within lowland floodplains while maintaining the simplicity necessary for feasible computations.

At present we still do not know what process representation should be included in a floodplain inundation model to achieve given levels of predictive ability. Ultimately, the best model will be the simplest one that provides relevant information while reasonably fitting the available data.

In this paper, AQUA, a numerical technique to simulate the surface water flow in large plain landscapes is presented. It aims to reduce the representation of floodplain hydraulics to the minimum necessary to achieve acceptable predictions. The method is based in a coarse mass inventory balance, accounting for inflows,

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outflows and sources in the two-dimensional support cells of a digital elevation model (DEM).

2. AQUA MODEL DEVELOPMENT

The basic and critical component of the AQUA model is a raster DEM with a resolution sufficient to identify the elements necessary to inundation prediction, such as depressions, dykes and channels. Sugumaran *et al.*, (2000) already shown the importance of this type of DEM for the floodplain management. Basically, this data consist of the vertical coordinates associated to each cell of a two-dimensional grid representing the region under study. Actually the DEM accuracy cannot be known *a priori* and may depend on the application, so an informed guess is required for model development. In time, we should be able to determine guidelines for this aspect of the modeling process. The construction of a high precision DEM is an open research field (Renouard *et al.*, 1995) is one of several works that address this particular problem.

Having defined our basic data source the next step is to consider the representation of the surface water flow. Floodplain inundation occurs when the water ceases to be contained in the rivers and spills onto the adjacent shallow lands. These floodplains act either as temporary stores for the water or additional routes for flow conveyance.

Let us consider a unit cell for a one-dimensional case shown in Fig. 1. The AQUA model pictures the cells connected by floodgates that are opened and closed in turns, allowing the water to flow driven by the elevation differences between cells. Additionally, water mass sources and sinks are associated to each cell, accounting for infiltration, precipitation inflows and outflows due to see page or evapotranspiration.

2.1 Surface Flow Algorithm

To calculate the surface flow between cells, AQUA isolates 3×3 neighborhoods around each cell, and lets the water drain to the lowest positions (Fig. 2). The algorithm is the following:

1. Calculate the amount of water contained in the neighborhood.
2. Arrange the cells according to their height.
3. Distribute the water in the cells starting with the lowest, and then continuing with the following, taking care that the water level equals in all the cells (Fig. 1).

The procedure is repeated iteratively until the entire grid is covered. This algorithm works well as long as the

FIGURE 1 Water balance between neighbor cells.

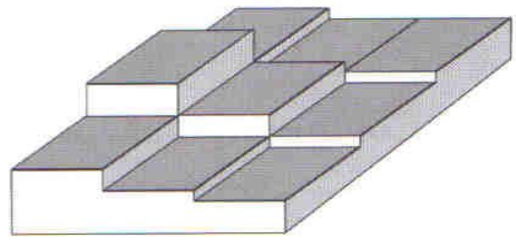

FIGURE 2 3×3 set of cells used for the water balance.

fluxes are low, for high fluxes result in numerical instabilities. To avoid this problem, a relaxation coefficient is included, which also plays the role of a time step control. Accordingly, the new water levels after a local drain step, is calculated as:

$$h_{\text{new}} = \alpha h_{\text{calc}} + (1 - \alpha) h_{\text{old}}$$

where h_{old} is the water level before the local drain, and h_{calc} is the water level calculated with the surface flow algorithm. The relaxation factors, α, takes values between 0 and 1, and should be determined to fit the experimental data. The lower the value of α the slower will be the flow process. In general, α can be dependent on the location, and therefore it may be interpreted as a conductivity coefficient or as the inverse of a roughness coefficient. Eventually, the incorporation of classical flood routing procedures would allow a realistic interpretation of the proposed routing algorithm.

2.2 Sources

Precipitation, infiltration and evapotranspiration are modeled in AQUA as sources in each cell. Let us assume the domain is a closed aquifer, that is, no income or outcome flows occur at the boundary. In this case the only incoming water come from precipitation. The precipitation is measured in a reduced set of points, and based in these data the source in each cell can be calculated by piecewise interpolation over the whole domain The interpolation procedure is carried out in two steps:

1. A Delaunay triangulation of the set of measured points is constructed. In addition, AQUA offers the possibility to freely add new precipitation measure points at any time.
2. Given the triangulation and a set of precipitation data in some nodes, AQUA computes the precipitation for all the cells interpolating linearly in each triangle. The value obtained is added to the current water level in the cell.

Infiltration is modeled as a negative source in each cell, which in general depends on the characteristic of the soil. Evapotranspiration is also treated as negative sources distributed in every cell, according to the local temperature and vegetation. Several models are presented in the literature to take into account this mechanism, the

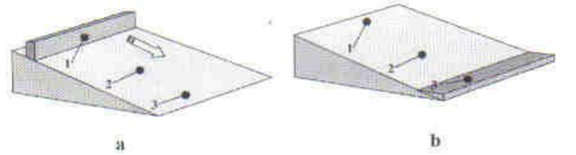

FIGURE 3 Drain downhill a uniform slope. (a) initial and (b) final state.

selection of the most appropriate method being a task of the user. AQUA provides the possibility of including particular algorithms for negative sources.

2.3 Computational Implementation

The algorithm was implemented to minimize the memory requirement. The program was able to process 4×10^4 pixels/s using a 100 Mflops/s system. Since the cost of the algorithm is linear with the number of pixels, thousands of km^2 can be easily studied interactively. Better performances can be achieved using an alternative implementation that keeps the cells ordered by levels. However, the latter will increase significantly the memory requirement.

Due to the relative low computational cost, AQUA can incorporate an interactive environment with graphic tools to visualize step by step the flood routing, either globally or simulating three-dimensional perspectives under OpenGL. Blue tones can be easily used to represent the water depth (see for example, Figs. 6 and 7).

3. ANALYSIS OF SIMPLE CASES

Several simple cases with known solution were studied in order to analyze the performance of the AQUA model. We show here a case of downhill flow of an initial amount of water along a uniform slope (see Fig. 3). No infiltration and evapotranspiration is considered. Figure 4 shows the evolution of the water level in three sample points at the top, middle and bottom of the domain. An arbitrary value of 0.02 for the α coefficient is taken, and therefore the

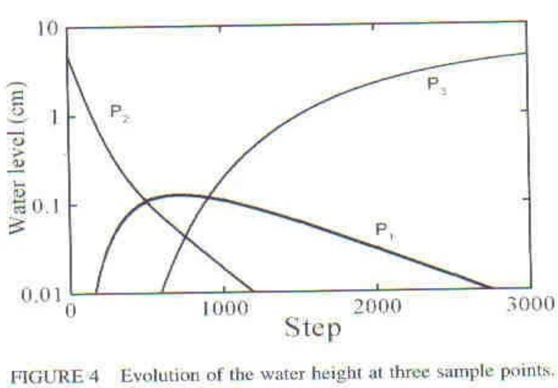

FIGURE 4 Evolution of the water height at three sample points.

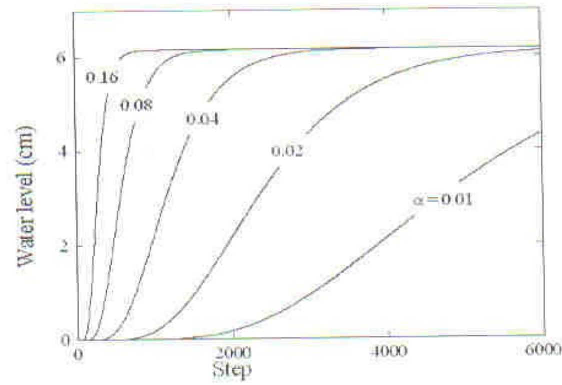

FIGURE 5 Influence of the conductivity coefficient α.

horizontal axis should be interpreted as computer iterations, corresponding to some time scale that should be determined by comparison against experimental data. As expected, the total water mass is conserved. The effect

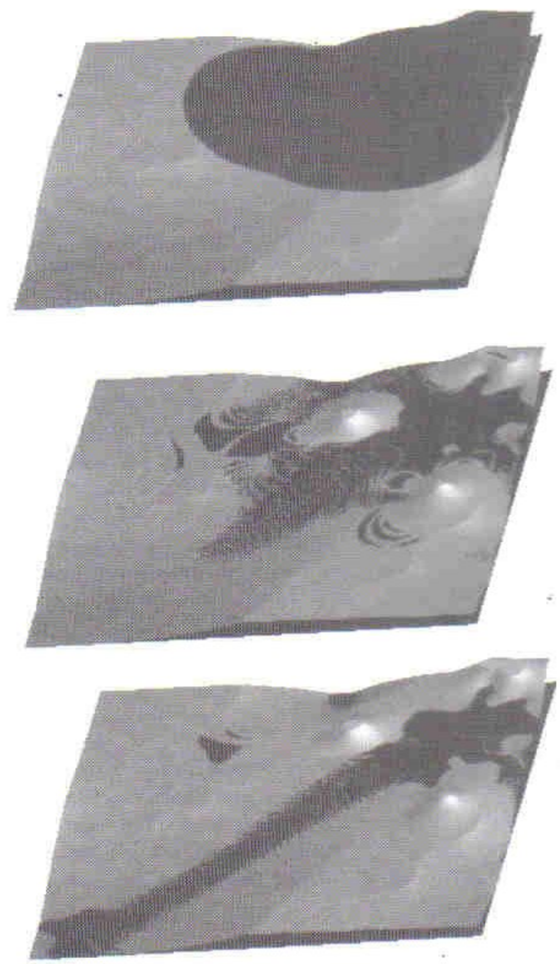

FIGURE 6 Sequence of the surface flow (black pixels represent water). Vertical scale is 1000:1.

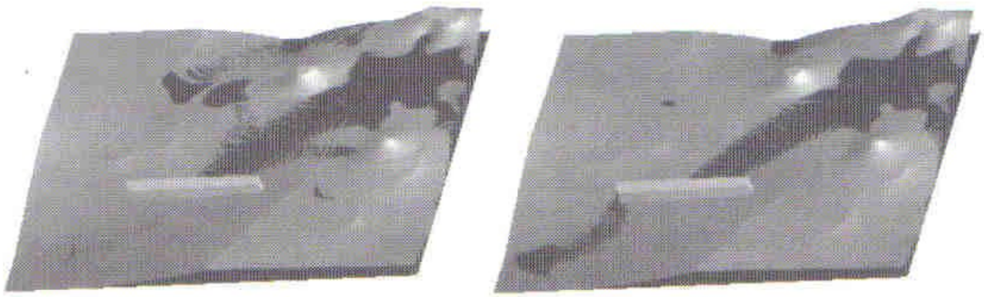

FIGURE 7 Influence of an artificial barrier on the surface flow.

of the conductivity coefficient can be seen in Fig. 5where the evolutions on the bottom sample point is plotted for different α values.

4. CASE STUDY

The model was applied to a region of $1600\,km^2$ in the Province of Buenos Aires, Argentina. The place is a shallow zone near Pehuajo City, experiencing frequent floodings caused by heavy rains and drainage from the higher northern regions. The used DEM was a matrix with 8 million cells of 15-m side and 1-m precision in height.

A flooding event initiated by heavy rains poured over the region was studied, simulating a similar situation occurred during the winter of 2000. Since the region was flooded repeatedly during recent years, it is reasonable to assume saturated soil and no seepage. The worst case scenario is surface water flow without evapotranspiration.

Figure 6shows a sequence of the surface flow after the precipitation. It can be seen that the water tends to drain along preferential channels following the elevation gradients. This feature was observed frequently in satellite photographs of the region. Figure 7 shows a demonstration of the capabilities of AQUA model to assess the floodplain managers in the mitigation planning. An artificial barrier was included in the water path, trying to avoid the flooding of the lower lands downstream. It can be observed in the simulation that the procedure will not be effective in stopping the water flow, and consequently different actions should be planned.

5. CONCLUSIONS

The AQUA model, a numerical technique to simulate the surface water flow in large plain landscapes was presented. The model is based on DEMs and rules for water interchange between adjacent cells. AQUA is applied to a $1600\text{-}km^2$ landscape corresponding to the Pehuajo region in Argentina, a zone that experiences frequent floodings. The simulations can determine flow pathways and magnitude of hydrologic fluxes during flood events, recreating alternative management scenarios. The new scheme is simple to setup and run efficiently, can be used by non-expert users and readily integrated with commercial GIS.

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