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Cetemps Hydrological Model (CHyM), a Distributed Grid-Based Model Assimilating Different Rainfall Data Sources

Marco Verdecchia, Erika Coppola, Barbara Tomassetti and Guido Visconti

Abstract Within the activities of Cetemps Center of Excellence of University of L'Aquila, a distributed grid based hydrological model has been developed with the aim to provide a general purpose tool for flood alert mapping. One of the main characteristic of this model is the ability to assimilate different data sources for rebuilding two dimensional rainfall distribution. The model can be used for any geographical domain with any resolution up to the resolution of the implemented Digital Elevation Model, namely about 300 meters in the current implementation. A Cellular Automata based algorithm has been implemented to extract a coherent drainage network scheme for any geographical domain. The algorithm for flow scheme extraction and for the assimilation of different rainfall data sources are described in details too. Several applications of such algorithms are also shown.

Keywords Hydrological modeling · Coupling of meteorological and hydrological models · Drainage network extraction · Different rainfall data assimilation · Cellular automata applications

1 Introduction

The coupling of hydrological with meteorological or climatic models appears to be an important challenge for next generation of researchers. Hydro- meteorological simulation is more and more relevant for the prediction of floods and the monitoring of severe events. Moreover a detailed hydrological simulation obtained with different climatic scenarios is a fundamental step to understand and predict the possible modifications of hydrological cycle induced by the changes in the climatic system.

Within the activities of CETEMPS Centre of Excellence of University of L'Aquila, a grid based hydrological model has been developed with the aim to provide a general purpose tool that can be off-line coupled with meteorological and climatic models. In order to accurately simulate the hydrological cycle at different

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space scale the CETEMPS Hydrological Model (CHyM) implements a sophisticated numerical algorithm to extract the drainage network for an arbitrary domain. This characteristic makes CHyM model easily portable on different UNIX platforms avoiding the need to use licensed software like the commercial Geographic Information System (GIS) to generate the streamflow network. It has also been noted (Ryan and Boyd, 2003) how, in many circumstance, commercial GIS uses algorithms leading to an oversimplified drainage network due to unrealistic smoothing of DEM matrix. The main difficulties for a realistic flow scheme extraction from the Digital Elevation Model matrix deal with solving the numerical singularities due to the finite horizontal and vertical DEM resolution. To overcome these difficulties a Cellular Automata (CA) based algorithm has been developed and implemented. In this paper the basic concepts about CA theory are discussed and a detailed description including many examples of the specific application is also given.

A CA based approach is also used to acquire different data sources to rebuild the rainfall spatial distribution at hydrological scale. This algorithm provides the possibility to use different data available at different time steps, each data set is acquired following a pre-defined sequence depending on the different reliability (for example rain gauges provide better measurements respect radar estimation, radar data, in turn, are considered better than satellite estimation and so on). We discuss the ability of this technique to merge different subdomains covered by different rain data sets.

The text is organized as follows.

- Section 2. A quick introduction to Cellular Automata theory is given and practical application for streamflow network extraction is discussed with many example. The ability of the CA based technique to minimize the DEM correction is also demonstrated as the possibility to retrieve a coherent drainage network for a very complex topography, like that represented by a drained lake. An easy algorithm to visualize and validate the drainage network as extracted by CA technique is also presented.
- Section 3. In the current implementation CHyM is able to acquire rainfall observations and predictions by different models and data base. More specifically it directly reads MM5 meteorological Model and RegCM climate model outputs. CHyM rebuilts on the assigned grid the rainfall field at hourly base using the different available data set at different time steps. For instance during operation activities we could think to use rain gauges observations and radar-satellite estimations for the "past" time steps and the meteorological model rainfall prediction for "future" time steps. The chapter describes the implemented algorithm to merge different sets of data when they are available, while a qualitative discussion about the improvement respect to a simple geometrical interpolation is also given.
- Section 4. A quick but complete description of the adopted approach to simulate the different physical processes contributing to hydrological cycle is given. CHyM explicitly solves the continuity and momentum equations to predict the surface runoff, while the Torthwhile formula is used to calculate the

evapotranspiration term. A simplified two reservoir scheme is used to simulate the infiltration process.

- Section 5. Due to the availability of relatively powerful low cost computing system, a complete grid based hydrological model like CHyM, could be able to realistically simulate also complex and wide catchments. Nevertheless the calibration or, at least, a reasonable validation of model forecast are often difficult because only few observed flow discharge time series are available. These difficulties especially occur for small basins. An effort to develop an empirical methodology to locate the areas where major flood risks occur seems important and useful especially for civil protection activities as for supporting local authorities during the decision making process. In this section we show as a detailed reconstruction of rainfall field and a realistic extraction of drainage network lead to the possibility to define an empirical flood alarm index that, at least for the case studies presented in the current paper, are actually able to localize the areas of the basin where the major flood events occur. Other possible application of CHyM model are also presented including few practical example.
- Section 6. Conclusions will be drawn emphasizing future developments of CHyM model, especially for what concerns the operational activities and the studies of the effects of climatic change on the hydrological cycle.

2 Cellular Automata Based Algorithm for Pit and Flat Area DEM Correction and Flowstream Network Extraction

2.1 Why to Develop a New Hydrological Model?

Cetemps hydrological activities had the startup in 2002 with the main aim to merge meteorological operational prediction and ground based and remote observations, available in the framework of other Cetemps groups, for the prediction and monitoring of severe wheatear events.

Because of poor competences of our groups in hydrological modeling, the development of a new model from scratch was surely a good exercise to acquire specific knowledge about the main problems in the field of hydrological simulation and prediction. Many models were already available in the scientific community (a good overview is given in and Singh and Frevert, 2002), but the building of a new numerical tool was surely a powerful method to understand the different approaches and techniques used to simulate the different physical processes contributing to hydrological cycle, and it was also a fundamental step to became familiar with main numerical difficulties in hydrological modeling. The presence of many young participants to ISSAOS 2005 let us to emphasize this concept and to induce young researchers to develop numerical methods instead of simply use existing tools often embedded in a “black box” interface where you are only asked to “click” somewhere on a window to obtain something. To develop a numerical method, instead of use a common tool, seems in the start phase a waste of time; on the contrary this represents a fundamental aspect for scientific community because it allows a better and diffused knowledge of the several numerical aspects of a prediction model, and it also leads to the possibility to compare different approaches and implementations within the scientific community. In fact, despite of the theoretical performance of a given numerical algorithm, its practical implementation in a numerical code and the consequent validation is an important and often non trivial aspect for a realistic simulation of any physical phenomena.

Few other important reasons induced us to develop a new numerical model and these reasons are essentially related to specific architectural characteristic of CHyM model that are not, or at least non often, implemented in other available hydrological models at the present. Probably the most important of these is the possibility to run the model in any geographical domain with any resolution, essentially the same feature implemented in most of atmospheric models. During operational activities it is often needed to run the model for a domain where major severe meteorological events are expected to occur, and then to refine the simulation running the numerical tool with a greater resolution in a subdomain where the probability of flood events appear higher. As an example an hydrological model with this features can be off-line coupled with a nested meteorological model, like MM5 Mesoscale model (Dudhia, 1993; Grell et al., 1994) using, at different spatial resolution the quantitative rainfall prediction obtained in the different nested domain simulated by the meteorological model.

A further peculiar feature of CHyM is the possibility to rebuild the precipitation field using different predictions and/or observations. During the operational activities it seems reasonable, for example, to use observed rainfall estimations for the past hours and meteorological prediction for the future time steps; with this approach it is possible to reduce the effect of uncertainty in the quantitative rainfall prediction by the atmospheric model, and, at same time, it does not limit the time interval of the simulation to the past hours where rainfall observations and/or estimations are available. We will carefully discuss the implementation of this feature in the next section.

In order to make easier the coupling with other atmospheric models and other sources of data, CHyM acquires rainfall estimation using a sequence of independent modules, each module uses a single source of data to rebuilt rainfall field in a subregion of selected domain. This characteristic allows the possibility to easily add the other modules, .i.e. other interface to atmospheric models. In the current implementation a dedicated interface has been provided to directly acquire MM5 model (Dudhia, 1993; Grell et al., 1994) and RegCM climatic model (Giorgi et al., 1993a,b; Pal, 2007) outputs.

Cetemps Hydrological Model code is written using standard Fortran 90 compiler, it consists in about 10000 rows and it is easily portable in the most popular unix platform, no commercial or other free tools have been used, and all the algorithm have been implemented using a native approach, except the graphic tools included in the package for which the standard NCAR GKS libraries package has been adopted. CHyM model is provided using three different package, the first containing the source code, the second containing data like DEM, landuse for all the globe etc., the last subpackage is the NCAR graphic package, also available starting from NCAR web page for all the unix platforms.

2.2 Drainage Network Extraction

The extraction of a coherent flow scheme is the first and fundamental step to simulate the hydrological cycle for a given geographical domain. In many distributed and lumped hydrological models (Singh and Frevert, 2002), stream network is usually extracted using commercial or free GIS software, however this "automatic" approach could cause an unrealistic modification of DEM or the algorithm could be too simple and not suitable for a realistic hydrological reconstruction of an arbitrary catchment.

In addition most of the licensed GIS software are usually very expensive and the use of this kind of tool for the drainage network extraction limits the possibility to easily carry out simulations in any domain due to the need of manipulating "by hand" some information like the flow direction matrix. Many different approaches have been proposed to overcome the difficulties to extract the stream network related to the finite horizontal and vertical resolution of DEM, the majority of the extraction algorithms use an eight flow directions (D8) approach like Tribe (1992), Jenson and Domingue (1998), Martz and Jong (1988), Martz and Garbrecht (1992, 1993, 1995) and Fairfield and Leymarie, (1991); few others include already a digital information for river and lake to compute a more realistic drainage network (Turcotte et al., 2001).

In order to understand the numerical difficulties in the extraction of a coherent flow scheme, let us do it for the domain of Fig. 1. We select this geographical domain for an example because it corresponds to the domain where CHyM model is operationally used, but also because this is a region of complex orography with more than ten different small river basins, the greater being the Aterno–Pescara catchment with a total drained area of about 4000 km^2. Figure 1 report the representation of DEM matrix as rebuilt by CHyM model for the selected domain; the domain is selected by the user specifying, in the main script, five parameters : the number of latitudes, the number of longitudes, the first latitude, the first longitude and the horizontal resolution. In the case selected for this example the horizontal resolution is about 300 meters and all the fields are defined on a 450 × 400 (lon-lat) grid. DEM matrix is calculated by CHyM using two Raw format data base, the first one having a resolution of about 300 meters and covering Italy, the second one is USGS data base covering all the world with an horizontal resolution of about 1 km.

From the matrix shown in Fig. 1, it can be calculated, for each grid point, the flow direction. According to the minimum energy principle, we assume that surface runoff occur with a strong preferential direction following the steepest DEM downhill gradient. Figure 2 reports a map of flow direction obtained with the above criteria and the eight different colours correspond to the eight surface route directions.

As a first validation the matrix represented in Fig. 2 is used to calculate the incline map reported in Fig. 3, the quantity shown in this map is the tangent of the terrain incline in the flow direction. From this plot it is evident the paths of the main rivers of the domain corresponding to pink zones where the inclination is close to zero. It is also easy to locate the watershed corresponding to the maximum of the inclination map. For a qualitative validation of the streamflow obtained with this first step it is enough to note, as an example, as the river paths and watersheds often corresponds to the administrative boundaries as it is in the reality.

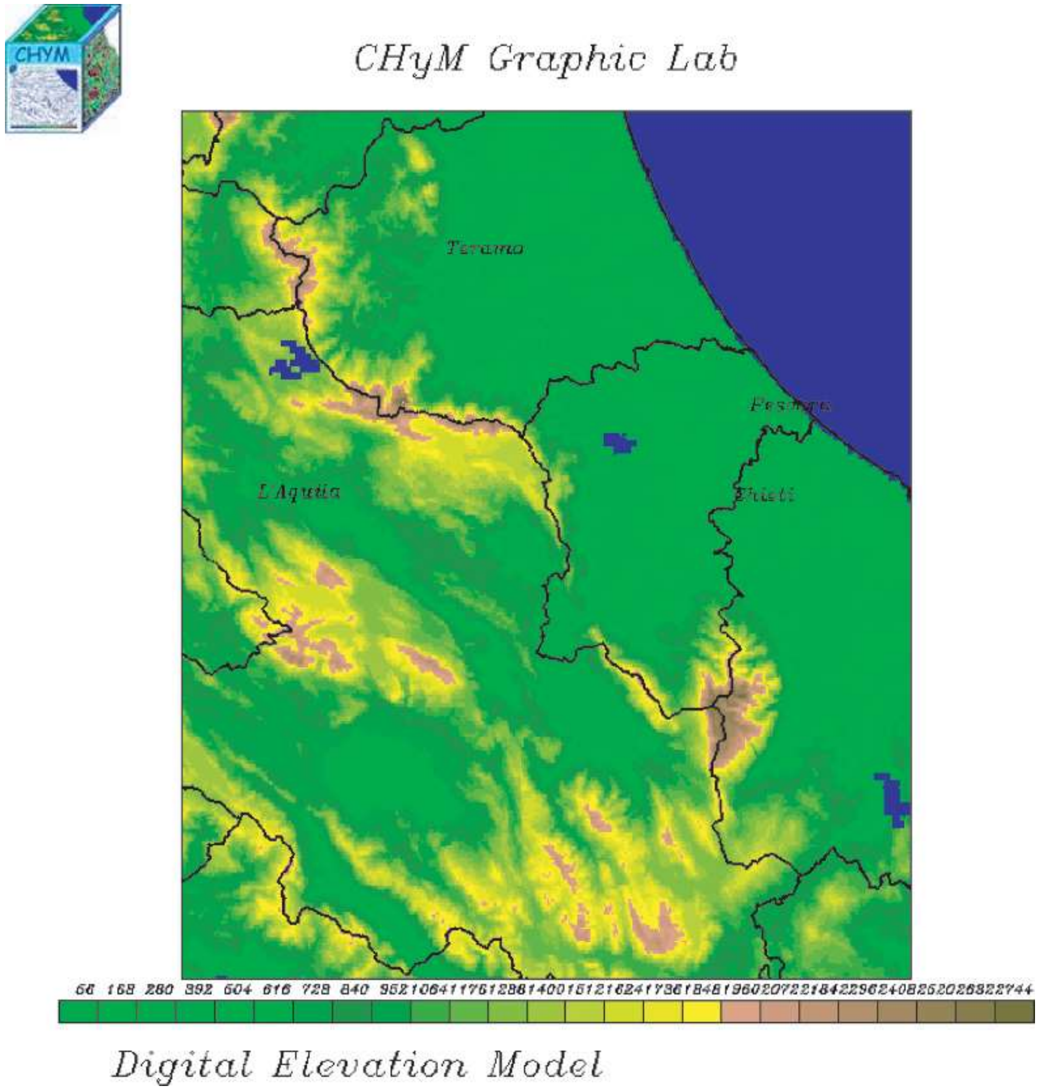


Fig. 1 Digital Elevation Model representation for a region of complex topography in the Central Italy

Of course a more quantitative validation is needed to test the actual capability of the extracted stream network to realistically simulate the actual drainage network. This is usually done calculating a sort of accumulation matrix, for example the total number of cells or the total area drained by each cell. A detailed description of the implemented algorithm to calculate the accumulation matrix will be given in the next section, here we just want to highlight as this matrix can be used to visualize the drainage network: the path of a river, in fact, is given by a sequence of cells with increasing drained area or increasing number of drained cells. A graphic representation of the river paths is shown in the "strange" Fig. 4.

This figure is obtained identifying as a channel all the cells in the accumulated matrix with a value greater than a threshold (O'Donnel et al., 1999), different colours corresponds to increasing values of the same matrix. As it can be easily seen the drainage network does not corresponds to the actual situation (shown in

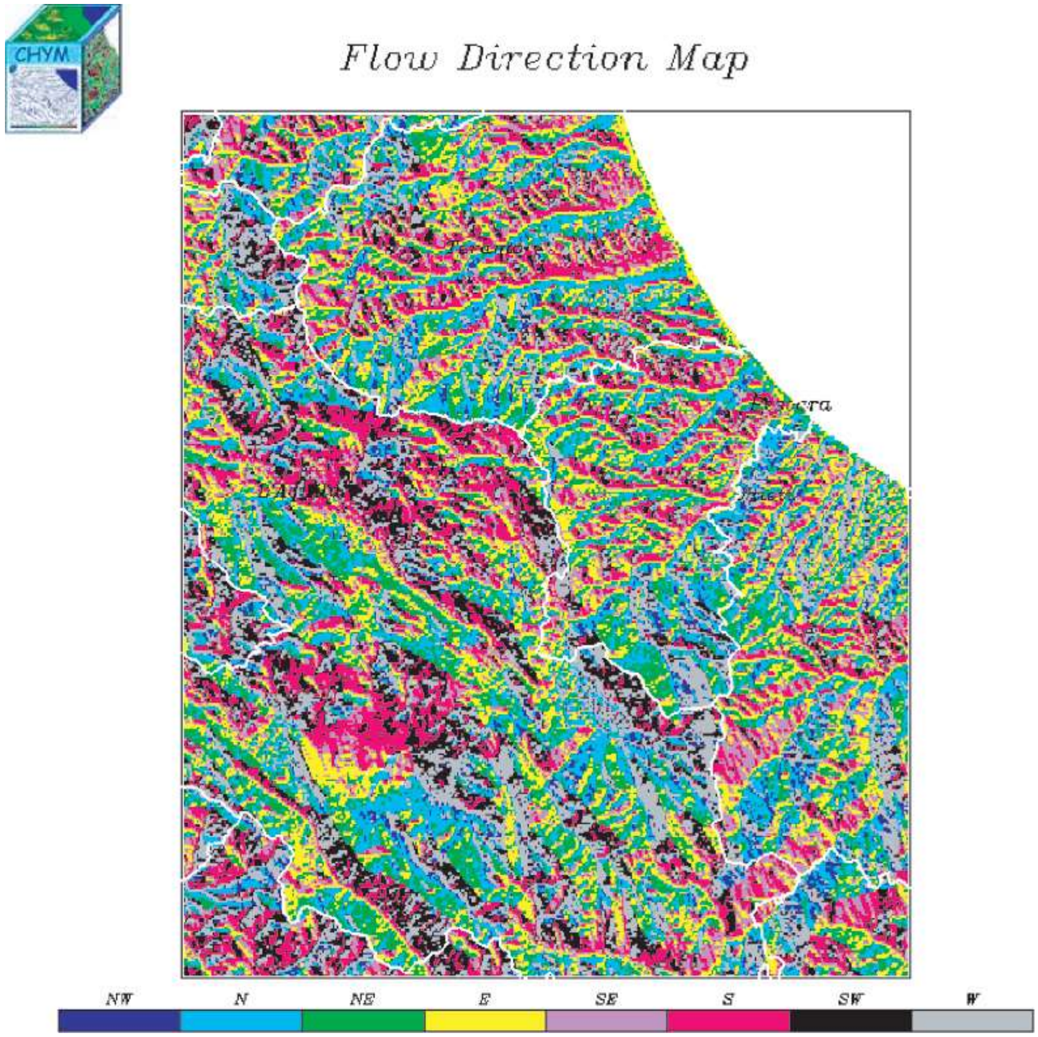

Flow Direction Map

Fig. 2 Representation of flow direction map for the domain shown in Fig. 1

next Fig. 7) at least because it is characterized by different segments not connected each other and then the water does not runoff towards the sea. The inefficiency of the algorithm is caused by the presence of singularities due to the finite horizontal and vertical DEM resolution. These singularities are usually classified as “pits” and “flat areas”.

The pits (or sinks) are DEM cells surrounded by neighbours that have higher elevation. In most of GIS software and other hydrological models, the sinks are removed increasing the DEM value to the lowest elevation of the adjacent cells, this technique is usually referred as filling algorithm (Marks et al., 1984; Martz and Garbrecht, 1992; Band 1986). It is easy to understand how this algorithm often simply moves the pit in one of neighbouring cells, therefore the procedure must be applied several times and it can lead to an unrealistic modification of DEM. Nevertheless the presence of these singularities causes an unrealistic numerical representation of the basin (Fig. 4) essentially because the pits cells are more often located along the main river path where the terrain inclination is lower.

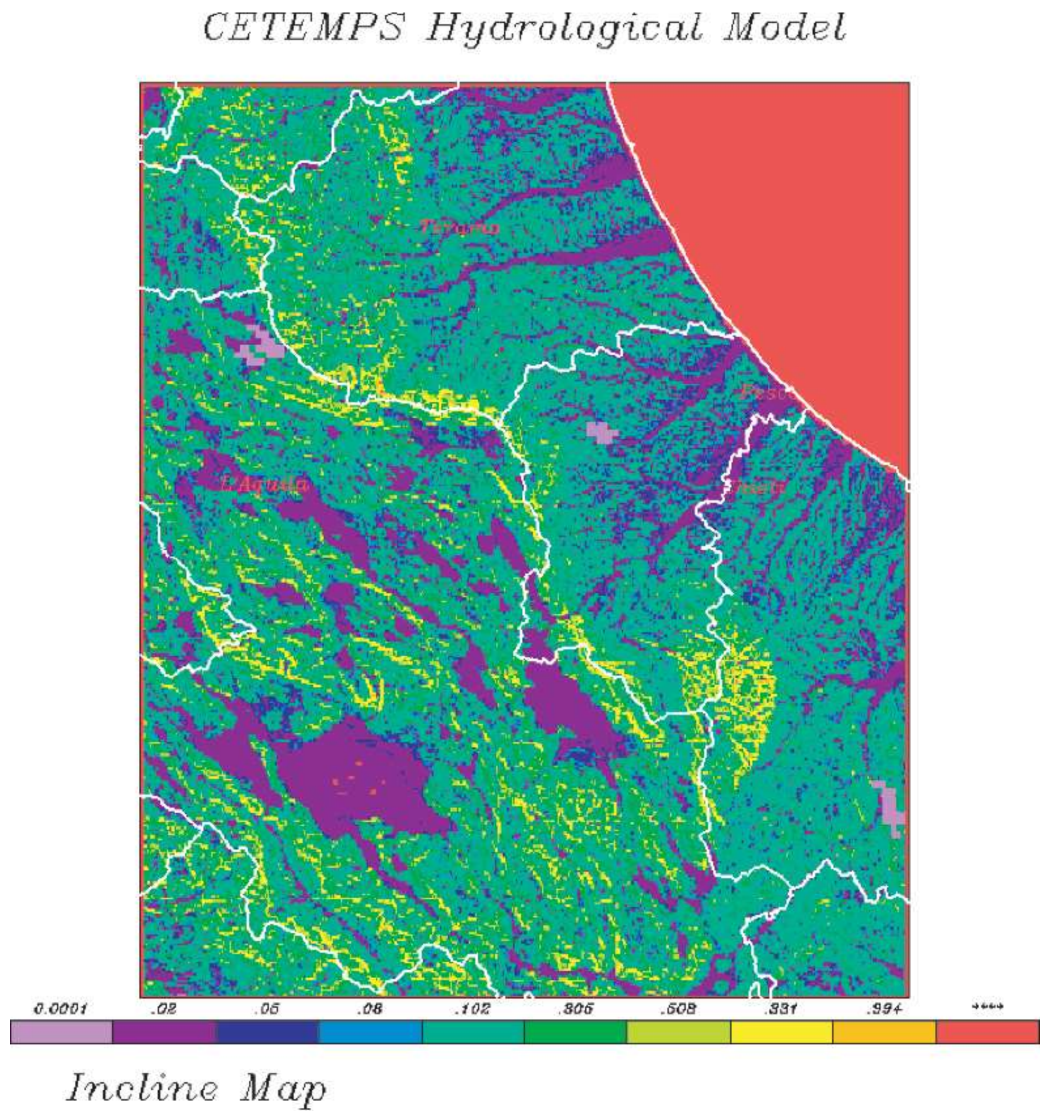


Fig. 3 Map of the incline for the domain shown in Fig. 1 as calculated by CHyM

The flat areas are sequences of adjacent cells having the same elevation. In this case a more sophisticated numerical procedure is requested to coherently determine the flow direction for the whole flat surface, examples of such strategies are described by Turcotte et al. (2001) and by Garbrecht and Martz (1997).

An example of DEM singularities is reported in Fig. 5 where a small portion of the domain of Fig. 2 is shown. For each cell we reported the terrain elevation and an arrow showing the flow direction for that grid point. It can be seen as few pits are located within this subdomain and the correction of this singularities appear not trivial. As an example it has to be noted that all the surrounding grid points of two “flat cells” in the mid-left of the figure drain toward these minimum cells, therefore it is not enough to determine the flow directions for the two singular cells, but also the drainage direction of the neighbouring grid points has to be coherently changed. In order to solve this problem in a general way, we developed an original

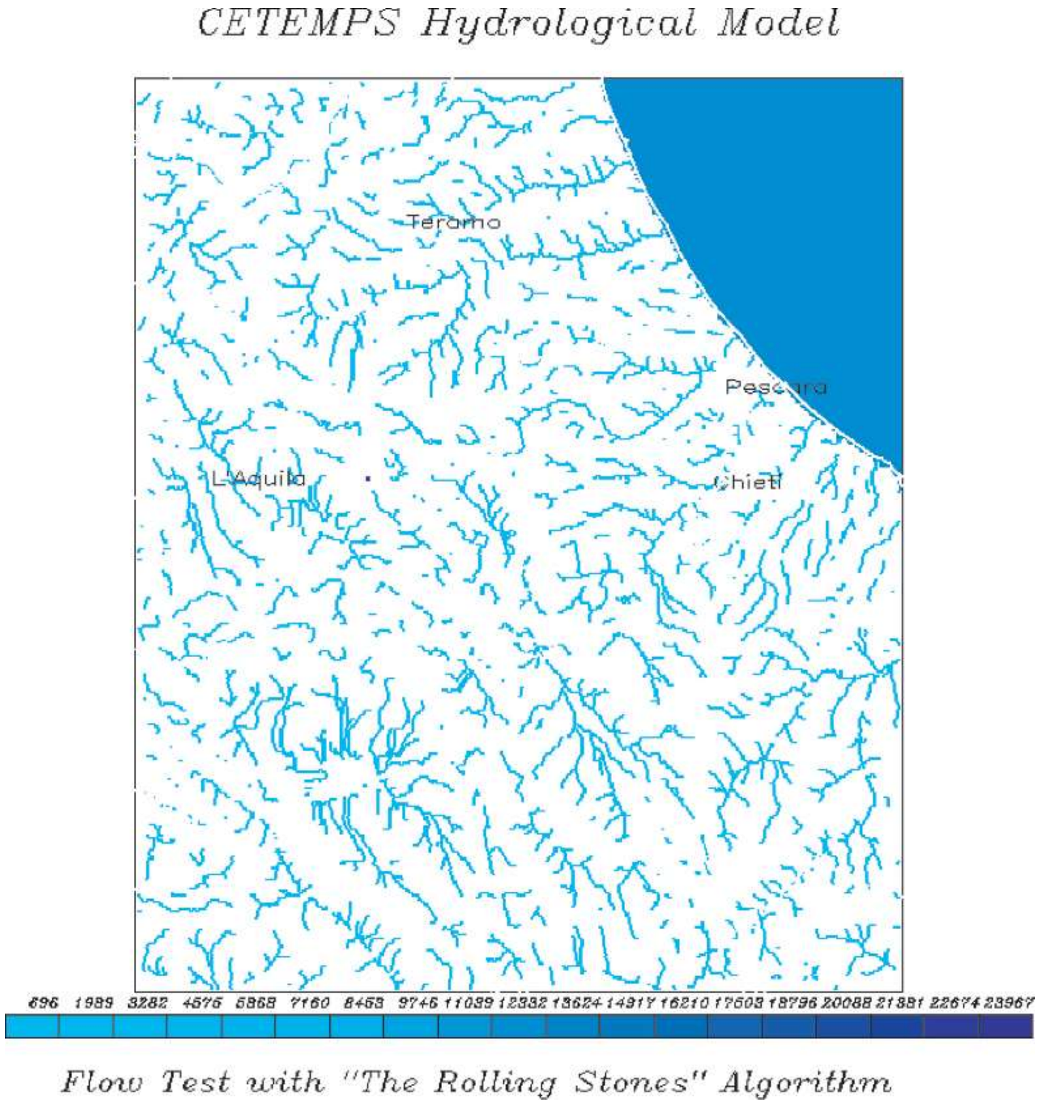


Fig. 4 Flow test obtained without DEM singularities correcton

and sophisticated algorithm based on the main concepts of Cellular Automata. In the next subsection we will introduce CA based application and we will discuss how to apply this numerical technique to drainage network extraction.

2.3 Cellular Automata Based Algorithm for Pits and Flat Area DEM Correction

Cellular Automata based algorithms are inspired to the observation that many biological systems, made of many singular parts, seem to have a collective and coordinated behaviour or they show to have a sort of computational capability. The basic concept is that, within a CA aggregate, each element, usually called "a cell", modifies its own status depending on the status of the surrounding cells. The actual

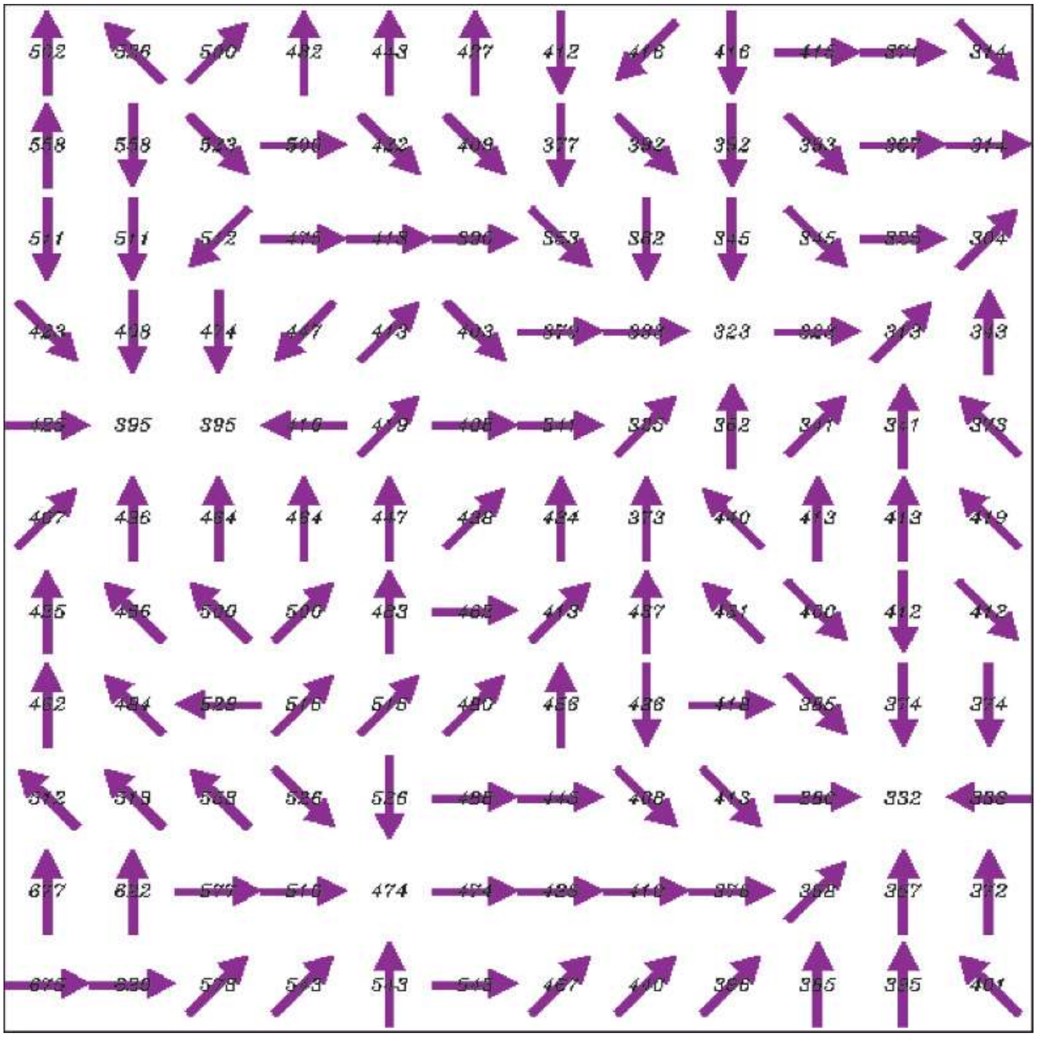


Fig. 5 Flow direction for a small portion of domain shown in Fig. 2. For each cell it is reported the terrain elevation (meters) and the flow direction. Flow direction is not reported for pits or flat area

evolution of the system depends on a local rule, used by each Cellular Automaton to modify its status, and it also strongly depends on the initial state of the system. Following Packard and Wolfram (1985), let us formally define these simple concepts:

- Cellular automata are discrete dynamical systems
- Space, time and states of the system are discrete quantities
- Each point in a regular spatial lattice, called a cell, can have anyone of a finite number of states
- The state of the cells in the lattice are updated according to a local set of rules
- All the cells in the lattice are updated synchronously

Many applications and "games" have been developed using these simple items, an interesting list can be find in Wolfram (1988). Cellular automata can also be considered as discrete idealizations of partial differential equations and because of their discrete nature they can be viewed as a simple parallel-processing device. CA are suitable for describing mathematical models for system in which many simple components act together for producing complicated patterns of behaviour.

Probably the most popular of CA applications is the so-called "game of life". In this game the CA are arranged in a two dim grid and each cell can have just two states: dead or alive. At each time step a Cellular Automaton will survive only if 2 or 3 of the 8 neighbouring cells are alive, otherwise it will die. Following this simple "local rules" we can obtain a surprising quantity of different collective behaviours depending on the initial state of the system. Just to give an idea, a typical initial configuration is known as "walker" because it reproduce exactly itself after a finite number of cycles but in one of adjacent location, this example can be find at the URL http://cetemps.aquila.infn.it/mvlib/exe20b.gif.

In order to develop a Cellular Automata application for DEM smoothing and pits and flat areas DEM correction, we suggest to modify the above general items for CA formal definition as follows:

- CHyM grid is considered an aggregate of cellular automata
- The status of a cell corresponds to the value of a CHyM field (DEM, in this case)
- The state of the cells in the lattice is updated according to following rule

$$h_i \to h_i + \alpha \left(\sum_j^8 \beta_j (h_j - h_i) \right)$$

- All the cells of the lattice are updated synchronously
- Update ends when the flow direction can be established for all the cells

In the formula for DEM update, the coefficient α is a small value (typically 0.1), while the coefficients β_j are weights taking into account the different distances between the centre of the cells and the sum is carried out on the 8 surrounding cells. With the above set of rules a single cell is smoothed according to the weighted average of the neighbouring cells. This algorithm result to be very efficient (we will see this with many tests and examples) for solving the pits and flat areas singularities as well. Nevertheless the application of this technique lead to an overall modification of DEM representation and of course this aspect results uneasy, therefore we can rearrange a sort of recipe for DEM correction as follow

2.4 Recipe for DEM Pits and Flat Areas Correction

- Smooth DEM using CA rules until Flow Direction can be established for all the cells
- Generate streamflow network using smoothed DEM
- Use the original DEM matrix for hydrological simulation but modify ONLY the cells draining toward an higher grid point

We usually refer to this procedure as CA2CHYM algorithm. With this technique we have a powerful method to obtain a coherent flow network in our domain and we also avoid the problem of an unrealistic modification of numerical terrain model. Before to quantitatively demonstrate these aspects, let us to see how the flow scheme reported in Fig. 5 has been modified. The results is shown in Fig. 6, it is important to notice as the flow direction has been established for all the cells, but the flow direction field has been modified also for the cells in the neighbourhood of singularities.

It is also useful to compare Figs. 5 and 6 in order to have an idea of the "complex" result of the CA based technique.

For validating the proposed CA algorithm, let us to analyze how many cells of our domain have been modified and if these modifications lead to an unrealistic representation of the actual terrain. To this scope we built an histogram with the distribution of DEM modifications for the whole domain. As stated in the above

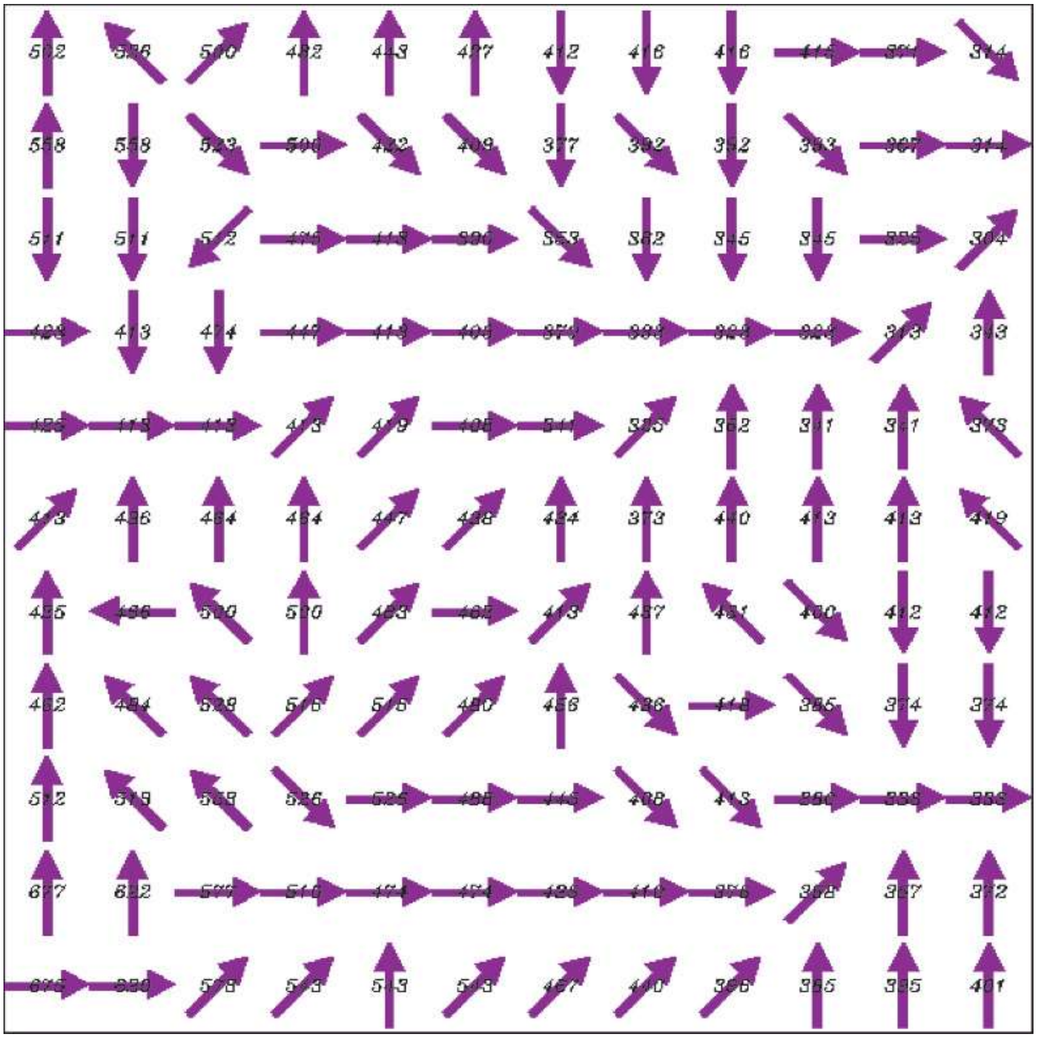


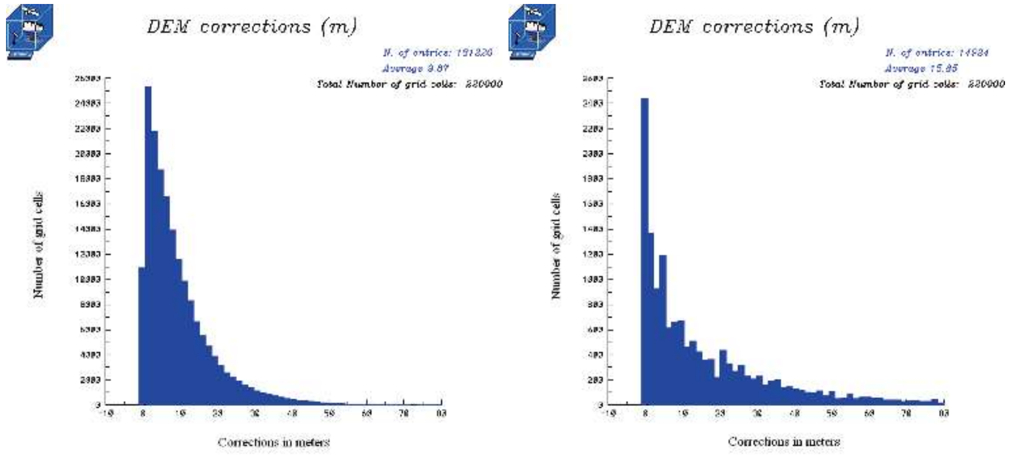
Fig. 6 Same as Fig. 5 but after the application of CA based algorithm

recipe for DEM smoothing, the modified terrain is used only to establish the flow direction while the original elevation model is modified only for those cells draining toward a cell with higher elevation. With this algorithm we strongly reduce the number of cells to correct and this is evident comparing the first two panels of Fig. 7, in the first panel (upper left of the figure) the histogram refers to the application of a "traditional" algorithm based on the iterative application of pit-filling algorithm. In the upper right part of the figure we report the same histogram but applying the "CHyM smoothing recipe", it is worth to notice that there is an order of magnitude between the two scales.

A further and interesting analysis is the spatial distribution of terrain modifications and these are reported in the lower panel of Fig. 7. It is interesting to note that the DEM matrix significantly changed, after the application of CA2CHYM algorithm, mainly in three different zones, these zones are indicated with the letters A, B and C in the figure. In the zone denoted by A it is situated an artificial lake and this area is actually drained by a network of artificial channels for the production of power supply and then we expect that a realistic drainage scheme cannot be obtained simply using the digital terrain representation. The zone denoted by letter B is located not far from L'Aquila where ISSAOS 2005 school took place, and this mountain location is characterized by an underground river coming from different sources of the "Rocca di Mezzo" kart plateau. The underground stream forms the famous (in Italy) caves, called Stiffe caves (they were also visited during the excursion by the participants to ISSAOS 2005 Summer School). Also in this situation we cannot aim to rebuild a realistic drainage network using only the surface elevation. Finally the attention should be addressed to the location denoted by C in the last panel of Fig. 7. In fact this is a drained lake (see an example Tomassetti et al., 2003) and, at present time, the existing plateau is drained by a complex system of artificial channels and then again a significant change in DEM field is needed to rebuild a drainage network for this zone. In fact, In all these cases CA2CHYM recipe shows to be a powerful and very efficient methodology for the extraction of stream network also in presence of a very complex topography. What is shown in Fig. 7 also gives a further reason to prefer the development of a new native algorithm for flow matrix extraction, in fact here we have the possibility to check if and where the application of the extraction technique lead to un unrealistic representation of actual surface routing.

The next step is now to calculate the accumulation matrix to verify if the extracted flow stream is actually able to rebuilt, in a realistic way, the drainage network for the selected domain. We have already applied this algorithm to produce Fig. 4, if we paint this matrix after the above discussed DEM smoothing we obtain what is reported in Fig. 8. The drainage network as established by CHyM is quite similar to what is observed, for those who are not familiar whit the streams and rivers of central Italy, note, for example, as for many segments the path of rivers coincides with administrative boundaries as it is.

Figures 4 and 8 are obtained mapping the accumulation matrix obtained after a systematic procedure we usually refer to as Rolling Stones Algorithm (RSA hereafter). This algorithm is not original or, in any case, is at least similar to other



DEM Smooting Algorithm 1 (DSA1) DEM Smooting Algorithm 2 (DSA2)

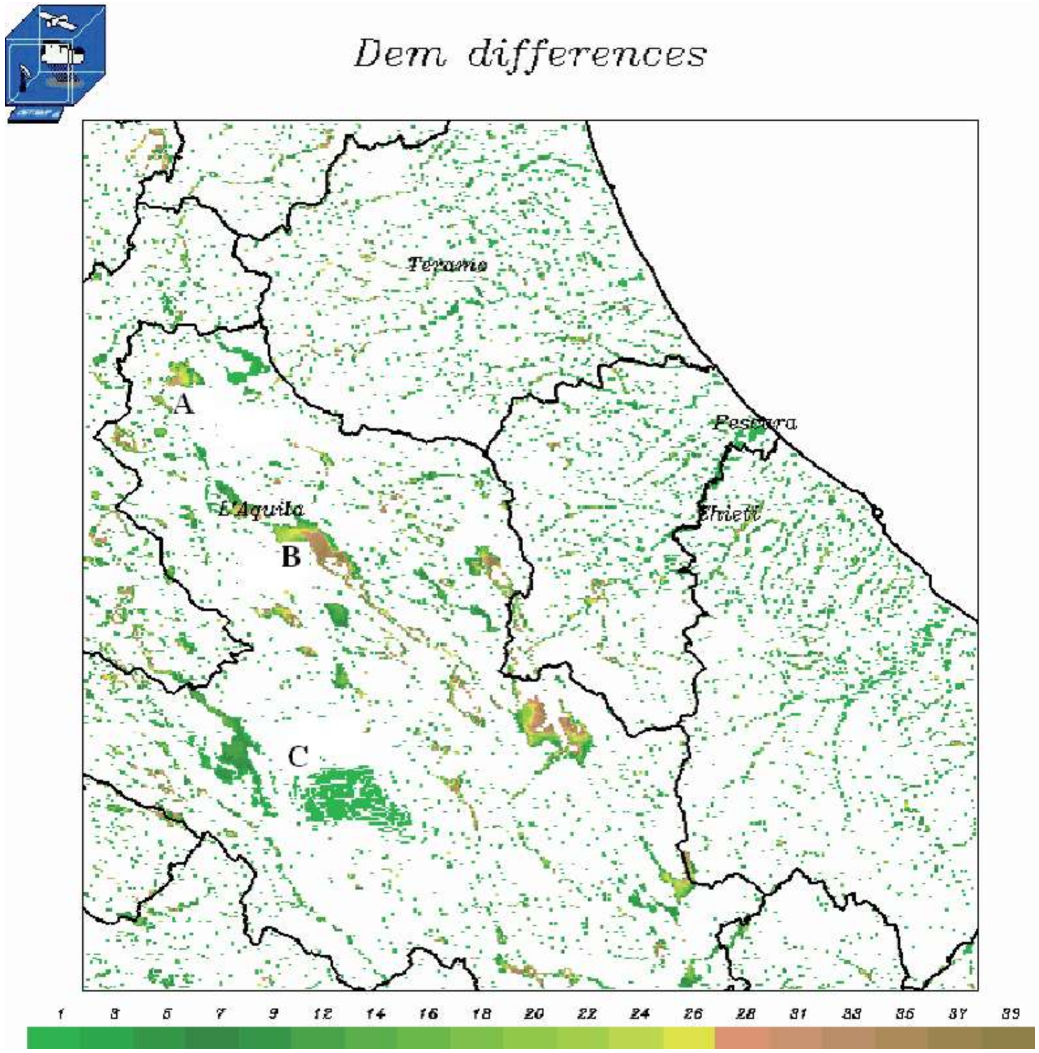


Fig. 7 Distribution of DEM modification applying traditional pit-filling algorithm (*upper left panel*) and CHyM smoothing recipe (*upper right panel*). The geographical distribution of the corrections is also shown in the lower panel

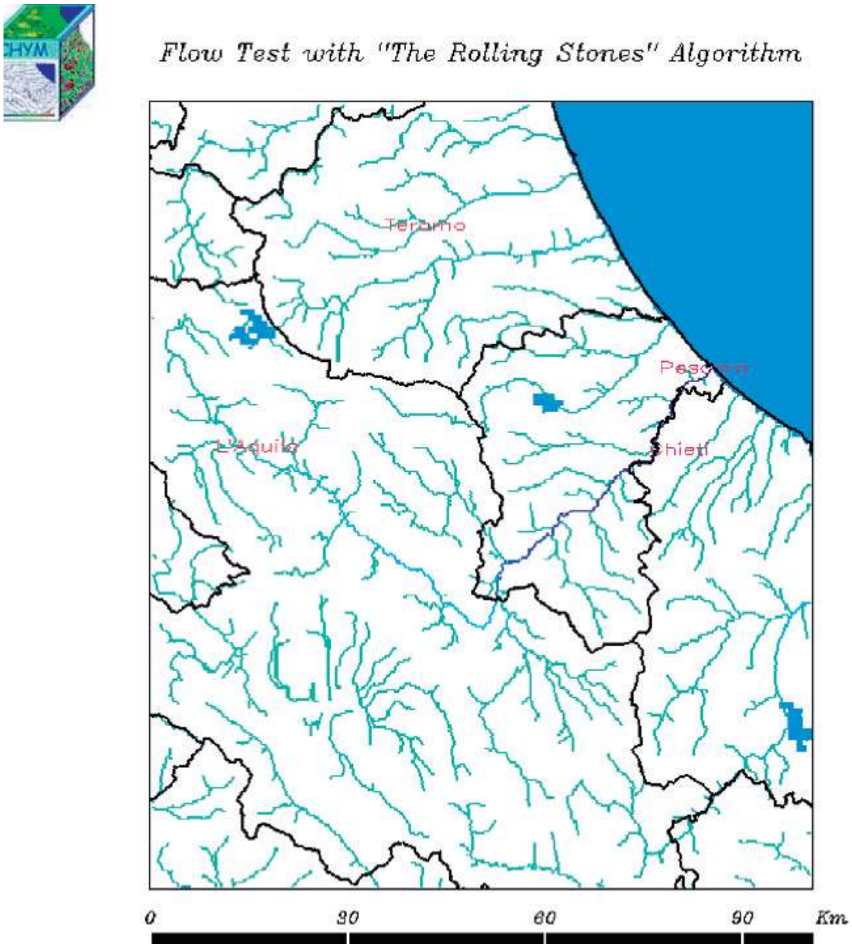


Fig. 8 As in Fig. 4 but after the smoothing of terrain using CA2CHYM algorithm

techniques applied in other hydrologic models, nevertheless there is not often a detailed description of it and then it should be useful to list the fundamental steps for the calculation of accumulation matrix. RSA algorithm can be summarised in the following description: a "stone" ideally rolls downhill from each cell toward the sea and each time that this stone goes through one cell a counter is incremented by 1 for that cell. If the algorithm is iterated until all the stones get to the sea, it can be calculated an accumulation matrix that contains the total number of cells drained by each grid point. If a quantity A is associated to each stone where A is equivalent to the area of the cell where the stone was at the beginning, for each cell it can be computed the upstream drained area. A similar approach can be used to calculate the total upstream drained rain by each cell; this matrix plays an important role in the definition of the flood alert index discussed later in the paper.

Once the accumulation matrix has been defined another algorithm has been developed to track the drainage network as it is shown, for example in Figs. 4 and 8. This algorithm is called Salmon Algorithm because it acts like salmons during the love season, moving upstream from the river mouth to the river springs. The mouth of the river is localized as the cell that drains toward a point in the sea and whose upstream drained area is greater then a fixed threshold (typically few hundreds of km^2). From the mouth cell the algorithm goes upstream to the neighbour cell whose drained area is the largest but it also keeps in a temporary vector the location of the surrounding cells whit a drained surface greater than the threshold (tributaries end). Once that the spring of the main channel of the watershed is reached (the spring is the first cell having a drained area lower than the threshold) the algorithm starts again from the tributaries end and reconstruct the first secondary channel.

The accumulation matrix is also used inside CHyM code for many tests and applications and an example is shown in Fig. 9 where the watershed of Aterno-Pescara river is shown. With this simple tool, implemented inside CHyM, we are able to verify if the whole basin we are interested in simulating is actually included in the selected geographical domain. Another important possibility is to simulate only the cells included in a selected basin. In fact this flag gives the possibility to

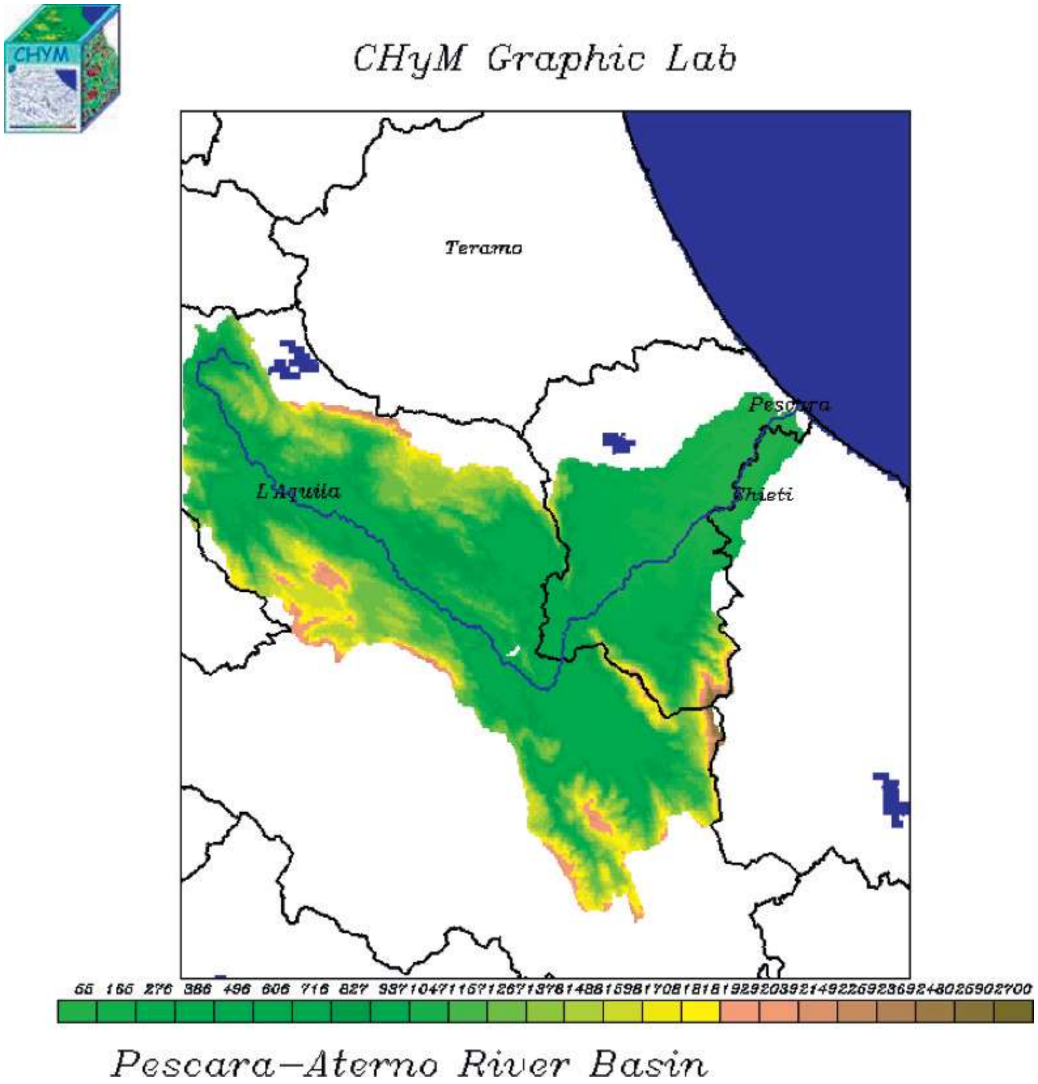


Fig. 9 The watershed of Aterno-Pescara river basin as rebuilt by CHyM algorithms

run the model in an arbitrary domain (i.e. not only a rectangular area) and therefore it is possible to strongly reduce the CPU time needed for the simulation.

In order to avoid confusion and to make the topic easier to understand, we have discussed within this chapter the application of CHyM algorithms for a geographical domain including the Abruzzo Region in the Central Italy; of coarse the performances of CHyM native algorithms for stream network extraction and visualization were tested for many geographical domains all over the world, an example is show in Fig. 10 where the drainage network has been rebuilt for Indian peninsula, and it is superimposed to the Land Use map downscaled at CHyM grid resolution using USGS database. Other tests for different domains are available at URL http://cetemps.aquila.infn.it/chym/examples.

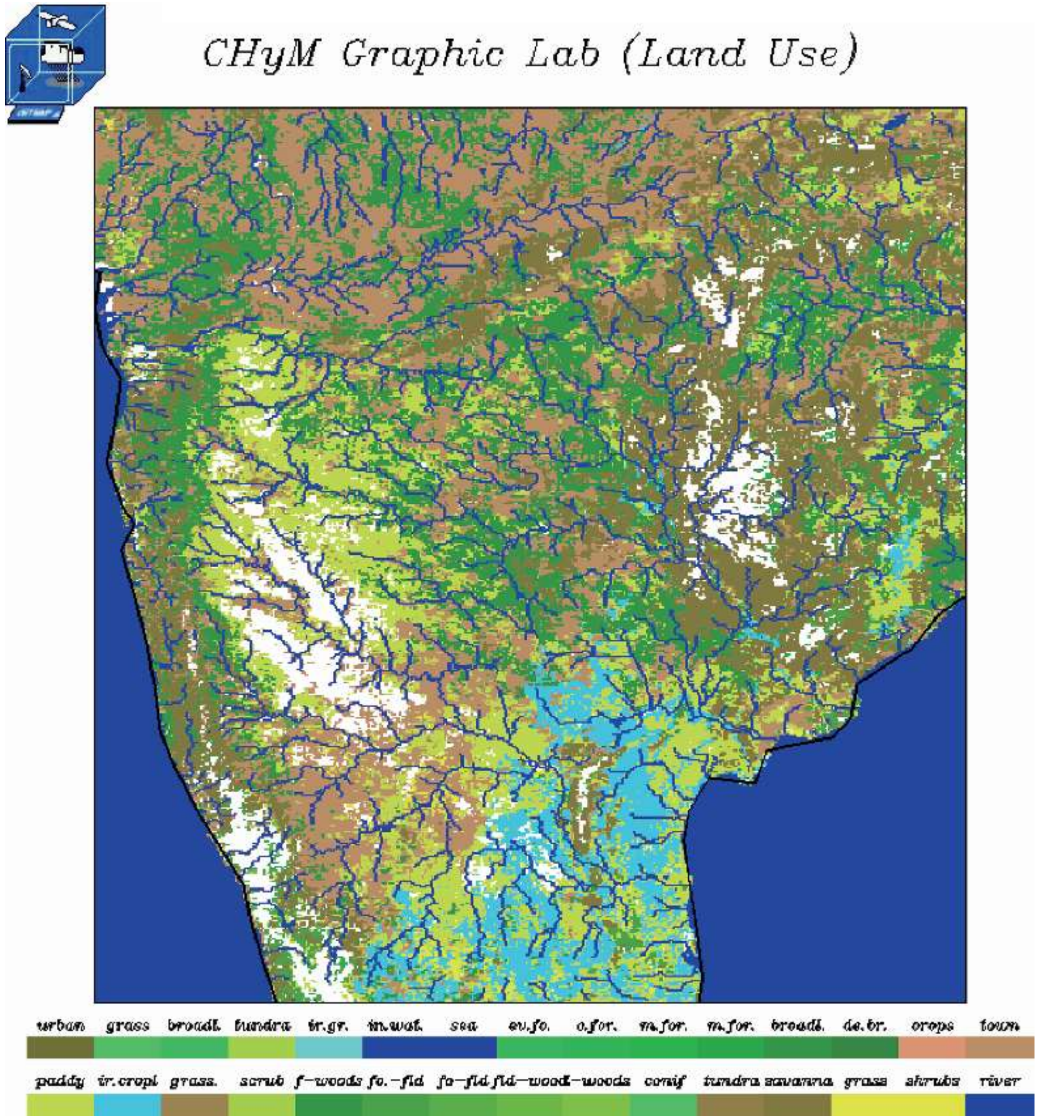


Fig. 10 The land use map downscaled at CHyM grid with superimposed the drainage network extracted with CHyM algorithm, for Indian peninsula

3 Assimilation of Different Rainfall Data Sets

Precipitation fields are characterized by large spatial and temporal variability and it has been long recognized that rainfall patterns play an important role in runoff generation. Many studies have described the strong non linear relationship between rainfall spatial and temporal distribution and river discharge (Goodrich et al., 1997), and also examined the hydrological response to the different precipitation patterns (Singh, 1997).

For hydrological research, the main obstacle for studying rainfall spatial patterns is the limited rainfall data, usually from sparse rain gauge networks. With remote sensing techniques it has been tried to overcome those problem (Grimes et al., 2003; Coppola et al., 2006) but the accuracy of rainfall estimations (Krajewski and Smith, 2002) and runoff sensitivity to sub-pixel rainfall variability (Michaud and Sorooshian, 1994) are very difficult to be taken into account.

An alternative to observations could be the quantitative rainfall prediction from meteorological models (Van der Linden and Christensen, 2003), but also the high resolution limited area model prediction are affected by large uncertainties and they are often not suitable to provide a realistic precipitation patterns at hydrological scale.

Several techniques has been proposed to merge different set of data in order to reduce uncertainties in rainfall estimation, the most recent being based on physical approach (French and Krajewski, 1994) or statistical algorithms (Todini, 2001). All those methods are often difficult to apply for operational hydrological activities because, for example, not all the data sets are usually available for all the time steps of the simulation. To overcome this problem we developed a more empirical but more general method with the aims to assimilate different available rainfall estimations or observations by taking into account the different nature of the data.

Before giving a detailed description of this methods let us to clarify few aspects of CHyM operational activities to better justify the development of a new method to assimilate different rainfall estimations. The operational context where CHyM simulations are carried out are resumed by the block diagram of Fig. 11. The blue boxes are external data sources: ECMWF provide daily large scale forecast; satellite data includes meteosat and MSG observation channels; the ARSSA and Idrografico boxes represent the real time acquisition of two different rain gauges networks available in the geographical domain where CHyM operational run are provided. The green boxes are internal database where data are stored with homogeneous format.

The orange boxes represent data processors or meteorological models: the data acquired by the rain gauges network are stored in an homogeneous format and with the same time (hourly) resolution in a local database; the satellite data are used to provide rainfall estimation and a data base containing the hourly remote sensing based precipitation estimation is also updated; a Single-polarization Doppler weather radar systems (see Vulpiani and Marzano contribute to the present ISSAOS 2005 proceedings) is used to obtain rain rate estimation and these data are also acquired and stored in another database. MM5 limited area model (Dudhia, 1993,

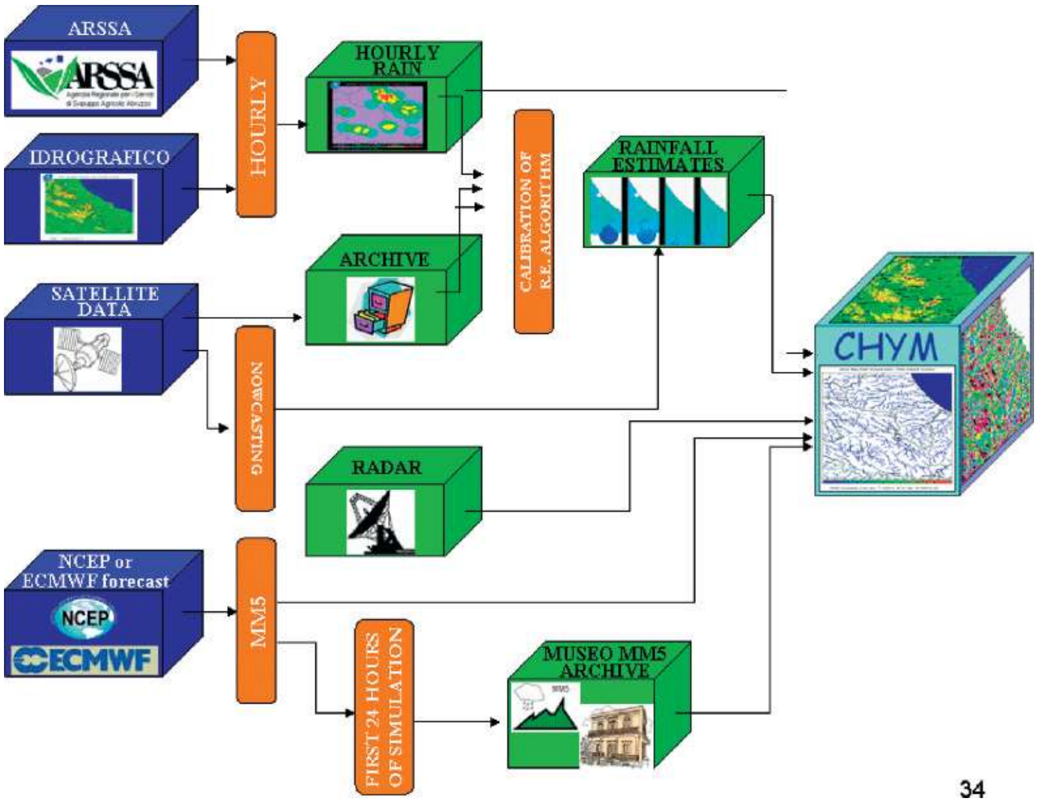


Fig. 11 Block diagram for Cetemps operational activities. The blue boxes are external data sources: ECMWF provide daily large scale forecast, satellite data includes meteosat and MSG observation channels, the ARSSA and Idrografico boxes represent the real time acquisition of two different rain gauge networks available in the geographical domain where CHyM operational run are provided. The *green* boxes are internal database where data are stored with homogeneous format. The orange boxes represent data processors or meteorological models. The goal of the whole chain is to provide all the meteorological fields and especially all the rainfall estimation for CHyM operational run

Grell et al., 1994) is initialized using ECMWF General Circulation Model forecast, and its operational run provide the quantitative rainfall prediction for the next three days in the Central Italy with an horizontal resolution of three kilometres, the rainfall prediction are then stored in a database with a temporal resolution of one hour, The final goal of the whole chain shown in Fig. 11 is to provide all the meteorological fields and especially all the rainfall estimations for CHyM operational run.

Figure 12 shows the sequence of different rainfall data sources used by CHyM hydrological model to rebuilt the precipitation field on its grid during daily operational simulation, each map corresponds to one hour of simulation. Different colours correspond to different observations or estimations used for rainfall field reconstruction. Pink colour locates the subdomain where MM5 model forecast has been used, green colour locate the subdomain where rain gauge measurements are available, while red colour corresponds to the subdomain where radar estimations have been used. It has to be noted how the situation is different at every time step and obviously only meteorological model predictions are available for “future” time

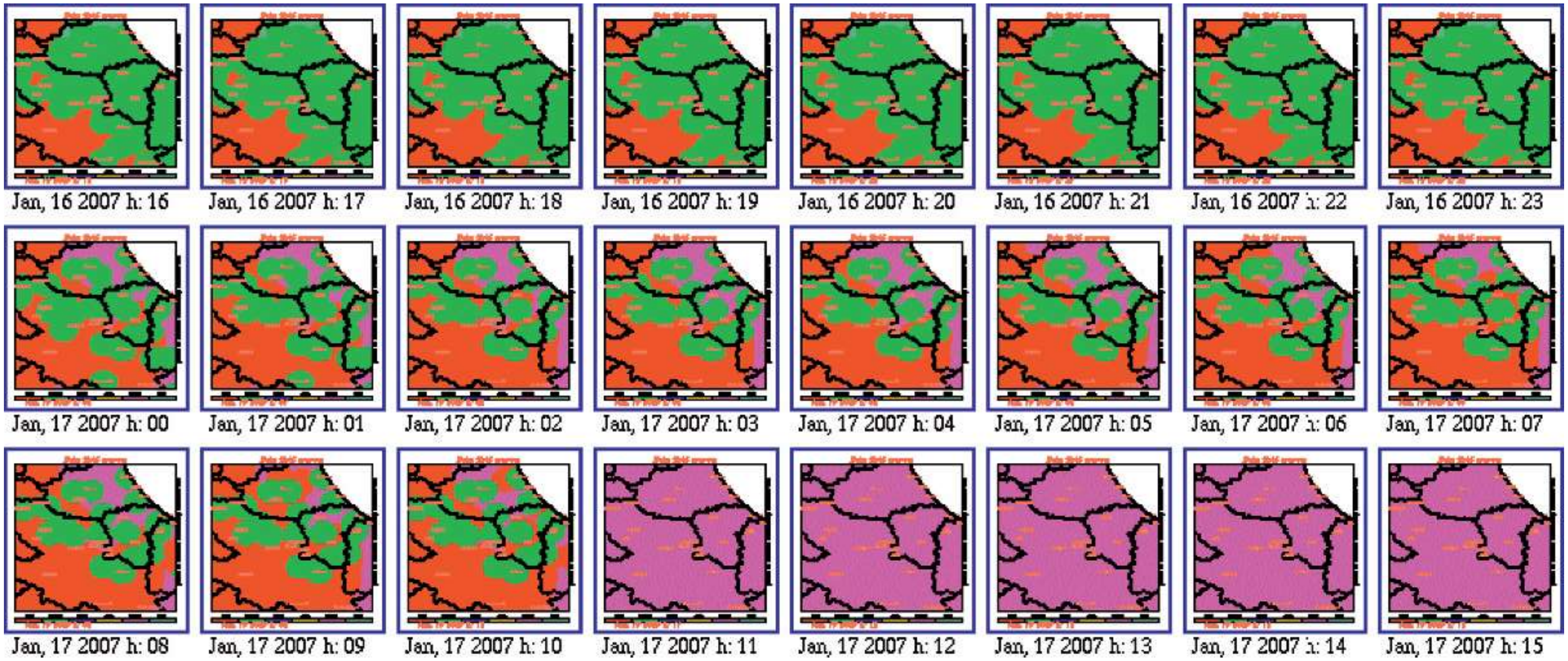


Fig. 12 An example of the sequence of rainfall data sources used by CHyM hydrological model to rebuilt the precipitation filed on its grid at different time step. Each map report the situation for one hour of integration and different colours correspond to different observations or estimations. *Pink colour* locate the subdomain where MM5 model forecast have been used, *green colour* locate the subdomain where rain gauges measurements are available, *while red colour* corresponds to the subdomain where radar estimations have been used for rainfall field rebuilding

steps. It is also important to note that, due to the different efficiency in real time rain gauge data acquisition, not all the rain gauge data are available for all the considered time step, this graphically corresponds to different size and extension of green spots at different hourly time step. In addition different situations occur when satellite and/or radar receiver is off line. Because of this dynamical, and unpredictable situation, a complete reconstruction of precipitation fields cannot be efficiently done using the most popular statistical based algorithms like the kriging, and therefore we developed an innovative technique based on the above described Cellular Automata concepts to merge all the data sources available at a single time step, the method is simpler compared to kriging algorithm, for example, but it results to be more realistic respect to a trivial geometrical interpolation like the Cressman approach.

3.1 CA Based Algorithm for Assimilating Different Rainfall Data Sources

The core idea of the methods is to assimilate the different data sets using a hierarchical sequence of modules each assimilating a single data set. The sequence of modules starts from that one that uses the most reliable data set like measurements (for example a tested rain gauge network) and it ends when the data set with greater expected uncertainty (usually meteorological model prediction) is used. Each module will rebuilt the precipitation field in a selected subdomain depending on the spatial distribution of available data. Such subdomain is defined as the ensemble of grid points having at least one measurement in a selected radius of influence r_m, being r_m a typical value of few kilometres and depending on the density of available data.

In order to describe with more details the algorithm let us to imagine a defined domain on which it has been fixed a lat-lon resolution grid and we want to assimilate a data set consisting in the hourly rainfall observations from a sparse grid. Each CHYM grid point is then defined of different type as schematically shown in Fig. 13. Cells of type 0 (red cells) are those for which is not of interest to estimate the precipitation, for example because they are points corresponding to the sea or they are located outside the catchment we are interested in. The cells of type 1 (white cells) are grid points for which we have not (yet) a precipitation estimation. Cells of type 2 (blue cells in the upper-left corner of the figure) are those for which the precipitation has been estimated in a previous module with a different data set, say data set 1 (DS1), and their precipitation value will not change with the current (and following) module. Within the cyan area we find blue cells that correspond exactly to the location of rain gauges we want to assimilate with the present module, in the figure these points are indicate as DS2 data, namely the measurements of the second data set. In these cells the value of precipitation is set to the value of the corresponding observation and they are from now on considered of type 2 (the value of the precipitation will not be changed any more).

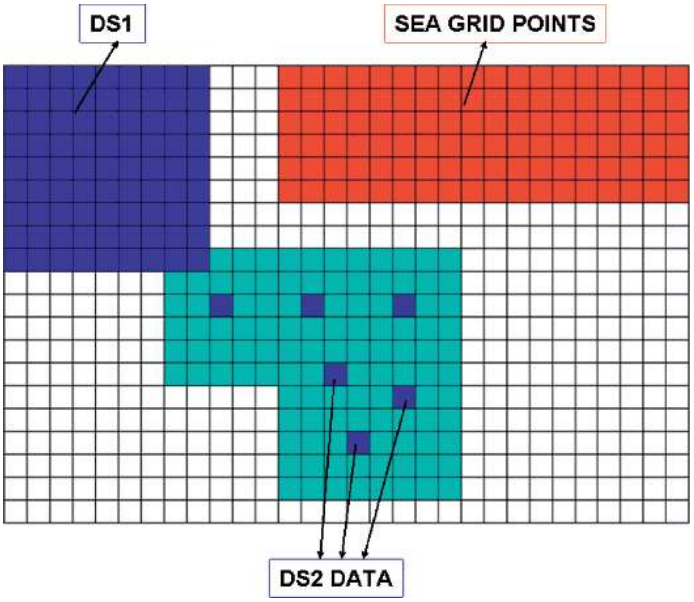


Fig. 13 Schematic description of CA based algorithm for merging different rainfall data sets. Each element of two dimensional grid corresponds to a CHyM grid point. The *blue* subdomain in the high-left corner corresponds to the cells where the rainfall fields has been calculated in a previous module by a first data set (DS1). The cyan area corresponds to a subdomain where the rainfall fields will be estimated with the current module using a second data set. The *blue* cells inside the cyan area represents the cell corresponding to the actual observations available in the data set 2 (DS2). The *red* area is outside the geographical domain of interest, for example they correspond to the sea or they are outside the watershed we are interested to. The precipitation in the white area will be estimated with the next modules

The cyan domain in the figure is defined of type 3 and corresponds to all the cells whose precipitation value will be established with the current module; as explained above, this subdomain is represented by all the cells having at least a measurement in a selected radius of influence r_m.

The further step is now to use a CA based algorithm similar to that described above for the DEM smoothing, for establishing a coherent value for the grid points of type 3, namely the cyan area of Fig. 13.

The basic idea we implemented is that when we deal with hydrological scale resolutions (few hundreds of meters) it becomes a good approximation to consider that the rainfall in a given grid point is the weighted average of the precipitation in the surrounding cells, with the weights that take into account the different distances between the grid points. The CA based algorithm essentially acts to find a coherent solution considering the precipitation at each grid cell as the weighted average of the precipitation in the neighbourhood.

The practical implementation of this method again use the basic concepts of Cellular Automata theory that we briefly described in the previous chapter. Here we introduce again the main CA items but in a more formal way. The rules used to update a CA system is usually defined a totalistic rules that establish the value of the central cell to depend only on the current value of the cell and the values of the cells in the neighbourhood. For a two dimensional regular lattice, like CHyM grid, each cell takes on n possible values and it is updated in discrete time step according to a rule θ that depends on the current status of the site and on the eight neighbour cells. The value $x_{i,j}$ of the i, j site evolves according to:

$$x_{i,j}^{t+1} = \theta \left(x_{i,j}^{t}, x_{i+1,j-1}^{t}, x_{i+1,j}^{t}, x_{i+1,j+1}^{t}, x_{i,j-1}^{t}, x_{i,j+1}^{t}, x_{i-1,j-1}^{t}, x_{i-1,j}^{t}, x_{i-1,j+1}^{t} \right)$$

For our application, we consider the precipitation field on CHyM grid as an aggregate of Cellular Automata and we try to select a simple rule that, after an iterative application, allows to obtain a solution where each cell will assume the average value of the neighbouring cells. The previous general rule becomes:

$$x^{t+1} = x^{t} + \beta \sum_{k=1}^{8} \alpha_k {x_k}^{t}$$

being β a small coefficient (typically 0.1). The sum is carried out over the 8 neighbouring cells and the α_k coefficients must take into account the different distances between the grid points. The evolution rule becames:

$$x^{t+1} = x^{t} + \beta \sum_{k=1}^{8} \frac{1}{r_k} {x_k}^{t}$$

where r_k is the distance between the central cell and the neighbour cell. Of course if we apply the above rule to the whole domain, the system will go to final stable state where all the cells will reach the same value and then we refine the algorithm assigning different rules to the CA belonging to different domains of Fig. 13. More specifically:

- The value of rainfall in the cells of type 3 are iteratively modified using the rule specified by the previous equation. For the boundary cells the sum is carried out using only the neighbouring grid points of type 2 or 3;
- The value of the rainfall in the cells of type 2 (points of measurements or estimates of a previous data set) remain unchanged;
- Iteration ends when the changes in the rainfall values became negligible (few percent) and all the cells of type 3 will be now classified of type 2.

In order to speed-up the numerical process all the cells of type 3 are initialized with a “reasonable” value calculated with a geometrical algorithm using the following formula

$$R_i = \sum_{j} \frac{1 - r_{ij}^2 \big/ r_m^2}{1 + r_{ij}^2 \big/ r_m^2} R_j$$

being R_i the estimated rain value, R_j one of the rainfall measurement available within a radius of influence r_m, and r_{ij} are the distance between rain gauge (or meteorological model grid point, etc.) locations and the considered cell. This interpolation method is usually referred to as Cressman algorithm (Cressman, 1959).

Looking at the general formulation the CA based technique could appear very difficult to understand or not easy to implement, in fact a simple example will clarify that this is not the case and also its practical implementation only requires the development of few tens of Fortran (or other scientific language) code. Let us consider a simple example: suppose we want to rebuilt the precipitation field on CHyM distributed grid, for a given time step, using a set of rain gauge measurements and, in the subdomain where rain gauges are not available, the quantitative rainfall prediction obtained by a meteorological model. To do this we will call the module manipulating the rain gauges measurements and then the module manipulating forecasted rainfall. The results obtained during the sequence of different interpolation steps are shown in Fig. 14.

In the first (upper left) panel the precipitation field is rebuilt using Cressman formula. The estimation is carried out only for the grid points having at least a measurement in a given radius of influence (typically of few Kilometres), the yellow area corresponds to the portion of the domain where we have not (yet) measurements of any type to estimate the precipitation, the different blue tone corresponds to increasing values of observed hourly precipitation. In the second panel (upper right), the field obtained with the previous formula is smoothed using the above described CA based algorithm. It is not the aim of this paper the validation of the proposed methodology, it is evident how the rainfall field presents a more realistic pattern after the CA smoothing, while in the first panel, obtained with a geometrical algorithm it looks just like a superimposition of circles. In the next panel (lower left) the grid points filled with previous rain gauges module are taken fixed and the rest of the domain is filled using MM5 model prediction and Cressman formula. Finally the second subdomain is smoothed with CA algorithm (lower right panel).

In order to make the comparisons easier, a small portion of the rebuilt precipitation field has also been reported in the panels of Fig. 15. Comparing the first two panels it is evident the ability of CA based algorithm to smooth the field rebuilt with Cressman formula to obtain a more realistic pattern. In the third panel it can be noticed as MM5 model probably overestimate the observed precipitation and the application of CA smoothing acts to reduce such overestimation. Other examples of the proposed technique are given in Figs. 19 and 20 and related discussion.

The above described sequence of algorithms allows to obtain, at each CHyM simulation time step, a realistic reconstruction of complex precipitation patterns, assimilating, in a hierarchical sequence all the data available at the considered time step. Of course we do not expect that this approach will perform better, respect to a statistical based technique; nevertheless the proposed technique offer a simple and powerful method to obtain a reasonable estimation of rainfall field for those situations (see Fig. 12 and related discussion) where a statistical method cannot be applied.

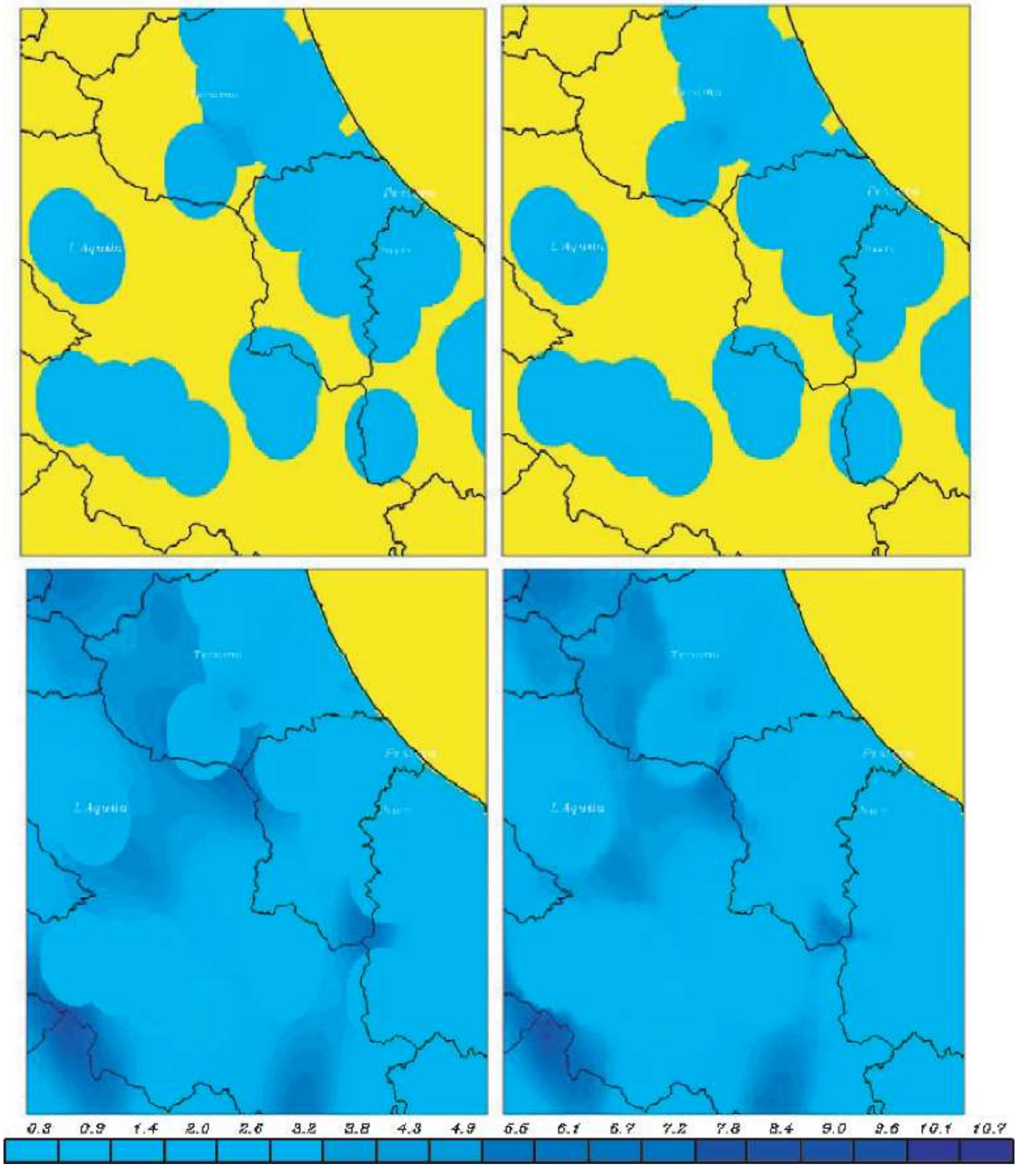


Fig. 14 The sequence of results obtained applying the sequence of modules for precipitation field reconstruction (mm/hour) from rain gauge measurements (*upper panels*) and from meteorological model forecasts (*lower panels*)

4 Parametrization of Physical Processes Contributing to Hydrological Cycle

To give a more complete description of CHyM model, the description of the parameterization of different physical processes that contribute to the hydrological cycle as they have been implemented in the current version of the model are here reported. None of the different parameterization are original respect to what implemented in many other models.

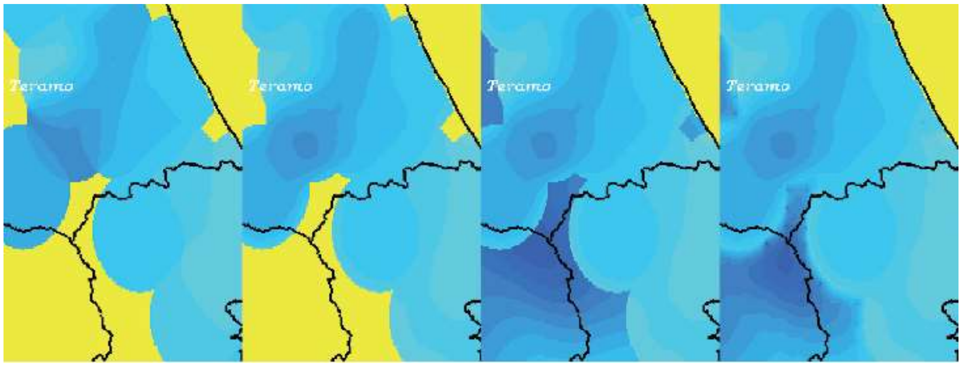


Fig. 15 Same as Fig. 14, but, in order to make easier the comparison, in this case we report a small portion of the considered domain. Comparing the first two panels it is evident the ability of CA based algorithm to smooth the field rebuilt with Cressman formula to obtain a more realistic pattern. In the third panel it can be noticed as MM5 prediction probably overestimate the observed precipitation and the application of CA smoothing (*last panel*) acts to reduce such overestimation

4.1 Surface Water Routing

Based on the kinematic wave approximation (Lighthill and Whitham, 1955) of the shallow water wave the equations used by CHyM model to simulate the surface routing overland and for channel flow are the continuity and momentum conservation equations:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q$$

$$Q = \alpha A^m$$

where A is the flow cross-sectional area, Q is the flow rate of water discharge, q is the rate of lateral inflow per unit of length, t is the time, x is the coordinate along the river path, α is the kinematic wave parameter, and m the kinematic wave exponent.

The kinematic wave parameter α is can be written as:

$$\alpha = \frac{S^{1/2} R^{2/3}}{n}$$

being S the longitudinal bed slope of the flow element, n the Manning's roughness coefficient while R is the hydraulic radius that can be written as a linear function of the drained area D as:

$$R = \beta + \gamma D^{\delta}$$

where β, γ and δ are empirical constants to tune with during the calibration. The exponent δ is usually very close to 1.

4.2 Evapotranspiration

The potential evapotranspiration is computed inside CHyM as a function of the reference evapotranspiration that is the evapotranspiration in soil saturation condition according to the formula:

$$ET_p = k_c \cdot ET_0$$

where k_c is the crop factor that is a function of land use. For details about the computation of the reference evapotranspiration refer to Todini (1996) and Thornthwaite and Mather (1957).

4.3 Infiltration and Percolation

The infiltration process is modelled using a conceptual model similar to those proposed by several authors as Overton (1964), Singh and Yu (1990). The infiltration term is given by:

$$I(t) = I_s(t) - P_s(lu)$$

where $I_s(t)$ and $P_s(lu)$ are respectively the infiltration and the percolation rate at the ground surface. The percolation rate $P_s(lu)$ is only dependent from the kind of land use (lu) of the considered cell and its value is established during the calibration of the model. The infiltration rate can be written as:

$$I(t) = I_{lu} - \kappa r(t)$$

where I_{lu} is the maximum of water that can be stored in the ground before the saturation and depends from the kind of land use while k is an empirical factor representing the fraction of rain $r(t)$ that infiltrates.

5 Some Applications of Chym Drainage Network of CHyM Model

Within the framework of hydrological operational activities, it is often required an alert system that is able to localize the area where floods have greater probability to occur. The estimation of the probability that a region will be affected by a flood would be of great advantages because we could focus accurate simulation in the most probable flood region saving time and computer resources. Moreover the possibility to have a realistic map of flooding risk could be an important information for the risk management activities carried out by the civil protection and local authorities. We will show in this chapter as the drainage network extraction technique implemented in the CHyM model and an accurate reconstruction of precipitation field at hydrological scale are sufficient to provide a flood alarm index that is able, at least in the case studies discussed below to localize the segments of drainage network where flood events are more likely to occur.

5.1 CHyM Flood Alarm Index

The use of a distributed hydrological model for the prediction of flow discharge requires a complex calibration activity. In addition only few complete discharge time series are available for numerical models validation while these time series are usually missing for small catchments. In a region of complex topography, like the Central Italy where CHyM model is used at present time, is therefore very difficult to validate a deterministic prediction of flow discharge for tens of small basins.

A more empirical but realistic approach could be the use of a stress index as an estimator of the probability that a certain segment of the simulated drainage network is undergoing to a flood. As a first simple approach this kind of index can be derived as a function of the rainfall drained by an elementary cell of the simulated domain and the hydraulic characteristic of the draining channel within that cell. The cross section of the river is usually considered, as a first approximation, a linear function of total drained area (see discussion about surface water routing in Section 4.1) and therefore a reasonable idea cold be to consider the ratio between the total drained rain and total drained area in the upstream basin of each cell. More specifically the CHyM stress index CSI for the cell i, j can be defined as follow:

$$CSI_{ij} = \sum_k \frac{w_k}{a_k}$$

where w_k indicates the rainfall in the cell k, a_k is the area of the cell k and the sum over k is carried out for all the grid points in the upstream basin of the cell i, j. For the practical applications discussed in the next section we consider the accumulated drained rainfall in a time interval of 48 hours because this time interval represents a typical runoff time for most of considered basins. The runoff time is usually defined as an average time that a drop of rain will take to runoff toward the sea. The stress index defined by the previous equation has also a simple physical interpretation: it represents the average precipitation for the upstream basin of a cell in the considered time interval. It is also important to note as CHyM stress index is calculated making a sort of spatial (all the upstream basin) and temporal (runoff time) average and this reduce the effect of different uncertainties in the reconstruction of rainfall fields from observation and/or meteorological forecast. Of course the most important reason to support the definition of this index is the observation that it actually seems to be a powerful method to localize the segments of drainage network where flood events actually occurred.

Finally we notice how the algorithms discussed in the Chapters 2 and 3 and implemented in the CHyM code are sufficient to calculate the CHyM stress index.

5.2 Application of CHyM Flood Alert Mapping to Different Case Studies

The CSI can be easily calculated using CHyM algorithms described in the previous sections and it has been tested for many case studies to check the actual possibility to detect the area that undergoes to major hydrological stress, few examples are given in Tomassetti et al. (2005) while here we report few other case studies.

The first case deal with the consequences of the meteorological critical event occurring during August 2005 between Austria, Germany and Switzerland. In this case many floods occurred in a wide domain, including many urban areas. The major damages were observed in the regions of Voralberg and North Tirol in west part of Austria and also in southern zone of Bavarian region (Germany). Figure 16 shows

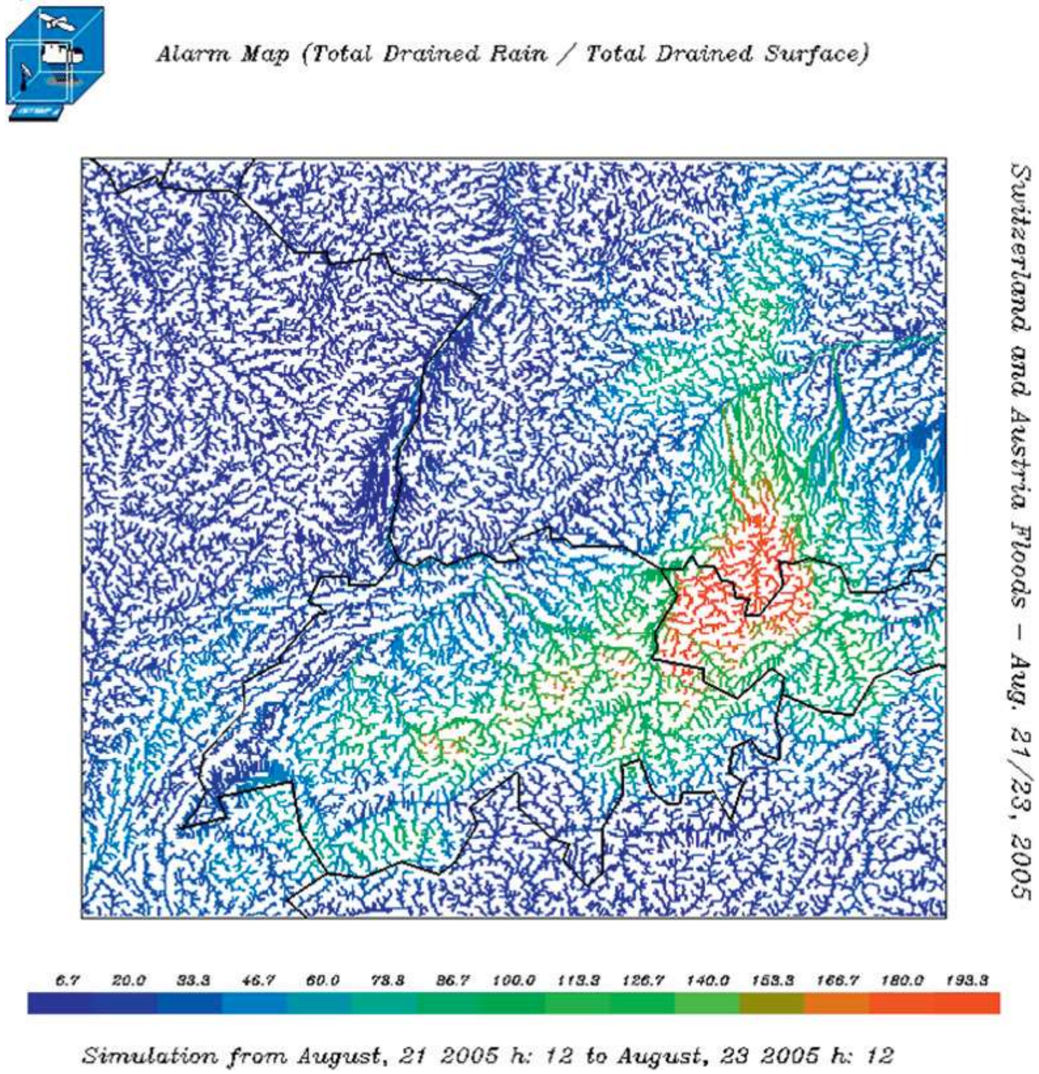


Fig. 16 The flood alert map obtained by CHyM model coupled with MM5 local area meteorological model, for the meteorological critical event occurring during August 2005 between Austria, Germany and Switzerland

the flood alert index map obtained with an off-line coupling of MM5 meteorological model and CHyM hydrological model, the hydrological scale resolution is, in this case, of 1 km. The colour scale used in the figure represents the stress index for each channel element of the considered domain, the maximum of the scale (red alarm) corresponds to 200 mm of rainfall in the last 48 hours. The areas of risk are well highlighted and localized and they actually corresponds to the locations where the major severe hydrological events were observed.

The hourly precipitation patterns were simulated with MM5 meteorological model (Dudhia, 1993; Grell et al., 1994), the model has been used in a configuration with three nested domain with innermost domain running at 3 km of horizontal resolution. The MM5 limited area model was forced with ECMWF General Circulation Model forecast.

The flood alert mapping for a second case study is reported in Fig. 17. In this case we refer to the severe meteorological event occurring between November 25 and November 26 2005 in the central Italy; from the meteorological point of view the situation is characterized by two different structures: a first one associated with high instability producing precipitation in the afternoon of November 25, and a second one producing a large scale trough entering from North-North-West and associated with high potential vorticity values and then causing intense precipitation

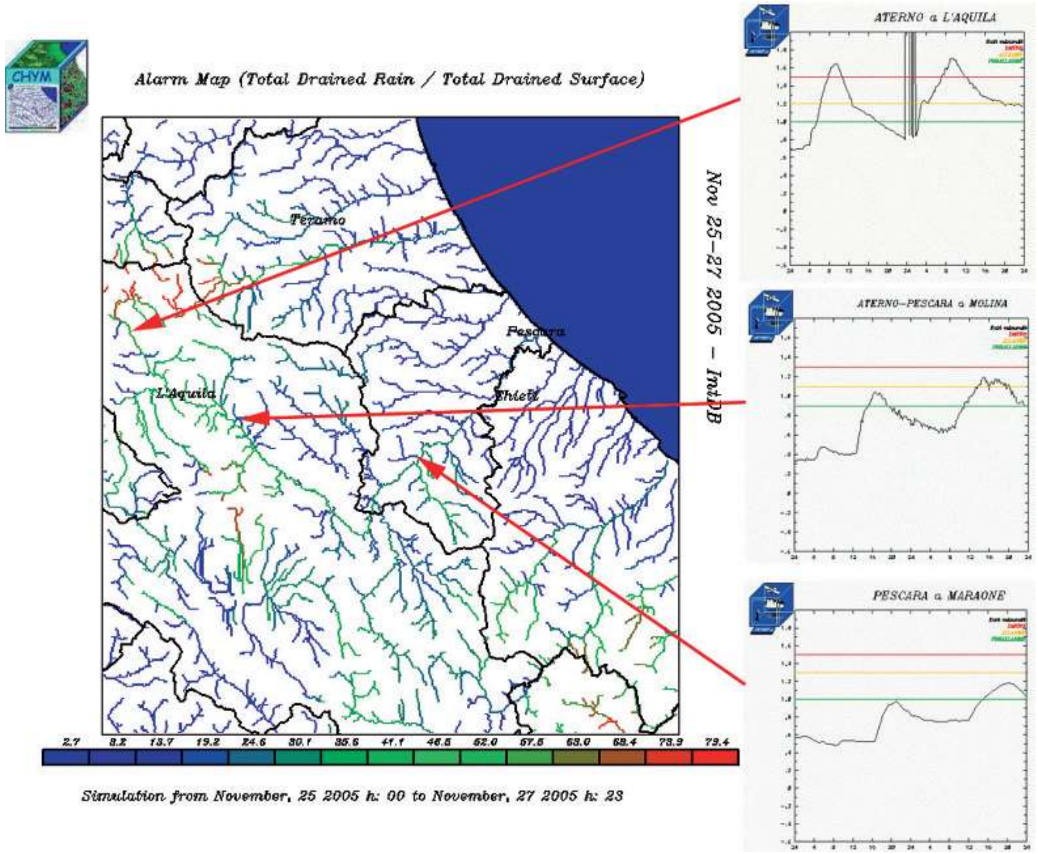


Fig. 17 The flood alert map obtained by CHyM model coupled with MM5 local area meteorological model, for the meteorological critical event occurring in Abruzzo Region (Central Italy) between November 25 and November 26 2005

phenomena. In this case the CHyM alarm map has been calculated on a grid with an horizontal resolution of 300 meters. Again the hourly precipitation patterns were simulated using MM5 meteorological model forced with ECMWF GCM forecast. The innermost MM5 domain, running at 3 km of horizontal resolution includes the whole domain considered in the hydrological simulation and shown in Fig. 17. In order to give a more quantitative validation of the proposed hydrological stress index, here we compare the predicted CHyM alarm map with the observed time series of hydrometric level in three different points of Aterno River basin (the size and the shape of this catchment are shown in Fig. 9). The small panels in the right part of the figure report the different time series, each compared with three different levels of alarm, these alarm thresholds for hydrometric levels were empirically established by Civil Protection local authorities in the last few years of observation. The arrows between time series panels and CHyM alarm map localize the position of hydrometers. It is very interesting to note how CHyM simulation correctly predicts a severe alarm in the location of first hydrometer: red colour for CHyM alarm map where the higher threshold value is actually reached. For the second hydrometer only the intermediate alarm level is reached and CHyM model correctly predicts a low level alarm (green in the map). The last observed time series only reach for few hours the first alarm threshold while CHyM simulation correctly predicts a low level alarm (intense blue) in this segment of drainage network.

It is worth to notice a couple of things about the previous case studies. The first observation is that in both cases a meteorological forecast was used to predict the alert map and, despite the intrinsic uncertainties in the quantitative rainfall prediction obtained with a meteorological model, the proposed alarm index actually localizes the segments of drainage network where the major severe hydrological events were observed. As already stated the quantity we define as alarm index is similar to a spatial (all the upstream basin) and temporal (48 hours) average of precipitation, and this acts to reduce the effect of uncertainties in the rainfall pattern reconstruction. Of course to have a risk indication in similar catastrophic events could be of big benefit for the local authorities and the responsible of civil protection activities.

Another important point is that the two case studies discussed above are carried out for catchments with very different size and characteristics but in both cases the same scale of stress index results to be a valid indicator of the area where the risk of floods is higher. This observation could lead to the conclusion that, at least in case studies reported here and in a previous work (Tomassetti et al., 2005), an average value of 150–200 mm of precipitation in the upstream basin is a reasonable limit to consider that a segment of drainage network is undergoing to risk. This conclusion is valid considering an appropriate time interval comparable to the runoff time of simulated catchment.

5.3 An Example of Coupling of CHyM Hydrological Model and the Climatic Version of MM5 Model

As discussed in the first chapter of the present paper, one of the most important feature of CHyM model is the possibility to acquire precipitation data from different sources, more specifically it has been designed to read the predicted rainfall fields from MM5 and RegCM atmospheric model. To give an idea of the potential applications we briefly discuss here the preliminary results obtained investigating the possible changes in hydrological cycle induced by the absence of glaciers in the Alpine Region of North Italy.

Changes in land use due to human activities may cause a significant change in typical meteorological and climatic conditions at the regional scale (see as an example Tomassetti et al., 2003). Nevertheless, there are many observations on the reduction in glaciers cover in mountain regions due to climate changes effects. In this context, it is usefull to couple different numerical models in order to investigate the possible effects of these changes in the hydrological cycle. This kind of study presents at least two different and interesting aspects, the first one being the possibility to simulate the future changes in water resource availability, while the second aspect is connected to the prediction of possible stresses in the whole drainage network, or only a few segments, due to the changes in the typical precipitation regime. A specific experiment has been designed to investigate the hydro-meteorological effects on the Po river basin associated with the melting of glaciers in the Alpine region. A climate simulation was carried out for March and April 2004 using two different scenarios for glaciers cover, the first one depicts the current situation, the second one represents an extreme scenario where all the glaciers disappear at an elevation below 3,000 meters. The simulations have been carried out using the climatic version of MM5 limited area model. Changes in the water resources upstream of the Po river drainage network are then computed using the CHyM model. Figure 18 illustrates the preliminary results for the two simulated months. It seems likely that an increase in the total amount of precipitation drained by the Po river (blue segments of drainage network) are due to glacier melt, as the average precipitation increases throughout the entire basin close to the mountains while the coastal section of basin seems to drain a lower quantity of precipitation (black segments of drainage network).

5.4 Prediction of Landslide Events Using CHyM Flow Scheme

It has been shown in Sections 5.1 and 5.2 as the total drained rainfall seems to be an important predictor of flood events. It is then straightforward to try to predict the occurrence of landslide using a similar approach.

In order to investigate this possibility we rebuilt the daily rainfall field, on CHyM grid with a resolution of about 1 km using ECMWF re-analysis from 1958 to 2002 and for a geographical domain including several regions of central Italy. An example is show in Figs. 19 and 20, where the different phases of precipitation field reconstruction are reported. In the left panel of Fig. 19 the ECMWF values are assigned to the corresponding cells of CHyM grid, because of the big difference between ECMWF and hydrological model grids, we also assign the same value to the cells in a neighbourhood of few grid points. In the next step (central panel) we assign a

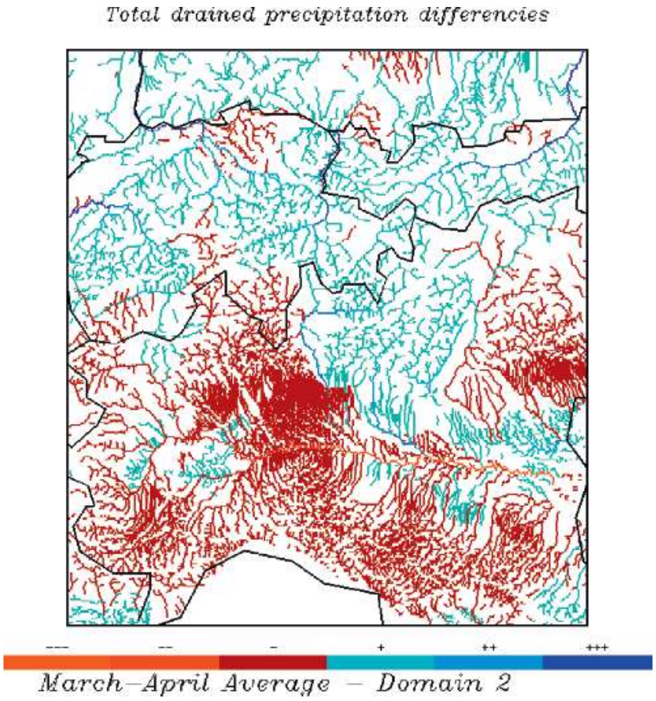


Fig. 18 Change in total drained precipitation induced by the absence of Glaciers in the Alpine Region of North Italy

reasonable value to all the other grid points using the Cressman formula discussed in Section 3.1. In the last phase (right panel) the rainfall field is smoothed using the CA based algorithm described in Chapter 3. Again it can be seen as the proposed algorithm gives a more realist reconstruction of rainfall spatial pattern respect to a simple geometrical interpolation (see also Figs. 14–15 and relative discussion).

This is also more evident in the case study of June 20, 1960 shown in Fig. 20, where the rainfall pattern appears more complex with the cores of precipitation field located in the north-east and south-east of the considered geographical domain, while no precipitation phenomena are observed in the western sector of the domain.

Once the daily accumulated precipitation fields are estimated at hydrological scale, CHyM routines are used to rebuilt the daily drained rain for the same domain. We suggest an empirical method to predict the major probability of landslide

Fig. 19 Downscaling of ECMWF rainfall data on CHyM grid for the case study of March 19, 1966

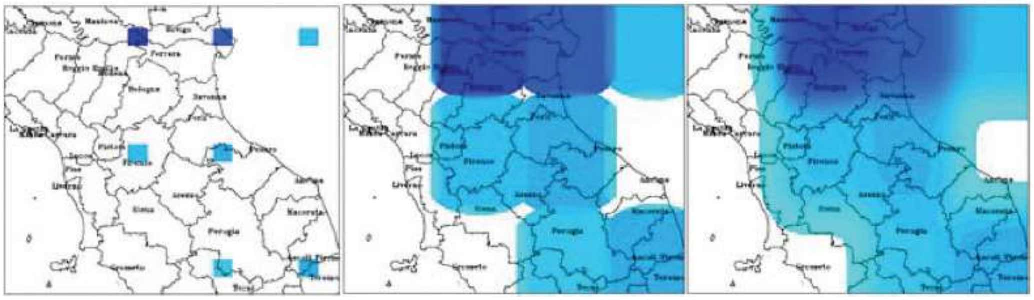


Fig. 20 Same as Fig. 19, but for the case study of June 20, 1960. The size of the selected area is about 200 km per side

occurrence: the warning level is reached for a given cell of the considered domain, when the total drained rain in the last N days becomes greater than a threshold value T_d, being N and T_d values to be optimized. We exclude from the analysis the channel-grid points, namely the cells whose drained area is greater than 100 km^2. The algorithm can be refined taking into account also the slope of the terrain obtained using the same procedure explained for Fig. 3, then we exclude from the probability of landslide occurrence all the cells whose maximum slope is lower than a reasonable threshold T_s. A further improvement could be to consider the specific land-use or land-type of the cell or the specific geologic characteristic of the terrain.

Examples of the preliminary results obtained with the practical application of the above described approach are shown in Fig. 21, for the severe meteorological event occurring during November 1966. The red X in the picture represent the location where landslide events actually occur, while the blue dots are the cells where our simple conceptual algorithm predict a landslide event. In the Fig. 21 we also draw the regional boundaries between Emilia Romagna and Toscana regions. It has to be noticed that a database including a complete map of landslide events are currently available only for Emilia Romagna region and this is the reason for which the locations of events appear only in subdomain above the cited administrative boundary. These results were obtained without considering the geological characteristic of the terrain and then they surely represent a very encouraging first test for the validation of the proposed technique.

5.5 Localization of Pollution Source Areas

The RSA algorithm briefly described in Section 2.3 has been implemented in a CHyM module to "paint" the drainage area of an arbitrary catchment, in order words this module calculates all the cells belonging to a basin (Fig. 9 shows an example for Pescara-Aterno river in the Abruzzo region). This feature could be very useful for many practical aspects, for instance it allows verifying whether the whole catchment we wish to simulate is contained in the selected domain. In addition, this tool allows

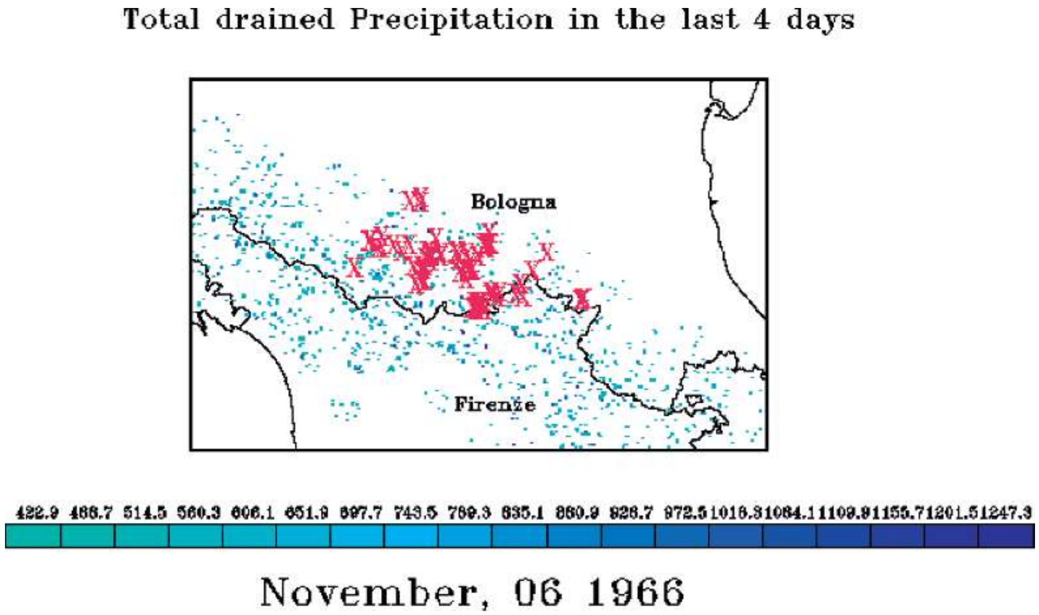


Fig. 21 Landslide events predicted by simple CHyM based technique. The red X in the picture represent the location where landslide events actually occured, while the blue dots are the cells where our simple conceptual algorithm predict a landslide event. It has to be noticed that a database including a complete map of landslide events are currently available only for Emilia Romagna region and this is the reason for which the locations of observed events appear only in subdomain above the administrative boundaries between Emilia Romagna and Toscana regions

to run the model only for the grid points belonging to a river basin, which may greatly reduce the required computing time. The module has been implemented in the most general way and it could be, in fact used to localize the drainage area for an arbitrary segment of a river. For example, suppose that following an intense precipitation event a strong gradient in the concentration of pollutants (say pesticides or nitrates) between two points of the river, A and B, is observed. Now it is realistic to assume that the pollutants have been carried by surface runoff. The CHyM module is able to localize the area that could be the source of pollution, and it will correspond to the entire area that is drained by point B, but not by point A if A is in the upstream basin of point B.

6 Concluding Remarks

A complete description of Cetemps Hydrological Model (CHyM) was given, we focused the attention on the description of original algorithms for drainage network extraction and assimilation of rainfall data from different data sets. CHyM is a distributed grid based hydrological model where the major physical processes contributing to hydrological cycle are simulated. Beside the possibility to predict in a deterministic way the discharge in any point of an arbitrary geographical domain, we showed as the combined use of an accurate flow routing scheme and a detailed reconstruction of precipitation fields leads to the development of many applications of the model for operational activities dealing with flood alert mapping or landslides events prediction, as for the investigation of the modification in hydrological cycle induced by the changes in precipitation variability.

Further information about CHyM model and related literature are available at the URL: http://cetemps.aquila.infn.it/chym

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