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Runoff cascades, channel network and computation hierarchy determination on a structured semi-irregular triangular grid

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Abstract

When developing a physically based mathematical description of hydrological processes over natural watersheds, the modeler faces the requirement of complete spatial specification of the various hydro-geological parameters as well as the ground surface characteristics. The usual approach, i.e. the use of representative average values in simplified configurations of the actual conditions, often leads to discrepancies. A detailed description of the topography is therefore needed but, on a complex topography, the accurate determination of overland cascades and streams often poses difficult problems.

The proposed method aims to provide some more insight into the above-mentioned problems. In order to simulate overland trajectories of runoff water and channel flow paths, the method represents the topography using a network of non-overlapping triangular surfaces of known properties (i.e. slope, orientation, area, soil texture, land-use), created with an appropriate digital elevation model. The simulated overland cascades may feed channels, terminate to local minima of altitude or reach the boundaries of the domain under consideration. The model allows for the use of variable resolution and has nesting capabilities.

The method has been applied on the Lucky Hills watersheds at Walnut Gulch, Arizona, using four different resolution schemes. The examination of the model's output shows that the various overland trajectories and channel flow paths are accurately computed in accordance with the model's specifications. Additionally, each simulated river network ended up at an outlet that precisely coincided (within the resolution) with the fixed position of the measurement station. No tuning efforts were undertaken and the model did not need calibration. This method seems to be advantageous compared to many of those in use, since it is fully automatic and time saving while proven to accurately simulate the drainage network. In addition, the method creates a detailed database easily accessible for the forthcoming assessment of the hydrologic response of the watershed in the frame of a distributed model.

Keywords: Distributed physically based hydrological models; Overland and runoff cascades; Semi-irregular structured triangular grid network; Computation hierarchy

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1. Introduction

Once the challenge in watershed hydrology was simply to predict water yield for reservoirs and perform flood mitigation analysis; now it is to simulate the flow of surface and subsurface water, sediment and pollutants within watersheds. The accurate determination of the water pathways regarding pollution (drinking water, irrigation, etc.) is therefore of

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primary importance in the process of both prevention and recovery. The accuracy of the related models depends primarily on the realistic representation of the distribution of important parameters such as orography, soil characteristics and rainfall within the real watersheds, which is often very complex. Therefore, the accurate description of the real situation is an essential requirement.

Unlike lumped models, distributed physically based models take into account the spatial variability of the above-mentioned parameters. Their use has been shown to be advantageous in hydrological modeling in the sense that they incorporate the physical conceptualization of both watershed characteristics and hydrological processes. For this reason, they have gained widespread acceptance. A fundamental issue that must be addressed by all users of these models is the definition of an acceptable level of watershed discretization. The level of geometry model complexity should be commensurate with the availability of input and verification data (Goodrich, 1991).

The accurate determination of the overland runoff cascades is one of the important problems the modeler faces when developing a distributed hydrological model. It is more than obvious that the effect of topographic convergence and divergence on flow characteristics on natural landscapes has a major impact on hydrologic and hydraulic variables (Grayson et al., 1995). Numerous approaches are applied in the frame of the various codes appearing in the literature. Moore et al. (1991), referred to three kinds of digital elevation models (DEM) used for the ground surface simulation in hydrological modeling; regular-grid models, using mainly adjacent rectangles (Morel-Seytoux and Al Hassoun, 1989; Abbott et al., 1986; Wesley and Keu, 1990; Loague, 1992; Garrote and Bras, 1995; Smith et al., 1995; Todini, 1996), contour-based models using streamlines and equipotential lines creating quadrangular cells (Grayson et al., 1992) and finally, triangular-grid models, using adjacent irregular triangles (Gandoy-Bernasconi and Palacios-Velez, 1990; Palacios-Velez and Cuevas-Renaud, 1992; Palacios-Velez et al., 1998).

The approach using rectangles may obviously lead to discrepancies as far as the description of the real ground surface is concerned, mainly due to the high level of subjectivity. Furthermore, the flow of water in the related models is commonly constrained to two orthogonal directions. On the other hand, the second approach is proved to be more sound in the sense that water flow is represented more realistically than in the common grid methods (Grayson et al., 1992). Generally, this approach requires a considerable larger amount of data even though the algorithm used is much simpler than that used in the other DEM models (Grayson et al., 1995; Palacios-Velez et al., 1998). Finally, the triangular-grid models are believed to be more sophisticated, allowing for the interactive creation and editing of the watershed topographic model based on adjacent triangular surfaces, which simulate the real topography in a more accurate way (Gandoy-Bernasconi and Palacios-Velez, 1990; Palacios-Velez and Cuevas-Renaud, 1992; Palacios-Velez et al., 1998). However, such methods often need user intervention in order to eliminate either spurious points or artificial discontinuities in describing the drainage network.

The DELTA/HYDRO module (Catsaros et al., 1997) of the DELTA code (Catsaros et al., 1993a,b) takes advantage of the capability of the DELTA_GAIA module to perform an accurate description of the topography by means of adjacent triangles of known properties, i.e. slope, orientation, area and land-use. All of the possible branches and paths through a single triangular facet and through the whole network of facets are taken into account, creating independent cascades without lateral influences. This feature along with its high level of automation and accuracy are the main advantages of the algorithm.

A detailed description of the current version of the DELTA/HYDRO procedure along with four illustrative examples of its utilization, are given in the following.

2. Geometrical analysis of a simulated watershed

2.1. Ground surface simulation

DELTA_GAIA (Catsaros et al., 1993a,b) starts from a digitized map of the area under treatment, containing the orographic data as a cloud of points given by their 3D Cartesian coordinates. User-supplied data, related to the polygonal contours of

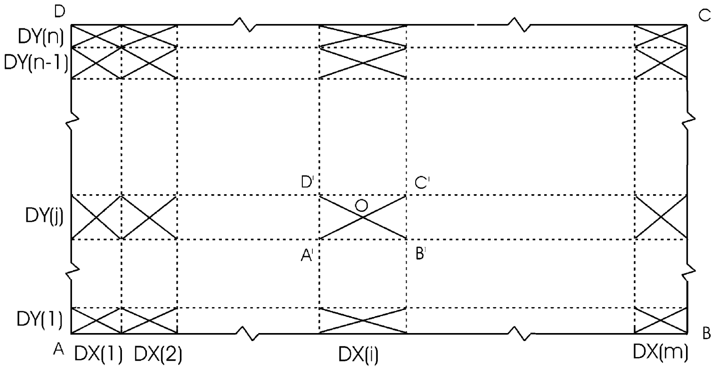

Fig. 1. *ABCD*: area under treatment, $A'B'C'D'$: cell (*i*,*j*), $A'B'O$, $B'C'O$, $C'D'O$, $D'A'O$: triangulation of the (*i*,*j*) cell.

the various regions encountered, are also required. In the context of DELTA_GAIA, a "region" is defined as a continuous area of homogeneous land-use and soil characteristics. DELTA_GAIA simulates the ground surface using adjacent triangular surfaces in number and size depending only on the accuracy required. Each triangle is characterized by its own geometrical (orientation, area, slope, etc.) and "region-dependent" (soil type, roughness, vegetation, etc.) properties. The steepest slope direction in any triangle (*ABC*) is given by the vector $\vec{S}$, computed as follows:

$$\vec{S} = \vec{V} \times (\vec{V} \times \vec{k})$$

where $\vec{V} = \overrightarrow{AB} \times \overrightarrow{AC}$ and $\vec{k}$ is the vertical unit vector, i.e. the vector with components (0,0,1) in a Cartesian system of coordinates.

The current version (1.1) of the DELTA_GAIA is conceived to simulate topographies using a semi-irregular structured triangular grid network. The user has to define a horizontal rectangular domain covering the area of interest plus an $(x - y)$ sub-division of the whole domain of $(DX(i),\ i = 1,\dots,m) - (DY(j),\ j = 1,\dots,n)$, into $m \times n$ rectangular cells according to its particular needs (see Fig. 1). Each $DX(i) - DY(j)$ cell is divided into four triangles based on its two diagonals. The horizontal coordinates of the vertices of the triangles coincide with the nodes of the user-defined output sub-grid. The altitudes of the nodes of the resulting triangular network are determined by the code by interpolation between the altitudes of neighboring data points. The obtained grid is obviously structured. It is also semi-irregular in the sense that neither the lengths *DX* nor the *DY*s are necessarily equal.

2.2. Simulation of cascades and rivers

Once the triangulation of the ground surface is achieved, control is passed on to the DELTA_CR module, which determines the overland runoff cascades and streams/rivers in the simulated watershed. The geometrical determination of the flow paths is based on the assumption that overland flow may be initiated from any non-horizontal ground surface triangle, if this surface experiences precipitation.

The determination of the complete network of water paths on the simulated topography is based on the assumption that overland flow is initiated from all non-horizontal triangular facets. Moreover, every water path is computed from its starting to its ending point, independently of its effective length, which the solution of the hydrological problem will determine, when the various physical phenomena (precipitation, evapotranspiration, infiltration, saturation, ponding, etc.) will be taken into account.

As explained in detail in Catsaros et al. (1997), depending on the deepest slope direction, the runoff water coming from an upstream triangle may (a) flow through the common edge of two triangles, enter and cross an adjacent downstream triangle following a plane triangular or trapezoidal path (unit); (b) be sub-divided towards two downstream triangular facets; and (c) converge on the common edge of two triangles and initiate a channel flow following this

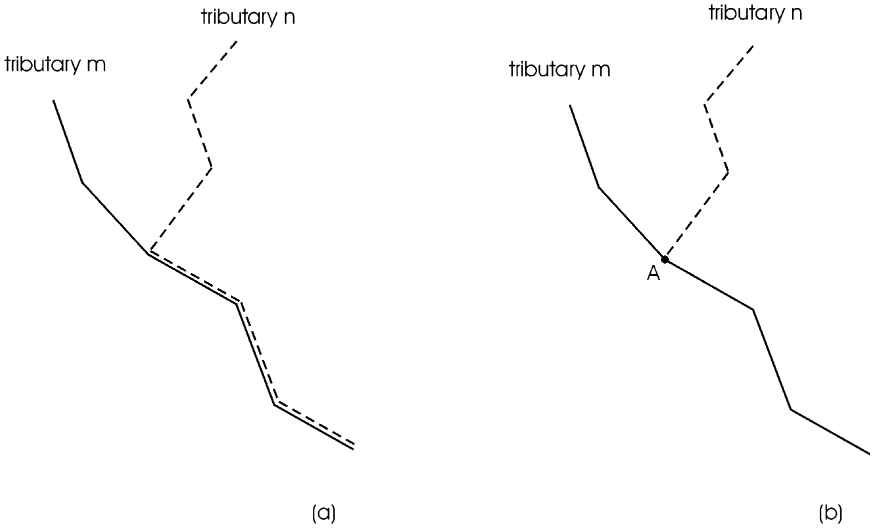

Fig. 2. Pair of tributaries (a) before processing and (b) after processing.

common edge (reach). Channel flow is allowed to develop only following consecutive edges of adjacent triangular facets toward the steepest slope direction. In the frame of DELTA_CR, all possible water paths are determined on the simulated topography and every water path is tracked from its starting to its ending point. A succession of consecutive units forms an overland cascade while a succession of consecutive reaches forms a river.

Track of every single overland cascade is kept by the code by saving all its geometrical characteristics in a "direct access" file. Flags are put every time a bifurcation (outlet from two different edges) is encountered. Once a single cascade branch reaches an end point (domain's boundary, local minimum of altitude or river's reach), the code automatically performs a "backspace search" in order to treat the more recent bifurcation encountered. It should be noticed that the DELTA_CR module determines the various units of a cascade starting from the upstream end toward the downstream one, until an end point is reached.

In the more general case of outlet from two different edges, the trapezoidal flow paths are drawn and the 3D Cartesian coordinates of their starting and ending points are saved in a single record together with the ID-number of the crossed facet and the ID-numbers of its downstream neighboring triangles. Moreover, each time a channel flow is initiated, a flag is put and the control is diverged to a "direct access" file where the characteristics of the stream are saved: successive records are produced, each one containing the ID-numbers of the adjacent facets between which the channel flow develops and the coordinates of the higher and lower point of each reach. A stream (or river) ends up either in a local minimum of altitude or in the domain's boundary. Since the code does not allow for interactive editing, all the spurious channel flow obstructions are erased automatically. Generally, nodes that are lower than all their immediate neighbors are characterized as minima of altitude. As soon as the code identifies such a "disturbance", an internal process is started in order to clarify its nature ("real" or "artificial" local minimum), by checking the flow directions from its immediate neighboring nodes and further down. If it is verified that it is an artificial local minimum, the code automatically fixes the "disturbance" by setting a new altitude to the node in order to maintain the prevailing slope tendency. Otherwise, the node is considered to be a local minimum where the flow is going to end up.

2.3. Simulation of river system network

As soon as all possible paths are set, control is given to the DELTA_NET module, which automatically determines the various river systems of the simulated watershed. In the context of DELTA_NET, a

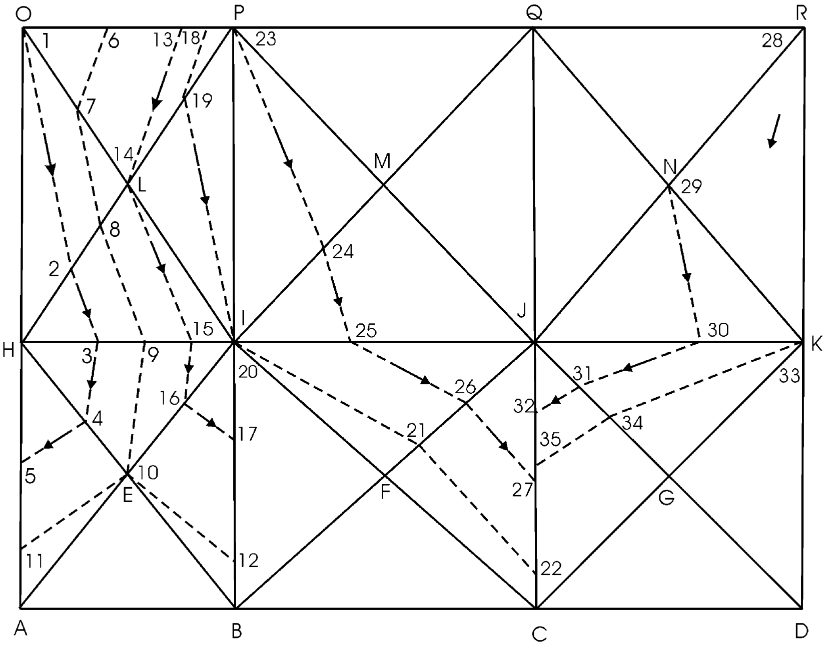

Fig. 3. The cascades initiated at triangle *POL* and *KNR* are feeding the reaches *HA*, *IB* and *JC*. The arrows show the direction of the deepest slope.

river system is an ensemble of streams (rivers) having a common outlet point along with all the overland flow cascades feeding their reaches. In the same context, a watershed is an area drained by a single river system.

The code groups in systems the rivers with a common outlet. An immediate consequence of this feature is that DELTA_NET automatically settles the various watersheds formed within a given topography by identifying the triangles contributing to a particular river system.

For each river system, a principal river is selected, which is the one with the highest number of reaches. The remaining rivers are characterized as tributaries and processed in couples, with an arbitrary order: the code examines sequentially all the tributaries with regard to existing common reaches. In case of a pair of tributaries, denoted as *m* and *n* in Fig. 2, sharing actually a number of reaches, the code assigns their common reaches to one of the two (to the tributary *m* in Fig. 2). Thereafter, tributary *n* is considered to end up at point *A* (junction *A*) and is regarded as a tributary to *m*. The process continues until all tributaries are processed and results in a tree-like structure.

The code keeps track of each tributary and its junctions with other tributaries or with the principal river of the system. Moreover, the code generates an output file containing all the necessary information on each tributary and its reaches, i.e. the geometrical characteristics and detailed description of every overland cascade feeding that reach. In accomplishing this task, DELTA_NET performs a re-assessment of the primary cascades' characteristics, which were computed by the DELTA_CR module. This is a necessary action in order to account for the flow divide caused by a runoff water outflow from two different edges of a triangle, as shown in Fig. 3, where the various situations encountered when analyzing a watershed are depicted.

The trivial case is that of a "regular" cascade like the one initiated in the triangle *KNR* (see Fig. 3). This cascade crosses the triangles *NJK*, *KJG* and *GJC*, feeding the part (32,35) of reach *JC*. On its way downstream, this cascade does not experience bifurcation, i.e. outflow from two different edges of a triangle. Consequently, no modification is needed and the characteristics of this cascade as they have been determined by DELTA_CR, are "accepted" by DELTA_NET.

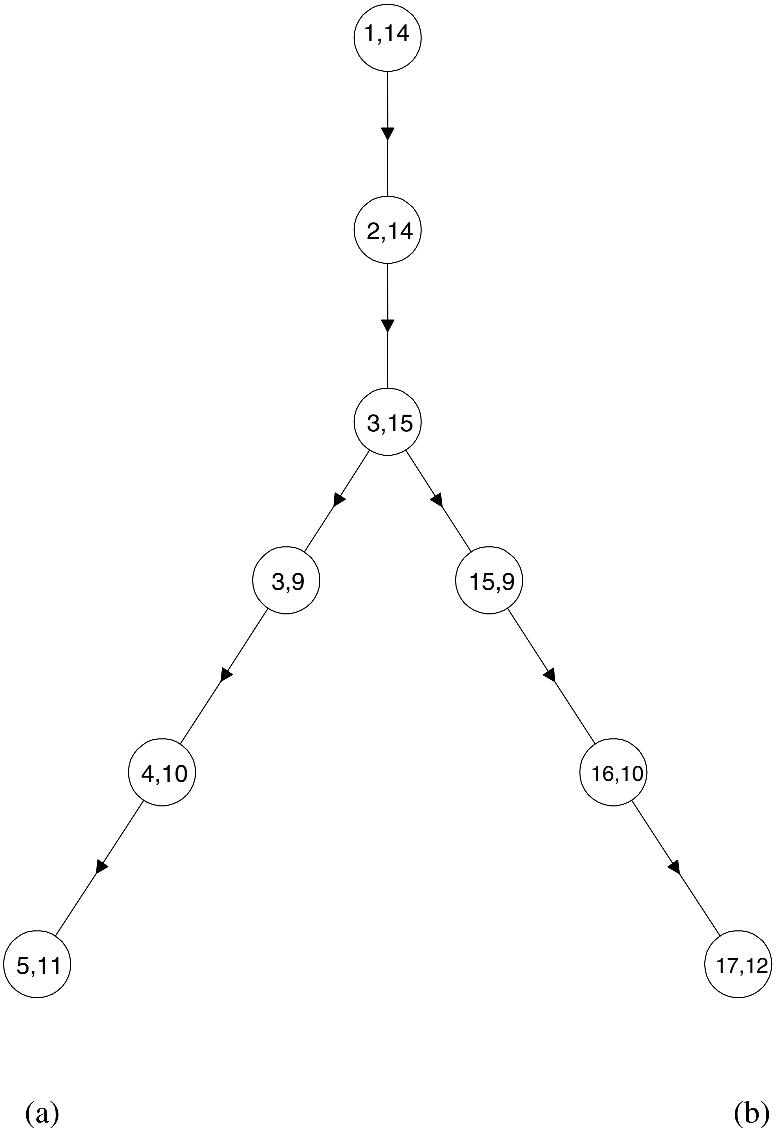

Fig. 4. Runoff cascade experiencing bifurcation.

This is not the case for the runoff water initiated in triangle POL, where DELTA_CR identifies two runoff-starting areas, namely (13,1,14) and (23,13,14). The first cascade crosses triangles *LOH*, *HLI* and *IHE*. As it passes through the last triangle, it experiences a bifurcation, creating two branches, the first feeding the part (5,11) of reach *HA* and the second feeding part (17,12) of reach *IB*. DELTA_CR keeps track of the following succession. It should be noticed that by that time, points no. 6–8 do not exist and point no. 9 is created by DELTA_CR only during the treatment of triangle *IHE*. Therefore (see Fig. 4 where only the outlet segments of the units are mentioned), runoff water flowing through the unit $(2, 14) \rightarrow (3, 15)$ will be directed and consequently cater to both cascades (a) and (b), through (3,9) and (15,9), respectively, creating an artificial over-estimation of the whole discharge. DELTA_NET rectifies the outline of these cascades starting from their downstream ends (5,11) and (17,12) and proceeding

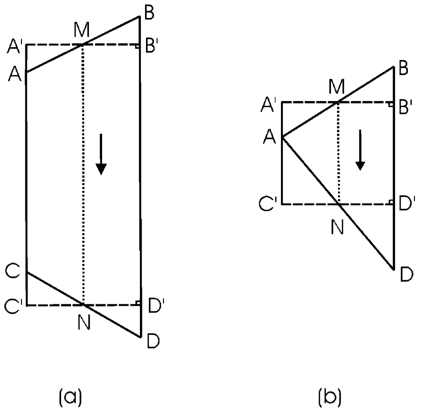

Fig. 5. Transformation of (a) “pure” and (b) “degenerate” trapezoidal units into rectangular paths. *M* and *N* are the mid-points of the inlet and outlet edges, respectively. The arrows show the direction of the deepest slope.

upstream: (4,10), (3,9), (2,8), (1,7) and (1,6) for cascade (a) and (16,10), (15,9), (14,8), (14,7), (13,6) for cascade (b). The same applies for the two cascades initiated in area (23,13,14), feeding parts (20,17) and (27,22) of reaches *IB* and *JC*, respectively.

Once a correct succession of units is obtained, DELTA_NET further rectifies their outline transforming them into runoff trajectories suitable for flow computations by any hydrological model (solution of the full de St Venant equations, kinematic wave approximation, etc.). In fact, the hydrological units created, when simulating the geometry of a watershed using DELTA, belong to two classes. The first one comprises “pure” trapezoidal trajectories such as $(2, 8) \rightarrow (3, 9)$ and the second comprises “degenerate” trapezoidal trajectories, which are in fact of triangular shape such as $(1, 6) \rightarrow (1, 7)$ or $(29, 33) \rightarrow (30, 33)$ (see Fig. 3). Both are transformed by the code into rectangular paths having the same area with the original units, as shown in Fig. 5, where $(A, B) \rightarrow (C, D)$ in (a) and $(A, B) \rightarrow (A, D)$ in (b) are transformed into $(A', B') \rightarrow (C', D')$. The code stores the characteristics

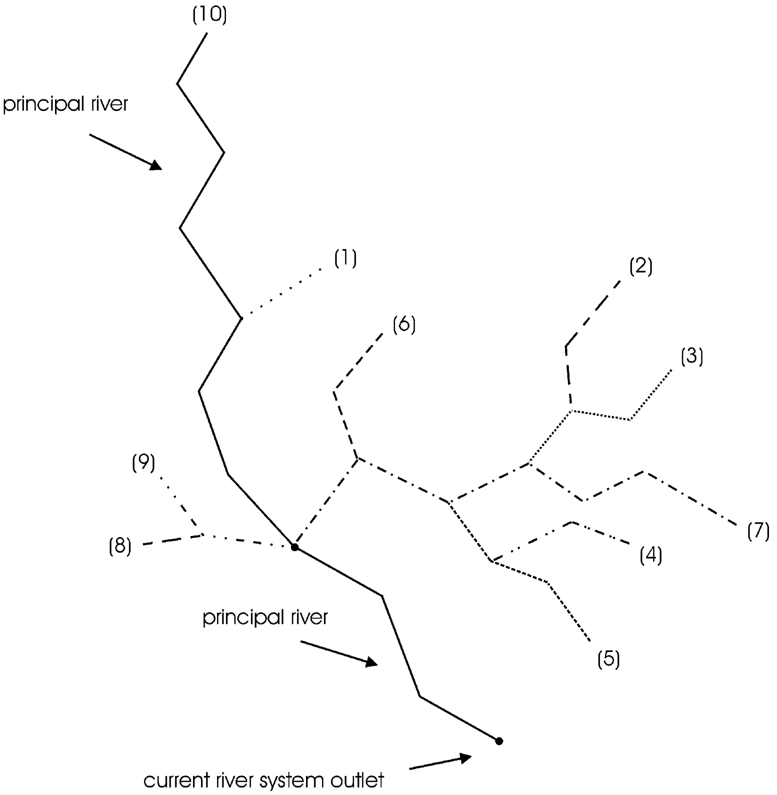

Fig. 6. Computation hierarchy within a river system; rivers are processed following their numeration.

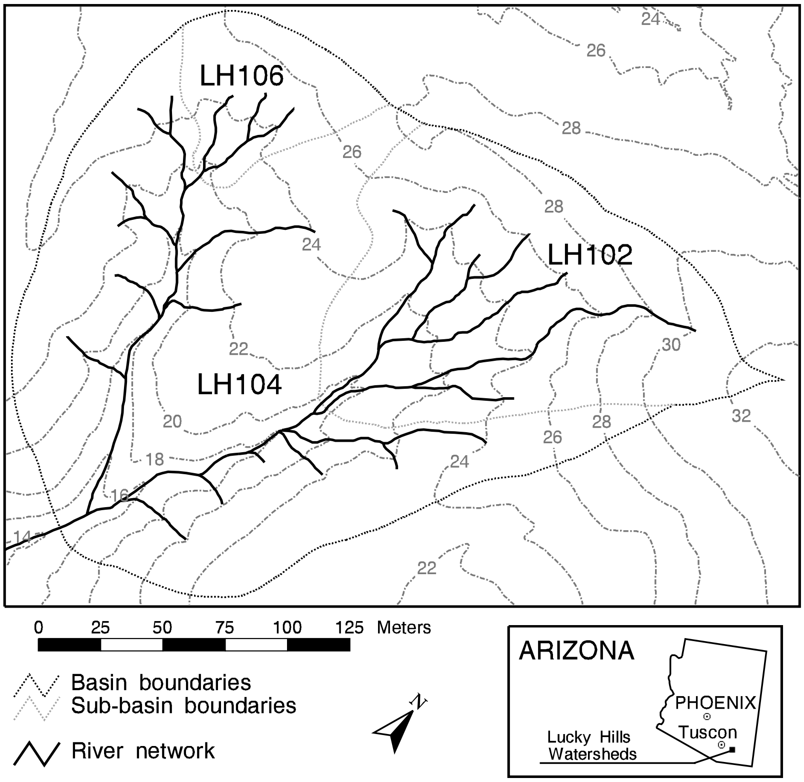

Fig. 7. Location and river network of the Lucky Hills watersheds.

of the transformed units, which are necessary for subsequent hydrological computations, i.e. flow length (MN) and flow width ($A'B'$).

The last purpose of the DELTA_NET module is to establish a physically correct computation hierarchy (i.e. the numbering system to be followed) for routing the water flow in the various components of each river system. The procedure consists of the following steps:

(i) Starting from the upstream end of the principal river, the various tributary junctions are processed following the logic of gravity.
(ii) For a river subsystem emanating from a given tributary junction of the principal river, the analysis sequence described in Gandoy-Bernasconi and Palacios-Velez (1990), is used.
(iii) In the case that more than one sub-system of tributaries emanates from a single junction of the principal river, the sub-systems are numbered consecutively, one after the other.
(iv) The principal river is processed at last.

This procedure is illustrated in Fig. 6, where the number attributed to each tributary denotes its order in the hydrological analysis process.

3. Application

3.1. The Lucky Hills watersheds

The small (4.4 ha) experimental Lucky Hills watershed is located in the western end of the Walnut Gulch Experimental Watershed near Tucson, Arizona, and it is under operation since the early 1960s, by USDA-ARS. It consists of three watersheds, i.e. LH104 and two nested LH102 and LH106, appearing in Fig. 7. The soil type is mainly sandy loam overlying bedrock at relatively shallow depths. The slopes are generally less than 30%.

Table 1
Lucky Hills watersheds simulation characteristics

Simulation	No. of columns (*DX*s)	No. of rows (*DY*s)	No. of nodes created	Total no. of triangles	No. of triangles simulating LH watersheds
Sim1	12	8	213	384	227
Sim2	16	12	413	768	437
Sim3	32	24	1593	3072	1771
Sim4	24	18	907	1728	1071

3.2. Application of DELTA/HYDRO

Four simulations of the Lucky Hills watersheds have been performed, in order to test the _GAIA, _CR and _NET modules of the DELTA/HYDRO code. Three of them (sim1 to sim3) are "blind" simulations (i.e. without particular tuning effort), representative of simulations performed by an inexperienced user, without deep knowledge of the peculiarities of the region under treatment. The fourth (sim4) is a description using variable resolution according to particular needs: sub-region with "sharp" topography, focus on detailed outlet of a particular sub-watershed, etc.

The hydrology of the area is well known: hydrological analysis (Goodrich et al., 1995) and numerous modeling activities have been undertaken in this area using various models such as KINEROS (Goodrich, 1991), SPUR (Wilcox et al., 1990), THALES

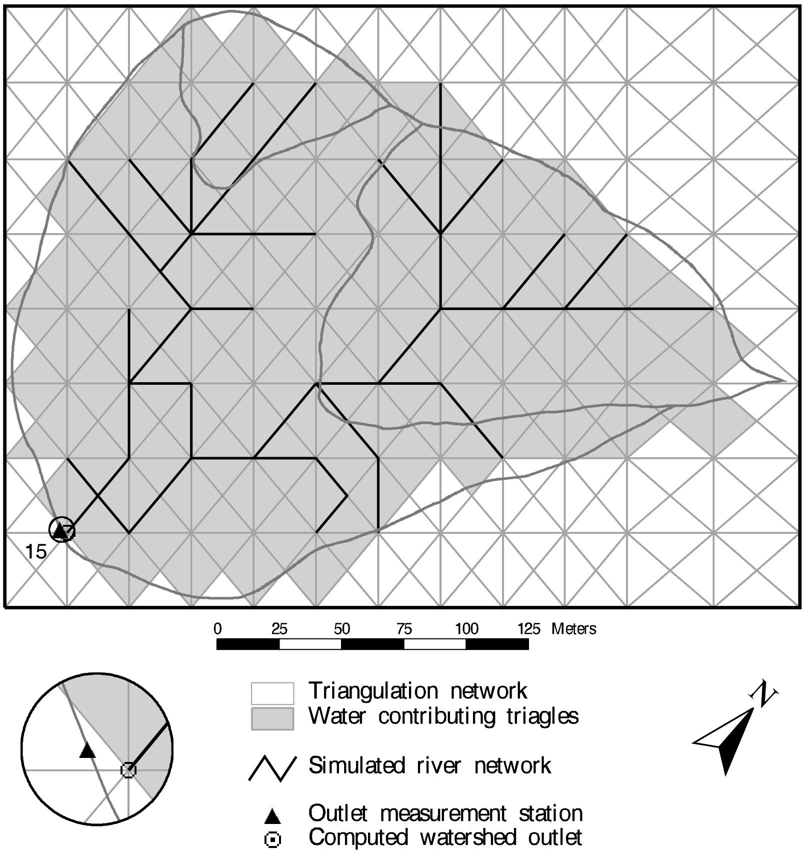

Fig. 8. Low-resolution simulation (sim1) of the Lucky Hills watersheds and river network.

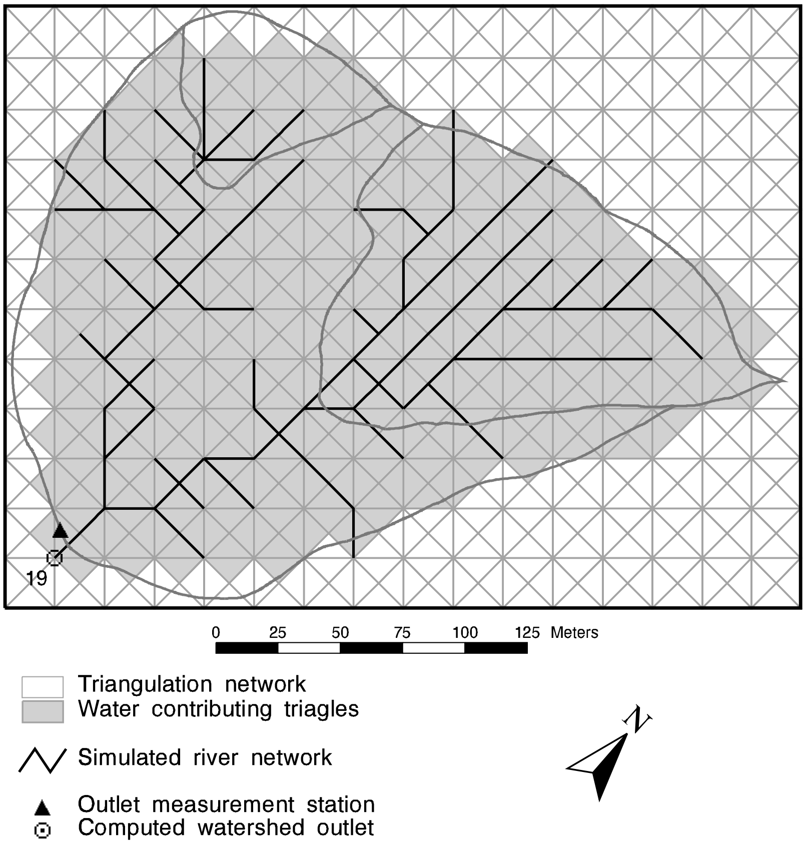

Fig. 9. Medium resolution simulation (sim2) of the Lucky Hills watersheds and river network.

(Grayson et al., 1992), SHIFT (Palacios-Velez and Cuevas-Renaud, 1992).

For the DELTA_GAIA module needs, a detailed topographical map (USDA-ARS) has been digitized. The digitization of the contour lines resulted in an orographic database of 5404 points. DELTA_GAIA produced the triangulation of the domain according to the procedure described previously, based on four different user-defined *DX*/*DY* resolutions. The characteristics of each simulation are shown in Table 1 and the corresponding triangulations appear in Figs. 8–11.

As soon as each ground surface simulation was concluded, control was passed on to the DELTA_CR module, for the determination of the overland cascades, streams and rivers of the watershed, following the procedure described before. In order to define geometrically all the possible water paths, precipitation has been assumed to occur on all triangles of the simulated area. In the most general case, the user can easily choose to consider any isolated part of the area that experiences precipitation.

Once all the overland flow cascades and channel flow paths were determined separately, the DELTA_CR procedure isolated and then linked only the trajectories that started as overland flow and continued moving downstream as channel flow, up to a common exit-node, which is considered as the watershed's outlet. For each simulation case, the number of triangles contributing water to the watershed's outlet is shown in the last column of Table 1. The final step of the simulation is performed by the DELTA_NET module, which created the river system network and rectified the cascades computed by DELTA_CR, as was previously explained. By this procedure, the principal river accompanied with a different number of tributary rivers for each simulation case was defined automatically.

The four applications of DELTA/HYDRO to the

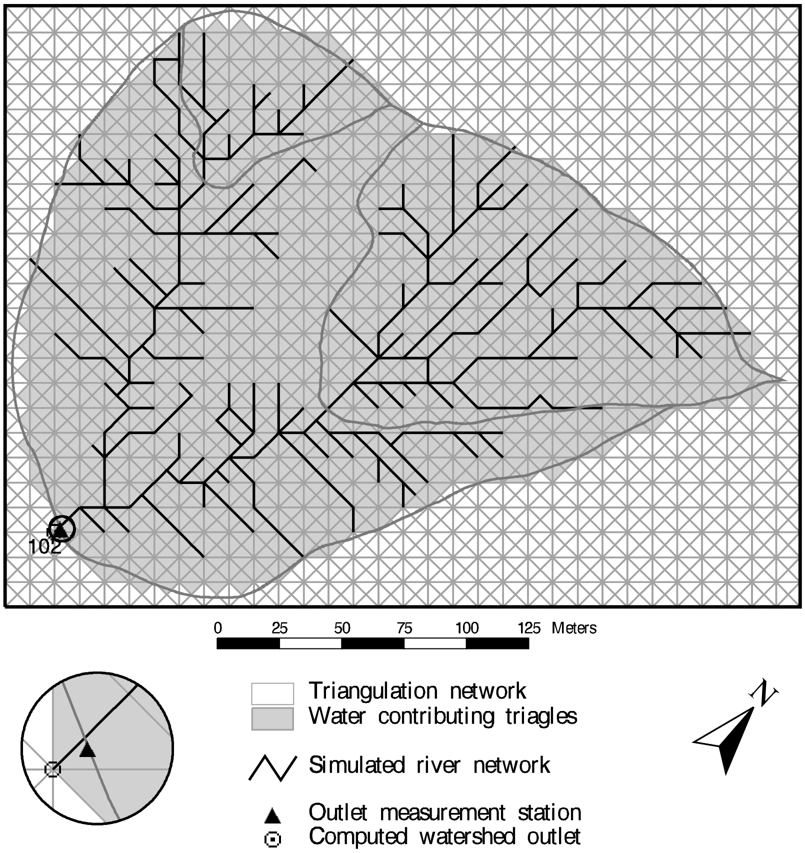

Fig. 10. High-resolution simulation (sim3) of the Lucky Hills watersheds and river network.

Lucky Hills watershed generated the river networks, which are shown in Figs. 8–11, with a corresponding computational time, which varied, depending on the simulation case, from 45 to 80 min in a HP9000/735 Workstation. The characteristics of the whole network for each case separately are presented analytically in Table 2.

3.3. Discussion

For reference and comparison purposes, the Lucky Hills watersheds divides and their “natural” river networks were obtained visually from the corresponding topographical map (USDA-ARS) and are shown in Fig. 7.

The three “blind” simulations (sim1 to sim3) produced using DELTA/HYDRO, result in river networks with the same (within the resolution) outlet location. Furthermore, the medium resolution simulation sim2 (Fig. 9), produces a river system that is very similar compared to the “natural” river network (Fig. 7). On the other hand, the low-resolution simulation sim1 (Fig. 8), gives a rough description of the net configuration whilst the high-resolution simulation sim3 (Fig. 10) creates a much more detailed network allowing for the representation even of minimal water courses, which cannot be seen on a map. The number of the various elements of each water network increases regularly with increasing resolution, as can be seen in Table 2, where the characteristics of each simulation are presented.

In each simulation case, all the water-contributing triangles are located inside the watershed borders with the exception of a small number of triangles that add water to the outlet but are located partly or entirely outside the watershed’s borders. This could be

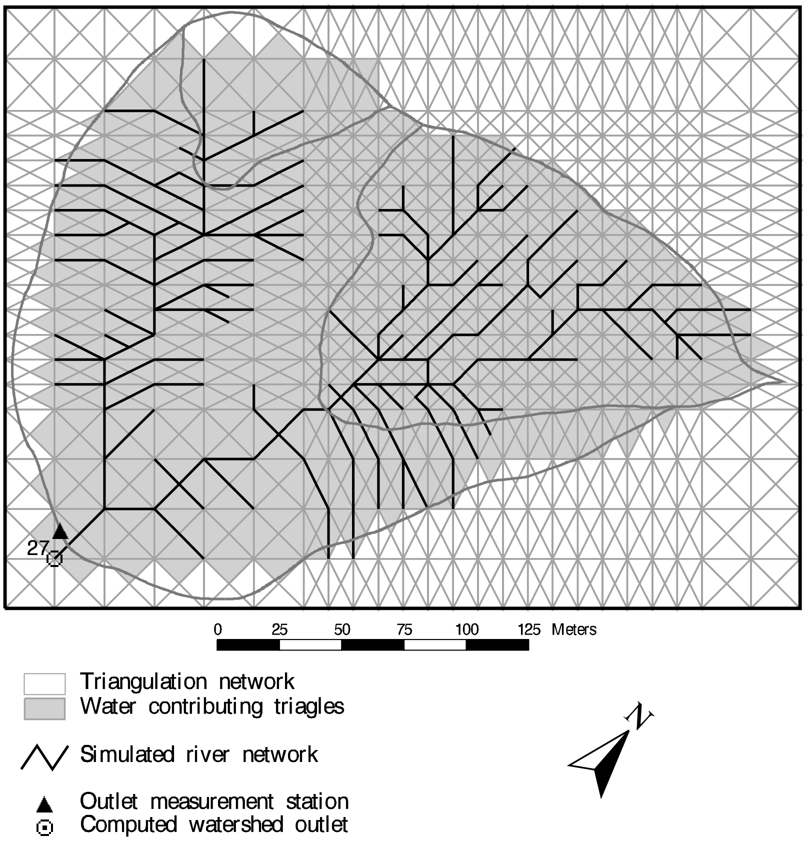

Fig. 11. Simulation (sim4) of the Lucky Hills watersheds and river network focusing on LH102.

attributed to the fact that the watershed's boundaries (Fig. 7) are visually obtained and manually "drawn" on the map and then digitized, introducing a degree of error. Furthermore, for each simulation, a limited number of triangles that are located inside the watershed's borders but near the orthogonal domain's borders seem not to contribute to the outlet, due to incorrect orientation. This could be attributed partly to the manually "drawn" watershed's boundaries as explained before and partly to the absence of contour lines in the area, which are necessary for the accurate computation of the altitudes of the neighboring nodes. Consequently, their computation by means of interpolation procedures introduced a degree of arbitrariness. The relative importance of these "spurious" contributing facets decreases with increasing resolution as can be seen in the sequence of simulations (sim1 → sim2 → sim3).

The nesting capabilities of the DELTA/HYDRO code are illustrated in sim4 (Fig. 11). In this

Table 2
Simulated river network characteristics in Lucky Hills watersheds

Simulation	Rivers	Cascades	Reaches	Max. reaches/river	Max. tributaries/reach	Max. cascades/reach	Exit node no.
Sim1	20	237	59	14	3	29	15
Sim2	33	485	117	21	4	32	19
Sim3	91	3237	378	38	3	215	102
Sim4	70	1538	261	31	3	114	27

simulation, the LH 102 sub-watershed is described in a much more detailed way than the rest of the Lucky Hills watersheds, taking advantage of the code's ability to use irregular *DX* and *DY* sub-divisions. This simulation produces an accurate outlet position, a detailed river network for LH 102 along with a rough indication of the river network configuration for the rest of the domain. The appearance of "spurious" contributing facets is attributed to the same reasons as in the simulations analyzed previously.

The existence of a few (up to three) apparently closed water paths in Figs. 8–11 has also been pointed out in simulations carried out by other algorithms (Gandoy-Bernasconi and Palacios-Velez, 1990). They are due to the presence of local maxima of altitude around which flow in reaches may initiate toward different directions.

4. Conclusions

The geometrical part of the DELTA/HYDRO code is suitable for the accurate analysis of watersheds of complex topography. The code creates the river network with an accuracy depending on the resolution chosen. DELTA/HYDRO determines every possible overland water path feeding the reaches of the river network. Furthermore, the code automatically settles the various drainage basins within a given watershed. It also has nesting capabilities addressing particular problems as focusing on the hydrological analysis of a single sub-watershed or on the accurate representation of a sub-region with particularly complex topography, without dramatically increasing the total number of triangular facets used. This feature alone will prove to be quite useful in cases of big watersheds with remarkable dissimilarities in the topography. This is not the case in the Lucky Hills watersheds where the whole domain is quite complex and limited in space; this is the reason why the use of regular Cartesian cells of appropriate size proved to simulate the area more accurately.

In any case, the resolution should always be chosen in order to provide sufficient detail for the adequate representation of both ground surface and the complex river system but without using an excessive number of triangular surfaces. Indeed, an excessively high resolution will result in an excessive number of water elements to be analyzed. The choice of the appropriate resolution depends on the complexity of the area under treatment, which determines the accuracy required, and on the needs of the distributed hydrological problem.

The procedure used in the DELTA/HYDRO code is completely automatic and does not need any user intervention in order to eliminate flow discontinuities. The "direct access" file structure used in order to keep track of the geometrical characteristics of the various overland cascades and channels, will provide an easy access to those data when the hydrological problem and the problem of on-ground transport of pollutants will be addressed in the frame of a distributed model.

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