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Journal of Hydrology 193 (1997) 204–213

Journal
of
Hydrology

The assignment of drainage direction over flat surfaces in raster digital elevation models

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Received 4 March 1996; accepted 3 May 1996

Abstract

Drainage direction assignment over flat surfaces in raster Digital Elevation Models (DEM) has been a stubborn problem for DEM processing methods. A new approach that improves upon current methods of flat surface treatment is presented. The approach is based on the recognition that in natural landscapes drainage is generally away from higher and towards lower terrain. To produce such a drainage, DEM elevations of a flat surface are modified to impose two gradients: one away from higher terrain, and one towards lower terrain. Subsequent processing of the DEM produces a drainage pattern over the flat surface that is topographically consistent and exhibits flow convergence properties. The proposed approach is not restricted by the shape of the flat surface, the number of outlets on its edge, or the complexity of the surrounding topography. A comparison with the drainage pattern of an established method that displays the 'parallel flow' problem shows significant improvements in producing realistic drainage patterns. The proposed approach extends automated DEM processing to digital landscapes for which existing methods cannot provide adequate flow directions over flat surfaces to conduct a drainage analysis. The necessary algorithmic details for implementation of the approach are provided. © 1997 Elsevier Science B.V.

1. Introduction

Truly flat landscapes seldom occur in nature. Yet when a landscape is represented as a Digital Elevation Model (DEM), areas of limited relief can translate into perfectly flat surfaces (the term 'flat surface' hereafter always refers to the DEM). Flat surfaces typically are the result of inadequate vertical DEM resolution which can be further exacerbated by a lack of horizontal resolution. They are also generated when depressions in the digital landscape are rectified by raising the elevations within the depressions to the

PII S0022-1694(96)03138-1

level of their lowest outflow. Such 'depression filling' of the DEM is often performed when using a flow routing approach to identify landscape characteristics (Jenson and Domingue, 1988; Mark, 1983; Martz and De Jong, 1988). Whatever their origin, flat surfaces are a problem when it comes to defining drainage or performing flow routing, because flow direction and aspect on a perfectly flat surface are indeterminate (Speight, 1974; Tribe, 1992). This problem arises in automated drainage analysis with both the widely used D-8 flow routing approach (Fairchild and Leymarie, 1991) and for the various multiple-direction and aspect-driven approaches (Costa-Cabral and Burges, 1994).

A variety of methods have been proposed to address the problem of drainage analysis over flat surfaces. These have typically been implemented in conjunction with the D-8 flow-routing approach and range from simple DEM smoothing to arbitrary flow direction assignment. However, these methods have limitations. DEM smoothing introduces additional loss of information to the already approximate digital elevations, while arbitrary flow direction assignment can produce patterns that reflect the underlying assignment scheme and are not necessarily realistic or topographically consistent. Even sophisticated methods which include flow convergence on flat surfaces (Tribe, 1992) have some arbitrary flow direction assignments and may require subsequent corrective adjustments to DEM elevations to accommodate the method (Martz and Garbrecht, 1995). For a short review of existing methods of treating flat surfaces, the reader is referred to Tribe (1992).

Given the above limitations, the application of automated DEM processing is often restricted to landscapes with well-defined topographic features that can be resolved and reproduced by the DEM. Small and infrequent flat surfaces are usually treated by one of the traditional methods without significant implications. However, low relief landscapes and/or low DEM resolutions produce a greater number of larger flat surfaces, which in turn may result in an inadequately defined drainage to address issues related to surface runoff. A better drainage identification over flat surfaces is needed to extend the capabilities and usefulness of automated DEM processing for drainage analyses.

This paper presents a new numerical algorithm that modifies flat surfaces to produce more realistic and topographically consistent drainage patterns than those provided by earlier methods. While the algorithm could be used to improve flow patterns over flat surfaces under any raster-based drainage analysis approach, this paper focuses on the application of the algorithm with a D-8 flow-routing approach. This focus arises, in part, because the algorithm was developed for incorporation into the DEM processing software module DEDNM (Martz and Garbrecht, 1992) which is based on a D-8 approach and is a core component of the TOPAZ landscape analysis tool. TOPAZ (*To*pographic *Pa*rameteri*z*ation) is designed for topographic evaluation, drainage identification, watershed segmentation and subcatchment parameterization (Garbrecht and Martz, 1995) and is used for the two applications presented in this paper. The more important reason for this focus, however, is that the D-8 approach is the most widely used for automated drainage analysis (Tribe, 1992) and, despite its limitations (Costa-Cabral and Burges, 1994), provides a reasonable representation of flow patterns for convergent flow conditions (Freeman, 1991) and maintains consistency between flow patterns, calculated contributing area and spatial representation of subcatchments (Martz and Garbrecht, 1992). The proposed algorithm is presented with the necessary technical details to facilitate implementation of the algorithm.

2. Fundamental approach

Since the D-8 method cannot access elevations beyond the immediate vicinity of the current raster cell, the necessary information required to define the drainage over the flat surface must be included into the DEM before processing. Thus, cell elevations of the flat surface must be incremented in a way to produce the desired drainage during the subsequent DEM processing. The elevation incrementation is based on the recognition that in homogeneous natural landscapes the drainage is generally towards lower terrain while simultaneously being away from higher terrain. Such a drainage is achieved by imposing two gradients on the flat surface: one towards lower terrain which draws flow towards the nearest downslope outlet, and a second which forces flow away from higher terrain. The steepness of the higher and lower terrain is not taken into account in defining these gradients. In areas bounded on several sides by higher terrain, the resulting drainage also exhibits flow convergence. The approach assumes that the gradients can be computed independently from one another, and that their linear addition is adequate to identify the drainage pattern over the flat surface.

The desired gradients are obtained by adding elevation increments that are infinitesimally small compared to cell elevation and vertical DEM resolution. Thus the elevation incrementation will not significantly alter the elevations of the digital landscape, yet it is sufficient to identify flow direction over a flat surface. Furthermore, the flat surface must have at least one cell at its edge that is at a lower elevation so that downslope drainage off the flat surface is possible. Aside from these two requirements, a flat surface can be surrounded by any combination of higher and lower terrain. Multiple, narrow and wide outlets are acceptable. It is re-emphasized that the elevation increment is applied only to DEM cells within flat surfaces. No DEM elevations outside flat surfaces are altered.

3. Solution procedure

For the practical implementation of the algorithm, the elevation increment was selected to be 2/100 000 of the vertical DEM resolution. Thus, if vertical DEM resolution is 1 m, then one elevation increment is 20 μm. Such a small increment results in an insignificant change in actual cell elevation, yet it is sufficient to numerically define a flow direction. The increment value of 2/100 000 was selected as opposed to 1/100 000 because the latter increment is needed for the treatment of exceptional situations that are explained later. The computational steps of the elevation incrementation are described and illustrated for the simple DEM shown in Fig. 1(a). The value in the upper-right corner of a cell is elevation and the lower-left value is the number of elevation increments. The DEM in Fig. 1(a) has elevation values of 7, 8 and 9 on its outside edge, a flat surface of 25 cells with elevation 6 in the middle, and one outlet on the lower edge defined by cell G3 with an elevation value of 5. In a subsequent section, computed drainage is also illustrated for two complex topographic situations.

3.1. Step 1: gradient towards lower terrain

The gradient towards lower terrain is imposed by incrementing the elevation of all cells

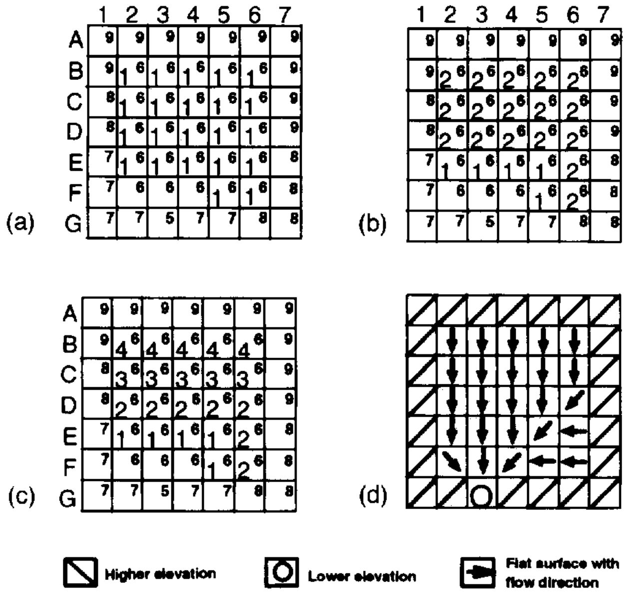


Fig. 1. Elevation incrementation for drainage towards lower terrain. Lower-left values represent the number of elevation increments, and upper-right values represent cell elevation. (a) Incremental elevations after the first incrementation pass; (b) incremental elevations after the second pass; (c) final incremental elevations; (d) flow direction as a result of elevation incrementation for drainage towards lower terrain.

in the flat surface that are not adjacent to a cell with an existing downslope gradient. In Fig. 1(a), cells with a pre-existing downslope gradient are cells F2–F4 which drain towards cell G3. The imposed incrementation (indicated by the number 1) introduces a downslope gradient from cells E2–E5 and from cell F5 to cells F2–F4. The incrementation is then re-applied to the remainder of the cells of the flat surface that still have no downslope gradient (Fig. 1(b)). This is repeated until all cells have a downstream gradient (Fig. 1(c)). In this way, a flow gradient towards lower terrain is constructed as a backward growth from the outlet(s) into the flat surface while at the same time satisfying all boundary conditions imposed by the higher and lower terrain surrounding the flat surface. The drainage resulting from the imposed gradient is shown in Fig. 1(d). It illustrates the well-known 'parallel flow' pattern discussed in Tribe (1992). If the example in Fig. 1 had two outlet locations, the gradients would have started at each outlet and grown backward until they intersected within the flat surface.

3.2. Step 2: gradient away from higher terrain

The gradient away from higher terrain is imposed by first incrementing the elevation of all cells in the flat surface that are adjacent to higher terrain and have no adjacent cell at a lower elevation. These are the cells in Fig. 2(a) marked with a 1 in the lower-left corner. All other cells on the flat surface either have a defined outflow (cells F2–F4) or are not adjacent to higher terrain (cells C3–E3, C4–E4 and C5–E5). The imposed increment introduces a downslope gradient away from higher terrain for all cells immediately adjacent to higher terrain. In subsequent passes the incrementations are as follows: (1) all cells that have been incremented previously are incremented again; and (2) all cells that

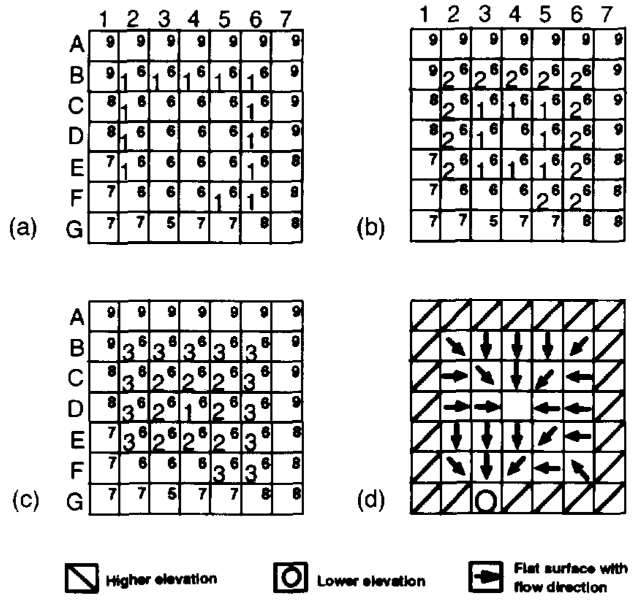
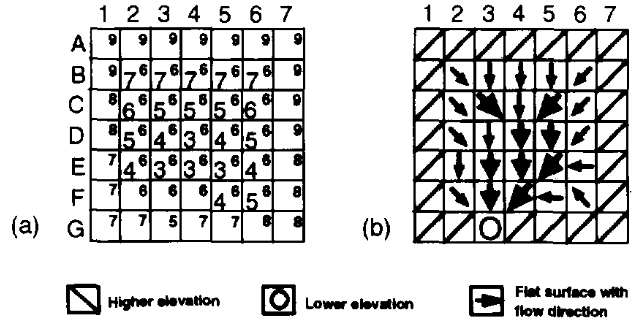


Fig. 2. Elevation incrementation for drainage away from higher terrain. Lower-left values represent the number of applied elevation incrementations, and upper-right values represent cell elevation. (a) Incremental elevations after the first incrementation pass; (b) incremental elevations after the second pass; (c) final incremental elevations; (d) flow direction as a result of elevation incrementation for drainage away from higher terrain.

have not been incremented previously, that are adjacent to an incremented cell, and that are not adjacent to a cell lower than the flat surface are incremented. The result of this incrementation is shown in Fig. 2(b). Cells that previously had a value 1 in the lower-left corner now have value 2, and cells adjacent to these have a value 1. This step is repeated until no unincremented cells remain on the flat surface (Fig. 2(c)). The result is a gradient away from higher terrain which is grown from the edges of the higher terrain into the flat surface. The drainage pattern corresponding to this gradient is shown in Fig. 2(d). Because the flat surface is surrounded by higher elevations, most flow directions point away from higher terrain. Exceptions are those cells that are adjacent to unincremented cells (F2–F4), to which they have a steeper downslope drainage.

3.3. Step 3: combined gradient and final drainage pattern

In a third and last step, the incrementations computed in the previous two steps are linearly added for each cell, as shown in Fig. 3(a). Adding the combined incrementation to the actual cell elevation results in a surface that is no longer flat and includes (1) a gradient away from higher terrain, and (2) a gradient towards lower terrain. Changes in cell elevations are small due to the infinitesimal nature of the incrementation. At this point one can define the drainage pattern as the flow direction along the steepest downslope path. However, an exceptional situation has occurred at cell D4. The gradient towards lower terrain (cell D4 to E4 in Fig. 1(c)) and the gradient away from higher terrain (cell D4 to E4 in Fig. 2(c)) are in exactly opposite directions and of the same magnitude. The incrementations cancel each other, leaving cell D4 without drainage. For these rather exceptional situations an additional



(a)

	1	2	3	4	5	6	7
A	^{9}	^{9}	^{9}	^{9}	^{9}	^{9}	^{9}
B	^{9}	7^{6}	7^{6}	7^{6}	7^{6}	7^{6}	^{9}
C	^{8}	6^{6}	5^{6}	5^{6}	5^{6}	6^{6}	^{9}
D	^{8}	5^{6}	4^{6}	3^{6}	4^{6}	5^{6}	^{9}
E	^{7}	4^{6}	3^{6}	3^{6}	3^{6}	4^{6}	^{8}
F	^{7}	^{6}	^{6}	^{6}	4^{6}	5^{6}	^{8}
G	^{7}	^{7}	^{5}	^{7}	^{7}	^{8}	^{8}

Fig. 3. Final elevation incrementation and drainage pattern. Lower-left values represent the number of applied elevation incrementations, and upper-right values represent cell elevations. (a) Final incremental elevations; (b) final drainage pattern, with larger arrow size representing larger upstream drainage area.

gradient from the affected cell towards lower terrain (Step 1) is imposed, using half an incrementation unit (1/100 000; half the incrementation of step 1 and 2). Using a full increment is not practical here because it could, under special circumstances, create another flat surface with upstream cells that are at exactly one increment higher than the current cell. The addition of half an incrementation to cell D4 removes the indeterminacy, and the drainage pattern shown in Fig. 3(b) is obtained. If the described exceptional situation were to encompass several adjacent cells, then the half incrementation must be added repeatedly following the procedure of step 1, until no flat surface remains.

4. Examples

The methodology for identifying flow patterns over flat surfaces is illustrated for two situations: a saddle and a valley floor. Software TOPAZ (Garbrecht and Martz, 1995) is used to increment cell elevation and compute flow direction.

4.1. Saddle example

The saddle situation depicted in Fig. 4 consists of a flat surface between higher terrain to the right and left, and three locations of lower terrain. Additional complications are introduced by a wedge of higher terrain protruding into the flat surface from the bottom, and a rectangular indentation of the flat surface into higher terrain at the top right corner of the figure. For this topography the computed drainage over the flat surface is shown by the arrows. The arrow size is about proportional to the upstream drainage area of the flat surface. Drainage is toward all three locations of lower terrain and away from higher terrain. A drainage divide is roughly situated in the middle of the saddle which is about midway between the locations of lower terrain. The midway point is forced by the inward growth of the gradient towards lower terrain (first incrementation step). Finally, flow convergence is consistently towards the middle of the flat surface and towards lower terrain, as one would intuitively expect in the absence of any other topographic forcing.

The drainage pattern produced by the presented relief incrementation (Fig. 4) is compared to one produced by the model of Martz and De Jong (1988) and Jenson and Domingue (1988) (Fig. 5). The drainage in Fig. 5 shows the 'parallel flow' pattern; the

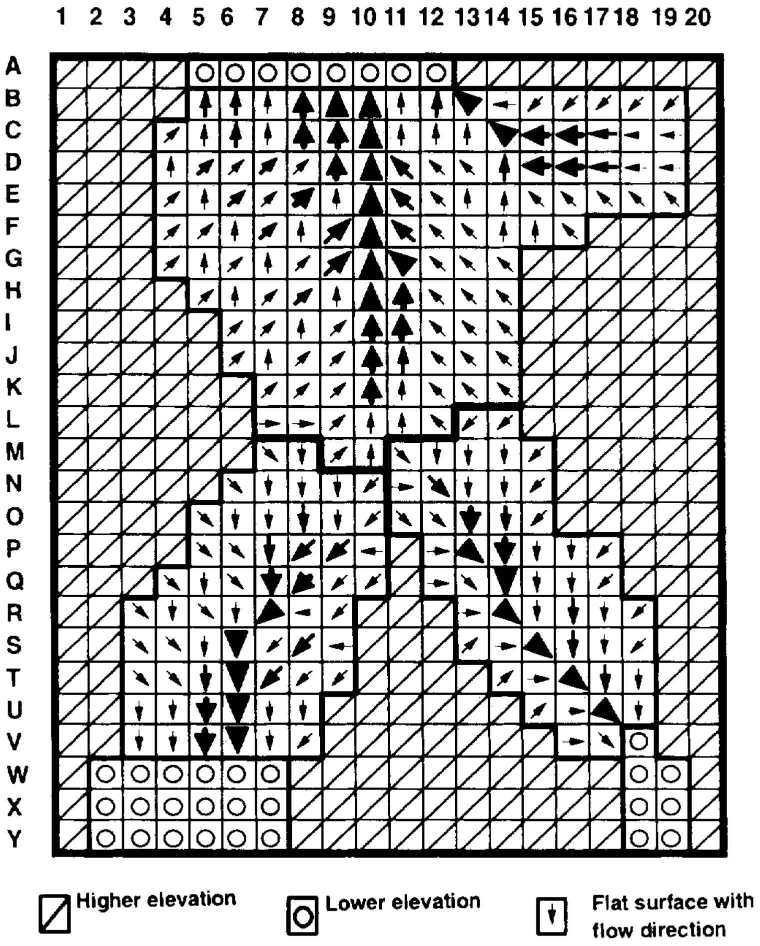


Fig. 4. Computed drainage pattern over a flat saddle topography. Arrows indicate drainage direction; arrow size is representative of upstream drainage area; drainage divide is indicated by heavy line.

drainage direction to the top outlet consists of strings of parallel drainage pointing upward. No significant flow convergence exists. In addition, runoff that flows from the higher terrain onto the flat surface follows immediately the edge of the higher terrain until the latter recedes away from the flow line. As a result, locations with the most upstream drainage area are not in the middle of the saddle but at the right and left edges of the top outlet. The bottom-left portion of the saddle shows problems similar to those of the top portion. Finally, the bottom-right portion of the saddle has a 45° main drainage line with parallel flow pointing towards it. This main drainage line is directly related to the corner of the outlet cell (cell V-18) and is not influenced by higher terrain surrounding the flat surface. The corresponding drainage produced by the proposed algorithm (Fig. 4) is much more consistent with the topography of the overall saddle configuration.

4.2. Valley example

The valley example consists of a curved valley with a flat floor flanked by higher terrain (Fig. 6). In addition, a small hill in the valley center creates an obstruction to drainage. The

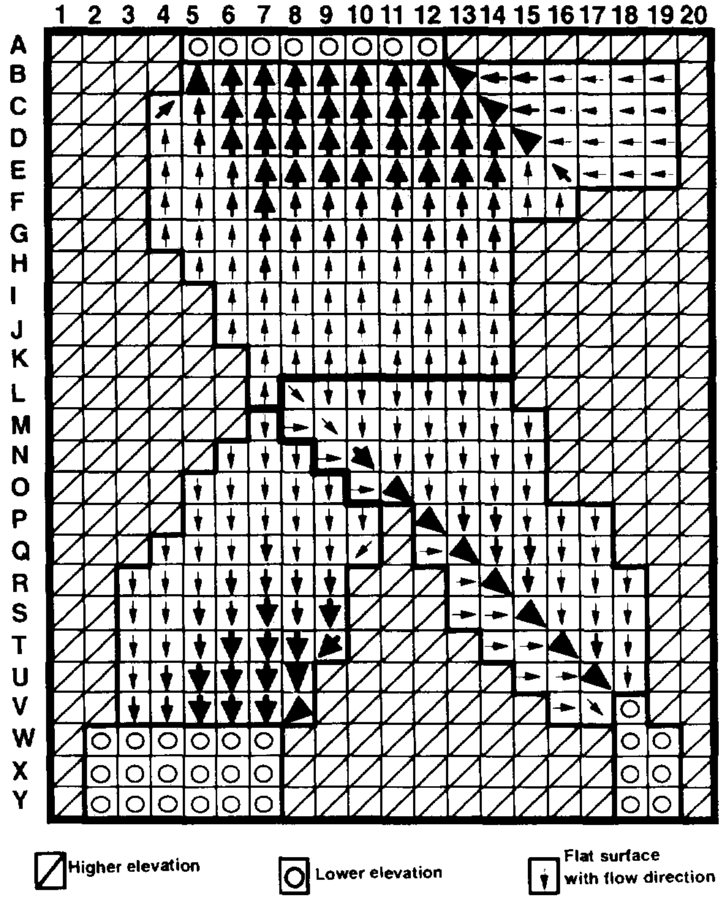


Fig. 5. Computed drainage pattern over a flat saddle topography by the model of Martz and De Jong (1988) and Jenson and Domingue (1988). Arrows indicate drainage direction; arrow size is representative of upstream drainage area; drainage divide is indicated by heavy line.

computed drainage is shown by arrows, with arrow size being representative of upstream drainage area from the flat surface. Fig. 6 clearly shows the path of the main drainage line around the inside corner of the valley bend. This path represents the shortest distance from the beginning (top) to the end (bottom) of the valley with a narrow buffer between valley side and main drainage line, as forced by the gradient away from higher terrain. Drainage from behind and below the small hill converge rapidly and join the main drainage line. Also, any tributary from the higher valley sides would enter the flat surface, follow the indicated arrows and joins the main drainage line within a short distance. In general, the flow convergence and drainage pattern within the valley are reasonable, given that the initial valley floor was flat and contained no topographic information to guide the drainage identification.

5. Summary and conclusions

A new approach is presented to solve the difficult problem of drainage identification over flat surfaces in DEMs. The algorithm increments cell elevations of the flat surface to

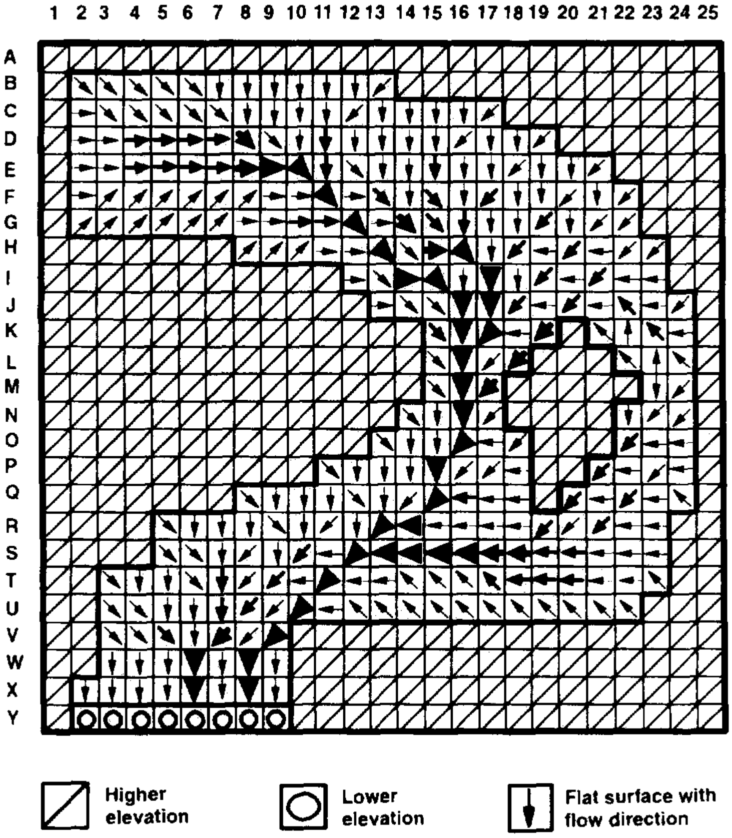


Fig. 6. Drainage pattern on a flat valley floor. Arrows indicate drainage direction; arrow size is representative of upstream drainage area.

include information on the terrain configuration surrounding the flat surface. As a result, two independent gradients are imposed on the flat surface: one away from higher terrain into the flat surface, and the other out of the flat surface towards lower terrain. The linear combination of both gradients, with localized corrections for exceptional situations, is sufficient to identify the drainage pattern, while at the same time satisfying all boundary conditions of the flat surface. In the subsequent DEM evaluation, the imposed gradients lead to a realistic and topographically consistent drainage over the flat surface. Two example applications, a flat saddle topography and a flat valley floor, are evaluated using software TOPAZ. Both examples show drainage with flow convergence and flow direction that are quite reasonable, given that no topographic information was initially available in the flat surface to guide the drainage identification. The computed drainage for the saddle topography was compared to the drainage obtained by the traditional approach of Martz and De Jong (1988) and Jenson and Domingue (1988). The computed drainage, as well as flow convergence and consistency with the surrounding terrain configuration, were greatly improved.

The procedure requires that at least one downslope outlet exists. The procedure makes no stipulations with respect to the topography of the terrain surrounding the flat surface. It works for flat surfaces that have either one or several point outlets towards lower terrain, for the situation where continuous portions of the edge of the flat surface border lower terrain, as well as for the situation of a flat mountain top entirely surrounded by lower terrain. Also, the complexity of the shape of the flat surface is not an issue.

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