

Hydrologic Interpretation of a Digital Elevation Model (DEM)

Definition of Flow Direction (Hydrologic): Water flows in the direction of the steepest downhill gradient.

Definition of Flow Direction (GIS): Every pixel is potentially surrounded by eight neighboring pixels. The slope in each of these eight directions may be calculated by taking the difference in elevation indicated by the DEM value at each of these eight neighboring locations and the value at the pixel being examined. This difference in elevation is then divided by the center-to-center distance between these pixels (this distance will be the cellsize in the cardinal directions and the $\text{cellsize} \cdot \sqrt{2}$ in each of the diagonal directions. The direction that yields the steepest downhill slope is the inferred direction of water flow. (This basic algorithm is sometimes referred to as the D8 method.)

Why are flow directions important?

Determination of flow direction at every point throughout a landscape allows the modeler to infer drainage areas, flow lengths, and delineate watersheds.

Can you provide a simple example?

Consider the following 3x3 DEM with a horizontal resolution of 30 meters and reported in vertical units of meters:

13	11	12
9	10	11
6	6	8

Notice that in general the elevations decrease from the top row to the bottom row. Let us calculate the slope in each of the eight directions from the central pixel:

Due East:

$$\text{Slope} = (10 - 11) / 30 = -0.0333$$

Northeast:

$$\text{Slope} = (10 - 12) / 30\sqrt{2} = -0.0471$$

Due North:

$$\text{Slope} = (10 - 11) / 30 = -0.0333$$

Northwest:

$$\text{Slope} = (10 - 13) / 30\sqrt{2} = -0.0707$$

Due West:

$$\text{Slope} = (10 - 9) / 30 = 0.0333$$

Southwest

$$\text{Slope} = (10 - 6) / 30\sqrt{2} = 0.0943$$

Due South:

$$\text{Slope} = (10 - 6) / 30 = 0.1333$$

Southeast:

$$\text{Slope} = (10 - 8) / 30\sqrt{2} = 0.0471$$

Notice that the slope in the east, northeast, north, and northwest directions is negative (indicating that the direction is uphill) from the center pixel. None of these directions are even possible flow directions. The largest positive slope is in the due south direction with a value of 0.1333. This is the inferred flow direction for the center pixel. The reader will notice that the elevation in the southwest direction is the same as in the due south direction, however, because of the greater center-to-center distance, the slope in southwest direction is slightly less steep. Because of this $\sqrt{2}$ factor, it is even possible in some cases for the elevation in one of the cardinal directions to be slightly higher than in the diagonal directions and the slope will still turn out to be steeper in the cardinal direction.

Can we examine a more complete example?

Consider the following 5x5 DEM where we add the additional stipulation that the flow cannot leave the boundaries of the 5x5 grid. (i.e. it is as if there are vertical walls bounding the overall grid.)

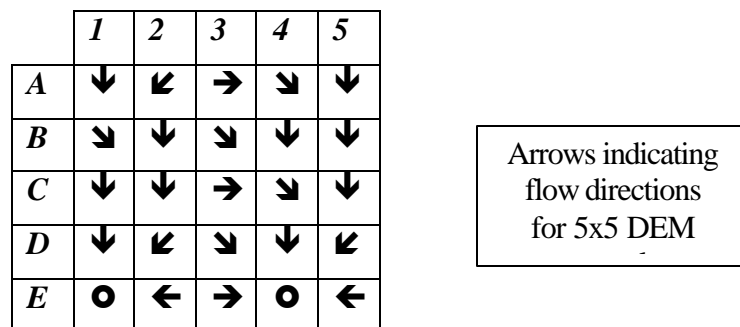
13	14	14	13	12
12	13	15	14	11
12	11	13	10	10
10	10	12	11	9
8	9	11	8	10

5x5 DEM
Example.

Before solving for the flow directions, the following observations can be made concerning this grid:

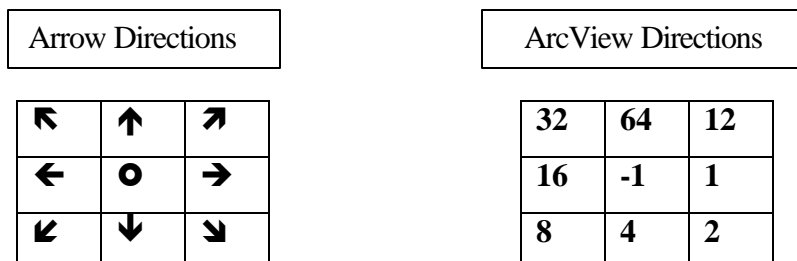
- As in the 3x3 grid, there is a general trend of decreasing elevations as we scan from the top rows to the bottom rows (therefore we would expect that most of the drainage directions will have a southerly component: south, southeast, or southwest).
- The middle column has relatively higher elevations than those in adjacent columns (therefore we would expect that this column will act as a divide between the right and left sides of the grid).
- There is a tie for the lowest elevations in the grid with a value of “8”. We will expect these two locations to act as “sinks” for this system.

The reader should be able to verify that the flow directions are as shown below. Notice that there is only one direction for each pixel, but that some pixels, for example pixel *C4*



is receiving flow from pixels *B3*, *B4*, and *C3*. Pixels *E1* and *E4* were the locations of tie for the lowest elevation. The flow directions here are undefined (or these pixels can be considered to be sinks). We are indicating the flow direction (or lack of one) by the “○” symbol. The reader should notice that the other observations made before determining flow directions have been borne out. There is a general tendency for southerly flow and there are no arrows (flow directions) that cross through the plane separating columns 2 and 3, confirming the existence of a drainage divide between these columns.

The arrows indicating flow directions are useful for the human eye to interpret, but unfortunately, the GIS needs some other method to “understand” which way the flow is going at a given pixel. The method used to denote these flow directions is arbitrary. ArcView uses powers of 2 increasing clockwise from due east: 1, 2, 4, 8, 16, 32, 64, and 128.



Applying the ArcView nomenclature for flow directions, we obtain the following flow direction matrix for the 5x5 DEM example:

	<i>I</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>
<i>A</i>	4	8	1	2	4
<i>B</i>	2	4	2	4	4
<i>C</i>	4	4	1	2	4
<i>D</i>	4	8	2	4	8
<i>E</i>	-1	16	1	-1	16

ArcView values
indicating flow
directions for 5x5
DEM example.

How do I use the GIS to determine flow directions?

The ArcView syntax for calculating flow direction is:

aGrid.FlowDirection(ForceEdge)

the ArcView help provides the following information about this statement:

Calculates the flow direction of each cell in the surface represented by aGrid. If forceEdge is TRUE, then all cells on the edge of the surface will flow away from the surface. If forceEdge is FALSE, then flow is calculated normally for edge cells with the edge being slightly lower than the cell. For the 5x5 DEM example, we have used a value of "FALSE" for ForceEdge (i.e we have imposed vertical walls confining the flow to remain within the field being evaluated).

Having determined the flow directions, we are now ready to determine the "flow accumulation" for the 5x5 DEM example.

Definition of Flow Accumulation (Hydrologic): Water accumulates along the flow paths dictated by the topography and defined earlier as the "flow direction". Adjusted to proper units, the flow accumulation is synonymous with drainage area.

Definition of Flow Accumulation (GIS): Using the flow directions determined earlier, flow accumulation at a given location is determined by following two rules:

1. If the pixel has no neighboring pixels draining to it, a value of "1" is assigned.
2. If the pixel drainage from neighboring pixels, it is assigned the value of "1" plus the sum of the flow accumulation draining from each of the neighboring pixels.

Notice that Rule 2 amounts to a recursive definition, one must start determining flow accumulation at the upstream end of all flow paths and work downstream, otherwise the drainage area of all neighboring pixels to a the pixel in questions may not be known.

Rules 1 and 2 are repeated across the entire DEM.

Why is flow accumulation important?

Flow accumulation once adjusted from a count of pixels to units of area is synonymous with drainage area. Calculating it as a spatially distributed quantity allows us to determine drainage area not at just one point, but at *any* point within the domain of the original DEM field.

What would the flow accumulation look like for the 5x5 DEM example?

Applying Rules 1 and 2 to the 5x5 DEM results in the following solution:

	<i>I</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>
<i>A</i>	1	1	1	2	1
<i>B</i>	3	1	1	1	4
<i>C</i>	1	5	1	4	5
<i>D</i>	2	6	1	1	10
<i>E</i>	10	1	1	15	1

Flow
accumulation for
5x5 DEM
example.

For example note that pixel *A1* has no arrow (flow) going into it – therefore Rule 1 applies and this pixel receives a value of “1”. In contrast, pixel *D5* receives flow from pixels *C4* and *C5* which carry flow accumulations of 4 and 5 respectively. Therefore, the flow accumulation for pixel *D5* is 4+5+1=10. Notice that the values in our two sink pixels, pixels *E1* and *E4* are 10 and 15, respectively. The sum of these two values is 25, which is equal to the area (in pixels) of our 5x5 DEM grid. Further, notice that the value at *E1* (10) is the area of this 2 column by 5 row “watershed” (recall the divide between columns 2 and 3 noted earlier) and the value at *E4* (15) is the area of this 3 column by 5 row “watershed”. It will always be the case that the flow accumulation at the outlet pixel of a watershed is equal to the drainage area (in pixels) of the watershed it is draining. If we know the resolution of the DEM being examined (e.g. 30 meter pixels) then the drainage area of the rightmost or eastern watershed in this 5x5 DEM is:

$$DA = 15 \text{ pixels} \times \frac{(30m)^2}{\text{pixel}} = 13,500m^2$$

How do I use the GIS to determine flow accumulation?

The ArcView syntax for calculating flow accumulation is:

aGrid.FlowAccumulation(weightGrid) + 1.AsGrid

the ArcView help provides the following information about this statement:

Calculates the flow accumulation for each cell. aGrid is a Grid of flow direction usually created with the aGrid.FlowDirection request.

weightGrid can be a Grid or Nil, and represents the weight to assign to each cell. If weightGrid is set to Nil a weight of 1 is used for each cell.

The process described here corresponds to the case of unit weight being assigned – i.e. weightGrid is NIL. There may be cases where a value for weightGrid should not be NIL, for instance by flow accumulating a grid containing curve numbers (i.e. the weightGrid is a grid of curve numbers) and dividing by the unit flow accumulation (drainage area) one obtains a grid of spatially distributed average curve number, throughout the entire field.

Notice the “+1.AsGrid”. This additional term appears as an adjustment to a discrepancy between the algorithm described in these notes and the rules applied by the creators of ArcView. The author feels that the rules described in these notes make more sense since they result in the outlet of any watershed having a drainage area equal to the area of the watershed. If this is not applied, then the determined flow accumulation (drainage area) will not include the area of the outlet pixel itself. This is a small discrepancy, especially when dealing with large watersheds, but the author prefers the aesthetics of this slight modification rather than the method strictly applied by the ArcView software.