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# Improvement of Surface Flow Network Prediction for the Modeling of Erosion Processes in Agricultural Landscapes

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**Abstract**

The modeling of soil erosion by water supposes an accurate and thorough understanding of the hydrology. Thus, it is critical to have a good delineation of the surface flow path. The flow network data are critical for important uses such as flood forecasting and watershed management. Geographic Information System (GIS) functions are able to compute a flow network directly from the digital elevation models. Because the flow directions are only based on the topography, the other factors controlling the flow directions are overlooked. In the agricultural areas, work such as tillage can have a large impact on the flow direction. We propose a 5-step procedure to account for such man-made features. The use of this procedure clearly improves the quality of the computed flow network. This procedure has been successfully implemented in a GIS and improves the prediction of surface flow and therefore improves water erosion modeling at the watershed scale.

*Keywords:* Overland flow; modeling; DEM; tillage direction; surface flow pattern; GIS

## 1 Introduction

The modeling of overland flow and soil erosion requires a good knowledge of surface water flow paths. Previous works have demonstrated that one of the main factors that explains the initiation and location of erosive phenomena is the area contributing runoff (Thorne and Zevenbergen, 1990; Auzet et al., 1995). Govers et al. (2000) and Le Bissonnais et al. (2005) found that the occurrence of erosion phenomena is strongly related to the runoff-generation process. It has also been shown that the flow paths and flow concentration processes inside a watershed are important (Takken et al., 2005). In fact, erosion caused by overland flow is a threshold phenomenon for which triggering occurs at specific times and locations (Boiffin et al., 1988; Papy and Boiffin, 1989; Ludwig et al., 1995; Le Bissonnais and Gascuel-Odoux, 1998). So, even if runoff models predict correctly the water flux at the outlet of a catchment using a standard flow direction algorithm, they may be not adapted for modeling erosion and simulating the effect of anti-erosion management schemes (Souchère et al., 2005; Furlan et al., 2012).

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For more than ten years, several studies have been performed to determine and model the location and the size of areas contributing to runoff within catchments, including their changes under the combined effect of farming operations and meteorological conditions (Ludwig et al., 1995; Desmet and Govers, 1997; Souchère et al., 1998; Govers et al., 2000; Takken et al., 2001). These studies demonstrated that furrows created by tillage operations could affect the flow directions as much as the topographic slope. However, most current hydrologic models, such as the WEPP (Flanagan and Nearing, 1995), AGNPS (Bingner and Theurer, 2007) and EUROSEM (Morgan et al., 1998) consider the topographic slope to be the only factor controlling the water flow path. Thus, even if these models include sophisticated water routing algorithms and up-to-date finite difference schemes to compute water fluxes, they cannot properly model the actual flow paths in agricultural watersheds.

Orlandini et al. (2003, 2011) developed methods to improved the classical D8 flow network calculation from Digital Elevation Model (DEM) (Tarboton, 1997). The path-based D8-LAD and D8-LTD reduced the flow drift without the inconvenience of introducing dispersive flow. However, they were tested in mountainous areas were steep slopes constrain the flow direction whatever the surface roughness and anthropogenic landscape features. Bailly et al. (2008) designed an approach for automated ditch network detection from LiDAR data in vineyard landscapes. This methodology appears transposable to other linear anthropogenic features under the condition that they are located on field boundaries and that they correspond to a sufficient elevation discontinuity so that they can be identified in LiDAR profiles. In addition, since is it based on the availability of LiDAR data, there is still a need for improving flow network determination in the case of low slope agricultural landscapes, taking into account more easily accessible tillage direction and roughness information. A predictive erosion model at the watershed scale was developed with the aim of balancing the amount of data required, the cost of their acquisition, and the description of fundamental erosion processes. This model, named STREAM, is based on the understanding and parameterization of prevailing factors at local scales from experimental results and on the specific features at the watershed scale (Cerdan et al., 2002a, b; Le Bissonnais et al., 2005). In this paper, we present the ‘flow network’ module implemented in the STREAM model. This module allows the model to account for the effect of the tillage operations on the directions of the surface water flow. The method in use is based on the

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modification of a regular model of the surface water flow network (i.e. a flow network model based on the topography only). From this topographic flow network, a flow network accounting for the tillage directions and preferential flow paths is built. The processing is raster-based (i.e. cell-based) and makes use of Geographic Information System (GIS) capabilities to analyze the soil surface water movement according to the terrain morphology, tillage direction, and preferential flow paths. The first part of this paper presents the 'flow network' module and the methodological developments required to introduce preferential flow paths in a regular DEM. In the second part, we apply the model to a test watershed, and we analyze and discuss the relevance of the results based on the methodological and hydrological standpoints. We then emphasize the main achievements and perspectives for future improvements of the 'flow network' module.

## 2 Material and methods

The 'flow network' module creates a network of flow directions for every point of the studied area, usually a watershed. The watershed is the reference unit for water and erosion management. Many algorithms have been published to compute a flow network on a grid DEM (e.g., O'Callaghan and Mark, 1984; Tarboton, 1997; Orlandini et al., 2003). The most sophisticated can define several flow directions for each cell, such as the "multiple flow direction" of Quinn et al. (1991). For our purpose of demonstrating the importance of taking into account the agricultural features for constructing an accurate flow network, we decided to use a simple "single flow direction" algorithm close to the well-known D8 algorithm (O'Callaghan and Mark, 1984). In our case, the network of flow directions is a set of cell-based data for which the module defines a unique flow direction for each cell. Because the published algorithms are topography-based only, we believe large discrepancies between the computed flow networks and the real network would be found wherever agricultural features have an effect on the flow directions.

In most existing networks of flow directions, the flow directions are defined based on the DEM only. Thereafter, a flow direction network computed from the DEM only is named 'topographic flow network.' The novelty of the 'flow network' module is its ability to account for the effects of human-induced features on the water flow directions in the agricultural watersheds. The improved flow

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network better mimics the actual flow network and thus enhances the prediction of the water flow locations and fluxes. Because of this improvement, the watershed manager will make more accurate decisions for the implementation of soil and conservation practices. Accounting for agricultural features implies some specific processing, as detailed below.

## *2.1 Data*

Three types of geographic and semantic data are required by the 'flow network' module.

### *2.1.1 Roughness*

The first mandatory layer represents the agricultural fields as polygons. This vector-type layer must cover the entire area to be modeled. Each polygon is associated with attributes describing the soil surface characteristics, such as the soil surface roughness. Following Souchère et al. (1998), the roughness is defined as the height difference (in cm) between the high points and low points of the soil surface microtopography. The roughness is defined at the scale of a square meter *along* the tillage direction (first roughness index) and *across* the tillage direction (second roughness index). These indices were specifically designed for the overland flow studies. They can be noted by visual inspection during field mapping. Each of the two roughness indices are tagged using a six-level scale (Table 1). Thus, two roughness attributes are recorded for each polygon. The polygons must also have an attribute describing the tillage direction in degrees (from 0 to 179°).

### *2.1.2 Topography*

The second mandatory layer is raster-type and represents the topography of the studied area. It is a DEM. The common area between the DEM and the agricultural field polygons defines the largest area that can be modeled by the 'flow network' module. To account for the edge effects caused by some numerical treatments, a 5-cell buffer is added around the area defined by the agricultural field polygons.

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#### 2.1.3 Preferential flow paths

The third layer is optional. It accounts for the preferential flow paths caused by objects such as the headlands (i.e., the unplowed land at both ends of a field after the primary plowing: headlands are usually plowed subsequently, across the primary plowing direction), open furrows (i.e., a long shallow trench in the ground left in the middle of the field or between two fields after plowing), and roads. This layer is vector-type with a line topology. Each line has attributes describing its hydrologic behavior. Depending on these attributes, changes in the flow directions of the underlying cells will be made, thereby modifying the flow network.

### 2.2 Computation of the flow network

The successive stages of the algorithm are illustrated in Figure 1.

#### 2.2.1 Stage 1 – Building the topographic flow model of flow directions

In a the Geographical Information System (GIS) software using square cell raster grids, one of eight possible flow directions is assigned to each grid cell. Each of these eight possible directions leads to one of the eight neighboring cells. The flow direction for the cell under inspection is computed from a raster DEM representing the topography by selecting the neighboring cell with the steepest descent. This generates a strictly convergent flow network (i.e., the flow of one cell is never routed to more than one other cell). When applied to a DEM free of sinks, starting from any cell and following the flow direction from cell to cell always leads to the edges of the studied area (the edges can be identified by cells with a special value called ‘NODATA’).

The first stage consists of computing the topographic flow network. It is called the topographic flow network because it is built by accounting for the topography only. This network is then used as a reference to build the flow network that accounts for the manmade features, as described hereafter.

#### 2.2.2 Stage 2 – Modifying the topographic flow network to account for tillage directions

In the cultivated fields, the flow directions are not always the topographic flow direction. The flow directions can be modified following some rules described in Souchère et al. (1998). In locations with large slope gradients, the actual flow directions are determined by the topography only, whereas in

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locations with gentle slopes, the actual flow directions can be determined either by the topography or by the direction of the tillage, depending on the soil surface roughness.

In fact, the tillage operations alter the surface roughness by making it anisotropic. As a consequence, the tillage operations can create preferential flow directions. Some of the tillage operations create such large roughness anisotropy that the flow will always follow the tillage direction. For example, the ridging of potato fields creates a large roughness across the tillage direction but a low roughness along the tillage direction. As a consequence, the flow is channeled by the ridges.

Souchère et al. (1998) assumed that the overland flow direction at a given location depends on two major variables: the slope intensity, and the angle between the azimuths of the steepest slope and of the tillage direction. To verify this assumption, they measured the slope with an Abney level and the angle between the two directions with a compass on 60 plots. At the same time, the actual overland flow direction was noted for each plot either by direct observation during rainstorms or by analyzing the traces left by overland flow just after the event.

Ten observations demonstrated that if the difference between the roughness across and the roughness along the tillage direction is greater than two levels (as defined in Table 1), the flow direction is always the tillage direction. For the other fifty observations (i.e. if the roughness anisotropy is equal or lower to two levels), the flow can be along the tillage direction or along the topographic slope. In this case, the observations were ranked in two sub-populations corresponding to: (i) plots where the observed overland flow follows predominantly the slope direction and (ii) plots where tillage imposes the overland flow direction. Using these data, an analysis of the variance and a discriminant analysis were performed using the two chosen variables – the slope intensity and the angle between the steepest slope and the tillage direction – to produce a suitable procedure for automatically determining the overland flow direction.

Souchère et al. (1998) used this discriminant function to categorize the grid cells into two sets: those with a flow direction along the topographic slope and those with a flow direction along the tillage direction. The discriminant function is:

$$Discrim = -0.6646\frac{angleW - 61.74}{19.95} - 0.6669\frac{slope - 5.45}{3.03} \qquad (1)$$

with *angleW* the angle (in degree) between the tillage direction and the topographic slope aspect, and *slope* the topographic slope gradient (in %).

The value *Discrim* is then used with a threshold equal to 0.1249 to assign the grid cells with the tillage direction (*Discrim > 0.1249)* or to keep the direction of the topographic flow network computed in the first stage described above (*Discrim* ≤ *0.1249*). The statistical analysis of Souchère et al. (1998) showed that 92% of the 50 test plots were correctly classified by the discriminant function, while the wrongly classified plots had intermediate situations in terms of (1) the slope gradient and (2) the angle between the tillage direction and the slope aspect.

After stage 2, there is a flow network accounting for tillage directions, but, resulting from the limitation of flow to only height possible directions per cell, a bias (or drift) is present in the flow directions. This will be corrected in stage 4 of the procedure. But before this correction takes place, the preferential flow paths are included.

### *2.2.3 Stage 3 – Modifying the tillage flow network to account for preferential flow paths*

If the user chooses to provide the optional layer describing the preferential flow paths, this information is processed:

- In the headlands, the discriminant function (1) is used with the tillage direction inside the headland. Typically, this tillage direction crosses the general tillage direction of the field but is parallel to one of the field edges.
- For roads, the direction of the topography is kept.
- For open furrows, the flow direction is set to be downslope, along the open furrow.

As a result of this third stage, the new flow network accounts not only for tillage directions but also for preferential flow paths. It now needs to be corrected from the drift.

### *2.2.4 Stage 4 – Cancellation of the drift in the tillage flow network*

When tillage directions are translated into flow directions (at stage 2), drifts in the modeled flow directions are introduced. The flow directions on square grids are set in 45° increments. The intermediate directions cannot be modeled at the scale of a single grid cell. The drift causes a misdirection of the flow (Fig. 2). The maximum drift angle is equal to 22.5°. This effect is especially

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sensitive for long fields: the modeled flow directions will lead the flow to cross the field edge instead of being parallel to it. This can lead to a misrepresentation of the flow network. Moreover, by changing the contributing area at the watershed outlet, the drift can cause miscalculations of the cumulated flow.

The effect is illustrated at the scale of several cells in Figure 3(a). The actual flow direction is along AB, at the azimuth at 30°. By following the grey arrows, the flow network should lead from point A to point B. However, with the grey arrows having an azimuth of 45°, they lead to point B' instead. The angle between AB and AB' is equal to the drift angle.

To accound for the drift, the modeled tillage flow direction needs to be corrected at a constant interval (every x columns or every y rows). The interval between the corrections is calculated based on trigonometry.

We define the drift $\alpha$ as the angle between *dirWA* (the actual tillage direction) and *dirWM* (the modeled flow direction before correction) (Fig. 2):

$$\alpha = dirWA - dirWM \qquad (2)$$

$\alpha$ ranges from -22.5° to 22.5°.

We define $\beta$ as the modeled flow direction before correction. $\beta$ takes one of the eight possible directions (0°, 45°, 90°, etc.).

Depending on the case, the correction consists of applying one of the following two formulas:

$$\cos\beta / \tan\alpha \qquad \text{(a)}$$

$$\sin\beta / \tan\alpha \qquad \text{(b)}$$

Table 2 indicates the formula to be used depending on the values of $\alpha$ and $\beta$, and determines whether the correction must be applied on an interval of rows (R) or columns (C).

The removal of the drift, by counterbalancing it at regular intervals, creates a better overall flow direction (Fig. 3(b)). The tillage flow network after the drift cancellation follows the line AB. This method of drift cancellation better models the tillage direction at the field scale.

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#### *2.2.5 Stage 5 – Removal of flow direction artifacts*

The introduction of constrained flow directions in the topographic flow direction model generates some artifacts. These artifacts are inconsistencies that make the flow network inappropriate for hydrological processing. The computation of the flow accumulation requires first the definition of the flow direction of all of the cells. The changes introduced by the tillage direction and the preferential flow paths are made at the scale of the individual cells without considering the flow directions in the neighboring cells. This creates four kinds of artifacts: converging flows, flow loops, crossing flows, and unspecified directions (Fig. 4 left). These artifacts need to be removed before the flow accumulation can be computed properly (Fig. 4 right). All of these changes in flow directions are made without taking into account the actual flow paths.

- *Converging flows.* Converging flows occur when two neighboring cells point to each other making it impossible to define a downstream flow path (Fig. 4(a) left). The solution consists of changing the flow direction of the current cell to switch it to the topographic direction (Fig. 4(a) right).
- *Flow loops.* Following a flow path that leads back to an already visited cell is considered a flow loop (Fig. 4(b) left), again making it impossible to define a downstream flow path. Again, the solution consists of changing the flow direction of the current cell to switch it to the topographic direction (Fig. 4(b) right).
- *Crossing flows.* This type of artifact occurs when the direction of the neighboring cell (white background in (Fig. 4(c) left)) is at 90° to the current cell (grey background). The solution consists of changing the direction of the neighboring cell by 45° so that it now flows into the current cell (Fig. 4(c) right). Doing so – instead of changing the current cell – ensures that no other crossing flow is being created by the change.
- *Unspecified directions.* Unspecified directions can be created during the computation of the flow directions when working within the open furrows. At stage 3, the modeling of the flow directions within the open furrows is achieved by artificially increasing the altitudes of the cells surrounding the furrows. Doing so ensures that the flow direction is identical to that of the underlying furrow. But, as a consequence, when a furrow crosses a thalweg, a local minimum appears in the DEM,

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causing a so-called 'sink.' Such a sink has the effect of disrupting the flow path network where it should normally lead to the edge of the study area. The sink cells receive an unspecified flow direction (Fig. 4(d) left). The solution to an unspecified direction again consists of switching it back to the topographic flow direction. This causes the open furrow to overflow at the location of the thalweg it crosses. Hence, this solution restores the usual behavior of an open furrow at the field (Fig. 4(d) right).

The automatic procedure to remove artifacts is run twice in the 'flow network' module. During the first run, the corrections are not applied to the cells labeled as open furrows. This avoids the creation of crossing flows. In most of the cases, this solves the artifacts around the open furrows, except for the unspecified directions. During the second run, all of the remaining artifacts are solved, including those located in the open furrows.

### *2.3 Test watershed*

The 'flow network' module was implemented in the "STREAM" watershed hydrologic modeling software (Cerdan et al., 2002b). This section details how the tillage directions and associated manmade features modify the flow network. The modeled flow network is compared to the actual flow network.

#### *2.3.1 Watershed description*

The watershed used to test the 'flow network' module is located in northern France, in the department of Seine Maritime, in the commune of Blosseville (Fig. 5). The agricultural watershed has a surface area of 87 hectares, with loamy soils sensitive to crusting. The lateral flows are mostly surface flows. The village, located at the outlet of the watershed, has undergone significant damage caused by muddy floods. To decrease the risk of flooding, a watershed management plan was set up. The STREAM model was used to evaluate the effectiveness of the soil and water conservation practices.

#### *2.3.2 Data requirements*

Except for the DEM, the method has been designed for using data that do not require any specific equipment (laser scanner, etc.) during the field data collection. A first field study was performed to

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obtain, for each agricultural field, the information necessary to model the flow directions: tillage direction, roughness along the tillage direction, roughness across the tillage direction, and location and type of preferential flow paths (Fig. 6) or (Fig. 7). In less than two hours, these parameters could be easily mapped by the visual inspection of all fields. It makes the use of the 'flow network' module cost-effective. In addition, the formation of an operator is easy. The information needed to build the DEM came from digitizing the contour lines of a topographic map and from a complementary survey of topographic points. It had a horizontal resolution of 5 m. Altitudes were stored as floating-point numbers.

This enables the prediction of soil surface characteristics could be deduced from information on crop type, soil surface texture, and rainfall regimes (Delmas et al., 2012). This enables to predict soil surface characteristics and their evolution during the cultivation season without further field study.

### *2.4 Validation*

The computed flow networks are compared to the observed rill network. Erosion rills are a direct and visible indication of flow directions inside a watershed. They were mapped using a theodolite. Given the size of the catchment, they could be mapped on only part of the watershed. A thorough cell-to-cell comparison of the actual versus predicted flow network would not have been possible because the actual flow directions cannot be detected everywhere.

First, the validation is performed by a visual comparison of the computed flow networks with the observed flow network. Then, to quantify the improvement induced by the proposed algorithm, the following methodology is executed:

- The flow networks, refined as much as possible, are computed both from the topographic flow network (TOPO) and the tillage flow network (TILL). The lines in the observed erosion network (OBS) are cut into 5-meter-long segments corresponding to the DEM resolution. For each segment of these 3 networks (TOPO, TILL, and OBS), the flow azimuth is computed (TOPOAZIM, TILLAZIM, and OBSAZIM). For each segment in the observed network (OBS), the nearest segment in both the topographic (TOPO) and the tillage (TILL) flow network is identified. This allows attributing the nearest TOPOAZIM and TILLAZIM to the OBS segment. At this stage, for

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each observed erosion line segment, its own azimuth, the azimuth of the topographic flow network, and the azimuth of the tillage flow network are known.

- The absolute acute angle (gap angle) between the observed and the topographic network azimuth is computed (TOPOGAP = modulo180(abs(OBSAZIM - TOPOAZIM))). The same is performed with the tillage network azimuth (TILLGAP = modulo180(abs(OBSAZIM - TILLAZIM))). The difference (Q) between these two angles (Q = TOPOGAP - TILLGAP) provides, for each observed segment (OBS) considered a ground truth, an indication of the improvement in quality obtained using the tillage flow network instead of the topographic flow network. A positive Q value indicates a gain in quality, whereas a negative Q value indicates a loss in quality. The value itself indicates the intensity of this gain/loss of quality.

## 3 Results and discussion

### *3.1 Model of the flow directions*

The first stage was to create the topographic flow network based on the DEM (Fig. 8(a)). The second stage makes use of the discriminant function to define the cells where the flow is controlled by the tillage direction. This stage also includes the effect of the preferential flow paths on flow directions. According to the discriminant function, the tillage operations control a large part of the flow directions inside the watershed (Fig. 9). In the northern part of the watershed, the tillage operations define the flow direction in most of the agricultural fields. After this stage, the tillage flow network shows a drift in the flow directions (Fig. 8(b)): in the northern part of the watershed, the flow network crosses the field boundaries. If overland flow is modeled using this network, water will be routed from one field to a sideway field, even if the tillage directions, which, at this location, should control the flow direction, are parallel to the field boundaries (Fig. 7). This clearly illustrates the drift of flow directions caused by the requirement for the flow directions to be along one of the eight directions at the cell scale. The tillage operations on the northern fields have an actual direction of 145°. At the cell level, the closest direction is 135°. This caused the flow direction of 145° (south-east) to be overstated among the flow directions in the uncorrected tillage flow network (Fig. 10).

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To alleviate this problem, the drift-cancellation method is used to shift by 45° some of the cells with the appropriate ratio. For the specific case of actual directions at 145°, some of the directions modeled at 135° are shifted to the direction 180°. After drift cancellation, the number of flow directions pointing at 135° is decreased in the corrected tillage flow network (Fig. 10). Simultaneously, the number of directions at 180° is increased. After the removal of the flow direction artifacts, the new network better accounts for the tillage directions and is consistent with the hydrologic uses (Fig. 8(c)): the flow network remains parallel to the field boundaries instead of crossing them sideways. Taking into account tillage operations and cancelling the drift also modified the watershed boundaries (compare Fig. 8(a) and Fig. 8(c)): two fields located in A on Fig. 8(a) are now fully connected to the outlet, which was not the case with the topographic model. This underlines also the need of using a DEM covering an area larger than that of the study area.

### *3.2 Validity of the tillage flow network*

The above section demonstrates that the tillage flow network sensibly incorporates manmade features in an agricultural watershed. The validity of the tillage flow network can be further estimated by a comparison with the actual flow network.

The actual flow network is the network of the observed rills (Fig. 8(d)). The visual comparison of Fig. 8(a) with Fig. 8(d) shows that the topographic network does not account well for the actual flow network. The same exercise with Figure 8(c) or Figure 8(d) provides a better match of the corrected tillage network with the actual flow network.

Figure 11 represents the frequency distribution of Q values. Out of the 1240 observed segments, the proposed algorithm modified 587 segments (47%) by more than 1°. Among these, 455 segments (77%) have a positive Q. Hence, most of flow directions modified by the proposed algorithms led to an improved flow direction. This clearly demonstrates that taking into account tillage directions improves the quality of the flow network.

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## 4. Conclusions and perspectives

In an agricultural context, and for a watershed with gentle slopes, the surface flow network is largely affected by agricultural practices. The flow network computed from the DEM solely does not match the actual flow network with enough accuracy to allow for a good modeling of the overland flow and soil erosion.

The topographic network model can be improved with information about the tillage operations and preferential flow paths (such as open furrows). Including this information introduces some artifacts in the flow directions. These artifacts must be corrected to create a flow network usable for hydrologic purposes. The most important artifact is a drift in the flow direction everywhere the flow direction is controlled by the tillage operations. A method to cancel this drift is proposed. It should be applicable to most of the cell-based flow networks. The automatic procedures to correct other artifacts are also presented.

The comparison among the topographic flow network, the corrected tillage flow network, and the observed erosion marks shows that the described method matches successfully the actual flow network. It also shows that using only the topography to account for the flow directions leads to large discrepancies in the agricultural areas.

The proposed method could be further improved. Currently, only the convergent flows are modeled because we are using a "single flow direction" algorithm. However, some field observations show that divergent flow can also occur, especially in sedimentation areas. Another flow network algorithm, such as the "multiple flow algorithm" of Quinn et al. (1991), could be implemented to account for this feature. The visual observations also showed that the flow directions can change depending on the water flux. For a small water flux, the flow depth is low and the flow direction is along the tillage direction. However, for a larger water flux, the flow depth increases and the furrows can overflow, increasing the flow to the topographic slope aspect. This phenomenon can occur during a single rain event and is not accounted for in the current method. No alternative method is currently available. New research will be needed to address this issue. However, future studies will have to face the difficulty of the distributed water-flux measurements inside an agricultural field. Taking changes in flow depth into account would lead to a network able to evolve during a rainfall event.

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Table 1 - Roughness heights and corresponding levels

| Roughness height | Level |
|---|---|
| From 0 to 1 cm | 0 |
| From 1 to 2 cm | 1 |
| From 2 to 5 cm | 2 |
| From 5 to 10 cm | 3 |
| From 10 to 15 cm | 4 |
| More than 15 cm | 5 |

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Table 2. Drift correction to be applied depending on the drift angle $\alpha$ and the topographic flow direction modeled before correction $\beta$.

| $\beta$ | $\alpha < 0°$ | $\alpha > 0°$ |
|---|---|---|
| 0° | a (R) | a (R) |
| 45° | b (R) | a (C) |
| 90° | b (C) | b (C) |
| 135° | a (C) | b (R) |
| 180° | a (R) | a (R) |
| 225° | b (R) | a (C) |
| 270° | b (C) | b (C) |
| 315° | a (C) | b (R) |

Note: 'a' and 'b' refer to the formula numbers in the text. 'C' ('R') means that the correction has to be applied at a given interval along the 'columns' ('rows')

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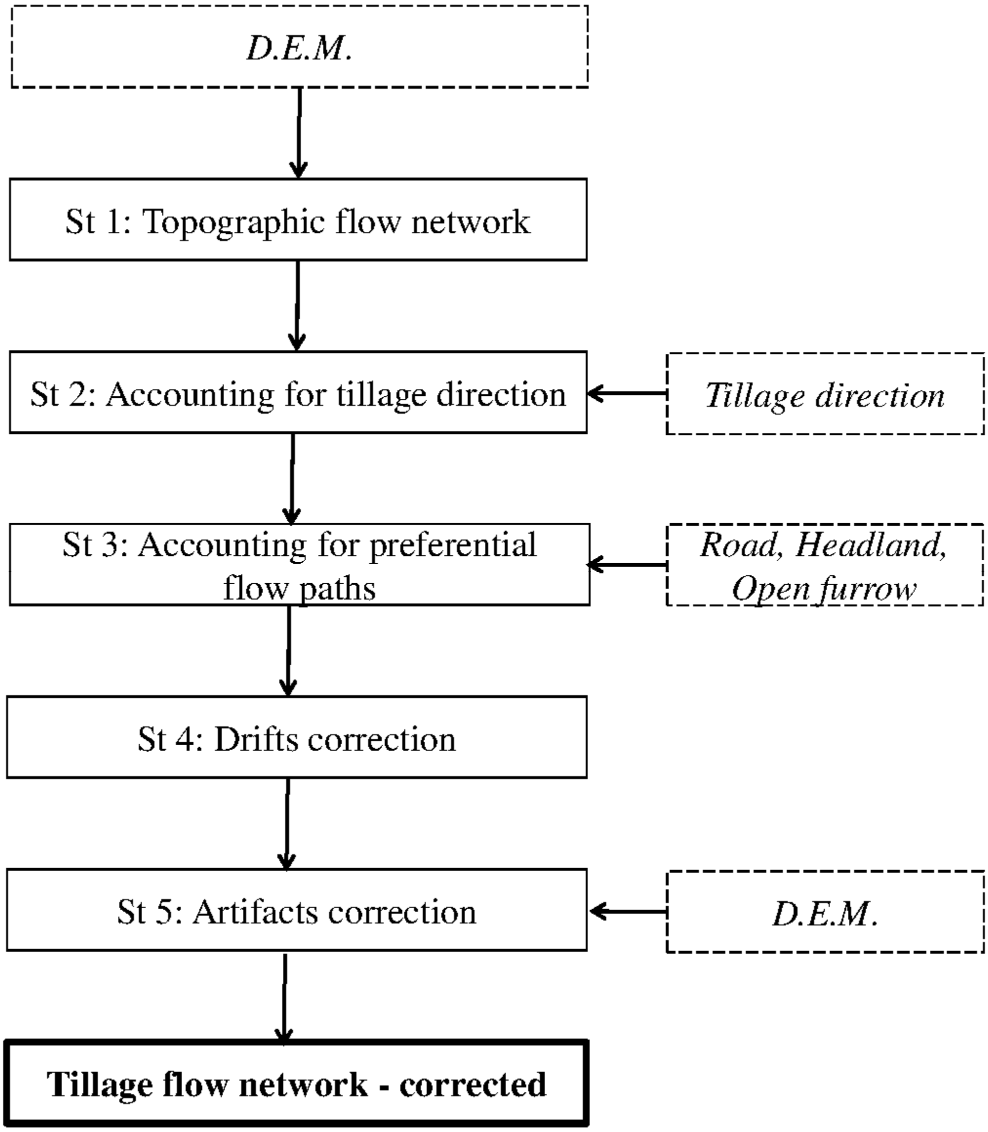


Fig. 1. Stages of the flow network algorithm accounting for tillage directions.

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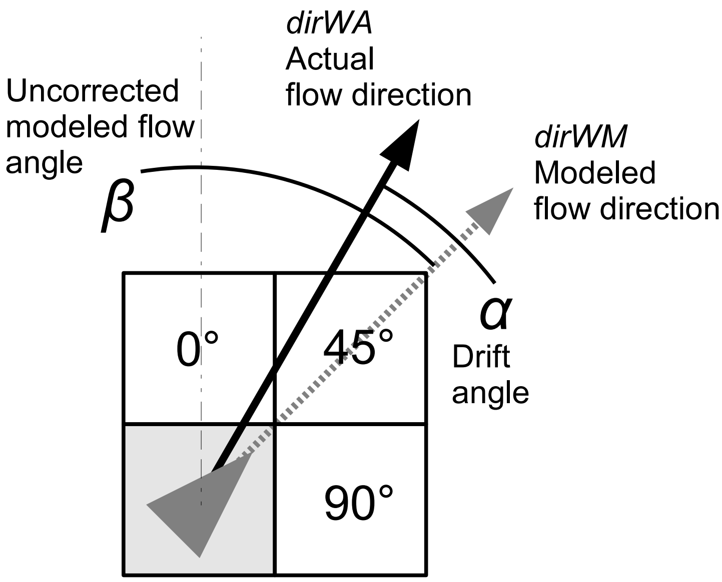


Fig. 2. Drift and drift angle. At the scale of a grid cell, the flow direction does not necessarily match the actual flow direction. $\beta$ represents the modeled flow direction. The drift angle $\alpha$ between the modeled and the actual directions can be as great as 22.5°.

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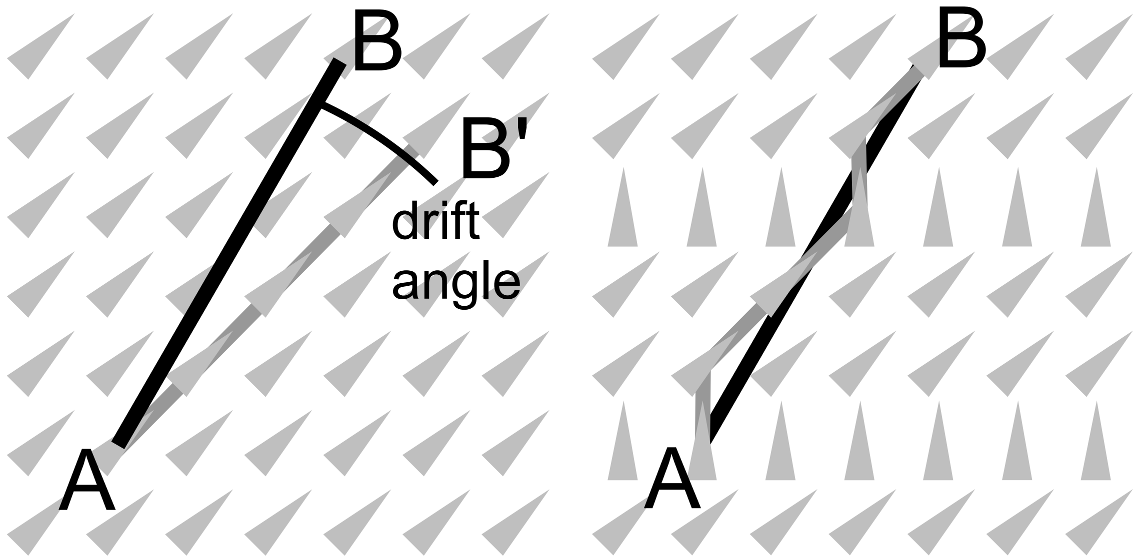


(a) (b)

Fig. 3. Drift and its correction. The actual flow travels from point A to point B. (a) The drift causes the flow to travel from point A to point B'. (b) The drift correction consists of tilting the flow direction at regular intervals. It restores a general flow direction matching the actual flow direction.

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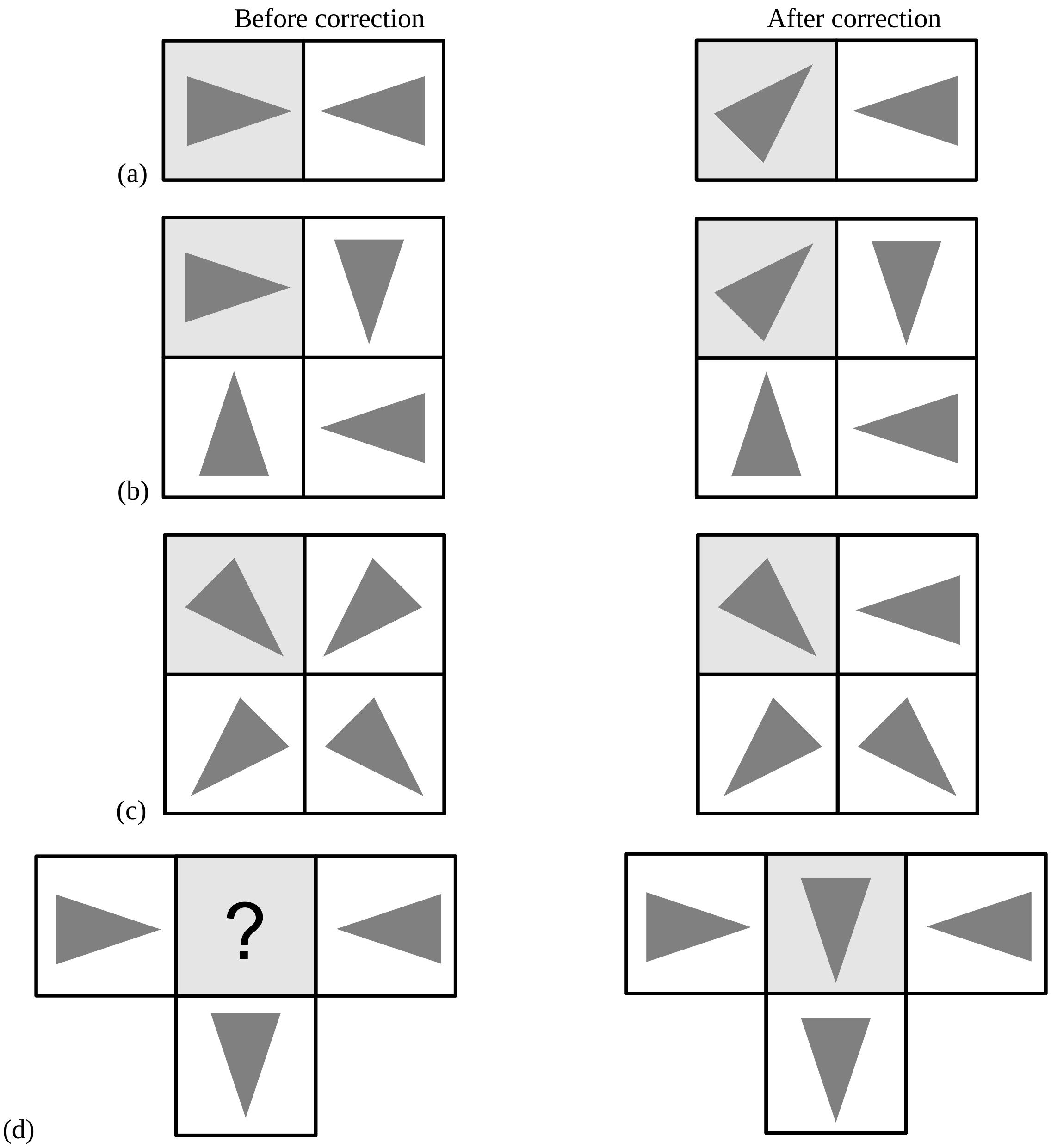


Fig. 4. Examples of flow artifacts and their corrections. (a) Converging flow, (b) Flow loop, (c) Crossing flow, (d) Unspecified flow direction. The cell under consideration has a grey background.

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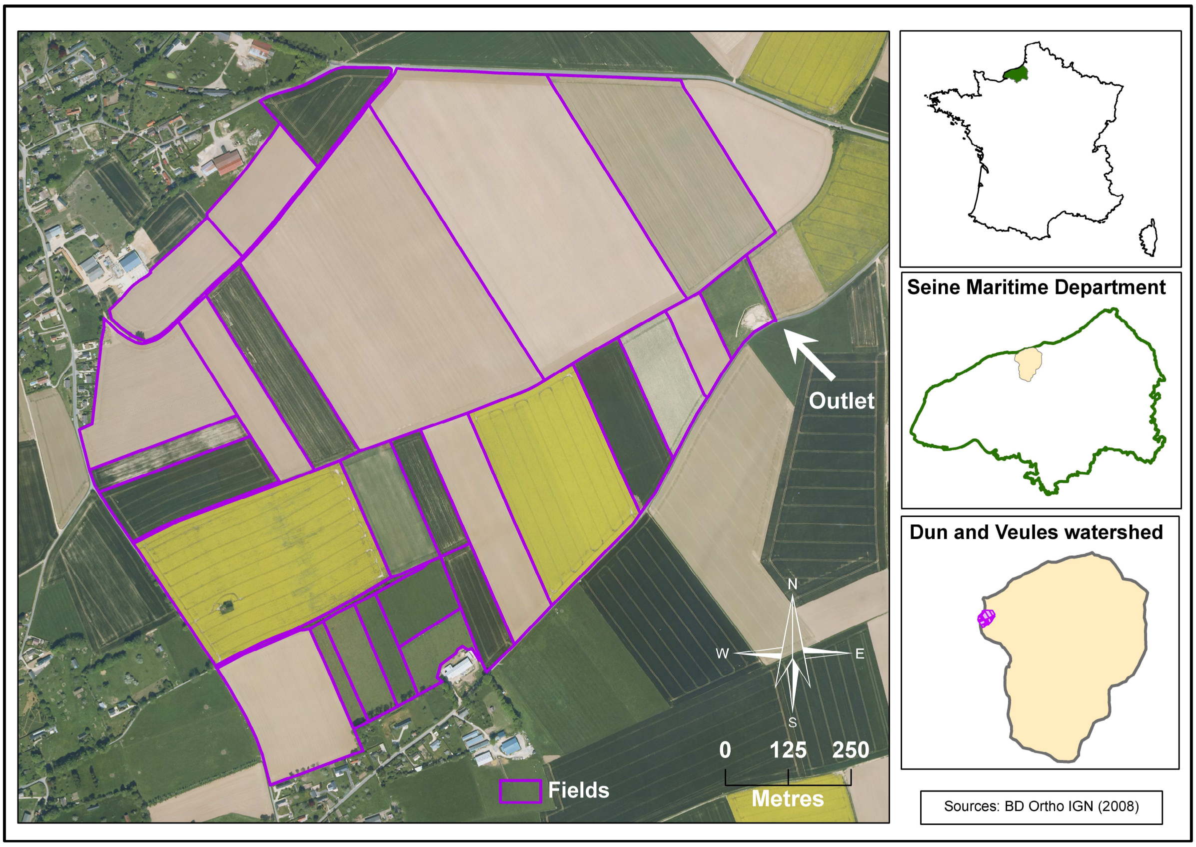


Fig. 5. Location map of the study area.

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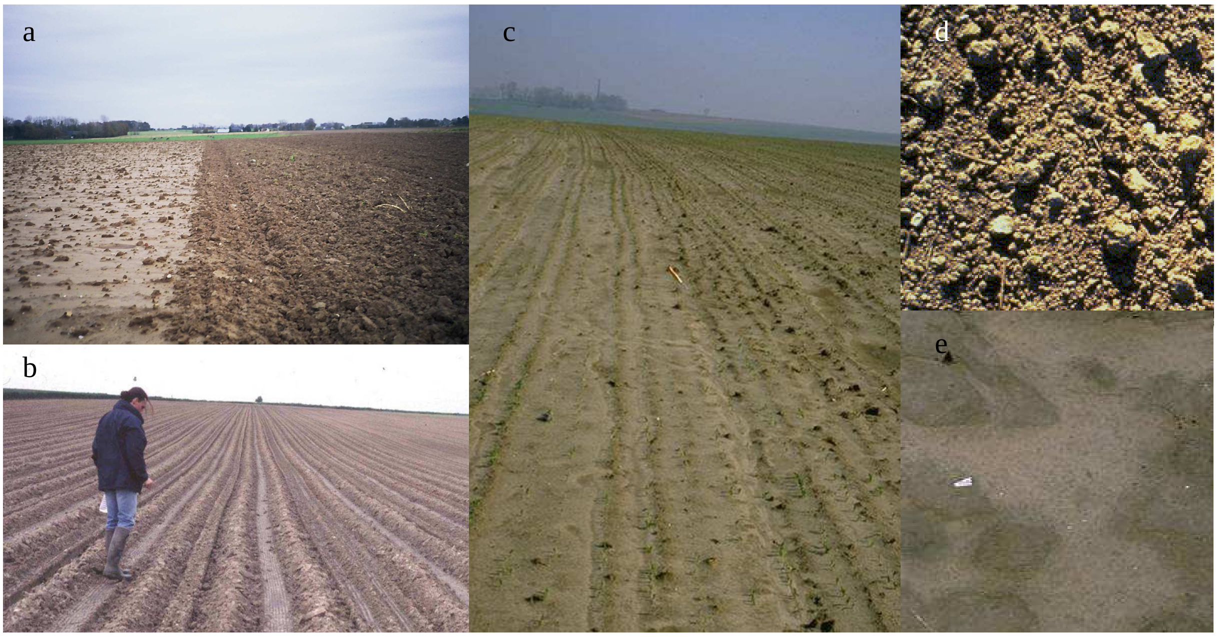


Fig. 6. Effects of the tillage operations on sealing, roughness, and surface runoff. (a) Crusted surface on the left, tilled on the right. (b) Tilled field with deep furrows. (c) crusted furrows. (d) uncrusted seedbed. (e) structural and sedimentary crusts.

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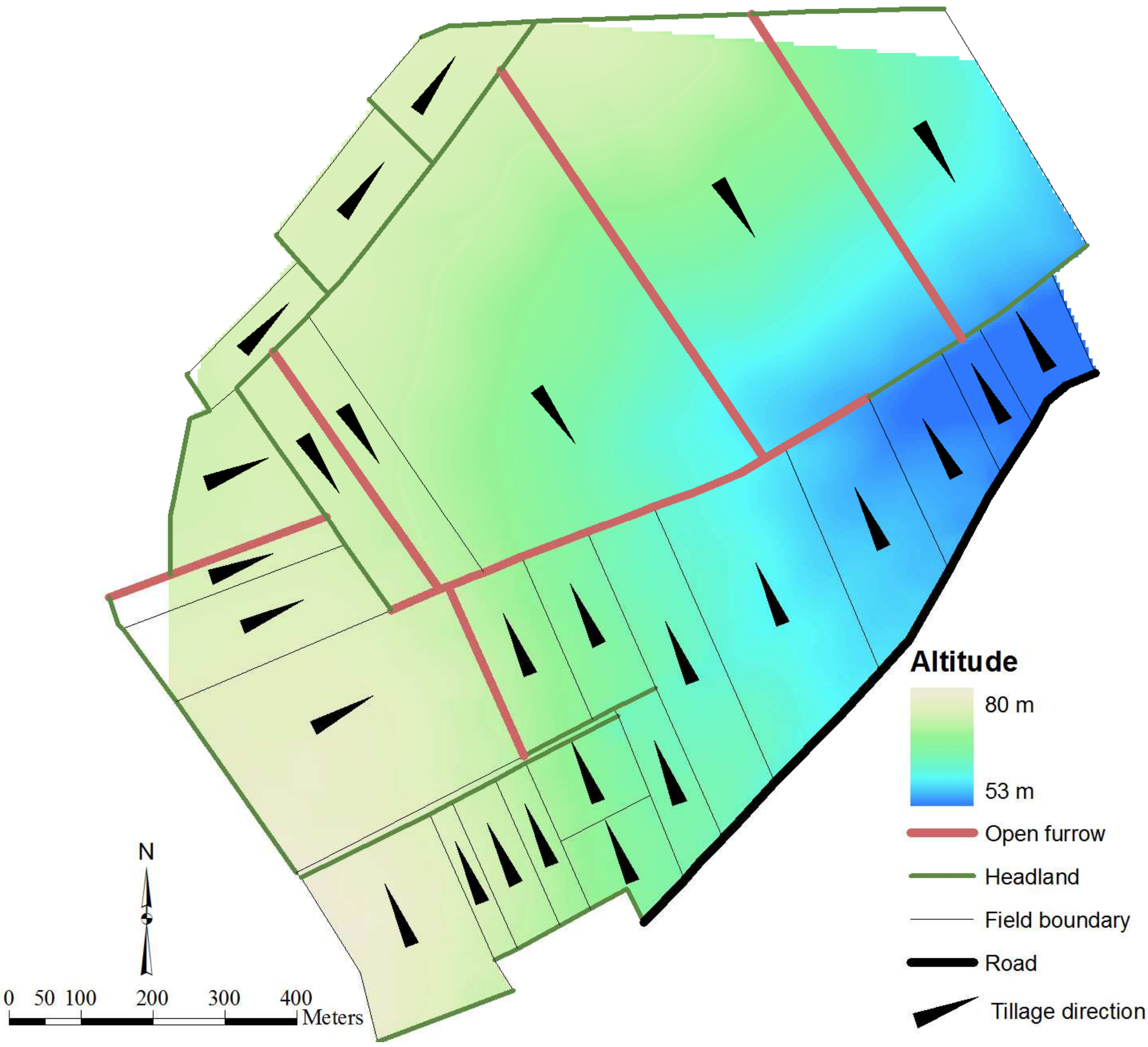


Fig. 7. Data used by the 'flow network' module.

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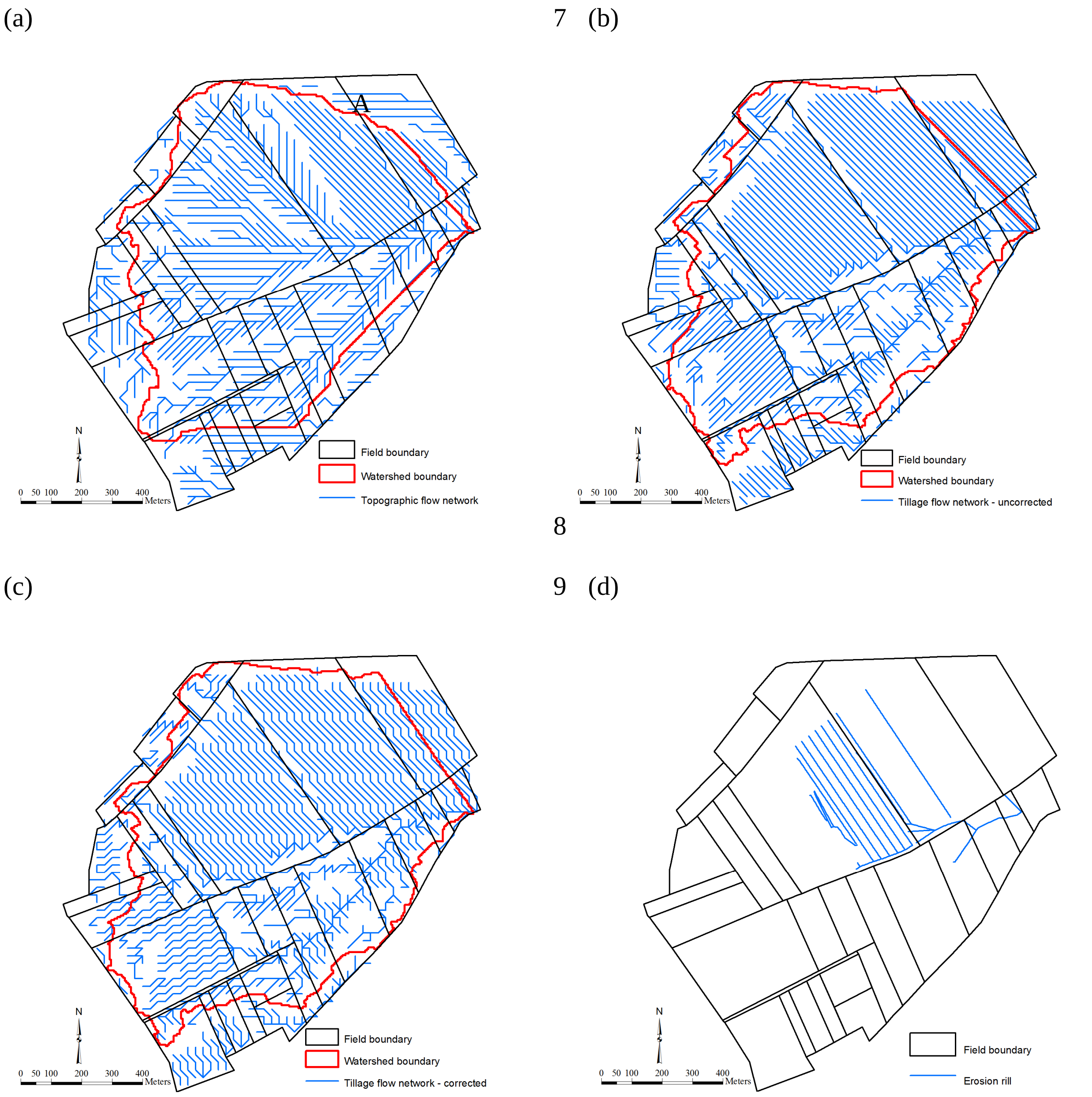


Fig. 8. Comparison of computed and observed flow networks. (a) Topographic flow model, based on the Digital Elevation Model only. (b) Tillage flow network before the correction of the drift. (c) Tillage flow network after the correction of the drift. (d) Erosion rill showing the actual flow direction as observed in the field.

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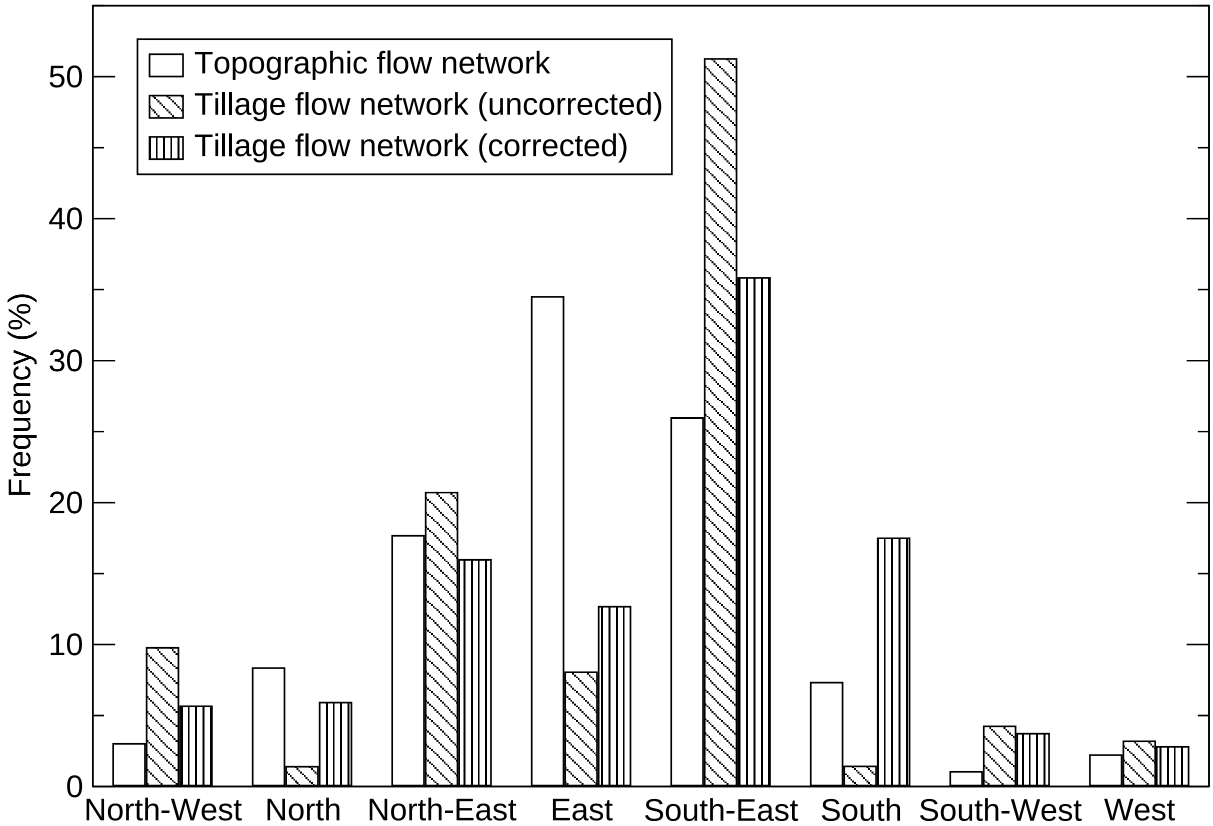
Fig. 9. Effect of the tillage and topography on flow directions. The flow can either follow the topographic slope directions (light tone/brown color) or the tillage directions (dark tone/green color).

2 


3 Fig. 10. Distribution of the flow directions for the computed flow networks.

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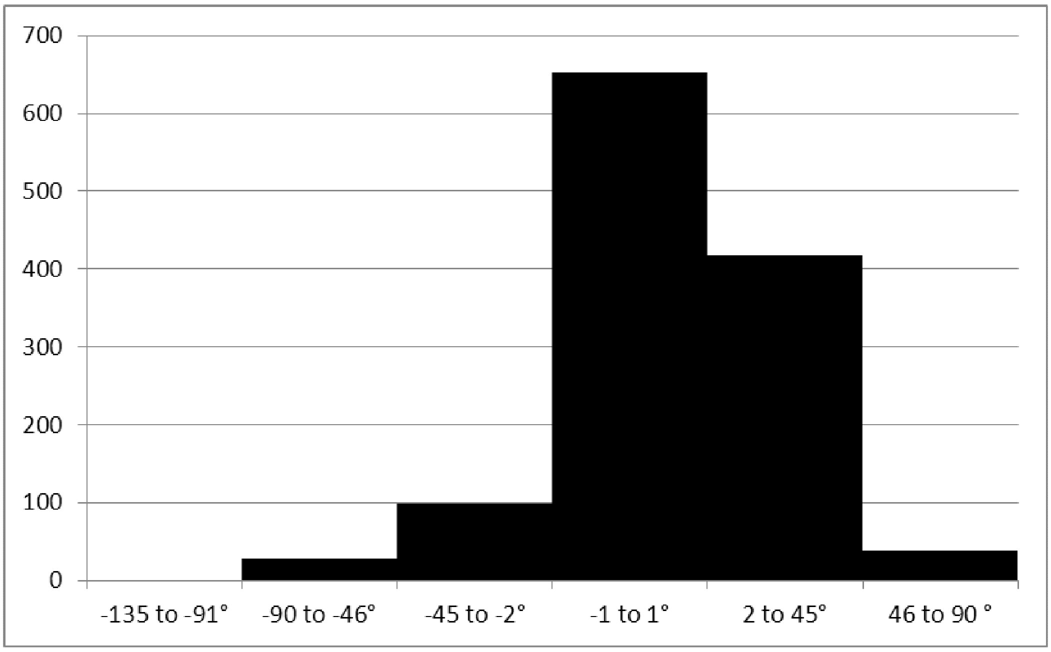


Fig. 11. Frequency distribution of the Q values. A positive Q value indicates a gain in quality brought by the proposed algorithm, whereas a negative Q value indicates a loss in quality.