Type of the Paper (Communication)

Modelling the effect of keyline practice on the soil erosion control

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Citation: To be added by editorial staff during production.

Academic Editor: Firstname Lastname

Received: date
Accepted: date
Published: date

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Abstract: The global agricultural sector needs the implementation of good soil management practices, in particular to prevent erosion and to improve water retention capacity. The introduction of tillage techniques along particular theoretical lines, called keylines, can make a significant contribution to improving the management of the soil and agricultural crops. The application of keylines is a relatively recent practice, still not well known and applied. With this preliminary work, we performed a comparative analysis of 2 small river basins (less than 100 ha), before and after keyline application, based on GIS computational models (TWI and SIMWE). The calculation models were elaborated starting from a DTM with 2 m resolution, obtained from a LIDAR survey. The comparative analysis, in qualitative terms, showed a positive effect of the keylines, both in terms of erodibility and infiltration of runoff water. The use of GIS models to verify the effectiveness in the planning phase can constitute a decision support system that guides agronomist technicians and farmers.

Keywords: Remote sensing, GIS model, TWI, SIMWE, Water regulation, Cropland

1. Introduction

The problems concerning erosion are well represented in the elaboration carried out by the JRC in 2015, which shows that Italy has the highest values of soil loss among EU countries with 8.77 t/ha against a European average of about 2.46 (JRC, 2015). More than 75% of the national territory is at risk of erosion [1] due to the high relief energy, and often associated with non-conservative management practices, which fuel the progressive thinning of the soil, affecting both productive capacity and physical-hydrological properties. Moreover, in Italy, 21.3 % of soils are at risk of desertification, and the soil degradation that has occurred over the last 40 years has caused a decrease of about 30 % in the water retention capacity of agricultural soils, also compromising their ability to respond to calamitous weather events [2,3].

If we focus on agronomic management, many techniques can be implemented in order to effectively contrast the erosion phenomenon.

Soil and water resource conservation are intimately related, and in this sense farm water management systems represent an essential tool.

In this context, where slopes are less severe, keyline design is an effective approach to tackling erosion [4].

Keyline Design is an agriculture water management system developed in the late 1940's by the Australian engineer and geologist P.A. Yeomans, whose aim is to increase water use efficiency within agricultural production systems [5,6]. One of the potentials of this design is that it can be introduced into a multitude of contexts: agroforestry, forestry design, ecological restoration, watershed design and management, and urban planning. Another important aspect of keyline design is the creation of effective water catchment areas.

Over time, some professionals [7,8] have reshaped and simplified the original design scheme, implementing a design that is easier in terms of execution and adaptability in different agronomic contexts, called keyline layout [9]. The main purpose of this system is to harness the force of gravity to slow down the surface runoff of water, intercept it, and distribute it slowly from the accumulation areas (valleys), where the level of superficial erosion is higher, towards the ridges, i.e. the areas that usually suffer from low water permanence, especially during the dry season. In this sense, keyline design can be a mitigation strategy for both erosion and drought phenomena where the slope of the land does not exceed 15%. In the agronomic context, this is achieved by designing a precise cultivation pattern in which tillage, cultivation operations, planting of permanent crops, hedges and tree strips follow the direction of the keylines. Keyline design always starts with a topographical survey (GPS, drone, remote sensing, total station) in order to obtain a contour map of the area under consideration. Taking a contour line as a reference, a line is drawn, called keyline, which, starting upstream of the reference curve, intersects it and crosses it with a slight slope. By following the keyline parallel upstream and downstream, a layout representing the cultivation pattern is outlined. Water is thereby forced to flow in the direction of the keylines through tillage and cultivation operations (e.g. ripping, harrowing, sowing, harvesting, etc.) for arable crops, aeration for pastures and permanent crops, and surface water regulation systems (e.g. ditches) (Figure 1). A keyline is considered efficient when, being reproduced in parallel upstream and downstream, it always induces the same water behaviour over the entire slope, or a large part of it, regardless of the contour lines. Keyline design is applied in many countries, including Italy [10], and is promoted by many farmers and agro-technicians, who report improvements in infiltration, storage and distribution of water in the soil; furthermore, increases in soil fertility have been recorded. However, these results have been achieved by combining keyline design with additional sustainable soil management practices, such as soil amendments, cover crops, minimum tillage, agroforestry systems, and rotational grazing. Although the keyline strategy has already been applied with broad empirical success, there is little scientific support for it [11–13].

Figure 1 - Example of tillage with soil aerator ripper in pastureland following keyline design

2. Materials and Methods

The study was carried out within two hydrographic basins in Mugello, in the province of Florence. These two basins present at the closing section a hilly lake for irrigation use, owned by an agricultural private company (Fig. 2). Both are part of a previous study on erosion [14]. This allowed us to work remotely, without the need to carry out data collection, surveys, but based on an already known territory [15]. Furthermore, we can say that in both cases there are normal erosion conditions, so the site under study is representative for a modeling approach.

The Galliano lake basin (ID = 3036) has an area of about 67 hectares, is located between 400 and 280 m asl, has an average slope of 8%. The basin of Lake Schifanoia (ID = 7719) has an area of 87 hectares, located between 280 and 240 m asl and 4% of average slope.

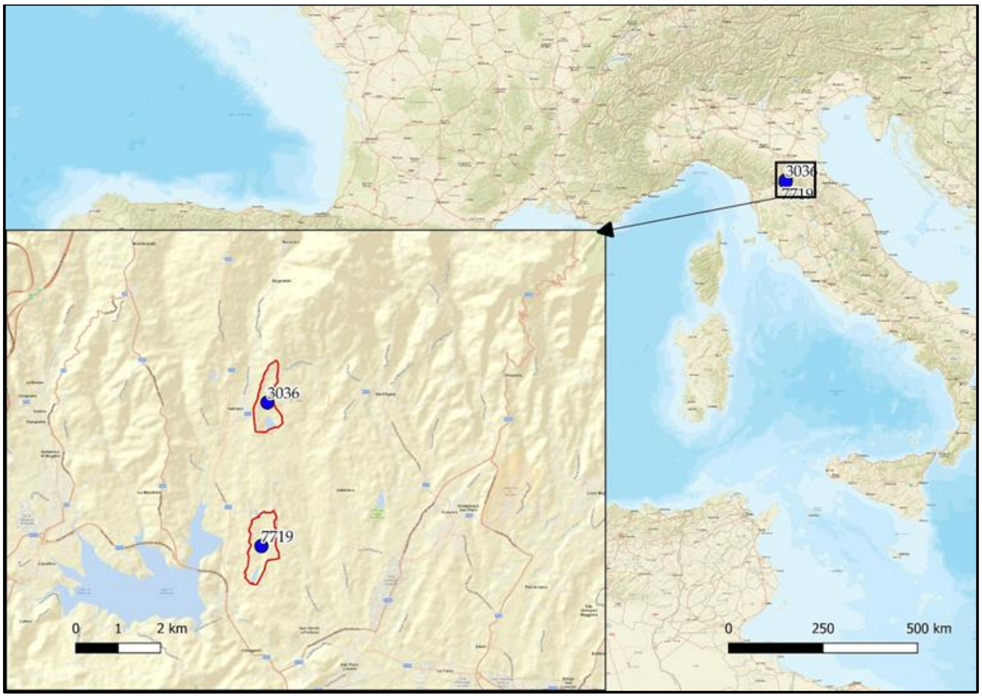

Figure 2 - Geographical position of the two basins analyzed. Basin 3036 - 11.3002759332; 44.0183733785. Basin 7719 - 11.2985087460; 43.9880056812.

From a cover and land use point of view, the basins are similar, mostly arable cropland and wood. Small portions builtup, limited road net and the lakes.

Keyline design has been applied to different rainfed arable land parcels, identified through photointerpretation from orthophotos, with total area of approximately 763 ha and average slope 6%, excluding plots with a slope of more than 15%, where, in addition, arable farming would be inadvisable. In the first phase of the design, a careful analysis of the current orography of the sites under consideration was carried out. Using LIDAR data (Light Detection and Ranging) with a resolution of 2x2 m, a DTM model (Digital Terrain Model) was created which allowed to derive a contour map with lines every 2 m. In the next step, the keyline layout was drawn using Autocad software. From the contour map, following the Pavlov methodology [9], a keyline was identified for each plot under consideration to be used as a guide, and subsequently drawn parallel below and above it. In some plots, due to the high orographic variability, it was necessary to identify an additional keyline guide, to ensure continuity in the functionality of the layout (Fig.3). In the areas of the sites under investigation characterized by numerous, sometimes very abrupt, changes of slope, it was not possible to apply keyline geometry to the full, but ease of execution was favored over faithful interpretation of the landscape. Indeed, in these areas, the keylines guide have undergone adjustments in order to achieve a realistic tillage pattern, i.e. one that is simple and safe (no risk of overturning for the tractor) for farm operators to implement in the field, but losing some of the beneficial effects of the keyline design.

The cultivation pattern design was carried out by assuming two different intervention strategies:

1. Surface water regulation: creation of temporary ditches every 25 m along keylines with a depth of 20 cm.

2. Tillage: subsoiling at a depth of 30 cm parallel to the keylines.

Lastly, water regulation was completed by assuming, for each strategy, the creation of 30-cm-deep collection ditches at the edges of the plots.

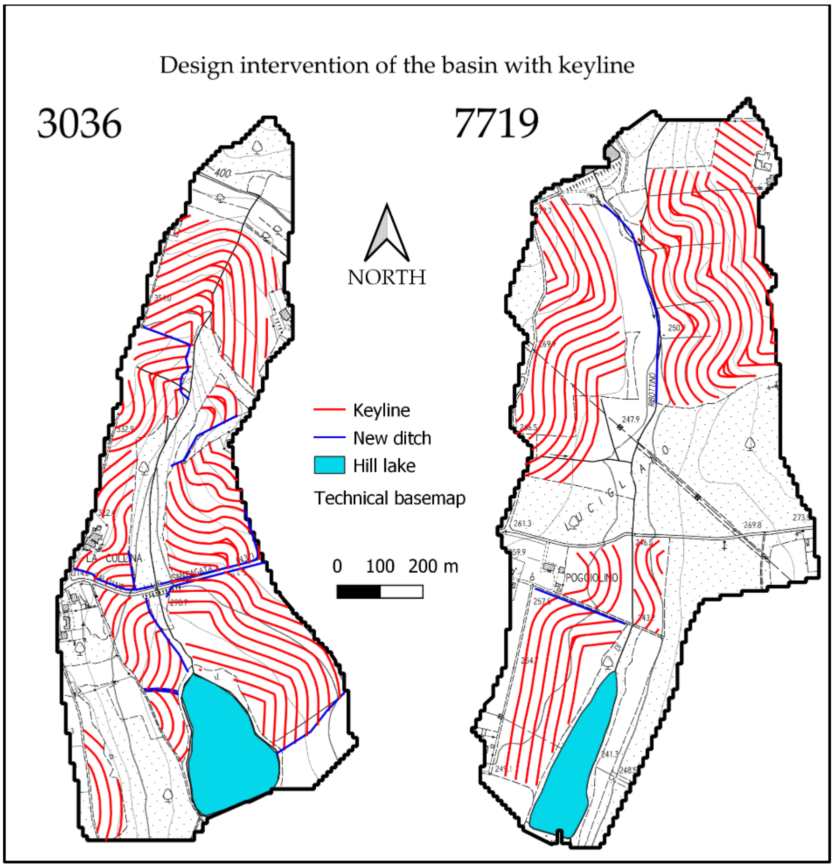

Figure 3 - Arrangement of keylines in arable land.

The effect of keylines was analyzed using two hydrological models: Topographic Wetness Index (TWI) and the Overland flow hydrologic simulation using path sampling method (SIMWE). TWI was elaborated with the aid of the SAGA GIS software, while SIMWE was elaborated on GRASS GIS. Both are well known in the scientific community and are applied in many works [16,17]. The two models allow to take into account both approaches of the keyline design, both the excavation of real ditches (interception by means of drainage channels of surface water), and the change in the soil infiltration capacity (tillage with aerator ripper). TWI was developed on the basis of a DTM (digital terrain model) with a resolution of 2 m, before and after the application of keyline design. The GRASS GIS processing algorithm, *r.carve*, was used to report the hydraulic arrangements on the DEM, which allows the DTM to be excavated along lines, specifying width and depth [18]. The evaluation of the changes between the two simulations resulting from the TWI is mainly qualitative. Using the SIMWE (r.sim.water) it was possible to simulate the effect of a rain precipitation of 50 mm for 10 minutes, obtaining the runoff (water discharge - cubic meter per second). The model has as input the DTM of the area, and the spatialized runoff coefficient based on the basin characteristics (soil, slope, cover), the same procedure for determining the runoff coefficient used in Cambi [17] was applied. The effect of the keylines has been inserted by modifying the runoff coefficient along them, reducing by 0.2 compared to what previously. This is to see the effect of keylines on the general balance in the catchment area.

3. Results

The results obtained from the hydrological models show an evident impact of the keylines on the runoff distribution and soil moisture within the basin. The excavation operation of the DTM shows evident changes in the water concentration in the cropland involved by the keyline system (Fig.4 and Fig.5). The introduction of 20 cm deep ditches, placed at a distance of about 25 m from each other, leads to a regulation of surface waters capable of reducing erosive phenomena in the portions between the keylines. The outflow follows the keylines apart from some cases where they are not enough (probably 20 cm is not enough to contain the flow) and then the water flows out in a disorderly way. The slope statistics generally show an increase in the wetness index, given the fact that the outflow in the keylines is much greater. They are not reported as they are not significant for a theoretical modeling simulation.

The runoff with the keylines, obtained from the simulation with the SIMWE, is less than the previous condition, and is clearly visible from Figure 6 and Figure 7. We notice a general reduction of the runoff in the whole area where the keylines are present, without noticing their morphology, as the terrain does not undergo changes from an elevation point of view, only the physical characteristics of the soil vary about the infiltration. In fact, the outflow follows the same direction, before and after, but it is reduced in absolute terms, as much more water returns to the slopes.

In absolute terms, the sum of the water discharge value of all the pixels, for each of the basins, in the simulation with the keyline, is lower. Respectively the basin 3036 shows a reduction of 8% and the basin 7719 of 12%. The difference between the basins is consistent with the dimensions, 7719 is larger than 3036.

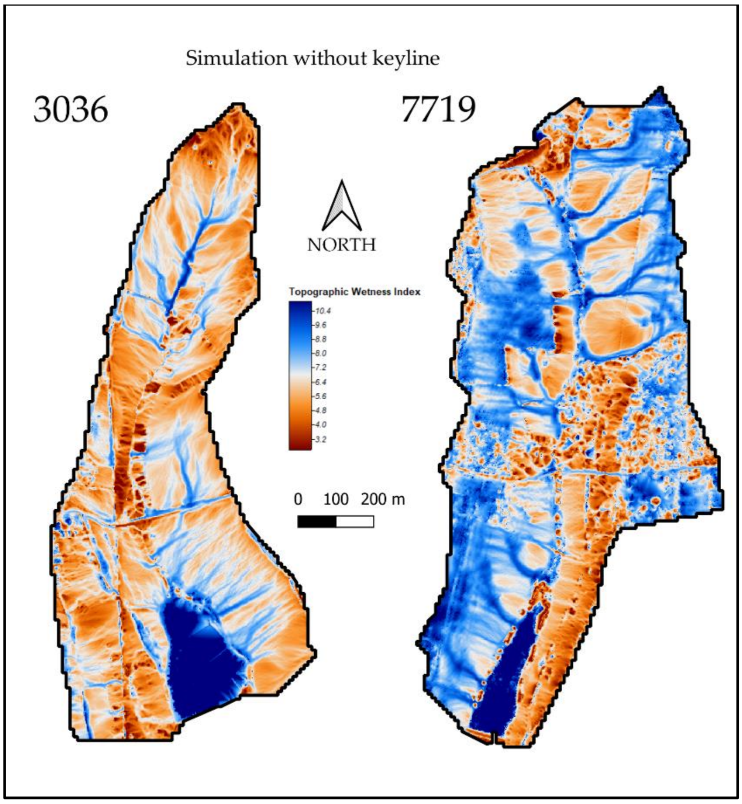

Figure 4 - Topographic Wetness Index (TWI) map without the keyline

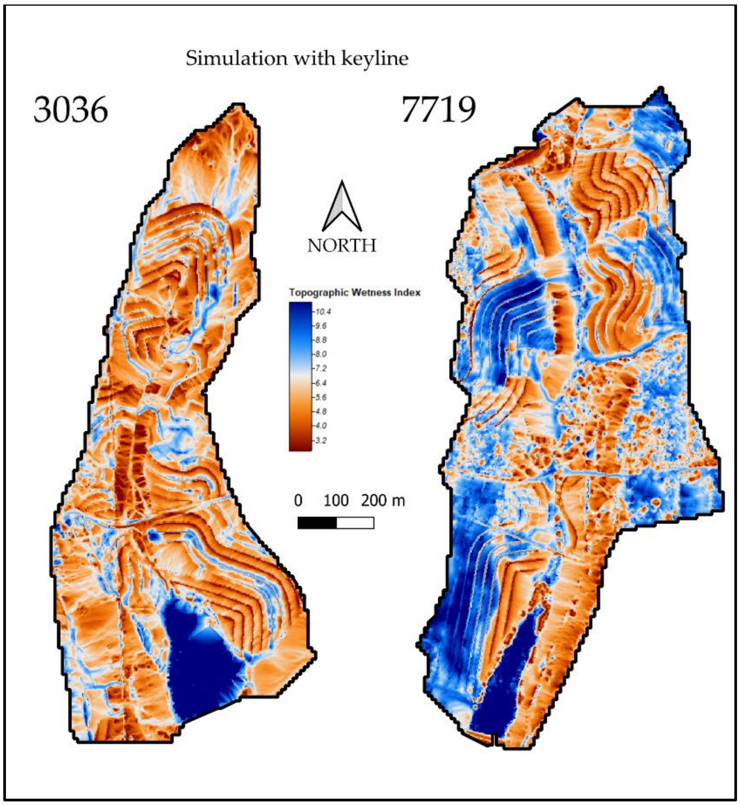

Figure 5 - Topographic Wetness Index (TWI) map with the keyline

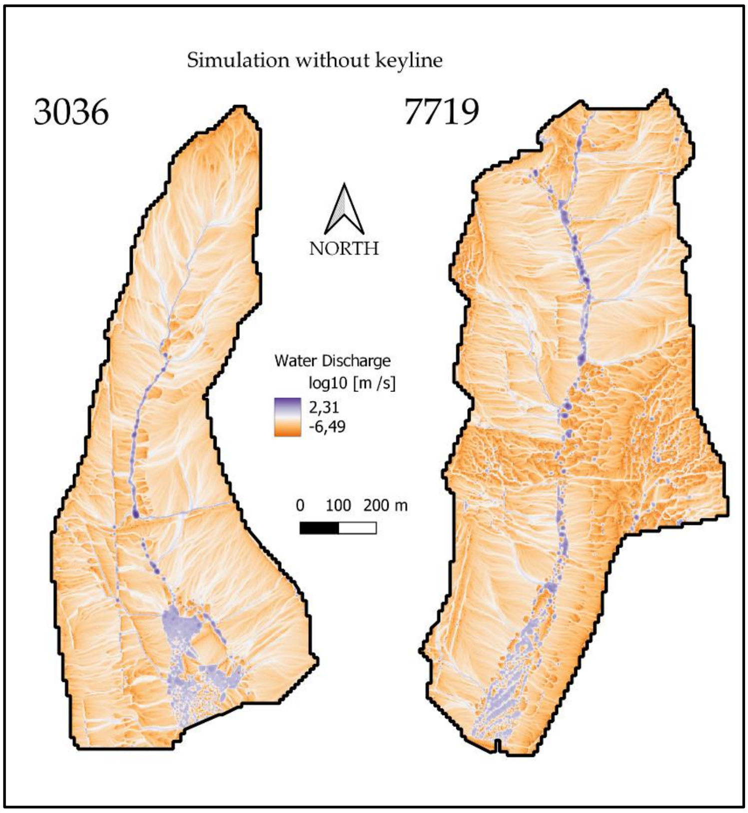

Figure 6 - Water discharge (SIMWE) map without the keyline

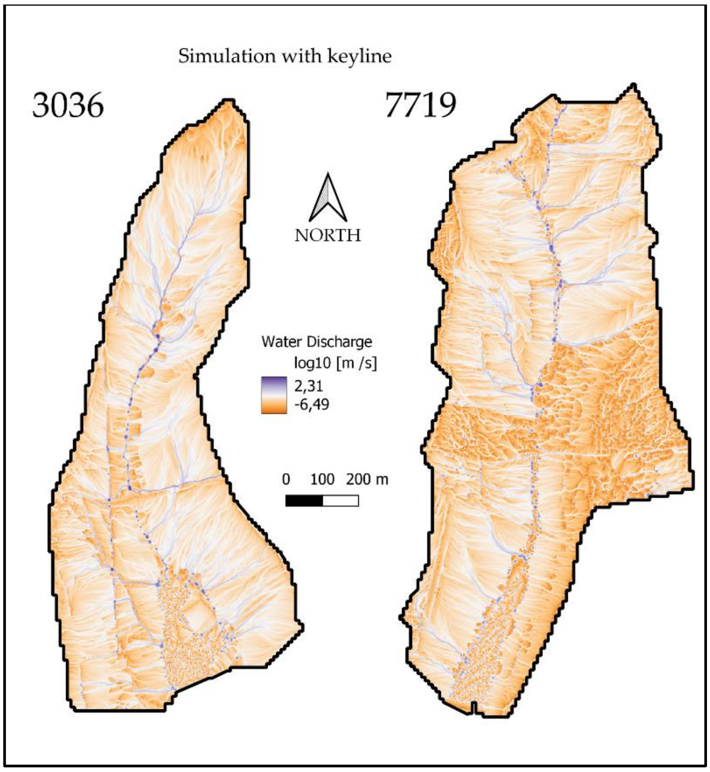

Figure 7 - Water discharge (SIMWE) map with the keyline

4. Discussion

The soil erosion phenomenon is a problem present in every slope area subject to cultivation, as every year centimeters of fertile soil are lost, hydrogeological problems occur, especially in addition to climate change [19]. The use of techniques for improving water regulation can make a significant contribution to reducing soil erosion, and can also increase the water accumulation and therefore a greater water reserve during the dry period.

The keyline technique shows, in this preliminary modeling analysis, a positive effect for these purposes. For both approaches applied, there are advantages to reduce the uncontrolled runoff and a greater permanence of water in the slopes. The positive effects are similar to those identified by Bazzoffi in his works on the water furrows [20–22].

The portions of territory that are not affected by the influence of the keylines are the result of the compromise between agronomic and hydrological needs, as the design must allow the farmer to work safely and feasible. It is acceptable to obtain a lower result in terms of water regulation.

The keyline design for this study was based on data, maps, and photointerpretation. No surveys were carried out, which usually allow for a more detailed analysis of the plots.

The digital terrain model used has a resolution of 2 m, and is an high resolution models. In this application, however, it shows some limits: as variations under the meter are not very noticeable. For the correct verification of the keyline effect it would be advisable to use DTMs with even higher resolutions, models that can be easily obtained with photogrammetric surveys by drones (UAV), in areas without or with reduced vegetation cover and with an extension limited to a few tens of hectares [23].

In addition to the positive aspects, some considerations are necessary which could lead to land degradation both for erosion and for water accumulation. In the first case, the arrangement of the ditches following the natural slope of the land could cause greater erosion problems, due to the greater runoff concentration [24]. Concentrated water increases its speed and therefore drag energy, causing localized but intense erosion. In this regard, it is necessary to verify well the arrangement of the keylines with the help of distributed morpho-hydrological models such as the TWI. To overcome these drawbacks, it is necessary to provide well-consolidated ditches, with small jumps (steep and pools) [25] in order to reduce the current speed. Or by keeping the channels grassed or vegetated in order to reduce the current speed with greater roughness [26,27]. Another solution can be to create flat ditches, in order to reduce the speed thanks to the lower slope, thus creating a profile such the terraced slopes [28].

In the second case, we have a greater water retention of the soils of the slope with positive effects for crops during the dry season. In clayey soils this could prove to be a problem, as between the higher density of the soil and the possible formation of compact layer due to tillage, soliflow phenomena could occur [29], or even landslides and instability.

Considering the above, the combination of the two approaches could be optimal to gain a greater benefit in terms of water regulation and infiltration. More specifically, the realisation of ditches should be followed by working parallel to the keylines along the entire slope, combining minimum tillage to prepare the soil for sowing, avoiding machinery that creates compaction and harms soil structure.

5. Conclusions

The keylines show an interesting practice of good management of cultivated land, with a good ability to reduce soil erosion, and improve the water retention capacity of the soil for greater resilience of crops during drought periods. In order to carry out a correct design of the slope arrangement, it is advisable to check the new layout of the territory, together with the characteristics that influence erosion: slope, type of soil, distribution of precipitation events, soil cover, etc.

With the following work it is shown that the models based on soil morphology (TWI and SIMWE) can constitute a real decision support system for the design of keylines and in general for agricultural hydraulic arrangements. The accuracy of the results also depends on the resolution of the digital terrain models.

6. Patents

This section is not mandatory but may be added if there are patents resulting from the work reported in this manuscript.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Figure S1: title; Table S1: title; Video S1: title.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, X.X. and Y.Y.; methodology, X.X.; software, X.X.; validation, X.X., Y.Y. and Z.Z.; formal analysis, X.X.; investigation, X.X.; resources, X.X.; data curation, X.X.; writing—original draft preparation, X.X.; writing—review and editing, X.X.; visualization, X.X.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript." Please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

Funding: Please add: "This research received no external funding" or "This research was funded by NAME OF FUNDER, grant number XXX" and "The APC was funded by XXX". Check carefully that the details given are accurate and use the standard spelling of funding agency names at https://search.crossref.org/funding. Any errors may affect your future funding.

Data Availability Statement: In this section, please provide details regarding where data supporting reported results can be found, including links to publicly archived datasets analyzed or generated during the study. Please refer to suggested Data Availability Statements in section "MDPI Research Data Policies" at https://www.mdpi.com/ethics. If the study did not report any data, you might add "Not applicable" here.

Acknowledgments: In this section, you can acknowledge any support given which is not covered by the author contribution or funding sections. This may include administrative and technical support, or donations in kind (e.g., materials used for experiments).

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