

Modelling the Effect of Keyline Practice on Soil Erosion Control

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Abstract: The global agricultural sector needs to implement 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 keyline system has been around for less than 100 years. With this preliminary work, we performed a comparative analysis of two 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 agronomists, technicians, and farmers.

Keywords: remote sensing; GIS model; TWI; SIMWE; water regulation; cropland



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1. Introduction

The problems concerning erosion are well represented in the elaboration carried out by the JRC (Joint Research Centre of the European Commission) 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 [2–6]. 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 [7,8]. In the agricultural sector, there are many techniques that 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 hilly cultivated areas, where slopes are less severe, keyline design is an effective approach to tackling erosion [9].

Keyline design is an agriculture water management system developed in the late 1940s by the Australian engineer and geologist P.A. Yeomans, whose aim is to increase water use efficiency within agricultural production systems [10,11]. One of the potential benefits 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 [12,13] 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 a keyline layout [14]. 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 away 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, and the planting of permanent crops, hedges, and tree strips follow the direction of the keylines. A keyline is considered efficient when, being reproduced in parallel upstream and downstream, it always induces the same water behavior over the entire slope, or a large part of it, regardless of the contour lines. Keyline design is applied in many countries, including Italy [15], and is promoted by many farmers and agro-technicians, who report improvements in the infiltration, storage, and distribution of water in their soils; 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, we have found few studies to verify its effectiveness [16–18] from a qualitative and not a quantitative point of view.

The objective of this communication is to show the effect of keylines on the rain runoff in hilly arable land by means of a simulation carried out with mathematical models elaborated in a GIS environment. The hydrological effects of keylines influence runoff and, consequently, soil erosion [19–25]. Other parameters that impact soil loss, such as cover, soil erodibility, and rainfall action, do not vary and therefore cannot be verified with a simulation.

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 (Figure 1). Both are part of a previous study on erosion [26,27]. This allowed us to work remotely, without the need to carry out data collection or surveys as the research was based on an already known territory [28]. Furthermore, we can say that there are normal erosion conditions in both cases, so the site under study is representative for a modeling approach.

The Galliano lake basin (ID = 3036, geographic coordinates: Long 11.3002759332; Lat 44.0183733785) has an area of about 67 ha, is located between 400 and 280 m asl, and the average slope is 8%. The basin of Lake Schifanoia (ID = 7719, geographic coordinates: Long 11.2985087460; Lat 43.9880056812) has an area of 87 ha, located between 280 and 240 m asl and a 4% average slope. From a cover and land use point of view, the basins are similar, mostly arable cropland and woodland, with small portions of built-up land, a limited road network, and the lakes.

Keyline design has been applied to different rainfed arable land parcels, identified through photointerpretation from orthophotos, with a total area of approximately 763 ha and an average slope of 6%, excluding plots with a slope of more than 15%, where arable farming would be inadvisable. The plot is a homogeneous portion of land included in natural constraints (watersheds, slopes).

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 a keyline, which, starting upstream of the reference curve, intersects it and crosses the reference curve with a slight slope. By drawing the keyline parallel to the upstream and downstream, a layout representing the cultivation pattern is outlined. In practice, 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 2).

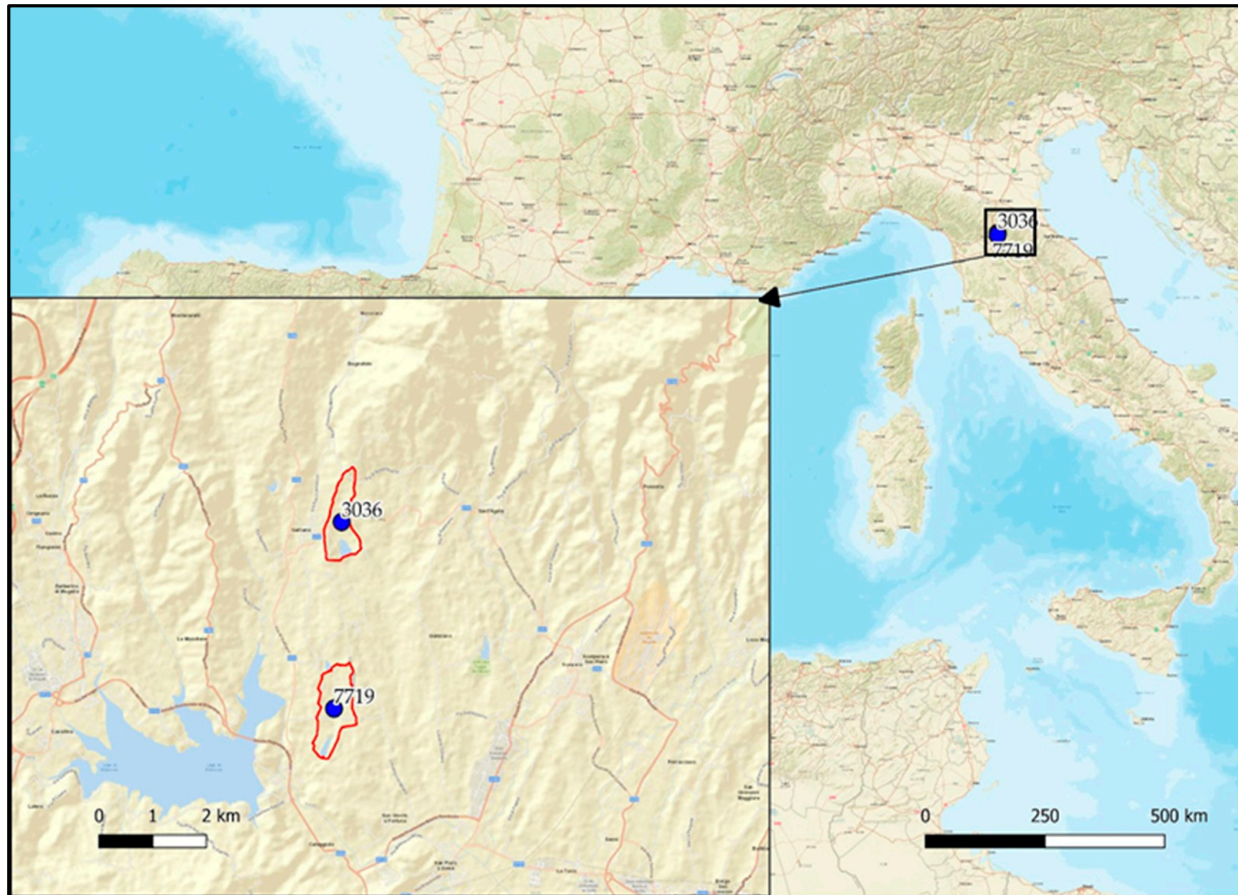


Figure 1. Geographical position of the two basins analyzed.

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 2×2 m, a DTM model (Digital Terrain Model) was created which allowed us to derive a contour map with lines placed every 2 m. In the next step, the keyline layout was drawn using Autocad software. From the contour map, following the Pavlov methodology [14], a keyline was identified for each plot under consideration to be used as a guide, and subsequent lines were drawn parallel below and above the keyline. 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 (Figure 3). In the areas of the sites under investigation characterized by numerous, sometimes very abrupt, changes in slope, it was not possible to apply keyline geometry to the full extent; however, ease of execution was favored over faithful interpretation of the landscape. Indeed, in these areas, the keyline guides 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 in exchange for losing some of the beneficial effects of the keyline design.



Figure 2. Example of tillage using a soil aerator ripper in pasture and following 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.

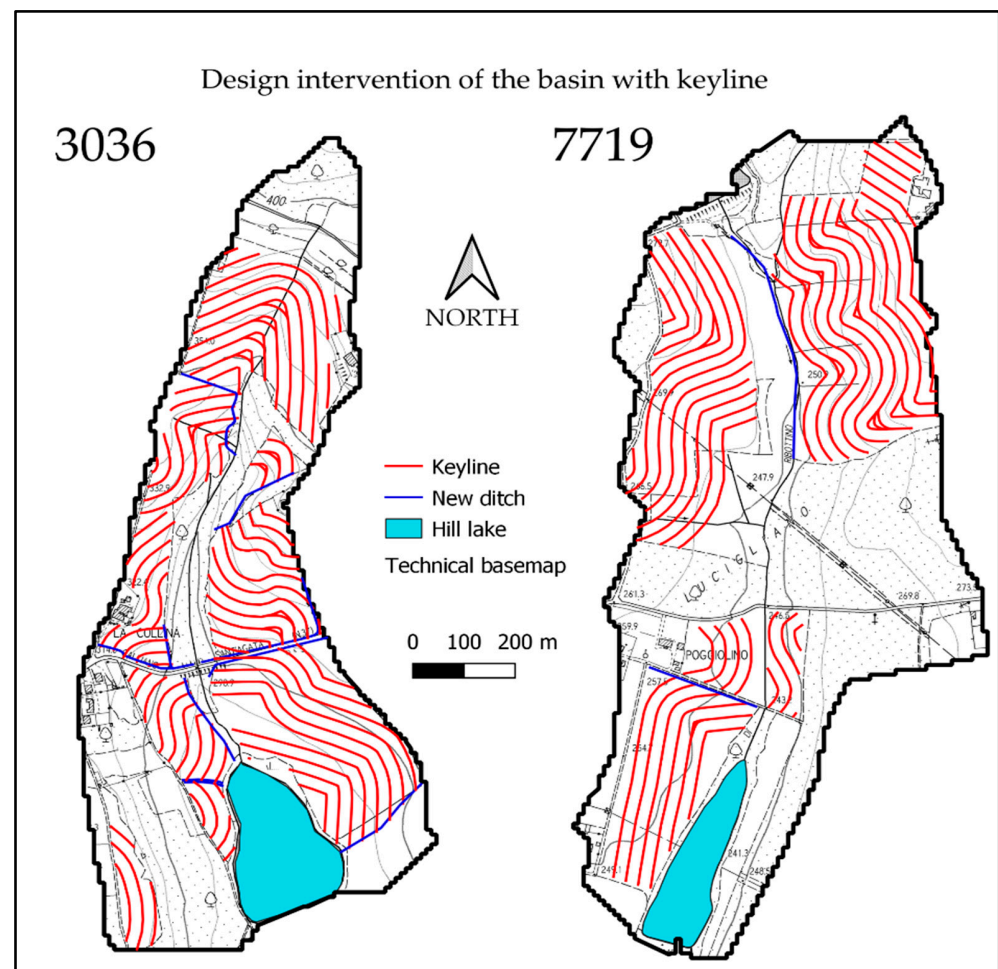


Figure 3. Arrangement of keylines in arable land.

The effect of keylines was analyzed using two hydrological models: the Topographic Wetness Index and a overland flow hydrologic simulation using the path sampling method. The Topographic Wetness Index (TWI) is based on the assumption that topography controls the movement of water in sloped terrain and thus the spatial pattern of soil moisture. High TWI values are found in converging, flat terrain. Low values are typical for steep, diverging areas. The simulation of water erosion model (SIMWE) estimates the net erosion/deposition at a point, under the assumption that the erosion and deposition are proportional based on the difference between the sediment transport capacity and the actual sediment flow, depending on soil and cover properties. The TWI was elaborated with the aid of the SAGA GIS software, while the SIMWE was elaborated on GRASS GIS. Both are well-known in the scientific community and are applied in many works [29–35]. The two models allow us to take into account both approaches to the keyline design, i.e., 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). The 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 [36]. The evaluation of the changes between the two simulations resulting from the TWI are mainly qualitative. Using the SIMWE (*r.sim.water*), it was possible to simulate the effect of a rain precipitation event of 50 mm for 10 min, 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), which is the same procedure for determining the runoff

coefficient used in Cambi et al. (2021) [30]. The classification is based on soil type, slope, and vegetation cover. The runoff coefficients are identified by crossing the parameters within a matrix. The effect of the keylines has been inserted by modifying the runoff coefficient along them, reducing by 0.2 compared to the previous coefficient. This is carried out to see the effect of keylines on the general balance in the catchment area. The reduction in the runoff coefficient was chosen using the same approach, considering the less weighted and compacted soil along the keylines.

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 changes in the water concentration in the cropland involved by the keyline system (Figures 4 and 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, with the exception of some cases where they are probably not deep 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.

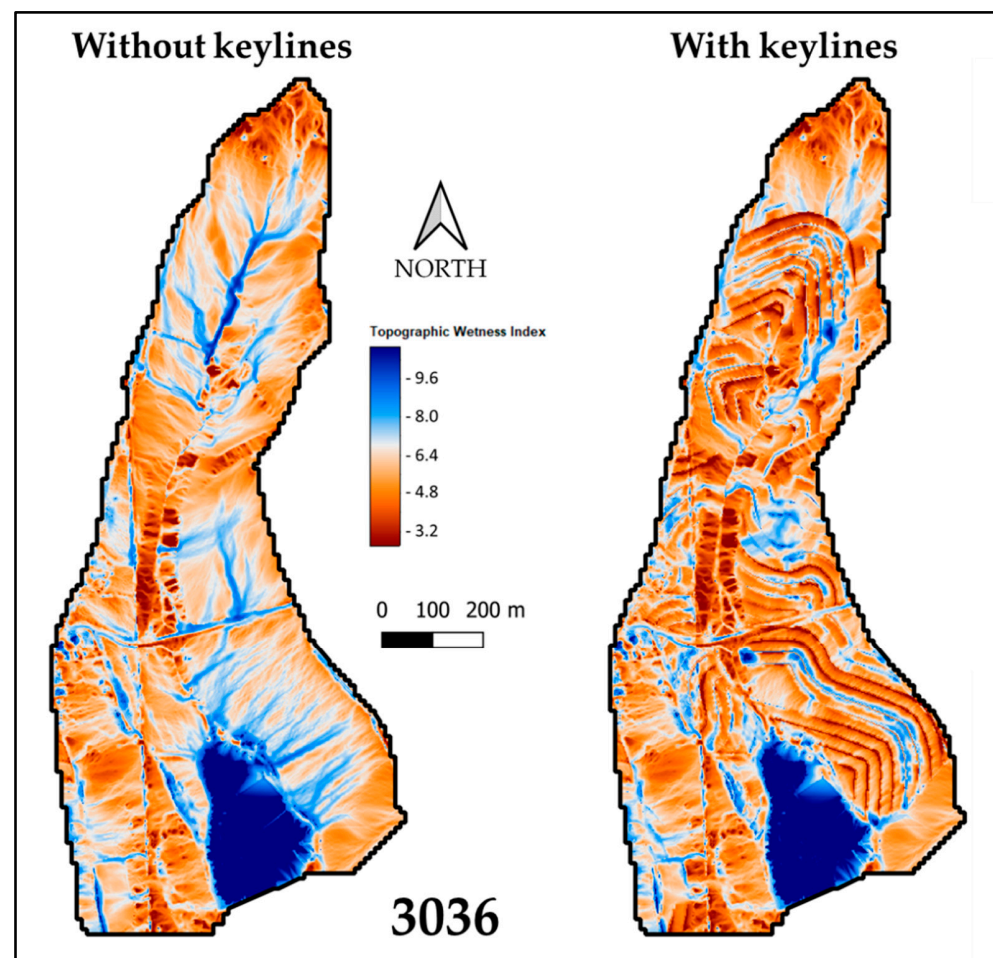


Figure 4. Topographic Wetness Index (TWI) maps with and without the keylines for basin 3036.

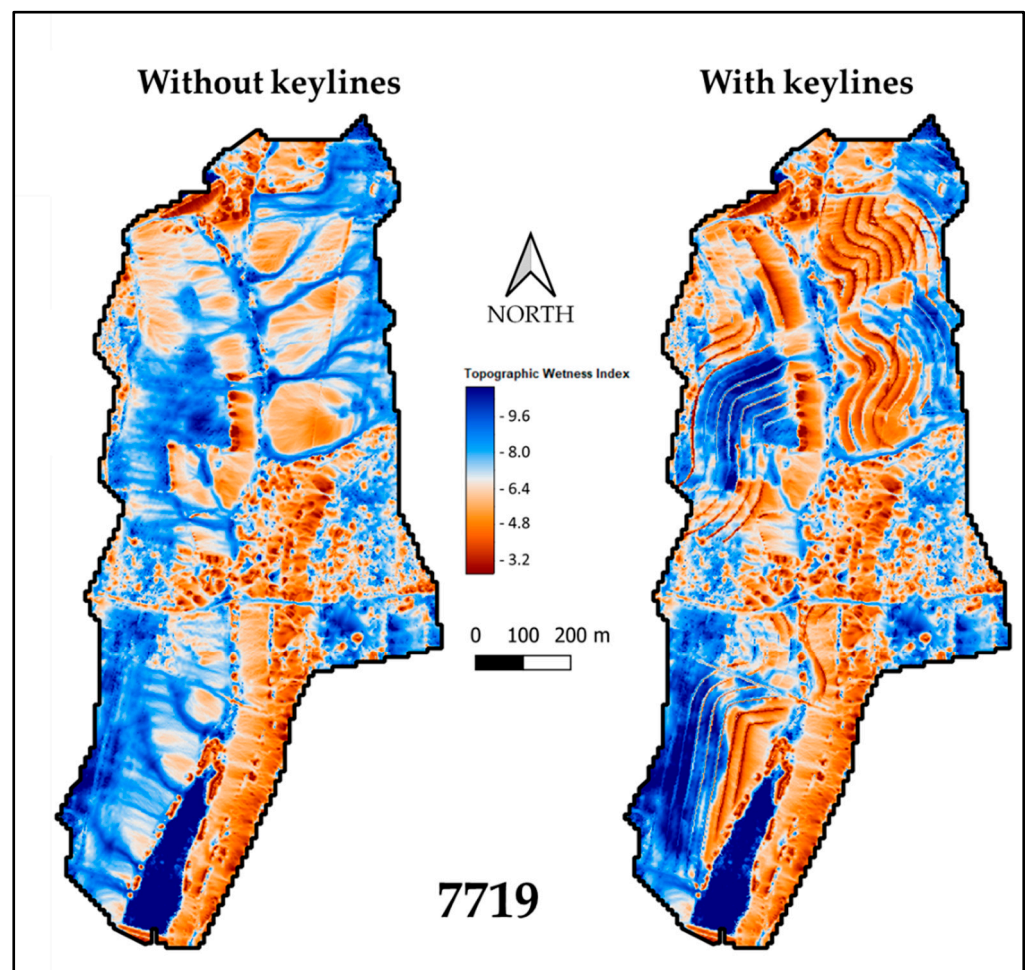


Figure 5. Topographic Wetness Index (TWI) maps with and without the keylines for basin 7719.

The runoff with the keylines, obtained from the simulation using the SIMWE, is less than in the previous conditions (Figures 6 and 7). We notice a general reduction in the runoff in the whole area where the keylines are present, without changing the flow direction, as the terrain does not undergo changes from an elevation point of view, only the physical characteristics of the soil vary in terms of the infiltration. In fact, the outflow follows the same direction before and after keylines are added, but it is reduced in absolute terms, as more water is retained on the slopes. In statistical terms, the mean water discharge value of all the pixels in the simulation with the keyline is lower for each of the basins (Table 1). Basin 3036 shows a reduction of 8%, and basin 7719 shows a reduction of 12%. The difference between the basins is consistent with the dimensions, and 7719 is flatter than 3036.

Table 1. Main results obtained from the analysis with the SIMWE model (UM: unit of measurement).

ID Basin	UM	3036	7719
Pixel	number	168,120	217,619
Basin Area	m ²	67.25	87.04
Total keylines	m	15,470.3	15,356.6
Keyline density	m/ha	230.1	176.4
Mean Water Discharge <i>without</i> keylines	m ³ /s	0.178	0.124
Mean Water Discharge <i>with</i> keylines	m ³ /s	0.164	0.108
Reduction	%	8.18	12.34

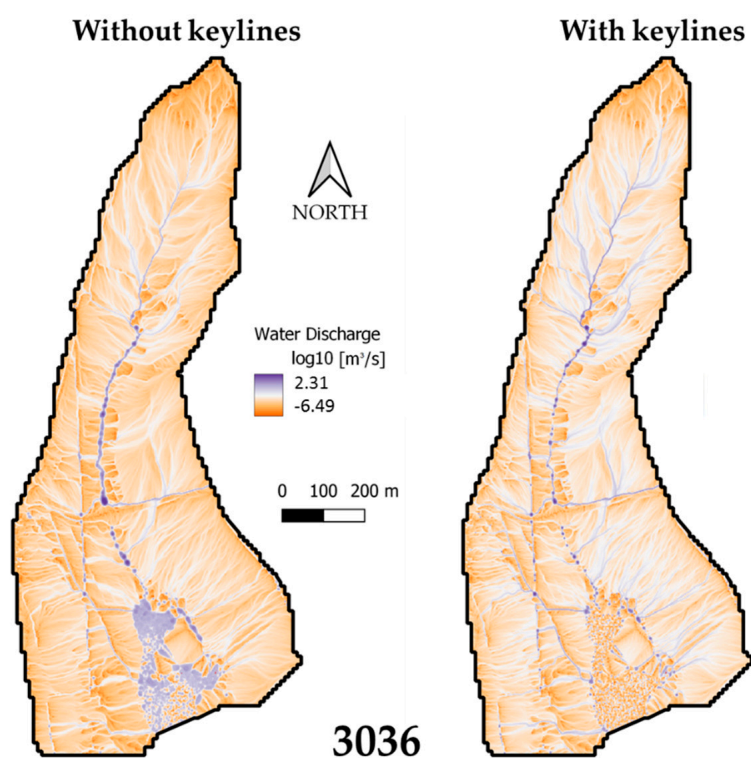


Figure 6. Water discharge (SIMWE) maps with and without the keylines for basin 3036.

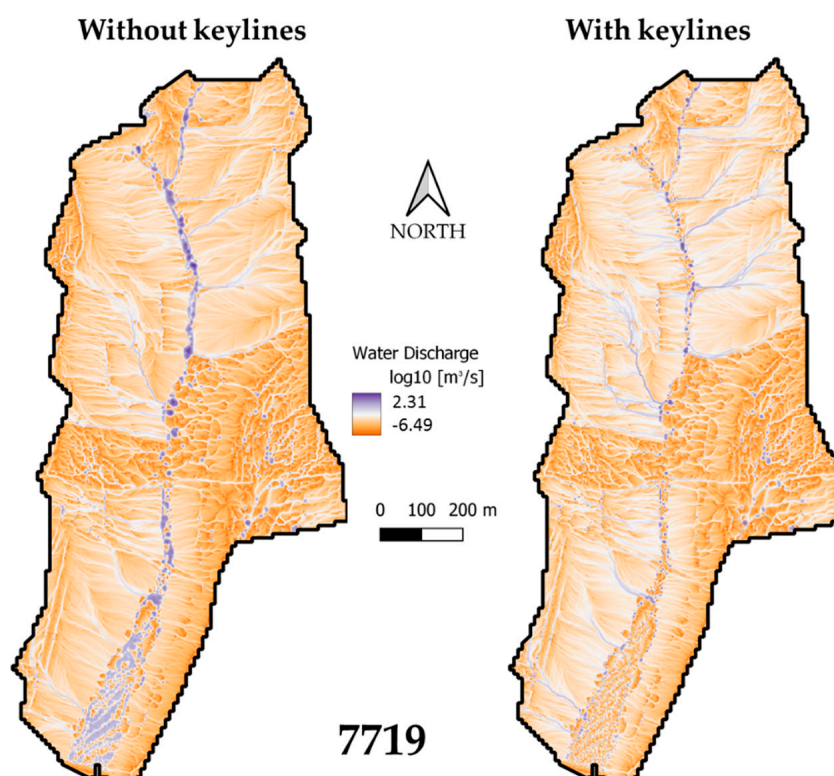


Figure 7. Water discharge (SIMWE) maps with and without the keylines for basin 7719.

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 and hydrogeological problems

occur, especially in addition to climate change [37]. The use of techniques for improving water regulation can make a significant contribution to reducing soil erosion and can also increase water accumulation, therefore establishing 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 water furrows [38–40].

The portions of territory that are not affected by the influence of the keylines are the result of a compromise between agronomic and hydrological needs, as the design must allow the farmer to work safely. It is thus 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 a high-resolution model. In this application, however, it shows an important limitation: variations of less than one meter are not very noticeable. For the correct verification of the keyline effect, it would be advisable to use DTMs with even higher resolutions [41–43], 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 [44].

In addition to the positive aspects, the consideration of some factors which could lead to land degradation, both for erosion and for water accumulation, is necessary. 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 [45–47]. Water increases its speed with greater concentration and therefore drag energy, causing localized but intense erosion. In this regard, it is necessary to thoroughly verify 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 stabilized ditches with small “steep and pools” [48] in order to reduce the flow speed or alternatively by keeping the channels grassed or vegetated in order to reduce the flow speed a result of greater surface roughness [49,50]. Another solution can be to create horizontal ditches in order to reduce the speed thanks to the lower slope, thus creating a profile like a terraced slope [51].

In the second case, we have a greater soil water retention 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 [52], or even landslides and increased 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 realization of ditches should be arranged 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 use of keylines is an interesting management practice of cultivated land, with a good ability to reduce soil erosion and improve the water-retention capacity of the soil for the greater resilience of crops during drought periods. In order to carry out the correct design of a 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, and soil cover.

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 for agricultural hydraulic arrangements in general. The accuracy of the results also depends on the resolution of the digital terrain models.

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