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ABSTRACT: Water is one of the most important erosive agents in roadside hillslopes. When these are built with ineffective drainage systems, erosion occurs, reducing road's service life. However, these systems are not receiving the appropriate importance, given their strategic value. Therefore, a new drainage system called 'branched' is proposed in this study. Its technical and economic feasibility is compared with those of the traditional system, which consists of drainages with lines that follow maximum hillslope, to assess differences in relation to erosion, construction and maintenance costs, and service life. Different parameters were analysed, such as the average velocity of water (mm^{-1}) running through the channels, its average specific energy (kJ), and its drag force (N). A scale model was constructed and used to test these factors before implementing it in natural terrain for testing it under field conditions. According to the theoretical and measured results, these factors were lower in the branched drainage than in the traditional one (from 24% to 34% in speed, from 37% to 60% in energy, and from 51% to 73% in force). The service life of hillslopes with a branched system of up to 0.5 m high and 1:2 grade is significantly longer than in those with a traditional drainage. Although the initial economic expense for the construction of the branched system is higher (€3534/m^3 as opposed to €2930/m^3 for the traditional one), its maintenance cost will be lower than the traditional one (€1230/m^3 per year for the branched one as opposed to €1332/m^3 per year for the traditional one). Consequently, under our experimental conditions, the proposed drainage will be profitable from the eighth year of construction, saving on the road maintenance in the following 15 years of service life.

KEYWORDS: Drainage, erosion, branched drainage, traditional drainage, roads

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Introduction

Water is considered one of the most erosive agents on the roads and their adjacent hillslopes.[1,2] Water erosion in hillslopes is a complex process that has been studied in numerous studies[3,4] not only because of the environmental impact produced by soil loss[5,6] but also because of the risks that could result from this loss, such as the pollution mixed with the water flowing down the hillslope,[7,8] the expositions of humans to these pollutants,[9] or the occurrence of landslide phenomena.[10] Many exposed subsurface soils on eroded sites tend to be more erodible than the original soils because of their poorer structure and lower organic matter. And the steeper and longer the hillslope of a field, the higher the risk of erosion, due to the greater accumulation of runoff. Indeed, the consolidation of small fields into larger ones often results in longer hillslope lengths with increased erosion potential due to the increased velocity of water, which permits a greater degree of scouring (carrying capacity for sediment).[3] In fact, the study of transport networks affected by erosion problems is gaining awareness as a very important topic in the scientific community.[11-14]

To study erosion processes on the adjacent hillslopes of the roads, it is necessary to assess those factors that have been defined in the literature as the dominant ones: hillslope angle and length,[14-17] soil composition,[18,19] hydraulic characteristics,[20,21] soil moisture,[22-24] precipitation intensity and frequency,[25-27] vegetation cover,[22,28,29] and connectivity[30] of the channels of the drainage systems.

In Spain, this problem affects 166 003 km of roads with an annual investment in maintenance of up to €1058 million (2016).[31] In the light of sustainable development, a coordinated multiscale policy should improve the effectiveness of mitigation of environmental degradation,[32] which would consist of works made with environmentally friendly materials and with designs that increase the resistance and duration (to minimize contamination during repairs).[32] However, traditional road design protocols lead to less dedication to innovative designs and more effort to maintenance. This maintenance expense is mainly dedicated to the cleaning of ditches and hillslope stabilization as a consequence of erosion. Due to these processes, accumulation of material in the channels of the drainage systems and in the roadside ditches is generated, as well as their flooding and hillslope instability that results due to the falling of stones.[33-37] All these factors may lead to landslides under certain conditions and may create serious problems such as the destruction of roads or the endangerment of human lives.[38-41]

To minimize soil losses and to protect the hillslopes, different technical solutions can be applied.[42] The selection of these solutions depends mainly on the economic resources available and the morphological, geological, and climatological conditions of the area. The most common technical solutions in Spain are concrete piles or screens with metal bolts, breakwater walls, concrete or gabion walls, geotextile or anchored triple-torsion metal mesh lining, drains and sub-drains, hydroseeding,[43] concrete-ditch lining, and downspouts. However, all these measures mean an extra cost in the works, so in most of the Spanish road hillslopes only a superficial compaction of the removed soil takes place. After the eventual removal of topsoil and scarification of the surface, the re-compaction of the soil is done to a depth of about 15 to 20 cm, depending on the stability conditions. There are even cases where for temporary or economic reasons, it is not possible to compact the terrain, but after the first rain some land furrows arise, following lines of maximum hillslope. This system full of furrows, with soil compacted or not, but with lines of maximum hillslope will be called 'traditional drainage system'. This lack of hillslope protection measures increases soil erosion as the terrain altered by humans is much more susceptible to be eroded.[44]

Another important parameter to take into account is the design of the hillslope and its coronation ditch (when this is planned to be built). This coronation ditch is always recommended because it is part of the drainage system and leads to the evacuation of water in an orderly manner, that is to say, directing the water strategically to avoid the creation of canals due to the concentration of water in the most vulnerable areas. This ditch is located at the top shoulder of the hillslope, and it collects and evacuates the water coming from its upper part towards the natural channels. The absence of this construction could mean the beginning of unwanted rills and ephemeral gullies along the hills. The precipitation which falls onto the hillslope tends to concentrate in certain evacuation channels also on the surface of the hillslope, which may coincide with areas of poorly resilient terrain, and if there is not an evacuation route for this water, it can also cause rock dragging and landslides in the more susceptible areas depending on the occurring conditions, such as sufficient land use, soil attributes like high organic matter content that leads to stronger soil aggregates, soil moisture, saturation, hillslope, and speed of vegetal covering. Sediment yield may then be increased in the road construction works and can lead to high maintenance costs. However, most of these problems could be avoided with an efficient drainage system that evacuates water in the least erosive possible way.[30]

Based on this, the design of a new drainage system is proposed. It is called 'branched drainage' and intends to minimize the erosion effects on the hillslopes, and consequently the maintenance costs. In this study, a comparison has been made between the traditional channels that follow maximum hillslope lines and the proposed branched drainage system to evaluate their technical viability, as well as the different production of sediments in both cases and the economic viability of the proposed new design in relation to the traditionally employed one. This can be used to evaluate the interest of proposing the new drainage system for new road and path works, which means influencing thousands of kilometres of road hillslope. The new drainage system is a great innovation in the traditional work on roads, given the lack of major advances in recent years and the lack of enough attention given to the prompt removal of water from many roads.

Material and Methods

Material

Scaled model and field experiments. Two models were used to carry out the experimental tests. The first one is a model built in the laboratory at a scale of 1:100, made up of 2 exactly equal sides, in which the strata of a generic mountain in Spain can be observed; it has a breakwater in the lower stratum (15 m in power), gravel in the middle stratum (15 m in power), and earth in the upper stratum (10 m in power). Move to the sub-base of the road composed of selected soil (1.5 m thick) and the base composed of artificial gravel of 50 cm thick and hot asphalt mix of 20 cm thick. The sides of the model and its front have the most characteristic hillslope of the Spanish linear works with a hillslope of 30°[45] and presents a representation of each of the 2 drainage systems to compare: the traditional and the branched one. Constant laminar flow rate is achieved thanks to a pump installed on the crest of the hillslope, with an AQUANIQUE FP 750 680 L/h pump (Figure 1D) in both cases.

To describe the hydraulic cycle, water is pumped from a tank below the coronation ditch so that, through the installed transversal drainage works, the water can reach both drainage systems that are installed on the hillslope in a parallel way.

A second model was built on a natural hillslope of the Monteleón Urbanization (42°39′00″N and 05°36′00″W), duplicating all the dimensions of the model (width, height, and length), but maintaining the same hillslope as the one in the model. In this way, it is possible to analyse the effect that the scale could have on the results. The soil selected was sandy loam and has a content of clay of 16%, with thick and weak granular structure, and soft structure. The top layer has few quartzite stones of 75 mm (7%), not altered. Many roots are medium, fine and very fine. This texture is complementary to the model experiments that are done in polyvinyl chloride (PVC) and in pure clay. This study was carried out in Leon (province of Leon), located in the region of Castilla y Leon, in the north-west of Spain (Figure 1). This is a transition zone between the 2 main climate areas in Spain: the continental and

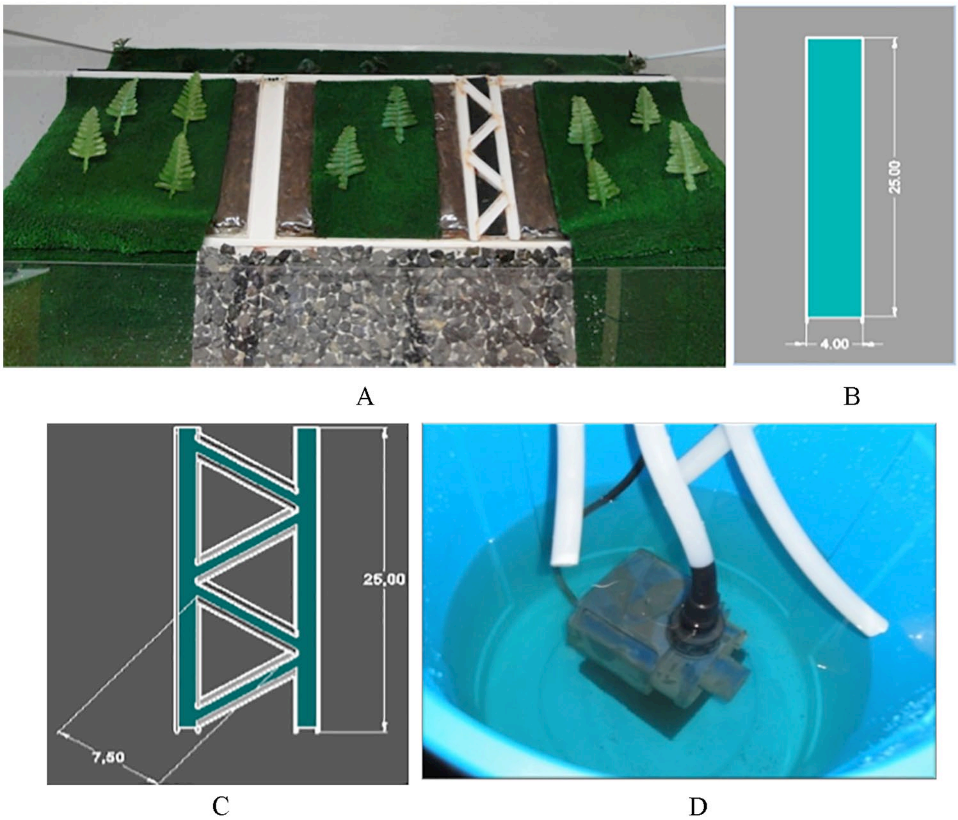

Figure 1. (A) Scale model of the 2 drainage systems studied: (B) traditional and (C) branched design and (D) pump AQUANIQUE FP 750 680 L/h.

the Mediterranean areas. The precipitation is about 556 mm[46] at about 840 m above sea level. Leon has a continental climate with long and cold winters and warm summers, but the main feature is a very irregular seasonal regime, which is greatly influenced by the Mediterranean climate. The rainiest seasons are spring and autumn, more precisely the months of April, May, and mid-December. Summer droughts are very common, with sporadic storm events, often with hail.[47]

The tests must be carried out under reproducible conditions, that is, with equal humidity and atmospheric pressure, and alternately in each drainage channel. To reduce possible accidental errors (eg, by manipulating the timer to measure times and calculate speeds), 30 tests are performed on each of the drainage systems.

Technical feasibility. In this article, with technical feasibility we refer to the determination of the factors that affect the erosive capacity of water. To achieve this value, different parameters that characterize the erosive power of the water are presented for both drainage systems such as the water average velocity, its average specific energy, and its drag force. All of these variables were calculated first theoretically and then experimentally to be sure that the experimental data collected were within the expected range.

First, a theoretical estimation of the mean velocity of water was done using the Manning equation[48]:

$$v = \frac{1}{n} S^{\frac{1}{2}} R_h^{\frac{2}{3}} \tag{1}$$

where S is the hillslope of the channel by 1 (m/m), n is the coefficient of resistance of the material (s^{-1}), and R_h is the hydraulic ratio of the channel (m).

The average specific energy of the fluid (E) was calculated in metres of water column (m) with the following equation[49]:

$$E = \frac{v^2}{2g} \tag{2}$$

where 'v' is the mean velocity of the water (m s^{-1}) and 'g' is the gravitational constant of 9.81 m s^{-2}.

The drag force was obtained from the following equation[50]:

$$F_a = C_d \times A \times \rho \times \frac{v^2}{2} \tag{3}$$

where 'F_a' is the drag force (N), and 'C_d' is the drag coefficient for a particle in water. When Re (Reynolds number) is higher than 1000 and constant, C_d is approximately 0.5.[51] All the experiments have Re > 1000 because the temperature, density, and viscosity of the water are constant.

'A' is the largest cross-sectional area depending on the drainage system (m^2), 'ρ' is the density of the water (999.97 kg m^{-3}), and 'v' is the mean velocity of the water measure in the

Figure 2. Photographs of the tests performed for the calculation of the average water velocity over the traditional system on polyvinyl chloride (left) and the branched drainage on clay (right).

experiments. The detailed computations and results can be consulted in full at data set from the University of León.[52]

First, the theoretical computations were performed to evaluate these characteristic parameters in both drainage systems. A detailed bibliographic review was carried out to find out how various authors advise the use of scale models as a method to simulate the processes occurring when water flows on a hillslope.[53-56] Therefore, a scale model 1/100 was constructed because it allows its easy handling and mobility.

Figure 1 shows the 2 drainage systems used: the traditional one, formed by a rectangular ditch that is usually used in the construction of roads, and the branched drainage, which is formed by 2 lateral ditches (perpendicular to the road direction) and central zigzag-shaped branches that drain into the lateral constructions. Both drainage systems were able to store the same volume of water. A 1:2 hillslope angle was selected because it is the angle recommended by the Spanish road regulations,[57,58] besides being the most commonly used.[55] To reduce the construction's cost of the model, widely available materials such as PVC, silicone, and clay were used. These materials are impermeable, so simulation in this study would only simulate the runoff processes without representing the infiltration ones. This fact does not prevent the use of the model that has been used to represent conditions of saturated soil, where the runoff processes are dominant and the infiltration also decreases with increasing hillslope angle.[23]

After the construction of the model, velocity tests were started. These tests consisted of calculating the time it takes for a drop of water to travel the distance from the starting point of the drainage system to its end. Four drops of dye were poured into each of the tests, as shown in Figure 2. The chronometer was started when the first drop of the dye touched the water and stopped when the last drop of the dye reached the end of the system.

As the length of the drainage systems is known, the velocity was calculated using the elapsed time measured according to the following formula[59]:

$$v = \frac{e}{t} \quad (4)$$

where 'v' is the mean velocity of the water (m s^{-1}), 'e' is the length of the channel (m), and 't' is the travelled time (s). From the average velocity of the water, its average specific energy and drag force were calculated in both drainage systems.

To analyse whether the substrate modified the velocity, tests were carried out on a bed of clay moulded on the model with 3 mm of thickness. Finally, to evaluate the scale effects, tests were repeated in full scale on the loamy-clay soil of a hillslope located at 42°39′00″N, 05°36′00″W. The same hillslope angle of the model and a length of 0.5 m were used in these tests (Figure 3).

Soil loss tests. To evaluate the soil's erodibility of the hillslopes under both drainage systems, sediment collection tests were carried out. They consisted in collecting the soil entrained by the runoff water under controlled laminar flow in both drainage systems by means of filters, which were afterwards compared.

Thus, clay was moulded above the PVC channels in the model. A constant flow of 5×10^{-4} m^3 s^{-1} was allowed to flow through both systems. At the end of each channel, a filter was installed and sediments were collected every 20 minutes for each corresponding period of time (Figure 4A). The filters were recollected after 80 minutes because before that time, the clay on the filters was negligible. This sampling was repeated 5 times in a row. The filters were then allowed to dry completely in a place without sunlight, at a constant temperature of 7°C, for 10 days. After this time, the pigments of the clay eroded by water and deposited on the filter could be observed. The method of comparing photographs using histograms of the filters with clay sediments was selected for this analysis. This is an objective method that is well suited to the goals of the experiment.[60] The use of the gravimetric method has been ruled out because, on some occasions, the amount of clay collected on the filters was so small that it was very difficult to measure it exactly. The photographs of the filters were made with a Nikon D2X camera (shutter: 1/60, aperture: F4.2, focal length: 50 mm) at a height of 0.65 m with the aid of a tripod. Each of the photographs had a size of 4288 × 2848 pixels.

A B

Figure 3. Sampling in natural terrain: (A) detail of the traditional and branched drainage system and (B) detail of the slope and the system from its front.

A B

Figure 4. Collection of filters for the soil loss tests in both drainage systems: (A) model and (B) natural terrain.

The software Adobe Photoshop CC 2015 was used for the treatment of the images, extracting the colorimetric histograms of each filter and comparing both the colour intensity and its dispersion. With this information, the evolution of erosion in each of the drainage systems was compared over time.

After performing these experiments in the model and to determine whether the scale influenced the sediment delivery, a field test was carried out on natural terrain. Measurements of each drainage system were adjusted to double in hillslope length than those used in the model. The experiment done with each drainage system was similar in hillslope and flow volume and discharge, but collecting the filters only once after 20 minutes of constant water flow under laminar regime over designs simulating both drainage systems in natural terrain because from the very beginning some soil was deposited on the filters. Ten sediment filters were collected for each system (Figure 4B). The number of tests performed was 2 times higher than the test performed with clay, due to the increased variability in the samples collected as a consequence of the greater possibilities of infiltration and sample losses. In this case, the method selected for the analysis of the filters was gravimetric. Each filter was weighed dry before field installation and then weighed with the collected sediment after being dried in an oven for 24 hours at 105°C (accuracy ± 0.1 mg).

Statistical analysis. Normality of the data was tested using Kolmogorov-Smirnov tests,[61] and homogeneity of variances was tested using the Levene test.[62] For the parametric analysis, differences in the studied variables (water average velocity, average specific energy, and drag force) between systems were established through an analysis of variance (ANOVA) test[63] and confirmed a posteriori with Tukey tests.[64] For non-parametric analysis, differences were determined by Mann-Whitney *U* test[65] (M-W). In all the cases, results were considered to be statistically significant at $P < .05$. All statistical analyses were carried out using IBM SPSS Statistics 21.

Methods

Economic feasibility tests. Finally, to estimate the service life of both drainage systems, 10 tests were carried out measuring the time until the hydraulic structure loses the preferential channelling capacity and water evacuation, that is, when clay cover disappears in more than 5 cm from the drainage system. This experience was then repeated at full scale on the natural terrain by measuring the time required by each structure to lose 10 cm of soil. Ten tests were also performed on each system.

After estimating the service life of both drainage systems and considering the damages generated through time in both of them, an approximate calculation of the construction and maintenance costs of each system can be made. The initial investment, conservation costs, and execution time were determined depending on the factors such as hillslope angle and length, soil texture and composition, existing construction methodology, and available economic and labour resources. To calculate the costs of the construction and maintenance of both drainage systems, common parameters have to be established, which was a hillslope with a 1:2 angle and 25 m in length, built with clay loam textured soil by a foreman and a labourer. The cost of the initial investment of the traditional system, and of its annual maintenance, was estimated using the generic price database published by the Ministry of Public Works and Transport,[66] and the software Presto. The approximate costs of the initial investment of the branched system were estimated by adding, to the initial investment of the traditional system, the economic expenses generated by the extra machinery and human resources needed for this construction of greater detail. For the estimation of maintenance costs in the branched system, it was taken into account that this design requires less maintenance because of the lower soil erosion generated and the increased resistance over time.

Results

Technical feasibility

First, the theoretical velocity was calculated in PVC, clay, and natural terrain for both systems. The results obtained (2.26 and 1.58 m s^{-1} in PVC, 0.995 and 0.69 m s^{-1} in clay, and 0.754 and 0.525 m s^{-1} in natural terrain for traditional and branched systems, respectively) showed that over all cases, the velocity in the branched model was 30% lower than in the traditional one. Differences are even higher when the values of specific energy (between 38% and 60%) and drag force (about 52%) were calculated.

Table 1 shows the average velocity of the water, its average specific energy, and its drag force in both drainage systems, calculated experimentally using the travel time of the dye drops. Values are presented for the tests carried out in PVC and clay models. It can be observed that in the traditional drainage, a higher average velocity is obtained, which implies a higher specific energy and a higher drag force of the water. This difference is significant at 99% for all the experiments performed in PVC and clay, being always higher in the former than in the latter.

Table 1. Experimental values of the average velocity of the water (m/s), the specific energy (water column in metres), and the drag force (N) obtained for the tests on PVC, clay, and natural terrain.

PARAMETER	UNIT	TRADITIONAL	KOLMOGOROV *P* SHAPIRO-WILK VALUE TRADITIONAL	DEGREES OF FREEDOM	BRANCHED	KOLMOGOROV *P* VALUE BRANCHED	DEGREES OF FREEDOM	ANALYSIS OF VARIANCE	RELATION
Scale model on PVC									
Velocity	m/s	0.079 ± 0.012	.195	30	0.052 ± 0.0066	.001	30	Mann-Whitney *U*	Traditional 34% more
Specific energy	m	$(3.29 \pm 1.01) \times 10^{-4}$	.012	30	$(1.41 \pm 0.4) \times 10^{-4}$	.074	30	Mann-Whitney U	Traditional 57% more
Drag force	N	$(6.5 \pm 1.98) \times 10^{-4}$	.074	30	$(1.7 \pm 0.5) \cdot 10^{-4}$	.001	30	Mann-Whitney U	Traditional 74% more
Scale model on clay									
Velocity	m/s	0.053 ± 0.005	.2	30	0.041 ± 0.003	.141	30	ANOVA	Traditional 23% more
Specific energy	m	$(1.4 \pm 0.3) \times 10^{-4}$	.2	30	$(0.87 \pm 0.13) \times 10^{-4}$	.2	30	ANOVA	Traditional 38% more
Drag force	N	$(2.8 \pm 0.5) \times 10^{-4}$	.2	30	$(1.1 \pm 0.16) \times 10^{-4}$	.141	30	ANOVA	Traditional 60% more

In the theoretical values, there are no standard deviation values because there is only 1 value of velocity. Abbreviations: ANOVA, analysis of variance; PVC, polyvinyl chloride.

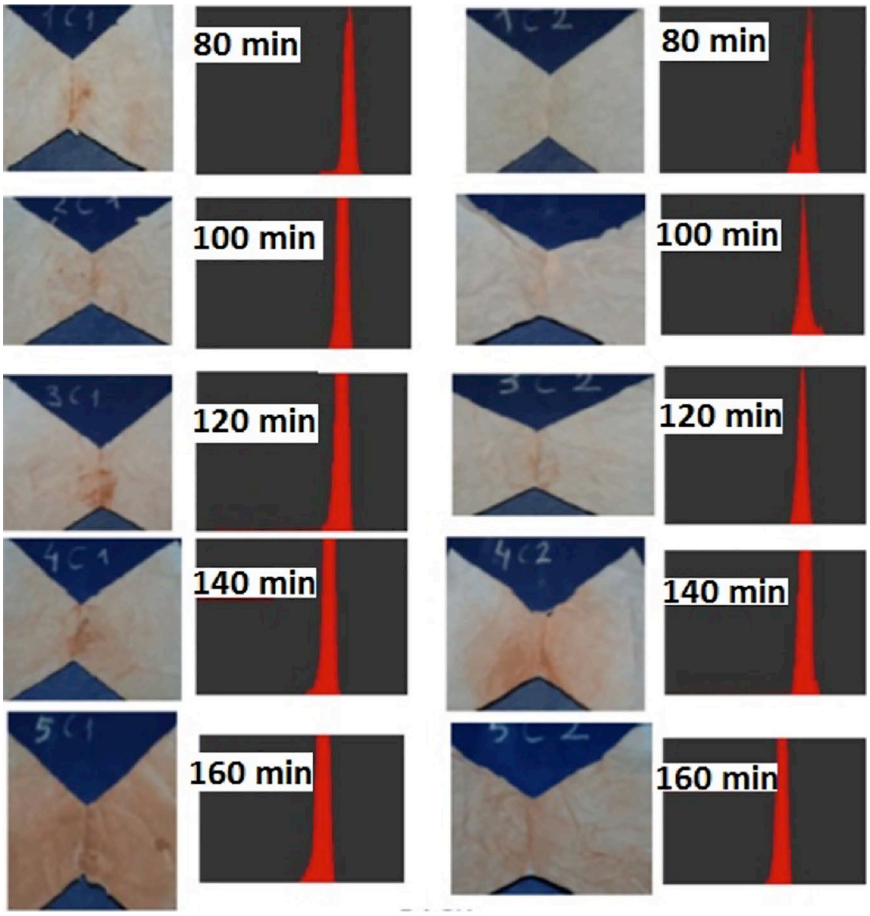

Figure 5. Photographs and colorimetric analyses of the filters collected in the soil loss test of the traditional system (left) and in the branched drainage system (right) when the tests were carried out in the clay model.

These differences between the 2 systems on the model were also evidenced in field studies in the natural terrain. The average velocity of the dye drop was 0.146 ± 0.007 m s^{-1} in the traditional drainage and 0.090 ± 0.006 m s^{-1} in the branched one (39% lower). Thus, differences in velocity, energy, and drag force were significant at 99%.

Soil loss

Photographs of the 10 filters with collected sediments were taken according to the procedure described in section 'Technical feasibility'. The study of their colorimetric histograms was focused on red because it was the predominant band in the clay. This allowed a cleaner analysis that was dedicated only to the searched values.

Filters collected during the first hour contained very little clay (Figure 5). Therefore, the first filter analysed corresponded to 80 minutes, where sediments were only observed in the traditional system. In the branched drainage, the first sediments were collected 40 minutes later, at 2 hours. The clay accumulation became more evident over time, and even small clay aggregates were present after 140 minutes in the traditional drainage filter and after 160 minutes in the branched one. The greatest change in the former appeared between 120 and 140 minutes, and in the latter between 140 and 160 minutes, coinciding with the appearance of clay aggregates.

On the contrary, data from soil loss tests performed on natural terrain at real scale are non-parametric, and according to the Mann-Whitney *U* test there are no significant differences between the collected weights (Table 2). In addition, it can be stated that over time, the branched drainage system showed less erosion (lower sediment transport).

A different response was observed between dry days (without rain on previous days) and wet days (after rain on previous days) on field experiments. Tests carried out on wet days showed the highest difference in sediment production between drainage systems, with the amount being collected from the traditional one being much larger. Based on this, it is possible to expect a better performance of the branched drainage in climates with higher probability of precipitation. However, much more tests with different meteorological conditions have to be performed to confirm this hypothesis.

Economic feasibility

Both drainage systems presented different erodibilities according to the results of the 20 service life tests performed. The scale model of the traditional system needed 18 cycles of

Table 2. Kolmogorov-Smirnov tests of the average weight of filters with sediment collected from traditional and branched drainage systems, on dry and wet days.

PARAMETERS	UNITS	TRADITIONAL	BRANCHED	KOLMOGOROV-SMIRNOV			STATISTICS	
				STATISTICS	N	SIG.	MANN-WHITNEY *U*	MANN-WHITNEY *U* SIG.
Weight	g	15.8 ± 14.2	9.4 ± 5.9	0.223	20	0.011	41	.496
TYPE	UNITS	DRY DAY	WET DAY	KOLMOGOROV-SMIRNOV			STATISTICS	
				STATISTICS	N	SIG.	F ANOVA	ANOVA SIG.
Traditional	g	11.3 ± 1.5	7.5 ± 0.98	0.207	10	0.200	8.69	.018
Branched	g	6.03 ± 62.5	25.5 ± 39.2	0.169	10	0.200	1566	.246

Tests were carried out on natural terrain at real scale. Mann-Whitney and ANOVA test values were obtained. Abbreviation: ANOVA, analysis of variance.

A B

Figure 6. (A) Last stage of the service life of the traditional system and (B) noticeable erosion on the branched drainage.

20 minutes each to present severe structural damage, whereas the new branched drainage withstood up to 24 cycles. Accordingly, it is assumed that the service life of a road hillslope with traditional drainage would be approximately 20 years, whereas the same hillslope under a branched drainage design would last up to 25 years, with both service life periods being significantly different (at 99%).

It was also detected that the damages occurred in different areas of both systems: in the upper part in the traditional drainage, under the coronation ditch, whereas in the branched one, damages occurred in the changes in direction (Figure 6).

When the 20 tests were carried out on natural terrain at real scale, there was a small decrease in the service life difference between the 2 systems, although significant differences were still found ($P < .05$). Table 3 shows the estimated service life of both drainage systems in the scale model on clay and in the natural terrain at real scale. It can be observed that the branched system withstood 128 minutes more, in average, than the traditional one, which corresponds to an increase of about 3 years. However, a higher number of tests are necessary to be able to define accurately how long this service life would be extended. Comparisons could not be made because there are no authors who have experimented with the branched design due to its originality.

Table 4 shows the execution time, the initial investment for construction, the maintenance cost, and the estimation of the service life for both drainage systems. To compare their cost, maintenance expenses of each year were added to the initial investment made in year 0. After 8 years, the costs of implementing both systems would be approximately €4.35/m^3. From this moment, the higher costs of the initial execution of the branched system would be amortized by the annual savings related to the lower maintenance expenses required (Figure 7). Therefore, the branched drainage would become profitable during the remaining 15 years of service life.

All the results have been carried out under controlled conditions so that both drainage systems had to be protected from

Table 3. Kolmogorov-Smirnov tests on the estimated service life of the traditional and branched drainage systems in the scale model on clay and in the natural terrain at real scale.

PARAMETERS	UNITS	TRADITIONAL	BRANCHED	KOLMOGOROV-SMIRNOV			DIFFERENCES
				STATISTICS	N	SIGNIFICANCE	
Scale model on clay							
Service life	h	6 ± 1 h	8 ± 1 h	0.143	20	.2	Branched 26% more
Scale model on natural terrain							
Service life	h	3 h 45′ ± 16′	4 h 23′ ± 10′	0.155	20	.2	Branched 15% more

Table 4. Execution time, initial investment for construction, maintenance cost, and estimation of the service life of both drainage systems.

	EXECUTION TIME, D	INITIAL INVESTMENT, €/M³	MAINTENANCE COST, €/M³/Y	SERVICE LIFE, Y
Traditional	7.0	2.292	0.257	20
Branched	8.4	2.539	0.226	23

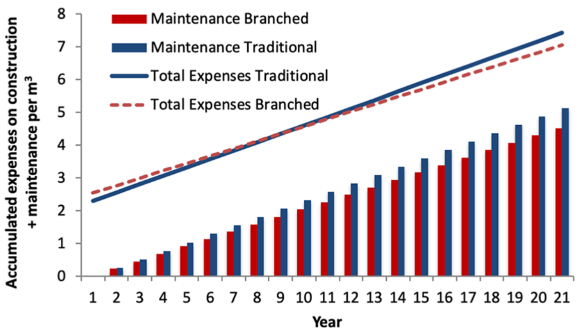

Figure 7. Accumulated expenses during years. Each line represents the sum of the expenses in the construction plus the maintenance.

the same erosive capacity. However, we know that the conditions in field conditions change a lot because they are influenced by changes in precipitation, overland flow, infiltration, or extreme events. Nonetheless, only small modifications have been applied in field studies because the tests were carried out over a month, and in that month the natural precipitation was not used for sampling but it did cause the soil to be sometimes dry and sometimes wet. We performed 30 trials to have a sufficient number of data for statistical analysis.

When comparing the traditional system with the branched one, it should be born in mind that the former has a number of advantages such as greater hydraulic capacity, shorter drainage time, and lower initial investment. On the contrary, the latter is able to reduce the average water velocity and dragging capacity, minimizes erosion, and has a longer service life.

Discussion

According to the obtained results, the theoretical average velocity of water was higher than the one obtained experimentally with the scale model in PVC. This may be due to the fact that the theoretical calculations were done using the Manning's general equation for open channel hydraulic, which does not take into account localized load losses or regime changes that occur along the drainage systems and can vary the water velocity drastically. Problems in applying this equation to a runoff model have been reported elsewhere.[67]

When exploring the data acquired from the PVC model, the water velocity in the branched system is much lower than that in the traditional one. This velocity is reduced as a result of the energy dissipation caused by the changes in fluid direction of the new drainage proposed. This decrease has been heightened by the increase in the water surface tensions with the walls of the new geometry. Besides this, it was necessary to use much more silicone to join the higher number of joints in the channels of the branched system model. According to Arakawa,[68] the use of silicone could result in the increase in water friction with the channel and, therefore, a decrease in its average velocity.

The analysis of the model on clay pointed to pronounced differences between both systems, albeit to a lesser extent. It is probably due to the effects of a higher vorticity produced by a generalized friction along the entire surface of the canal,[69,70] which caused a decreased velocity. In addition, another aspect to take into account would be the greater depth of the branched drainage compared with the traditional one (with the objective of keeping the same hydraulic capacity in both systems). Some authors have stated that the greater the depth, the greater the vorticity.[71]

When these analyses were performed in the natural terrain at real scale, differences between the 2 systems were also important like the ones found in the experiment with PVC and clay (around 25%-35% more velocity in the traditional drainage than in the branched one, in both clay and natural terrain). However, the values of velocity detected between the clay and the terrain experiments were a bit larger than those in the terrain. These differences were probably due to the influence of the scale of the experiment and also because of the scarce water infiltration of the model. However, in a clay loamy soil, part of the water could infiltrate and modify the results widely.[22] There are authors who do not agree with this statement, indicating that infiltration does not affect the velocity of surface water.[72] Moreover, another aspect that changes considerably is the presence of a coronation ditch on the top of the model hillslope and its lack in the natural terrain.[44] This aspect modifies the distance between streams of both systems, which is an essential aspect for landslides, which in turn varies their erodibility.[73]

Human error, when measuring, must also be taken into account, especially in the measures carried out on a small space as the scale model. The mistake that can be made in the reaction time with respect to the total time of measurement can mean a high percentage. However, it should be noted that all measurements were always made by the same researcher, and in all cases they coincided in pointing to a significant velocity decrease in the branched system. It is also necessary to bear in mind the higher difficulty of differentiating colours in a darker background flow (ie, clay) or in a more turbulent one (ie, natural terrain) due to irregularities of the terrain. Despite these difficulties, differences were always significant at 99%.

Based on the erosion tests, sediment yield from the traditional system was higher than from the branched one. This can be related to the wider drainage channel of the former that enables a greater entrainment of fine particles.[74] Another explanation to this difference was suggested by Kanjanakaroon et al,[75] who found that the deeper the channel, the easier the head-cut erosion development. However, in this study, although the water level is deeper in the proposed branched system, its erosion yield was lower. This means that the protection produced by the new geometry of the branched design is higher than the effect of its deeper channel.

When comparing the sediment yields measured in the natural terrain, it is possible to think that there is an influence produced by small variations in very local hillslope angles (due to irregularities in the terrain). However, they would be negligible in any case according to Kanjanakaroon et al,[75] who stated that there are no significant differences between the sediment yields of a hillslope whose angle was modified from 1:1 to 1:1.5 or 1:2.

Sediment yield in the clay channel was higher after about 2 hours. This fact is not in agreement with the results of other authors who stated that the highest sediment yield occurs at the onset of rainfall episodes.[25] However, it may be related to the protective effect of clay in which significant erosion is produced only after a hole is opened in the drainage.[76]

Erosion in the clay loamy soil was much higher[77] in both drainage systems. The first type of erosion that occurred was the sheet erosion that was responsible for detaching and delivering the most superficial particles of sand due to small collapses in the upper canals that carry the water, which produce a small amount of water which could flow freely down the hillslope into the field experiment. This laminar erosion was not collected or assessed in this study because our interest was within the drainage systems only. Then, rill erosion was produced within the channels of the drainage systems, removing sand and clay particles. This erosion was detected thanks to the abundant collection of particles and sand retained in the filters and transporting pebbles, boulders, and, finally, larger stones. These processes were partially observed in the natural terrain experiments, although due to the small number (10 in each drainage system) and short duration of such tests, it was not possible to quantify their magnitude.

Finally, regarding the study carried out on the estimation of service life and economic feasibility of the branched system, the increased resistance detected throughout all the experiences performed supports strongly the new design. This resistance could be explained by the marked decrease in water velocity caused by the hydraulic jumps and vorticity associated with the branched pattern.[70] This effect could also be responsible for the delay in the production and transport of sediment in this system.

In the traditional drainage, the breakdown occurred in the upper part of the system, probably because of a small hydraulic jump that originated in the joint of the coronation ditch with the hillslope drainage (Figure 6), which is the more sensible zone of this design.[78] Despite this finding, some authors degrade the hydraulic jump height and the water velocity as the main causes of this erosion, highlighting soil composition as the key responsible.[18]

On the contrary, the breakdown in the branched system could be observed at the intersections, resulting in collapsed zones on the sides of the zigzag (Figure 6). This erosion could be produced by water friction against the perimeter, which is the origin of the shear layer and the source of vorticity.[79] These erosion zones would vary in intensity depending mainly on the scale size and their behaviour as viscous or Newtonian fluid,[80] the channel depth,[26] or the regime type.[81]

It should be noted that in any of the 2 drainage systems studied, it was observed that breakdown happened from the base of the hillslope as several authors have stated.[82,83] In addition, the results could vary between the scale model and the natural terrain tests, because in the former there was an upstream ditch, whereas in the latter, water was not channelled.[44] This fact modified the length between streams, which in turn varied the susceptibility to erosion and hillslope landslides.[73]

As discussed by Salbego et al,[84] the use of preventive measures to protect road hillslopes from erosion is 30% more economical than applying passive or emergency measures a posteriori. Accordingly, the use of the branched drainage, instead of the traditional one, can be considered a preventive measure against erosion in road hillslopes. This new design would need a higher initial investment, but its lower maintenance costs together with its longer service life make his system a very suitable and cheaper measure to be used in the construction of road networks.

Indeed, there is room for improvements in this research. The next step will be the analysis of subsurface lateral flow and infiltration, which was not analysed in this experiment. The aim of this article was to design a drainage system that generates less erosive impact, and this objective has been completed. The design of an experiment with infiltration would have introduced a greater number of variables that would have made the comparison of both drainage systems very difficult, due to the enormous variability in the infiltration existing in the studied soil. However, an experiment is underway to design another model which will allow a new comparison, this time taking into account these lateral flow and infiltration effects, and whose results could then be adapted to field experiments.

Another interesting question that we would be able to answer in the future would be how these 2 drainage systems will behave under extreme events, but the design of the possible method to carry out these stress tests is something that is still in the validation phase, with experts to select the best way to test it.

Conclusions

Theoretical results pointed out that in the branched drainage, the average velocity of water was lower, and therefore its specific energy and drag force were also lower than in the traditional system. This result was confirmed in tests carried out in a scale model built on PVC, on clay, and, to a lesser extent, in the natural terrain. In both drainage systems studied, the longer the time that water flows, the more erosion occurs. Nevertheless, in the traditional one, the first clay aggregates started being eroded at 2 hours, whereas in the branched one, sediments appeared at 2 hours and 20 minutes. These sediments were delivered off-site to filters used to collect them 40 minutes later in the latter than in the former. Therefore, the higher resistance to erosion of the branched drainage is more noticeable the longer the water flows. In the experiments performed in the natural terrain, mean velocity of the water, its specific energy, and dragging force in the branched drainage were also lower than in the traditional system. Accordingly, sediment yield in the latter was higher than in the former. A slight influence of the environmental humidity has been found in the gravimetric tests. A greater number of experimental tests will be needed to obtain definitive values. If water flows over clay, the estimated service life of the branched drainage may be 5 years longer than that of traditional drainage or about 3 years on natural terrain. Although the initial investment of the branched design is higher than the one of the traditional system, its construction is economically feasible in hillslopes with a hillslope angle of 1:2, being profitable from the eighth year, which can represent economic savings in the following 15 years of service life. Consequently, the use of the proposed branched drainage, instead of the traditional one, can be considered a preventive, very suitable, and cheaper measure to be used in the construction of road networks. It is recommended to carry out further complementary experiments that consider the impact of lateral flows and extreme events in the comparison of both drainage systems.

Author Contributions

María Fernández-Raga: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Supervision, Visualization,Writing - original draft, Writing - review & editing. Iván García Díez: Conceptualization, Data curation, Formal analysis, Investigation, Writing - original draft. Julian Campo: Writing - original draft, Writing - review & editing. Julio Viejo: Funding acquisition, Investigation. Covadonga Palencia: Formal analysis, Investigation, Writing - review & editing.

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