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Digital Terrain Modelling of Drainage Channel Erosion

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Drainage channels constructed on highly erodible soils in some areas of Southern Navarre during 1988 have undergone severe erosion, including bed and bank degradation. This erosion triggered lateral gully development that affected adjacent cultivated fields. These processes are similar to those observed in permanent gullies in the area. One severely eroded channel representative of the area was selected for further examination. The amount of erosion was determined by comparing the initial size of the drainage channel with its present condition using digital terrain models and a terrain representation system. Results show that average soil losses along the eroded reach are 3·62 m^3/m, highlighting the necessity of using improved design methods. Current simulation models can aid in determining such design criteria. If drainage channels are to be constructed in areas of highly erodible soils, they should be shorter and restricted to the lower regions of the watersheds with gentler slopes. Sudden changes in bed slope should be avoided, and adequate erosion control techniques within the channel should be considered. The measurement method used provides detailed information on channel erosion processes with a reasonable effort.

1. Introduction

Channelling of streams is a controversial but common engineering practice for the purposes of flood control and drainage. The construction of channels often leads to severe erosion processes (Simon, 1994) associated with adverse environmental and economic impacts. Drainage channels constructed on cultivated fields are a particular type of channelling, and usually included in land consolidation projects. The increase in erosion risk can be easily explained from the simple relationship proposed by Lane (1955) for the case of erodible channels (Simon, 1994):

$$QS \propto Q_s d_{50} \tag{1}$$

where Q is the water discharge, S is the channel gradient, Q_s is the sediment load and d_{50} is the median particle size of the eroded material.

When a natural stream is channelled, i.e. transformed into a straight and uniform channel, its gradient increases because the stream is shorter as a result of elimination of meanders. On the other hand, the formation of a narrower channel increases the flow discharge per unit width. According to Eqn (1), these modifications permit a proportional increase in sediment load, as well as in the size of eroded particles, or in both at the same time, often occurring quite rapidly over time.

Guidelines for designing drainage channels can be found in recent publications (Sevenhuijsen, 1994). Some available simulation models can be a useful tool for designing purposes (ASCE, 1990, 1998a and 1998b; Casalí *et al*., 1996; Langendoen *et al*., 1998), although necessary calibration is costly and initial information required is difficult to obtain. Drainage channels are usually inexpensive structures and they often have poor strategic value. Consequently, few resources are used for their design, which is usually determined by intuition or experience of the designer, and conditioned by the machinery available, instead of considering rigorous criteria. As a result, severe channel degradation can occur. Thus, there is the necessity of knowing the magnitude of the problem and its characteristics. These geomorphic processes are not very well known, and experimental data are needed in order to develop and test simulation models. Accurate and convenient measurements of degradation and aggradation in channels is difficult, especially in large channels where simple measuring methods such as a microrelief meter or tape measure cannot be used. Digital terrain models (DTM) were developed about 40 years ago (Miller & Laflamme, 1958). Today this technology is routine and can be easily used to make morphologic measurements (Hidalgo *et al.*, 1998). In this paper, the erosion within a representative drainage channel excavated in Southern Navarre is carefully described and measured using a method based on a digital terrain model. The feasibility of the approach to study channel erosion processes is discussed.

2. Material and methods

2.1. *Description of the study area*

The study area is a 48·6 ha watershed known as La Abejera, located near the village of Pitillas (Navarre) (*Fig. 1*), about 50 km south from Pamplona. This area is affected by severe erosion (Donézar *et al.*, 1990a and 1990b; Casalí *et al.*, 1999) and it is representative of other areas in this township and the nearby towns. An area of 30·8 ha is usually cultivated with winter grains, barley or wheat. Average cereal yields are low, about 3000 kg/ha/yr, with great yearly variability. Main drainage-line slope of the watershed ranges from 10% in the upper part to 0·5% in the lower part. The upper 14·4 ha watershed area is not cultivated, with slopes higher than 10%, and most of the vegetation is thicket and the rock fragment content by mass is about 30%. The remaining 34·2 ha are occupied by an accumulation zone where soils are deeper and slope varies from 1 to 5%. This accumulation zone is completely cultivated except for 3·4 ha where severe permanent gully erosion occurs. The climate is continental Mediterranean, with a mean temperature of 13°C and an annual rainfall about 500 mm (Elías & Ruíz, 1986), although yearly variability can be quite large. Mean monthly rainfall fluctuates between 60 mm in May and 20 mm in July. The parent material of the soil is a mixture of clay and loams interbedded with sandstone paleochannels of Miocene age. Some sodic salts are present in the parent material, which are slowly dissolved by groundwater, causing clay dispersion in the soils. Soil texture is generally loamy, although silt–loam soils can be found in the low-land areas. Silt is the most abundant size fraction in soils, ranging from 42 to 62% in the upper layer. Electric conductivity of the saturation extract reaches 53·9 dS/m with a sodium absorption ratio (SAR) of 32·5 mol$^{1/2}$/m$^{3/2}$ in the low-land areas. Soil structure is platy, which reduces the infiltration rate, and crust formation is frequent. Bulk soil densities range between 1470 and 1610 kg/m^3. In Navarre, similar highly erodible soils can be found in the 6·2 × 10^4 ha occupied by the Ujué facies (Gobierno de Navarra, 1997).

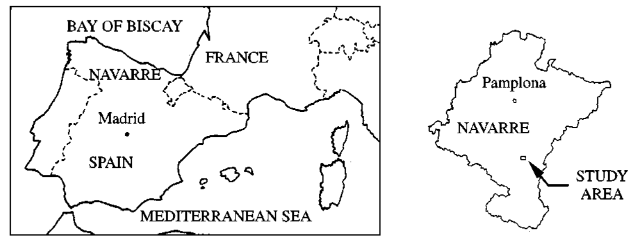

Fig. 1. Location of the study area

A drainage channel was excavated using a digger through the watershed in 1988 as part of the land consolidation project of Pitillas. The 2060 m channel extended upstream until it reached the steep non-cultivated areas, and extended downstream from the La Abejera watershed until it reached the existing lower-order channel of the drainage network. The channel was constructed following approximately the natural watershed slope: in the upper 270 m, the slope of original channel was about 1·9%, in the next 840 m slope was 1·2%, and in the last 950 m, slope was 0·5%. Original channel cross-sections were trapezoidal, 1 m wide at the bottom and 0·5 m high. Bank slopes were 1 : 1. Only the upper 610 m of the channel intersected the La Abejera watershed.

2.2. *Description of the measurement method*

Volume of eroded soil in the channel was measured by comparing the initial size of the channel before erosion with its current size using digital terrain models. The first step involved detailed topographic surveying of the channel using a total station. Cross-sectional profiles were measured along the channel every 2 m, and in each cross-section coordinates of 6–10 points were obtained. Field work took about 20 h (2 days). A digital terrain model of the initial drainage channel was also obtained from the original technical project from which it was possible to define the direction line (planimetric coordinates), grade-line (altimetric coordinates), and cross-section characteristics. In order to get a high-quality digital terrain model, break-lines were defined. These lines limit the areas with different slopes, and are: toe and bank top of the original channel, lines that define the actual limits of the channel, and other lines defining changes in slope within the channel. After obtaining the two digital models, eroded volume was calculated using the section method. Cross-sections were assigned and the channels were divided into 2 m long sub-reaches. In each cross-section, the area eroded is the difference between the actual and the initial cross section. Eroded soil volume for each sub-reach was calculated by multiplying the average eroded cross-sectional area of successive sections by the distance between

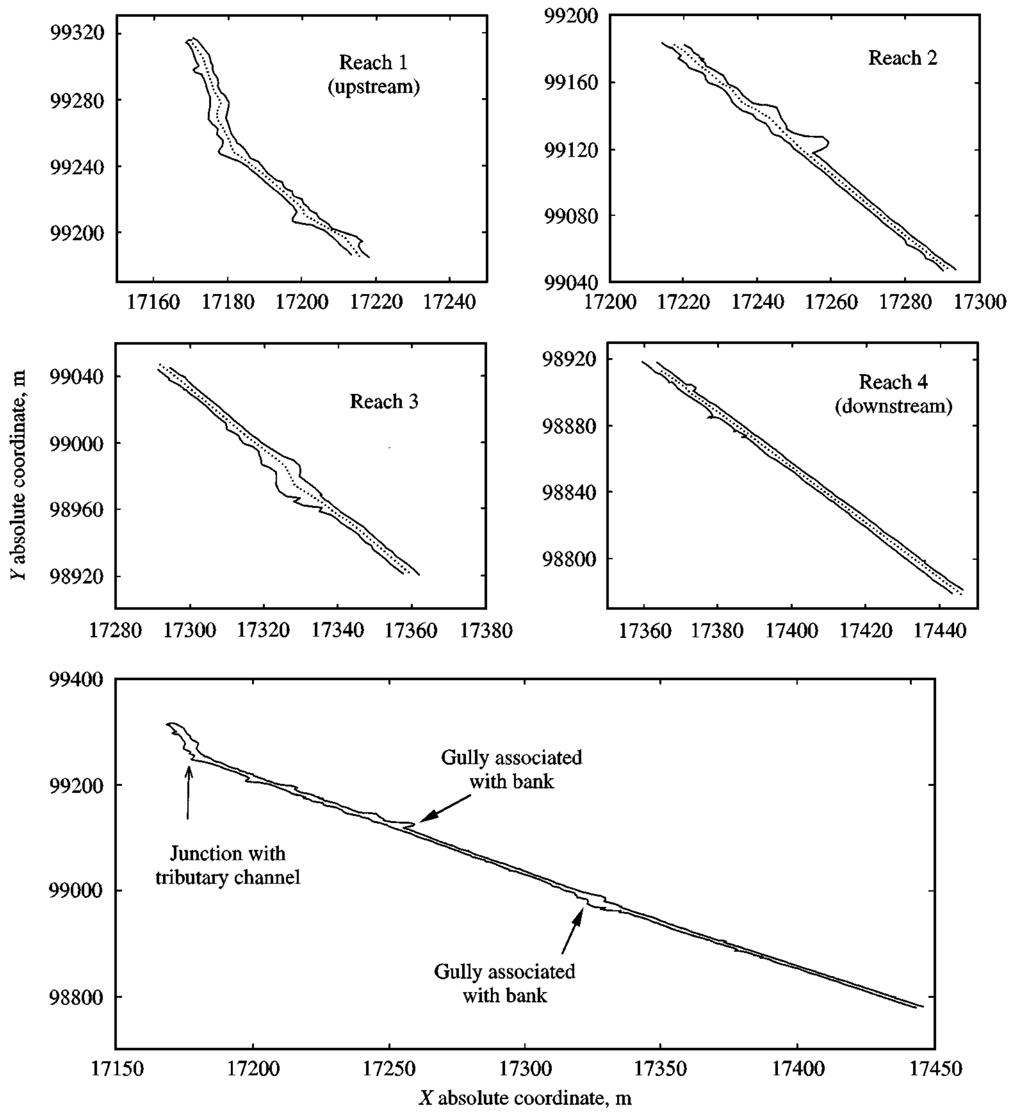

Fig. 2. Actual channel boundaries from the digital terrain model in a general and detailed representation. Location of some morphological features is shown. Dotted line is the direction line

them. Total channel erosion was calculated by adding the amount of erosion estimated for each sub-reach. *Figures 2 and 3* show results from the terrain representation system.

3. Results and discussion

Two different zones were found in the 2060 m long channel. The upper 610 m suffered severe erosion, whereas the remaining lower 1450 m neither degraded nor aggraded. Finally, downstream of La Abejera watershed and channel, sediments deposited where the slope became very flat on lower-order channels, which rendered them useless. The topographic survey was restricted to the first 610 m of the drainage channel, corresponding to La Abejera watershed. Applying the described methodology, the total amount of erosion measured in the drainage channel was 2208 m^3 or 3·62 m^3/m. The risk of severe erosion after digging this channel could be deduced from Sevenhuijsen (1994), who advised that stable channel reaches constructed on highly erodible soil should be shorter than 50 m. There are several causes for the large amount of channel erosion observed. Longitudinal slope was increased by eliminating meanders and unit flow discharge increased while the flow was concentrated on a narrower stream. As a result, flow was more erosive according to Eqn (1). Besides, natural vegetation on the

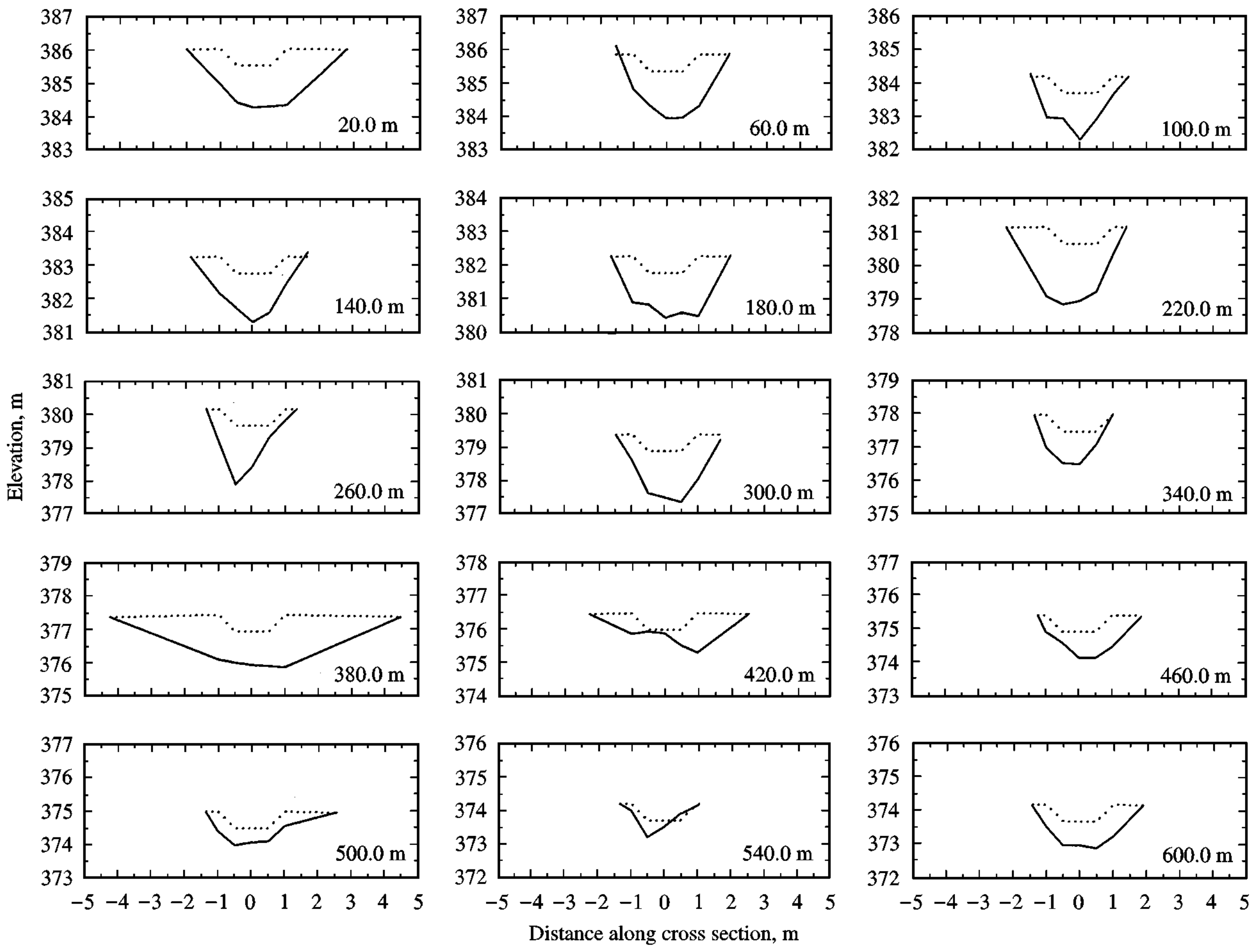

Fig. 3. Actual (solid line) and original (dotted line) channel cross-sections at 40 m intervals along the channel obtained from the digital terrain model

channel was eliminated and did not appear again, so roughness decreased, increasing the velocity of the flow and its transport capacity.

Although flow discharge increased, erosion increased until it reached a maximum at about 200 m from the upstream end, and then decreased (*Fig. 4c*). This may be due to saturation of transport capacity with sediments from upstream reaches and the sudden decrease in slope (from 2·5% to 1·05%, *Fig. 4d*), which decreased flow transport capacity. Channel width and depth tended to decrease downstream (*Figs. 4a and b*). The upper areas of the watershed and the upper reaches in the channel have a steeper slope, and this area is vegetated and rocks are frequent. Thus, the incoming flow carried little sediment, increasing its capacity to erode (Foster & Meyer, 1972). The evolution described herein is similar to the evolution observed in some channel degradation experiments (Newton, 1952; Suryanarayana, 1995), models simulating similar conditions (Alonso & Combs, 1990; Choudhury, 1995), and ephemeral gully morphology found in the same area (Casalí *et al*., 1999). Tributary junctions were actively eroded areas (*Figures 2–4*), promoting block sloughing and channel widening due to a sudden increase in flow discharge, turbulence, and irregularities in the channel boundaries. Channel depth reached a maximum at the block failure areas, suggesting that a critical depth of about 2 m is needed to trigger block formation (*Fig. 4b*). In general, bed and bank erosion are equally important along the channel (*Fig. 3*). Just downstream of the most eroded positions, erosion decreased dramatically (*Fig. 4c*), probably due to flow saturation with sediments from blocks and decreasing greatly the capacity of the flow to erode (Foster & Meyer, 1972).

Bed degradation and widening increased bank slope and bank height, making them more unstable (Osman & Thorne, 1988; Alonso & Combs, 1990). This explains the abundance of bank sloughing and sliding. Several mechanisms of block sloughing were found but it is difficult to recognize them as mechanisms described in the literature. Tension cracks, as those described in

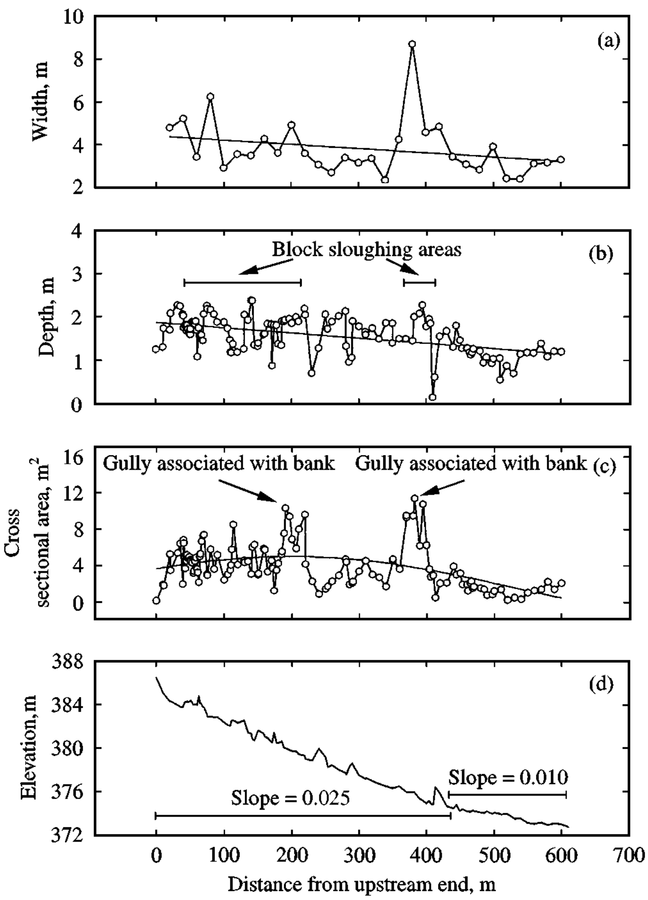

Fig. 4. Evolution of width (a), depth (b), cross-sectional area (c) and elevation (d) versus distance from upstream end

alluvial soils (Lohnes & Handy, 1968), developed before blocks were formed. Frequently, blocks do not fail but water flows through the deep tension crack that surrounds the block, isolating it from the channel walls.

Detachment of small soil debris and its accumulation on the channel bed and on bank toe was also detected. These materials from soil matrix come from various weathering processes. Very light rain can wash away much of these sediments, which have very little resistance to erosion. Several authors detected this phenomenon in Iowa (Piest *et al.*, 1975; Bradford & Piest, 1980), which was responsible for most of the sediment yield in permanent gullies. Some gullies have developed laterally in the banks of the channel in the upper reaches. These gullies were called gullies associated with banks (Poesen & Govers, 1990), and their origin was related to piping that was very common in the area (Gutiérrez *et al.*, 1988; Del Valle de Lersundi & Del Val, 1990). Sometimes gullies associated with banks join ephemeral gullies in the fields, which in turn increased sheet and rill erosion within them. Erosion processes in the artificial channel can be seen as an example of permanent gully evolution common in the area (Gutiérrez *et al.*, 1988; Del Valle de Lersundi & Del Val, 1990). This evolution is difficult to observe because most gullies present are old and have reached a quasi-equilibrium condition.

Consequences of the degradation process include: soil losses from the channel itself; soil losses from adjacent cultivated fields by piping and bank failure; gullies associated with banks and ephemeral gullies; acceleration of sheet and rill erosion on adjacent fields; annoyance for cattle, people or vehicles in the adjacent fields; pollution of aquatic environment by sediments; loss of the conveyance capacity in lower part of the channels, and; the large expense needed to rejuvenate the channels.

Similar events occurred in other drainage channels close to the study area, and this shows that such structures clearly cause great instability in the system. In the future, new channels should not be constructed on highly erodible soils unless absolutely necessary. Existing natural streams should convey runoff. The upper part of the watersheds with steep slopes should remain undisturbed or performances should be isolated. Dug channels have to be designed by rigorous criteria to define properly the location, slope, length and shape-size of the cross-sections. Control techniques such as revegetation or rock filling should always be considered (Poesen & Govers, 1990; Laflen *et al.*, 1985; Grissinger, 1996). Discontinuities in the channel like a channel head in the upstream end, slope changes or junctions to other constructions such as roads should be protected against erosion. Simulation models properly calibrated are very useful when designing drainage channels in large homogeneous areas. The adopted approach allowed a comfortable and precise measurement of erosion in a big and irregular channel, an objective difficult to achieve with simpler, more conventional methods. Besides, it allowed a careful description of channel morphology providing a detailed and versatile information, more useful than that achieved from simpler conventional methods. The adopted method is a suitable tool to study erosion processes in channels and gullies.

4. Conclusions

Drainage channels constructed on highly erodible soils in Southern Navarre (Spain) have caused a significant amount of erosion. A more accurate design of these structures is needed. Simulation models could play a very important role in achieving such goals. In the future, drainage channels should not be built on this kind of soil unless it is absolutely justified. In general, channel design locations should avoid the upper part of basins and slope changes. These structures have to be constructed simultaneously with control techniques. The proposed measurement method yields a great deal of information, which allows a detailed study on channel erosion processes.

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