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Channel and flood plain response to reforestation in the Dragonja basin, southwestern Slovenia: linking past and present

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Abstract This paper presents the results of ongoing research concerning the effects of natural forest regeneration on the sediment budget of the 91 km^2 Dragonja drainage basin in southwestern Slovenia. Several techniques were combined to reconstruct the development of the flood plain as a result of land use changes in the last 50 years. These techniques include the use of historical records of land cover, measurements of present-day stream samples of suspended sediment load, reconstruction of the flood plain sedimentation rates with ^{137}Cs, as well as dating river incision and calculating erosion rates through geomorphological mapping, tree ring analysis, lichenometry and aerial photographic interpretation. The collected data show that because of the ongoing reforestation in the Dragonja valley the sedimentation rate on the flood plain and the suspended sediment load have decreased and the erosion rate in the river bed has increased. With the reforestation the river transports less water but even less sediment, which means there is energy to incise into the river bed.

Key words flood plain; channel morphology; Dragonja; Slovenia; suspended sediment; hysteresis; caesium-137

INTRODUCTION

River channel and flood plain changes caused by deforestation and intensification of agricultural land use have been studied widely. Conversely, the geomorphological effects of widespread drainage basin reforestation have received far less study. With respect to the flood plain sediment budget and channel morphology after vegetation recovery, various processes may interact. A decrease in sediment inputs to the river system may induce stream incision. At the same time, the sediment transporting capacity of the river will diminish as a result of its decreased discharge because of the increasing water use of the growing vegetation. The combined effects are likely to produce a complicated transient response.

As a result of several decades of depopulation, the previously severely eroding 91 km^2 Dragonja drainage basin in southwestern Slovenia (Fig. 1) has seen a steady increase in the proportion of (mostly broad-leaved) forest (from *c.* 20% in 1971 to >60% in 1994 (Globevnik & Sovinc, 1998). With the return of the forest, profound changes in the flow regime and the morphology of the main river have taken place. Notably a gradual reduction in average annual and dry-weather flows (3.5% and 10% per year, respectively), and a 60% decrease in channel width in the lower reaches between 1975 and 1994 have occurred (Globevnik *et al.*, 1998). The reduced water and sediment flow rates both pose a potential threat to the continued functioning of wetland reserves near the outlet of the drainage basin and limit the possibilities for renewed agricultural development in the area. In addition, a distinct change in river channel form has been observed, which greatly influences the aquatic habitat of the Dragonja River.

This paper presents several techniques that are being used to reconstruct and understand the development of the Dragonja flood plain in relation to the cited land-use changes. This information is also used to link the present-day behaviour of the river to the flood plain sedimentation of the last 50 years.

STUDY AREA

The 30-km-long Dragonja River, situated in the southwestern part of Slovenia, has a drainage basin area of approximately 91 km^2 (Fig. 1). The flood plain varies in width from 150 m in the upstream part of the river basin to 500 m in the downstream part. In a large part of the flood plain the river has made several sets of terraces. The upstream part of the Dragonja consists of two sub-basins, the Rokava (Pinjevec) drainage basin (20.1 km^2) in the north and the Dragonja drainage basin (31.8 km^2) in the south. The

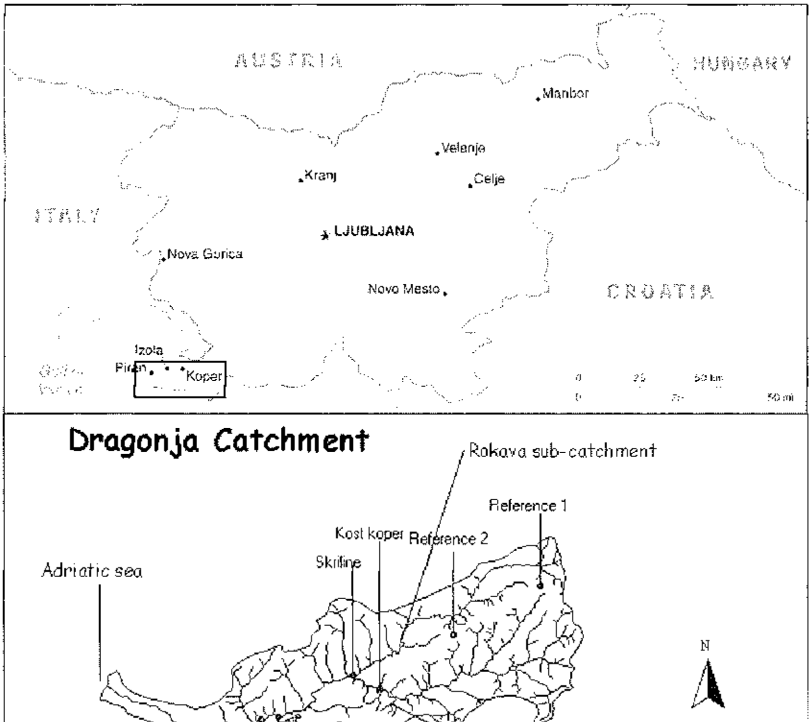

Fig. 1 Location of study area, the Dragonja catchment, with locations of ^{137}Cs cores.

elevation of the drainage basin ranges from *c.* 400 m at the headwaters to sea level at the river mouth (Fig. 1). The geology of the basin consists largely of gently north dipping flysch, which consists of highly calcareous silt, clay and sandstone. The soils consist mostly of carbonate rendzina. The climate of the Slovenian Istria can be classified as sub-Mediterranean (Köppen-type C_w). The long-term discharge record from the Dragonja (1971–1994) shows an average discharge of 1.10 $m^3 s^{-1}$, with an average low flow of 0.22 $m^3 s^{-1}$, an average rainfall/runoff coefficient of 0.36 and a time to peak of 3 h. However in this period these records show a significant decrease in the frequency of high flows (Q >1.5 m^3) and an increase in low flow discharges (Q < 0.05 m^3) because of the reforestation of the drainage basin (Globevnik & Sovinc, 1998).

METHODS

Suspended sediment and bed load

The amount of sediment currently being transported by the river was quantified using several techniques. Suspended sediment was sampled at the outlets of the two subcatchments, the Rokava and the upper Dragonja subcatchment, using automatic water samplers (ISCO-type) during floods. Bed load transport was estimated using a combination of volumetric (accumulation behind weir) and stone tracing techniques.

Reconstruction of flood plain sedimentation rates using ^{137}Cs

Caesium-137 can provide a valuable tracer of sediment movement (Walling *et al.*, 2000; Panin *et al.*, 2001). The method used to interpret the ^{137}Cs profiles of the cores in this study was based on the "principle of stretching". The position of the first peak in the profile (going upwards) is considered to correspond with the depth of the surface in 1960 and the second peak with the surface of 1986 (Walling & He, 1992). To correct for initial infiltration of the deposited ^{137}Cs, reference cores were taken at locations where no deposition or erosion has taken place in the last 40 years. The soils of the study area are clayey and have a high calcium content and are thus likely to have immobilized the ^{137}Cs quickly (Livens & Loveland, 1988). The sites for coring (Fig. 1) were selected on the basis of representing a larger area, the chance of having undergone sedimentation in the last 40 years and the state of the surface. Because ploughing disturbs the ^{137}Cs profile, aerial photographs taken in 1953, 1976, 1985 and 1994 were used to check whether the sites had been in agricultural use.

Geomorphological mapping

Geomorphological mapping was carried out in the summers of 2000 and 2001, and involved taking precisely measured cross-sections as well as detailed mapping of the river bed and associated flood plains and terraces. The mapping was conducted in the lower and middle reaches of the river and the whole active river plain was mapped in detail.

Dating river incision by tree ring analysis and lichenometry

River incision phases were dated by determining the age of trees growing on the stream terraces. Juniper trees were the main species dated using tree ring counts, as these are known to colonize abandoned fields first. This information was complemented by a lichenometric approach, used to determine the age of one species of lichen growing on rocks that were no longer being transported or submerged for long periods of time (Lock *et al.*, 1979). This approach involves constructing a diameter–age curve from lichen growing at sites with a known age (such as old buildings and grave stones) which is then used to estimate the age of the lichen on rocks and can be taken to correspond with the beginning of the incision of the river.

Aerial photograph interpretation

Aerial photographs of the upstream part of the Dragonja drainage basin taken in 1953 and 1994 were used to compare the width of the river bed and the vegetation changes associated with the regeneration of the forest.

RESULTS

Suspended sediment

In between flood peaks, suspended sediment concentrations are very low (<0.02 g l^{-1}), while during floods they can reach as much as 3.5 g l^{-1}. The main sources of suspended

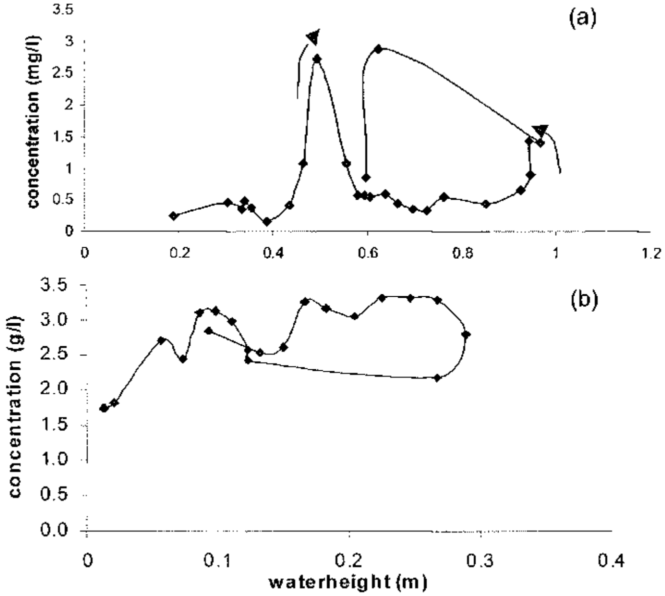

Fig. 2 Anti-clockwise hysteresis observed for two floods in the Rokava tributary on (a) 11 October and (b) 4 November 2000.

sediment are the bed and banks of the river channel, and actively eroding hillside cliffs on which vegetation establishment is slow. Sediment sources may be reflected by hysteresis in the relationship between river discharge and suspended sediment concentration (Lenzi & Marchi, 2000; Asselman & Middelkoop, 1998). For example, an anti-clockwise discharge–suspended sediment concentration pattern, indicates that sediment eroded well away from the stream is transported at the time of the discharge peak and during the recession. The two storm events on the Rokava tributary shown in Fig. 2(a) and (b), both have a distinct peak in sediment concentration at the start of the discharge wave. This indicates that at the beginning of the event the fine material in and around the river bed and banks, which have either been detached by raindrops or

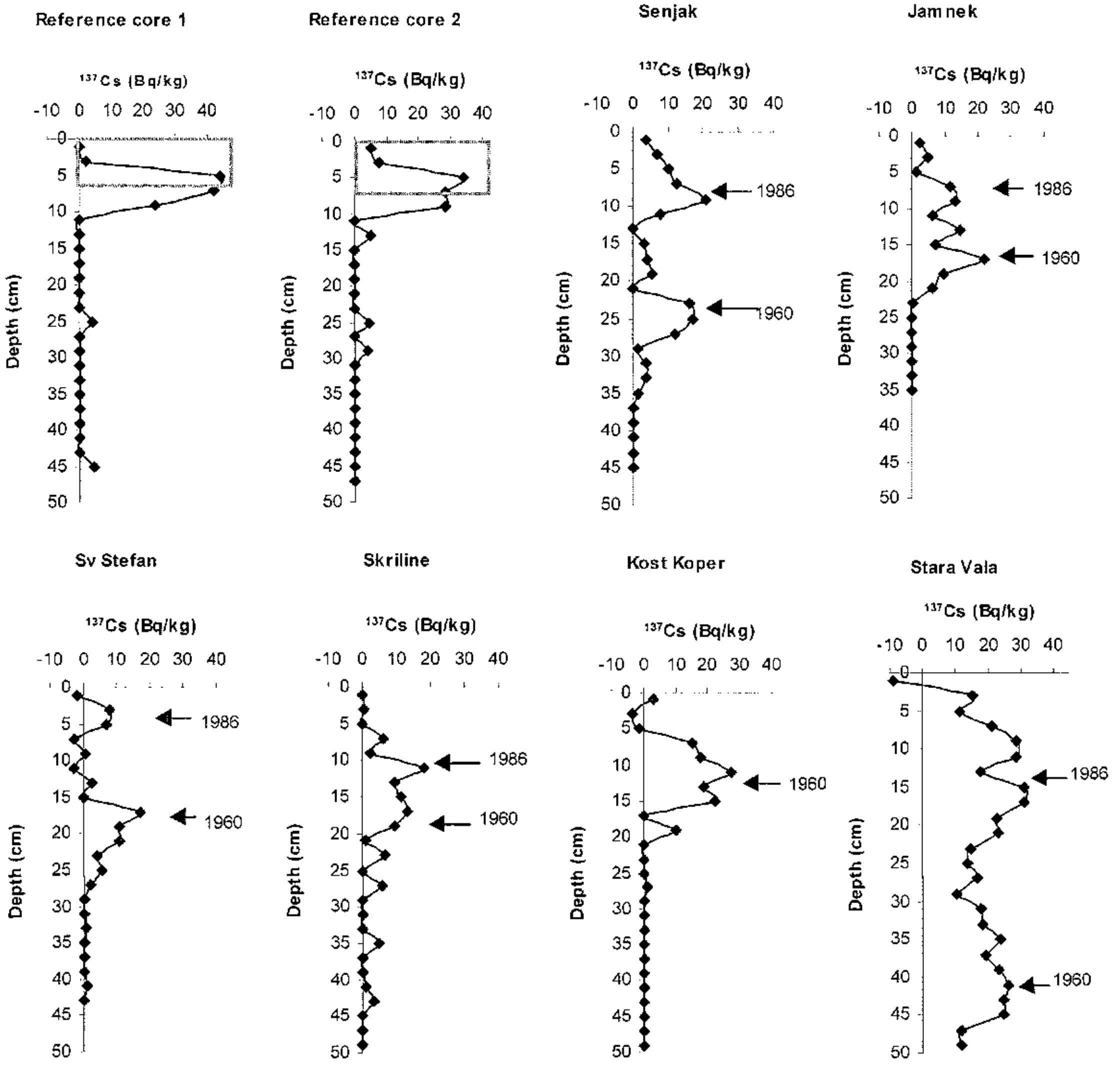

Fig. 3 Profiles of activity of ^{137}Cs (Bq kg^{-1}) in two reference cores and at several locations on the flood plain of the Dragonja River. Arrows indicate the actual depth of the 1960 and 1986 peaks.

were deposited there during previous events, are flushed. Because discharge peaks rise very quickly, suspended sediment concentrations are diluted and start to fall (Fig. 2(a)). The second peak in concentration then represents suspended sediment coming from eroding agricultural areas (mostly vineyards) and trails located further upstream and upslope.

Caesium-137

The ^{137}Cs profiles of the reference cores exhibited a typical peak at a depth of 7 cm, indicated by the box in Fig. 3, suggesting that the ^{137}Cs initially infiltrated approximately 7 cm into the soil. The profiles for the sedimentation areas were corrected accordingly (Table 1). Almost all profiles show two peaks (Fig. 3) from which sedimentation rates were calculated for the periods 1960–1986 and 1986–2000 (Table 1).

The cores taken in depositional areas at Senjak, Jamnek, Sv Stefan, Skriline, Kost Koper and Stara Vala all show substantial sedimentation, especially in the period between 1960 and 1986. After 1986 the sedimentation rate is much lower and in some cases sedimentation seems to have stopped (Table 1). As expected, sedimentation rate is inversely related to the height above the present river bed. The sample locations were classified according to their relative positions with respect to the present-day river bed (Fig. 4). Average sedimentation rates are listed in Table 1. Point bars (unit A) are located closest to the river and flood most often. Therefore, the sedimentation rate is highest in this unit. Units B and C represent terraces at 1.5 m and 2.5 m above the river bed, respectively. These terraces receive correspondingly less sediment from floods (Table 1).

Table 1 Depth of the peaks in the ^{137}Cs profiles and calculated sedimentation rates and the average sedimentation rates for units A, B and C for the periods 1960–1986 and 1986–2000 as calculated from ^{137}Cs data (see Fig. 4 for explanation of units).

	Peak depth 1960 corrected for infiltration (cm)	Peak depth 1986 corrected for infiltration (cm)	Sedimentation rate (cm year^{-1}) 1960–1986	Sedimentation rate (cm year^{-1}) 1986–2000	Unit	Mean sedimentation rate (cm year^{-1}): 1960–1986	1986–2000
Skriline	10	5	0.25	0.33	A	0.5	0.33
Stara Vala	32	10	0.80	0.67	A		
Senjak	18	0	0.45	0	A		
Jamnek	10	4	0.25	0.27	B		
Sv Stefan	10	0	0.25	0	B	0.25	0.14
Kost Koper	9	Possibly erosion	0.22	-	C	0.22	-

Geomorphological mapping, aerial photograph interpretation, tree ring analysis and lichenometry

In terms of the sediment budget, the Dragonja basin is not in a steady state. The river is currently incising sediment that has accumulated during a previous period of more active sediment generation, transport and deposition. From historical data it is known that the drainage basin was severely eroding in the 1950s (cf. Fig. 5). Since then, soil erosion has been reduced by 60% due to vegetation regeneration and anti-erosion measures (Globevnik *et al.*, 1998). The main erosional processes that occur along the banks of the Dragonja River are undercutting and parallel flow. Bed load transport in these unregulated rivers is remarkably active, for example, 25 m^3 of gravel was deposited behind a low weir in the Rokava tributary by one flood. Most of this material originated from a limited number of sites where the stream cuts into the valley sides, to produce actively eroding cliffs in bedrock up to 50 m high. A minor part of the bed load comes from erosion of older river sediment, into which the river is cutting at present. This down cutting and narrowing of the active river bed can be seen clearly on aerial photographs (Fig. 5).

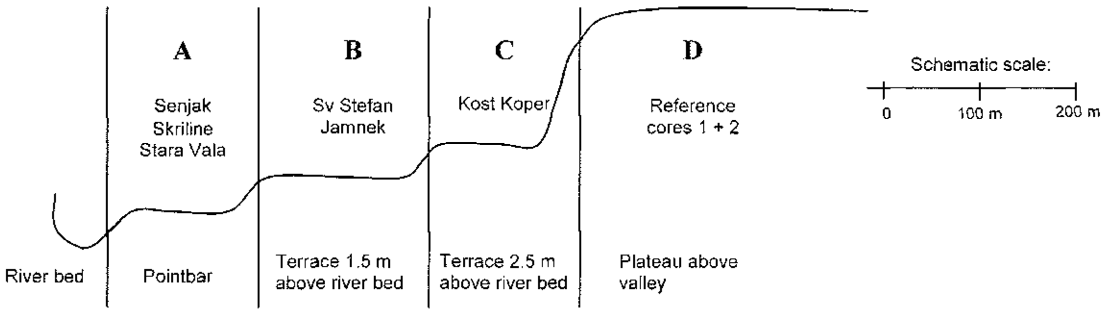

Fig. 4 Schematic cross-section of the river valley showing the units used for the interpretation of the ^{137}Cs profiles.

As shown in Fig. 5 the vegetation has invaded the former river bed, and the present river has cut into its own bed material which was probably still actively transported in 1953. During the geomorphological survey this section of the river was mapped in detail, both in planview and cross-section (Fig. 6). Two distinct terraces were recognized, 1.0 m (mapping units 4 and 6) and 1.5 m (mapping units 1, 3, 8, 9 and 10) above the river bed. On the 1953 aerial photograph it can be seen that the 1.5 m terrace was part of a flood plain as it is at present (Fig. 6). The level of around 1 m above the river bed has clearly only recently been invaded by vegetation. Most trees and bushes are juvenile with the oldest trees being approximately 25 years old (tree ring analysis). On the 1.5 m terrace, lichens on rocks were abundant and showed an average diameter of 24.7 cm, corresponding to 64 years of age. The lichens on the 0.5–1.0 m terrace were much less abundant and showed an average diameter of 9.9 cm, corresponding to 22 years of age. Using this information, the amounts of material eroded and transported by the river in the reach presented in Fig. 6 between 1953 and 2000 can be calculated. Since the creation of the 1.5 m terrace (Table 2) some 64 years ago, 3550 m^3 of material was estimated to have been eroded suggesting an average erosion rate of about 55 m^3 $year^{-1}$. Repeating the exercise on the basis of the 1.0 m terrace incision (aged 22 years) yielded 1795 m^3 or an average erosion rate of 81 m^3 $year^{-1}$.

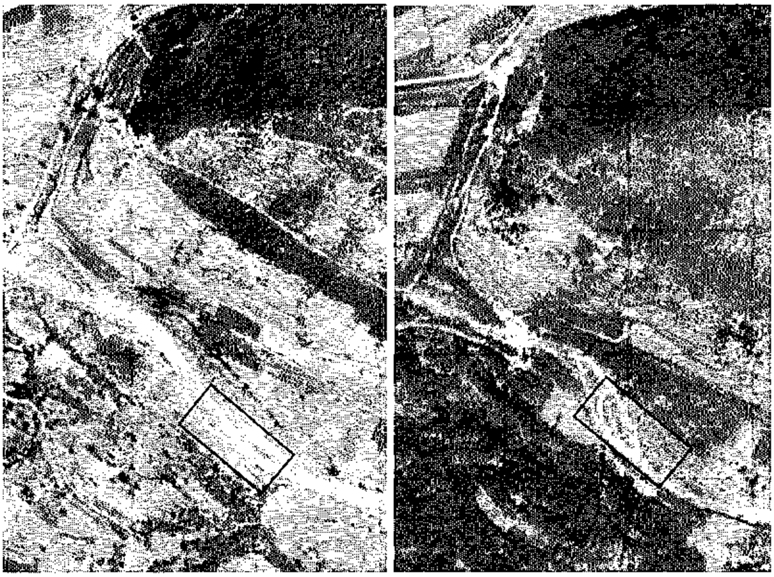

Fig. 5 Aerial photographs from the area around the confluence of the Dragonja and Rokava tributaries taken in 1953 (*left*), and in 1994 (*right*). Boxes indicate the mapped section shown in Fig. 6.

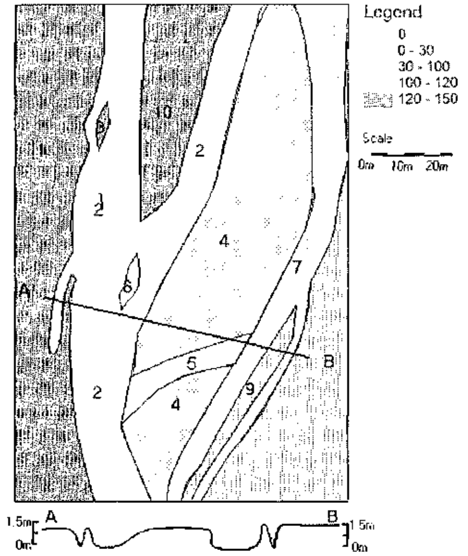

Fig. 6 Schematic drawing of mapped river bed section. A–B indicates measured cross-section displayed at the bottom of the figure. See Table 2 for explanation of numbers.

DISCUSSION

Flood plain and terrace sedimentation

The decrease in sedimentation rates on the flood plains (Table 1) is consistent with historical evidence of land-use change (Globevnik *et al.*, 1998) and the records of the

Table 2 Calculated amount of eroded sediment per morphological unit as displayed in Fig. 6.

Mapping unit	Form	Area (m^2)	Height above river bed (m)	Volume eroded since incision of:	
				1.5-m terrace (m^3)	1-m terrace (m^3)
1	Flood plain	1006.7	1.5	0.0	0.0
2	Incised river bed	1222.1	0	1833.2	1222.1
3	Eroding island	10.7	1.5	0.0	0.0
4	Eroding mid-channel bar	1189.7	1.0	594.9	0.0
5	Incised river bed	98.3	0.3	118.0	78.7
6	Eroding mid-channel bar	17.1	1.0	8.6	0.0
7	Incised river bed	549.6	0.1	769.6	494.7
8	Flood plain	649.2	1.2	194.8	0.0
9	Eroding flood plain	88.8	1.2	26.6	0.0
10	Eroding mid-channel bar	359.7	1.5	0.0	0.0
Total				3546	5

discharge for the Dragonja from 1971 until 1994, which show a decrease in the frequency of high flows ($Q > 1.5\ m^3$) and an increase in the frequency of low flows ($Q < 0.05\ m^3$) (Globevnik & Sovinc, 1998).

Although there are no actual measurements of sediment load for the period before reforestation, it is known from the current measurements that most suspended sediment transport takes place during floods. Obviously, overbank deposition will only occur when the flood plain is flooded. Therefore a reduction in the frequency of large floods will produce lower sedimentation rates on flood plains. Another factor playing a role in the system of overbank deposition is the total amount of suspended sediment transported by the river. From the ongoing field observations and the literature (Russell *et al.*, 2001; Rijsdijk & Bruijnzeel, 1990) it is known that agricultural land (mostly vineyards) and dirt roads provide more sediment (fines) to the river than forested areas. Surface erosion on the forested slopes in the area is considered minimal, although several cliffs at the foot of these slopes continue to be active suppliers of coarse material. The anti-clockwise patterns in the suspended sediment–discharge graphs (Fig. 2) indicates that the most important source of suspended sediment is located away from the stream, i.e. on eroding parts of the hillslopes. These hillslopes have partly (70%) been reforested over the last 50 years and subsequently supply less sediment to the river.

Erosion

As a result of the less intense floods and decreased sediment load of the river in recent years, vegetation is invading the active river bed. The vegetation slows the water down and sediment starts to accumulate, which in turn encourages more plants to grow in the old river bed. However, the remaining narrowed channel experiences stronger currents, which induces erosion and downcutting of the channel. The high parts of the old river bed, in fact, have now become a flood plain. The erosion rates in these sections of the river have increased over the last 64 years.

Therefore, because of the ongoing reforestation in the Dragonja valley the sedimentation rate on the flood plain and the suspended sediment load have decreased, but the erosion rate in the river bed has increased.

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