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Sediment transport along the gullies in flysch badlands – an example from SW Slovenia

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Abstract: Sediment transport along erosion gullies in flysch badlands under Sub-Mediterranean climate is presented. Presented are weekly measurements, compiled measurements by months, as well as correlations of sediment transport with selected weather data. Sediment transport was measured up to 19 kg m^{-2} and was largely dependent on special weather conditions.

Keywords: badlands, gullies, erosion processes, flysch, Istria, Slovenia

Introduction

The northern part of Istria peninsula (so called Slovene Istria, SW Slovenia) and the Dragonja River basin (app. 90 km^2) (Fig. 1) in particular has been a study area of several studies of hydrological and geomorphic processes since the end of the 20th century (Globevnik et. al. 1998, Petkovšek & Mikoš 2003, 2004, Tol 2006, Keesstra 2007, Keesstra et al. 2005, 2009, Šraj et al. 2008, Staut & Mikoš 2008).

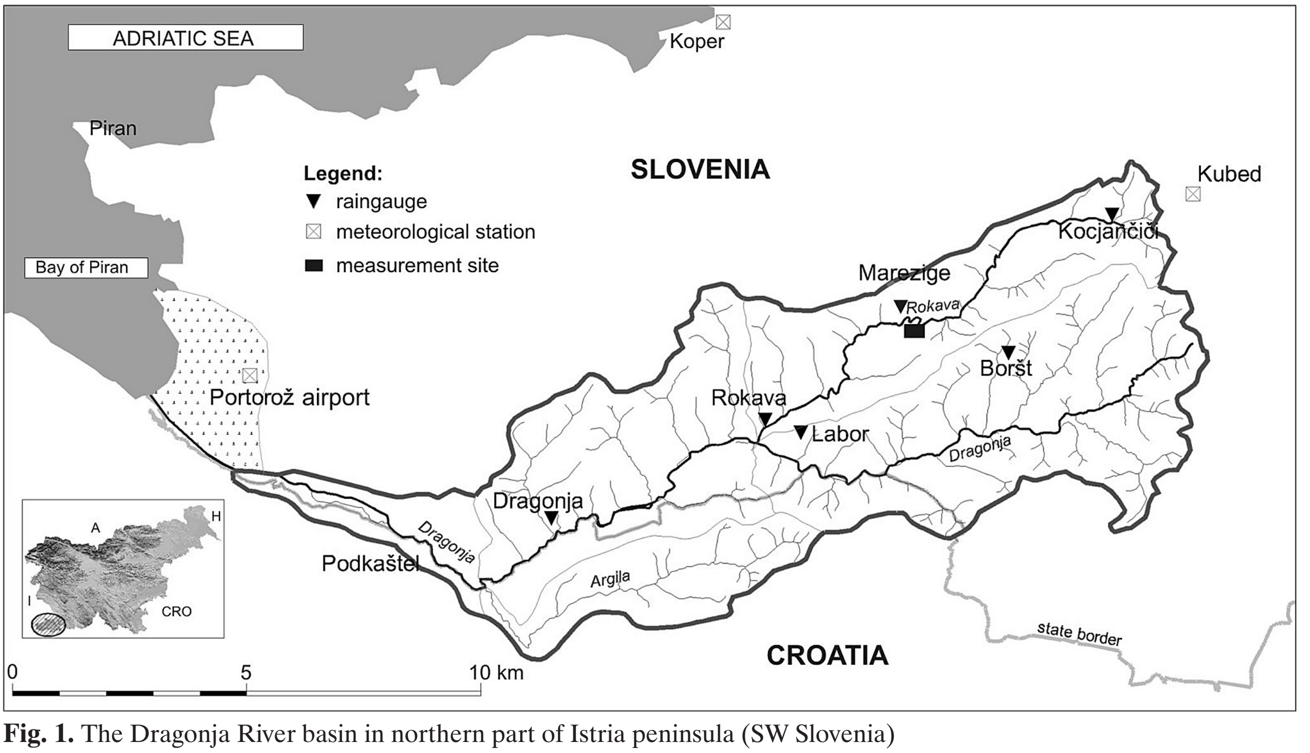

Fig. 1. The Dragonja River basin in northern part of Istria peninsula (SW Slovenia)

Fig. 2. Gully with marked spot where barrier was constructed (photo Matija Zorn)

Fig. 3. Barrier in a gully (photo Matija Zorn)

Among them were also measurements of interrill and rill soil erosion on different land uses (Zorn & Petan 2008, Zorn 2008, 2009a), as well as measurements of erosion processes in the badlands (Zorn 2009b). The latter included: the rockwall retreat of steep bare flysch slopes, sediment transport of flysch debris along gullies, and geomorphic processes on talus slopes. In this paper we present the measurement results of sediment transport of flysch debris along the gullies.

Badlands are a morphogenetic feature of the flysch part of Istria. There are linear forms such as gullies (Figs. 2 to 4) or torrent beds and plane forms in the shape of steep walls. Badlands in general occur

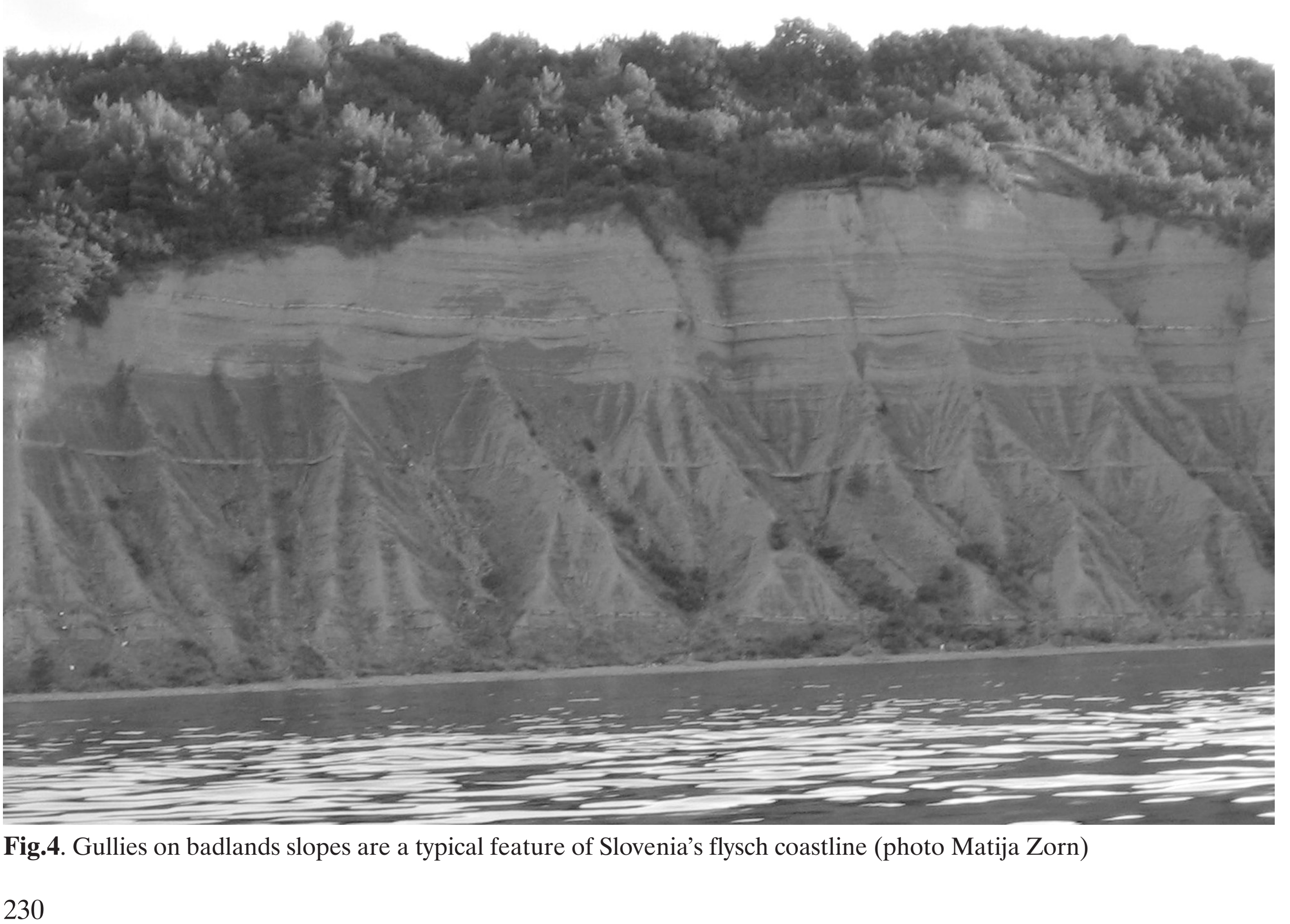

Fig.4. Gullies on badlands slopes are a typical feature of Slovenia's flysch coastline (photo Matija Zorn)

in the area where: "*soft, predominantly horizontally bedded, relatively impermeable rocks are exposed to rapid fluvial erosion*," and their formation can be hastened by accelerated erosion (Campbell 1997). Natural preconditions (erodible rock and dissected surface) are essential for the formation of badlands, but human activity can also be held responsible for their formation (Harvey 2004). The microrelief features that occur on them have a relatively short life span because erosion processes are rapid. "*Although badlands evoke an arid image, they can develop in nearly any climate … where vegetation is absent or disturbed*" (Howard 2009). Closely related to badlands are gullies that record accelerated erosion into regolith or soft rocks (Howard 2009).

Badlands play two essential roles in the geomorphic system: on one hand they are an abundant source of eroded material, and on the other they are an important factor in slope formation (Harvey 2004). In the case of Slovene Istria the predominant bedrock is flysch and the climate is Sub-Mediterranean. The thickness of flysch sequences is usually a few centimetres to a few decimetres and they are composed predominately of marl and sandstone. The occurrence of badlands is on one hand connected to the lateral erosion of the Dragonja River and on the other to the intensive forest clearance by the Venetians in the 15th century. Today big afforestation is characteristic for the river basin; and badlands decreased in the last fifty years from 2.74 km^2 (in 1957) to 0.36 km^2 (in 2003) (Staut & Mikoš 2008).

Methods

According to Poesen & Hooke (1997), there is no standardized methodology for measuring gully erosion or any universal model for studying it. For our measurements we constructed a barrier in a gully (Figs. 2 and 3) and took measurements on a weekly basis.

Near the barrier we set up an automatic rain gauge (ONSET RG2-M) to monitor the amount and intensity of precipitation. Regrettably we were unable to monitor the temperatures and the wind in the same way, so we had to be satisfied with data from the nearby meteorological station in the port of Koper. Using the work of Ogrin (1995) we adapted the acquired data to the weather conditions in the valleys in the hinterland of Koper.

Measurement results

The measurements took place between 24.2.2005 and 26.4.2006 in a gully with a catchment area of 994.28 m^2 and an average inclination of 46°.

The measurements were not long-termed, but as Howard (2009) put it: "*processes* [in badlands] *are rapid enough that rates of landform change can be measured with reasonable accuracy over periods of just a few years*".

Over the entire 14-month period of measurements, 19,997.57 kg or 11.68 m^3 of debris was deposited behind the barrier. The sediment yield in the gully amounted up to 18.83 kg m^{-2} per year. The sediment transport was not even throughout the year but was largely depended on special weather conditions. As much as 52% of the annual amount of debris was captured in just one week between 19.1.2006 and 26.1.2006, while another 30% was captured in seven weeks with more than 3% of the annual captured debris. In the remaining 44 weeks, only 18% of the annual amount of debris was captured (Fig. 5).

The extreme values were the consequence of dry rock (debris) flows that were triggered in the gully in these weeks. The preconditions for such extremes are a sufficient quantity of debris in the gully and a wind that completely dries the debris to a certain depth. Moist clayey debris is harder to move and moves only with heavy precipitation.

Comparisons between sediment yield and precipitation or temperature conditions at the time are presented in Figure 6.

To establish more general trends in the transport of debris along the gully throughout the year, we compiled our measurements by months.

The most debris was transported along the gully in the first three months of the year, and the secondary peak occurred in August (Fig. 7). August was the month with the highest erosivity of precipitation, but relative to the amount of debris captured it is far behind the first three months of the year. January stands out due to the dry rock (debris) flows in the week before 26.1.2006. Dry rock (debris) flows also occurred in the same conditions in February and March, but there was less debris available in the gully.

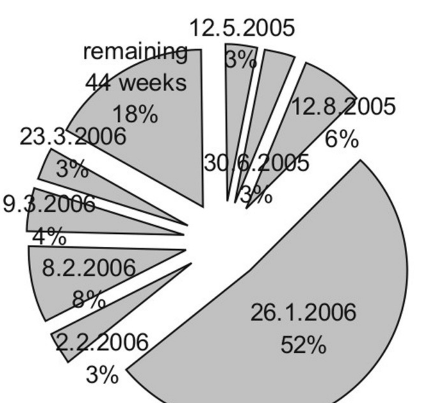

Fig. 5. Weeks with more than 3% of the annual sediment transport along the gully in measurement period between 28.4.2005 and 26.4.2006

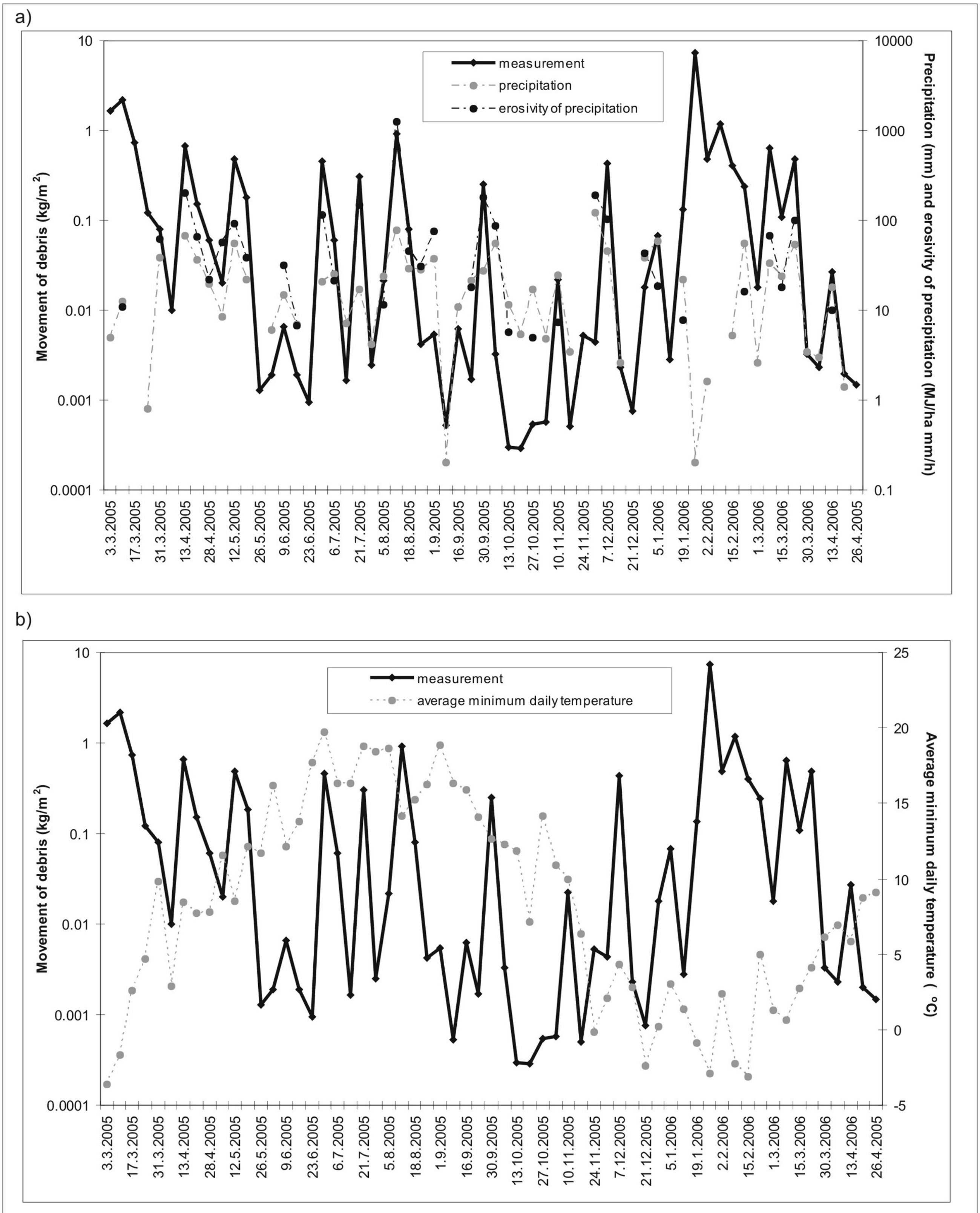

Fig. 6. Weekly measurements of sediment yield along the gully with (a) precipitation and (b) temperature conditions at the time

It seems that sediment transport is most intensive in winter. A major regression and approximately the same amount of debris moved follows in the spring and summer with absolute low values in the fall, which is undoubtedly related to the slowing of sediment production (Zorn 2009b) from the slopes in the summer and the correspondingly lack of debris in the gully. These correspond with the writings of Howard (2009) that erosion processes on badlands slopes exhibit complex temporal variability.

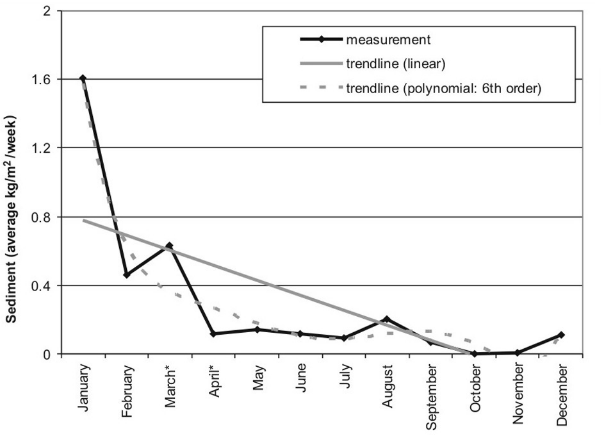

Fig. 7. Sediment yield of flysch debris along the gully by months ([*]average of two-year measurements)

Correlations with weather conditions

We correlated the sediment transport of flysch debris along the gully with selected weather data. Using Pearson's Correlation Coefficient (*r*) we looked for linear statistical correlations between the sediment and individual weather parameters (Table 1; Fig. 8). We also calculated the multiple linear correlation coefficient (*R*) between flysch debris and all the selected weather parameters together. For the 16 selected variables the proportion of explained variance for measured sediment transport data lies between 0.5201 ($n=61$; $p<0.0009$; $R=0.7212$) and 0.5495 ($n=42$; $p<0.0586$; $R=0.7413$).

Individual temperature parameters show mostly a small negative statistical correlation with the sediment transport along the gully with the exception of the number of days with negative temperatures, which shows a medium-positive statistical correlation. To facilitate the assessment of the correlation between low temperatures and sediment transport, we correlated the sediment transport with temperature parameters in the cold part of the year; however, the correlations showed no substantial differences (with the exception of maximum daily temperatures with a slightly higher statistical correlation).

The precipitation parameters show almost no statistical correlation with sediment with the exception of erosivity of precipitation (erosivity was calculated using the formula in RUSLE2 model), which shows a small positive statistical correlation (Fig. 8e). In spite of the calculations, during the period of measurements it was possible to observe that heavy enough precipitation resulting in a sufficiently strong surface runoff can move more than 3% of the annual captured debris.

The wind parameters show a greater statistical correlation with sediment than most of the precipitation parameters, and we established a small positive statistical correlation. The role of the wind is related to the observed flows of dried rock (debris).

Table 1. Correlations between the sediment and weather conditions

Parameter	Pearson's correlation coefficient (r)	t-test n = 61 [a]n = 42
maximum daily temperature	–0.2394	–1.8939
average maximum daily temperature	–0.3055	–2.4647
minimum daily temperature	–0.3103	–2.5076
average minimum daily temperatures	–0.3501	–2.8712
number of days with negative temperatures	0.4145	3.4983
amount of precipitation	–0.0652	–0.4621
maximum 10-minute precipitations	–0.0110	–0.0779
maximum 30-minute precipitations	0.0110	0.0779
maximum 60-minute precipitations	0.0015	0.0105
average 10-minute precipitations	–0.0154	–0.1088
erosivity of precipitation	0.2761	1.5735[a]
average wind speed	0.2582	2.0527
maximum wind gusts	0.2842	2.2772
average maximum wind gusts	0.2681	2.1377

Temperature parameters exhibit the highest statistical correlation with sediment, followed by wind parameters; precipitation parameters are in last place and exhibit almost no statistical correlation, with the exception of erosivity of precipitation.

With the generalization of data (Fig. 9) by months and seasons correlations between temperature or wind parameters and sediment is increasing, e.g. to high or even very high by seasons. On the other hand correlations connected to precipitation are decreasing with the generalization of data, e.g. erosivity even "moves" from positive correlation on a weekly scale to middle negative correlation by seasons.

The reason for this can be find in the fact that the biggest sediment transport occurs when there is no precipitation, e.g. during the winter when the erosivity is at its lowest, and during the summer at the time of the highest erosivity of precipitation but with relatively low quantity of debris in the gullies.

Conclusions

According to Campbell (1997) gully erosion in badlands has not been as intensively studied as gully erosion in soils or regolith, in particular on agricultural land (for example Poesen et al. 2006). Campbell (1997) links this to the fact that badlands are not interesting from the agricultural aspect and have no economic value despite the fact that they are "highly visible" in the landscape.

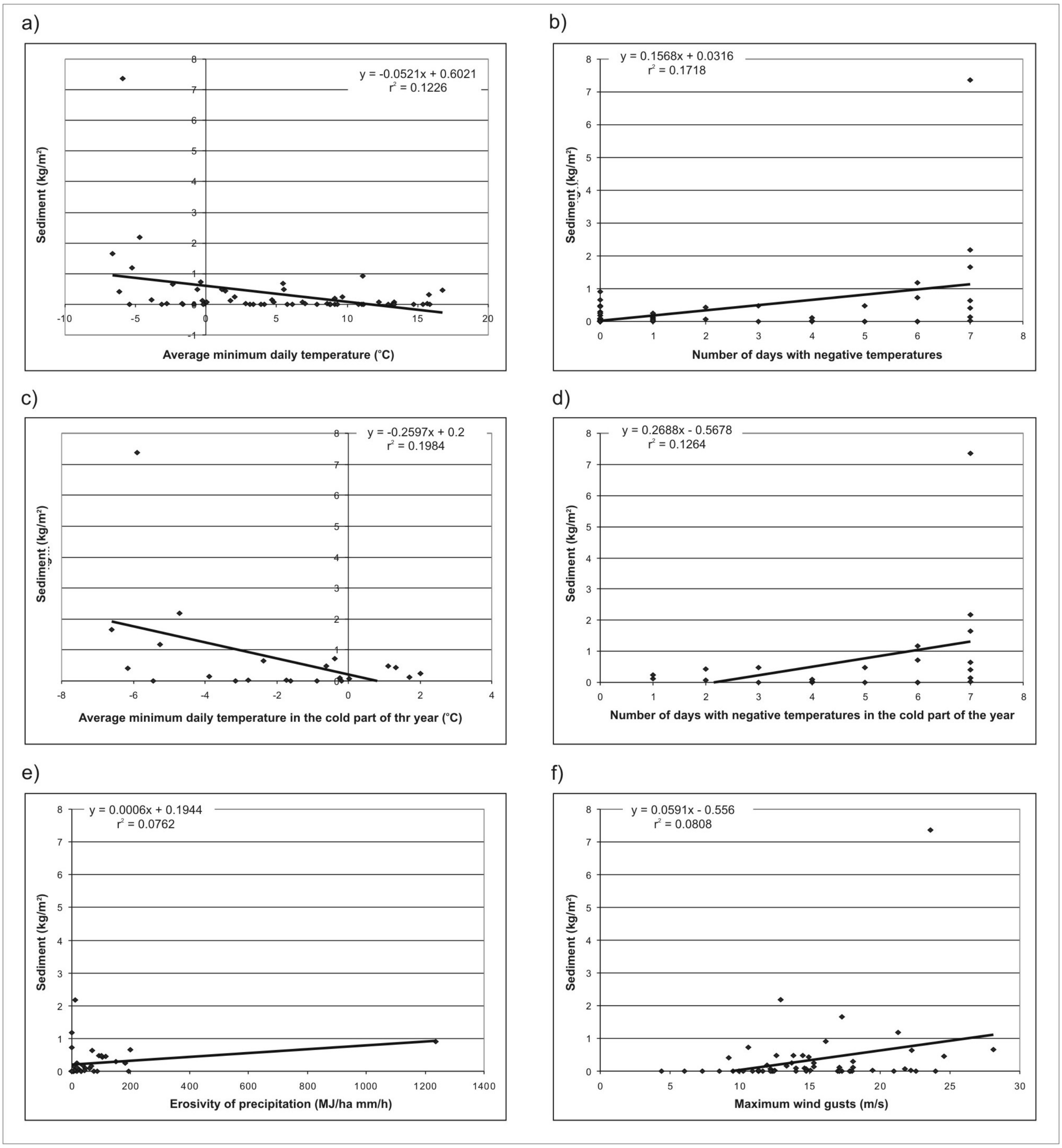

Fig. 8. Relationships between sediment and: (a) average minimum daily temperature, (b) number of days with negative temperatures, (c) average minimum daily temperature in the cold part of the year, (d) number of days with negative temperatures in the cold part of the year, (e) erosivity of precipitation, and (f) maximum wind gusts

Nevertheless, gullies in badlands provide an easy path for sediments to reach the fluvial systems. "G*ully erosion is the main source of sediment at the catchment scale*" (Valentin et al. 2005). From the literature is known that badlands that constitute 2% of the river basin surface area can contribute as much as 80% of annual eroded suspended material (Campbell 1997). Sediment yield along the gullies in flysch badlands in Slovene Istria (in Dragonja River basin badlands comprise app. 0.36% of the catchment) amounts up to 18.83 kg m^{-2} per year. We estimate that if all this material reaches the fluvial systems it contributes up to 10% of yearly sediment yield in the Dragonja River basin which is estimated to be around 188 kg m^{-2} per year (Globevnik 2001).

We observed the highest sediment transport in cold part of the year with high pressure conditions and numerous alternations of temperatures below and above 0°C accompanied by strong winds (suitable conditions for the occurrence of dry rock (de-

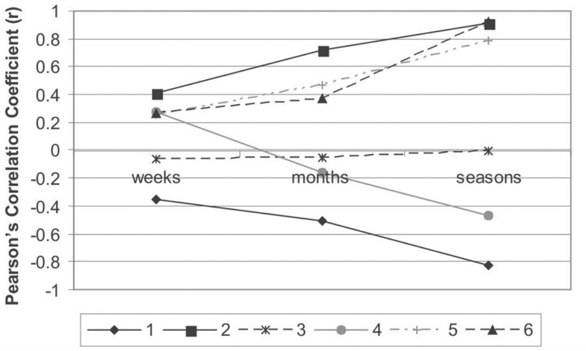

Fig. 9. Changing of Pearson's correlation coefficient with the generalization of data by months and seasons for selected weather conditions

1 – average minimum daily temperatures; 2 – number of days with negative temperatures; 3 – precipitation; 4 – erosivity of precipitation; 5 – average wind speed; 6 – average maximum wind gusts

bris) flows in the gullies), and in warm part of the year with high erosivity of precipitation. Absolute lows in sediment transport were in warm part of the year with low precipitation, and in late autumn when sediment transport was low despite of relatively high precipitation but connected to the lack of debris in the gullies.

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