© *Acta hydrotechnica* **21/34 (2003)**, Ljubljana
ISSN 1581-0267

UDK / *UDC*: 551.311.2:556.04:556.51:556.535(28.2.249)(497.14) Prejeto/*Received*: 30. 10. 2003
Predhodna objava – *Preliminary scientific paper* Sprejeto/*Accepted*: 17. 1. 2004

MERITVE EROZIJSKIH PROCESOV V EKSPERIMENTALNEM POVODJU DRAGONJE, JZ SLOVENIJA
MEASUREMENTS OF EROSION PROCESSES IN THE EXPERIMENTAL CATCHMENT OF THE DRAGONJA RIVER, SW SLOVENIA

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Prispevek obravnava nekatere rezultate meritev v povodju Rokave, ki je del eksperimentalnega povodja Dragonje. Večinoma so meritve potekale v času od jeseni 2000 do spomladi 2002. Merili smo pretok vode, lebdečih in rinjenih plavin, dinamiko erozije sedimentov na klifih ter padavine, na podlagi katerih smo določili dejavnik erozivnosti padavin in odtoka R. Rezultati kažejo, da srednje letno odplavljanje lebdečih plavin znaša okrog 1500 ton oziroma 750 kg/ha/leto. Pri meritvah klifov smo uporabili kombinacijo fotogrametričnih snemanj in meritev z erozijskimi žebljiči, kar nam je dalo vpogled tako v skupno količino sproščenega materiala kot v kratkotrajno dinamiko erozije s klifov. Klifi so najaktivnejši pozno poleti, letno pa prispevajo v rečno mrežo okrog 100 ton drobnega materiala letno. Erozivnost padavin je tako prostorsko kot časovno izrazito neenakomerna. Najbolj erozivni so meseci od julija do novembra.
Ključne besede: *eksperimentalno povodje, Dragonja, Rokava, sedimenti, klifi, erozivnost padavin*

The paper presents and analyses the results of some of the measurements in the Rokava catchment, which is a part of the Dragonja catchment. Measurements were carried out mostly between autumn 2000 and spring 2002. The measured quantities included water discharge, suspended and bedload discharge, dynamics of sediment production from cliffs, and measurements of rainfall, which were used to compute rainfall and the runoff erosivity factor R. The results show that the mean annual suspended sediment yield is around 1500 tonnes, which is equal to 750 kg/ha/year. Cliffs' activity was monitored with a combination of photogrammetric surveys and erosion pins, which gave us both the total sediment production from cliffs and its short-term dynamics. Cliffs are most active in late summer. They contribute approximately 100 tonnes of fine sediment into the stream network. Rainfall erosivity is highly variable, both spatially and temporally. The rainfall erosivity is highest in the period between July and November.
Key words: *experimental catchment, Dragonja, Rokava, sediments, cliffs, rainfall erosivity*

1. UVOD

Pri preoblikovanju zemeljskega površja ima pomembno vlogo erozija. Erozija je posledica različnih eksogenih dejavnikov, kot so na primer delovanje tekoče vode, snega, vetra, temperaturnih nihanj in težnosti. Glede na vzrok nastanka delita Pintar & Mikoš (1983) erozijske pojave takole:

- pojavi kemičnega, biološkega in fizikalnega preperevanja,
- vetrna erozija,
- snežna erozija,

1. INTRODUCTION

Erosion of Earth's surface plays an important role in geomorphologic processes. In general, erosion can be caused by different exogenic factors, such as force of running water, snow, wind, temperature oscillations and gravity. Depending on the driving force, Pintar & Mikoš (1983) consider the following erosion processes:

- chemical, biological and physical weathering,
- wind erosion,

– ledeniška erozija,
– vodna erozija,
– plazna erozija in
– podorna erozija.

V hidrologiji uporabljamo pojem erozija tal tudi v ožjem pomenu, kot vodno erozijo. Z njim označujemo pojave površinskega spiranja in odplavljanja zemljin zaradi delovanja padavin in tekoče vode. Erozija tal je v večini primerov rezultat naravnih dejavnikov. V nekaterih primerih pa jo pospešuje tudi človekova dejavnost. Najbolj značilni primeri so kmetijstvo, rudarstvo in gradbeništvo (Hahn *et al*., 1994). Ta prispevek obravnava predvsem procese vodne erozije, ki so na obravnavanem območju najbolj prisotni.

Dinamiko erodiranja zemljin sestavljajo procesi sproščanja, premeščanja in odlaganja (Meyer & Wischmeier, 1969). Pri sproščanju se predvsem zaradi dežnih kapelj delci ločijo od matičnih tal. Površinski vodni tok zrna premešča navzdol po pobočju. Premestitvena zmogljivost vodnega toka narašča s hitrostjo, ko pa se hitrost zmanjša, običajno zaradi zmanjšanja naklona pobočja, nastopi odlaganje (Hahn *et al*., 1994). Dinamiko in bilanco sedimentov v povodju podaja slika 1. Podrobnejši pregled procesov je podan v Petkovšek (2000).

V tem prispevku podajamo rezultate meritev odtoka vode, odplavljanja zemljin in erozije s klifov. Meritve smo opravili na severovzhodnem delu eksperimentalnega povodja Dragonje, to je v povodju Rokave (slika 2). Povodje Rokave je dobro razčlenjen gričevnat svet, s površino 20,4 km^2 in srednjo nadmorsko višino 250 m. Najnižja točka je sotočje z Dragonjo (75 m NMV), najvišja pa 415 m NMV. Povprečni vzdolžni padec doline je v zgornjem delu 2,2 %, v spodnjem delu pa 1,4 %. Srednji nagib površja je 25 %. Meritve smo izvajali v sodelovanju z Vrije Universiteit Amsterdam v okviru projekta "Dragonja: Forest – Soil – Water – Climate Interactions" (Dragonja: medsebojni vplivi gozda, tal, vode in klime).

Povodje Dragonje je v zadnjih desetletjih doživelo večje spremembe rabe tal, kar je vplivalo na režim odtoka vode ter sproščanje

– snow erosion,
– glacial erosion,
– fluvial erosion,
– landslides and rockfalls.

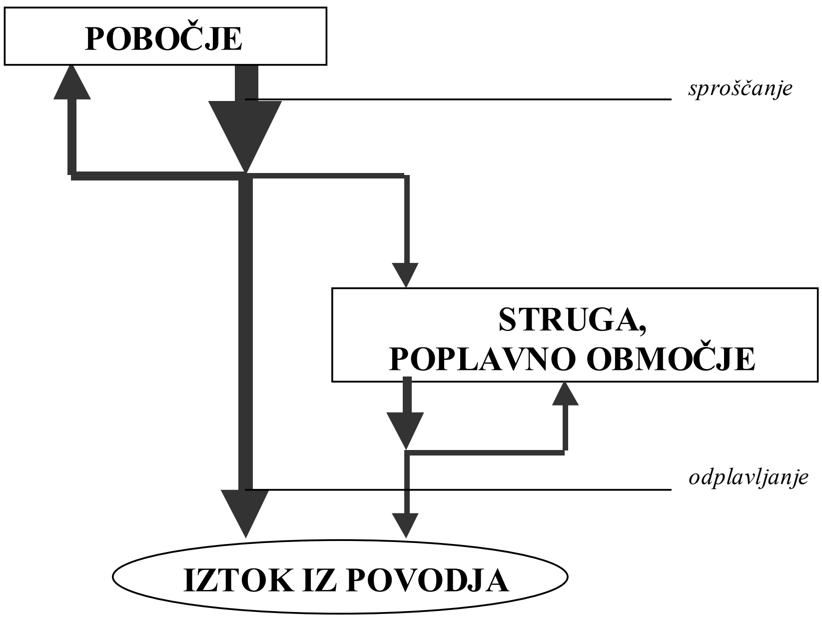
In hydrology, the term soil erosion is usually used in a narrower context, as water erosion. It denotes the processes of superficial soil detachment and transport due to raindrop impact and running water. Soil erosion is a natural process. In some cases, however, human activity accelerates the natural phenomenon. These activities are agriculture, mining and construction (Hahn *et al*., 1994). This paper analyses the processes of water erosion, which are most important in the studied area.

The soil erosion process consists of soil detachment, transport and deposition (Meyer & Wischmeier, 1969). Detachment is a process caused mainly by raindrop impact, which separates the soil particles from the ground. Overland flow transports the particles downslope. The transport capacity of the overland flow increases with flow velocity. Downslope, the angle of the slope usually decreases, therefore flow velocity also decreases and deposition takes place (Hahn *et al*., 1994). The sediment dynamics in a catchment is shown in Figure 1. More details are given in Petkovšek (2000).

In this paper, the results of the measurements of water runoff, sediment yield and sediment production from cliffs are given and discussed. Measurements took place in the Rokava catchment, which is a part of the Dragonja experimental catchment (see Figure 2). The Rokava catchment is formed of hills with a well-developed stream network. The area of the catchment is 20.4 km^2, the mean elevation is 250 m a.s.l. The lowest point is the confluence with the Dragonja (75 m a.s.l.), the highest point is at 415 m a.s.l. The average longitudinal slope of the valley is 2.2 % in the upper part and 1.4% in the lower part. The average slope of the surface is 25 %. The measurement campaign was a joint project with the Vrije Universiteit Amsterdam called "Dragonja: Forest – Soil – Water – Climate Interactions".

In the last decades, the Dragonja catchment underwent significant changes in land use. This also influenced water runoff and sediment in odplavljanje zemljin (Globevnik & Sovinc, 1998). Viri navajajo na podlagi vrednotenja z Gavrilovićevo enačbo (Gavrilović, 1970), da se je sproščanje od sedemdesetih let (PUH, 1971) do danes zmanjšalo za skoraj 70 % (Globevnik, 2001).

yield regime (Globevnik & Sovinc, 1998). Authors that used the Gavrilović equation (Gavrilović, 1970) state that sediment production (PUH, 1971) for nearly 70 % decreased from the seventies (Globevnik, 2001).



Slika 1. Dinamika, bilanca ter območja odlaganja in erodiranja sedimentov v povodju. Puščice, obrnjene navzdol, ponazarjajo premeščanje, puščice, obrnjene navzgor, pa odlaganje. Debelina puščic je v razmerju s količino sedimentov za namišljen primer. Prirejeno po Reid & Dunne (1996).

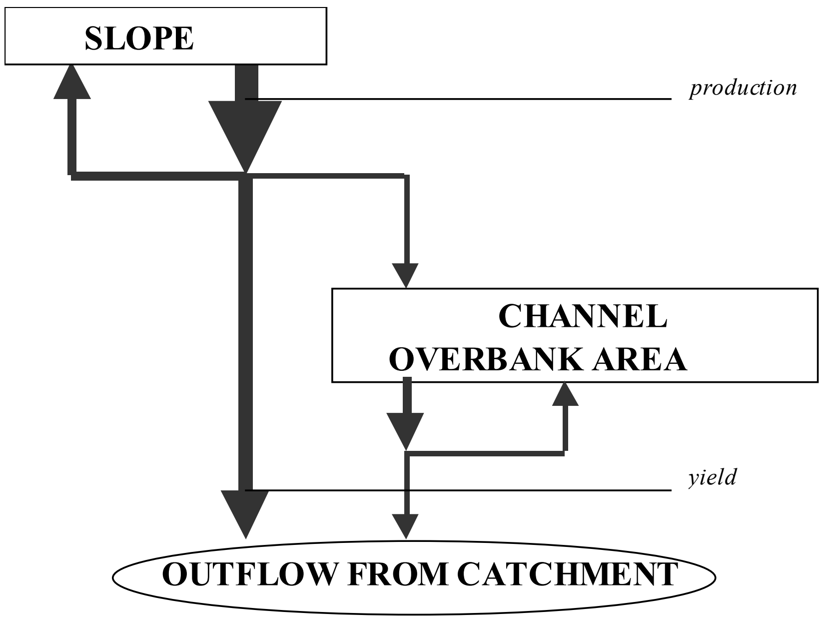
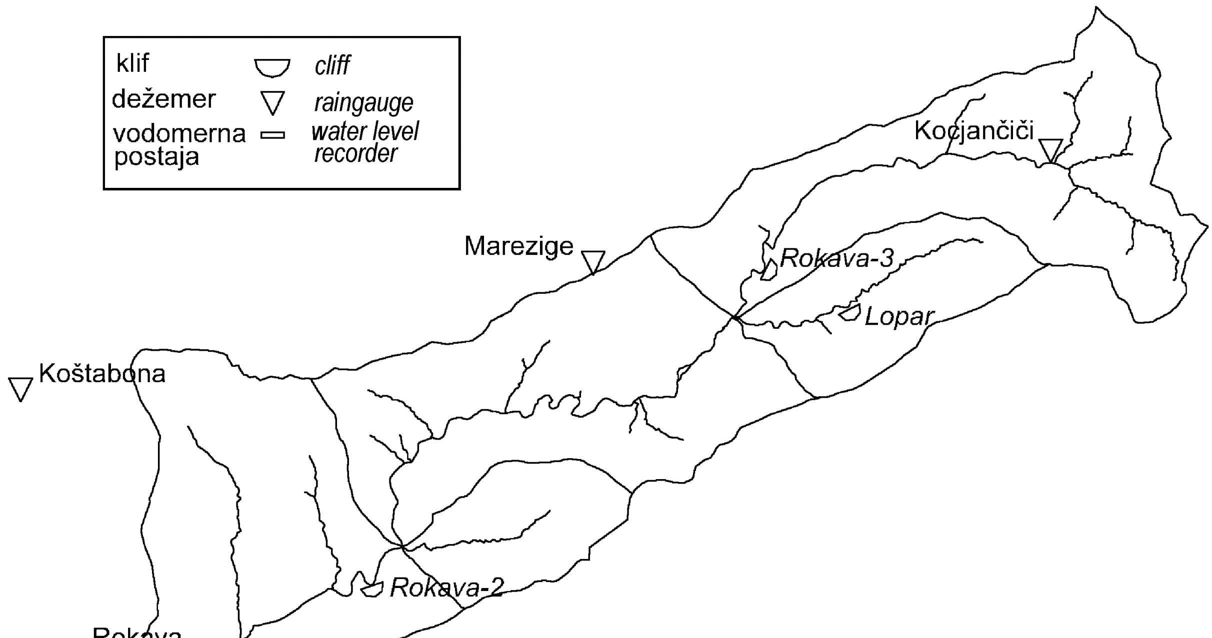


Figure 1. Schematics of sediment dynamics in a catchment. Arrows directed downwards represent erosion; arrows directed upwards represent deposition. The thickness of the arrows represents the approximate magnitude for a typical catchment. After Dunne & Reid (1996).

Slika 2. Položaj povodja Rokave znotraj eksperimentalnega povodja Dragonje v Slovenski Istri brez dela povodja na Hrvaškem.
Figure 2. Location of the Rokava catchment inside the experimental watershed of the Dragonja in Slovene Istria without the part in Croatia.



Slika 3. Merske lokacije.
Figure 3. Locations of measurements.

2. METODE

Meritve, s katerimi smo ocenjevali sproščanje in odplavljanje zemljin, so vključevale meritve padavin, meritve pretoka vode in lebdečih plavin ter meritve erozije s klifov. V podpovodju Rokave smo izbrali tri klife z različno stopnjo aktivnosti. Meritve so pokrivale obdobje dveh let med letoma 2000 in 2002. Merske lokacije so podane na sliki 3.

2.1 MERITVE PRETOKA, LEBDEČIH IN RINJENIH PLAVIN

Na lokaciji Rokava je bila postavljena vodomerna postaja z avtomatskim vzorčevalnikom ISCO 3700. V stabilnem reguliranem delu struge, širine okrog 5 m, je bil zgrajen široki prag, ki ga je za potrebe projekta zgradilo lokalno vodnogospodarsko podjetje Hidro Koper. Za njim sta bili postavljeni dve tlačni sondi Druck Ltd. PDCR-830 (Hobby & Minneboo, 2001). Prva sonda beleži gladino vode v konstantnih časovnih intervalih (10 oziroma 20 minut). Druga sonda beleži gladino vode v daljših časovnih intervalih (1 ura), vendar tudi vsakič, ko je sprememba večja od predpisane vrednosti (0,5 cm). Podatki z druge sonde se shranjujejo v pomnilnik instrumenta Campbell 21X, ki obenem ob vsaki spremembi gladine za več kot 5 cm sproži proceduro odvzema vzorca vode z avtomatskim vzorčevalnikom vode ISCO 3700. Ta lahko brez praznjenja odvzame največ 24 vzorcev po 500 ml, kar zagotavlja precejšnjo avtonomnost vzorčevanja lebdečih plavin. Zajemna glava je bila postavljena pod širokim pragom, kjer je voda dobro premešana. S tem smo zagotovili ustrezno reprezentativnost vzorca. Velikost odvzetih vzorcev je bila med 400 in 500 ml. Koncentracija C_s [g/l] lebdečih plavin je bila določena tako, da je bila najprej izmerjena prostornina vzorca V_s, nato pa vzorec izparjen pri 105 °C, sušina pa stehtana. Koncentracija je bila izračunana kot razmerje med maso sušine m_s in prostornino vzorca V_s.

Pretoki vode so bili določeni s pomočjo pretočne krivulje, ki je bila določena z

2. METHODS

The aim of the measurements was to assess the sediment production and sediment yield from the catchment. Measurements included measurements of rainfall, water and suspended sediment discharge and monitoring of sediment production from cliffs in the period 2000–2002. Three cliffs with different activities were chosen in the Rokava sub-catchment. Locations are shown in Figure 3.

2.1 MEASUREMENTS OF WATER DISCHARGE, SUSPENDED SEDIMENT AND BEDLOAD

At location Rokava, a water level recorder and automatic water sampler ISCO 3700 were set up. In an approximately 5 m wide, stable regulated part of the stream, a broad crested weir was constructed by local water management company Hidro Koper. Two pressure transducers of type Druck Ltd. PDCR-830 were placed just upstream (Hobby & Minneboo, 2001). The first transducer recorded the water level at constant intervals (10 or 20 minutes). The second transducer recorded the water level every hour, but also at every 0.5 cm change in water level. The data from the second transducer was logged to the Campbell 212X datalogger. The datalogger triggered the water sampler every time when the change in water level exceeded 5 cm. The automatic water sampler ISCO 3700 could take 24 samples of 500 ml without being emptied. This allowed for satisfactory automatisation of the process. The intake was placed just under the broad crested weir, where the water was well mixed. Thus the representativeness of the samples was ensured. The volume of samples was between 400 and 500 ml. Concentration C_s [g/l] of suspended sediment was determined by determining the exact volume of the sample V_s. Then, the sample was evaporated at 105°C and the dry residual weighted (m_s). The concentration was then calculated as the ratio between m_s and V_s.

The discharge of water was determined from the discharge curve. The discharge curve was determined by occasional measurements občasnimi meritvami pretokov. Pretoki so bili izračunani s trapezno integracijo specifičnih pretokov po širini, ti pa so bili izračunani iz izmerjene hitrosti in globine. Hitrosti so bile merjene z elektromagnetnim merilcem hitrosti OTT Nautilus C2000 (merilno območje 0 ÷ 2,5 m/s).

Določitev prostornine odtoka za posamezen poplavni val je potekala po naslednjem postopku. Najprej sta bila določena začetni t_z in končni čas t_k poplavnega vala. Za začetek poplavnega vala je veljal tisti čas pred nastopom konice, ko je bil pretok najmanjši. Za čas upadanja t_r (od vrha do konca poplavnega vala) je bila izbrana fiksna vrednost, ki je bila na podlagi primerjav poplavnih valov ocenjena na 12 ur. Nadalje je bilo predpostavljeno, da je bazični odtok Q_b do nastopa vrha poplavnega vala enak pretoku ob začetku poplavnega vala, od tam naprej pa linearno narašča do vrednosti na koncu poplavnega vala. Končno je bila prostornina poplavnega vala izračunana z integracijo razlike med izmerjenim pretokom v strugi Q in bazičnim odtokom Q_b:

of discharge at different water levels. The discharges were computed from the measured velocities and cross section geometry. Velocities were measured by electromagnetic flow sensor OTT Nautilus C2000 (range 0 ÷ 2.5 m/s).

The volume of surface runoff for each flood wave was computed by the following procedure. First, the time of the beginning t_z and the time of end t_k of the flood wave was determined. The time of beginning was defined as the time before the peak with lowest discharge. For the recession time t_r (from time of peak to ending time) a fixed value was chosen. The t_r was estimated to 12 hours. Further, we assumed that baseflow Q_b in the time period between the beginning and peak was equal to the discharge at the beginning t_z of the flood wave. From then on, it increased linearly till the end of the flood wave. The volume of surface runoff was computed by integrating the difference between the total discharge Q and baseflow Q_b:

$$V = \int_{t_z}^{t_k} (Q - Q_b) \cdot dt \qquad (1)$$

Letno stopnjo premeščanja rinjenih plavin smo ocenili na podlagi zaprojevanja zaplavnega prostora za pragom vodomerne postaje.

The annual bed load rate was estimated from the volume of the sediment deposited behind the broad crested weir.

2.2 MERITVE SPROŠČANJA S KLIFOV

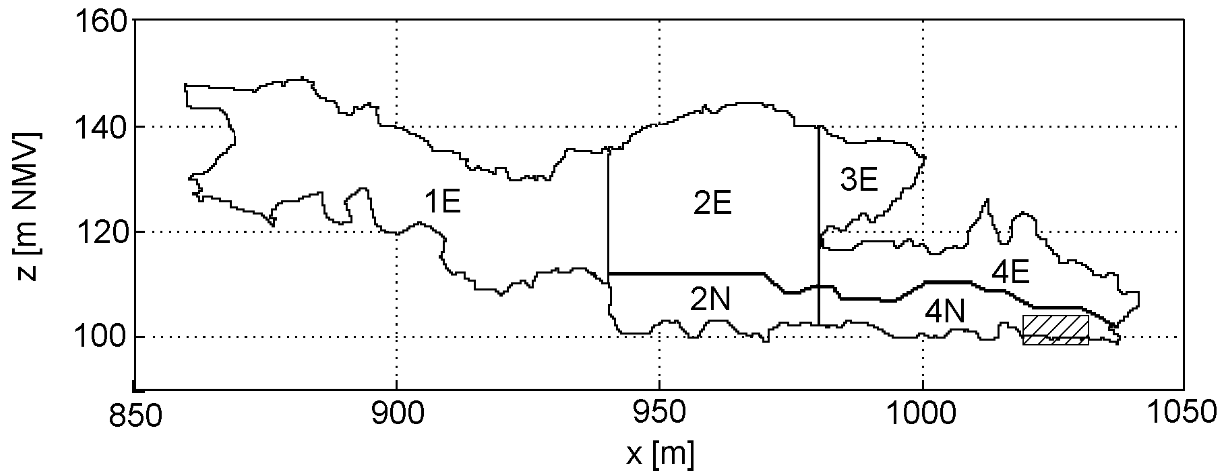
Pri meritvah klifov smo uporabili zanimivo in uspešno kombinacijo fotogrametrične meritve in meritev z erozijskimi žebljiči. Tako smo izmerili tako skupno sproščanje kot tudi kratkotrajno dinamiko sproščanja sedimenta s klifa.

V povodju Rokave smo na podlagi kart identificirali aktivne klife, to je take, ki niso v zaraščanju in lahko na njih še vedno pričakujemo velike stopnje sproščanja. Vsem klifom smo določili velikost, na največjem klifu (Rokava-1, sliki 3 in 4) pa smo opravili tudi podrobno fotogrametrično meritev v treh časovnih presekih.

2.2 SEDIMENT PRODUCTION FROM CLIFFS

For the monitoring of cliffs an interesting and powerful combination of photogrammetric surveys and measurements with erosion pins was used. In this way, we were able to measure both total sediment production as well as its short-term dynamics.

The active cliffs were identified from maps. Every bare steep surface that was not vegetated in the lower part was considered an active cliff. The areas of all active cliffs were measured. On the biggest cliff (Rokava-1, Figures 3 and 4) three photogrammetric surveys were performed.



Slika 4. Klif Rokava-1 v pogledu. Legenda: E – erodirajoči deli klifa; N – odlaganje sedimentov. Šrafirano območje smo spremljali z erozijskimi žeblјiči. Koordinate so lokalne.
Figure 4. Front view of the cliff Rokava-1. Legend: E – eroding areas of the cliff,; N – deposition areas. Hatched area was monitored by erosion pins. Coordinates are local.

Na manjših klifih smo izmerili nekaj značilnih točk, s čimer smo lahko ocenili njihovo velikost. Za določanje razdalj smo uporabili laserski razdaljemer DISTO pro (Leica Geosystems, 2001). Natančnost razdaljemera, kot navaja proizvajalec, je ± 5 mm, merimo pa lahko razdalje do 100 m. Višino točk smo določili po enačbi (2). Oznake razdalj so prikazane na sliki 5. Kljub veliki natančnosti razdaljemera, zaradi manj zanesljivih meritev višin ocenjujemo natančnost metode na ± 10 cm.

The area of smaller cliffs was determined by measuring a number of topographically characteristic points. The distances were measured by the laser distance meter DISTO pro (Leica Geosystems, 2001). The accuracy of the device, as stated by the manufacturer, is ± 5 mm. The distances up to 100 m can be measured. The elevation of points was determined by equation (2) and as shown in Figure 5. In spite of the very accurate distance meter, the overall accuracy was estimated to ± 10 cm due to less accurate measurement of elevation.

$$z = (h_1 - h_0) \cdot \frac{d_1}{b_1} \tag{2}$$

Meritve največjega klifa ob Rokavi smo naročili pri Geodetskem inštitutu Slovenije (GI, 2001; 2002a; 2002b). Natančnost dobljenih 3D-točk je v zgornjem delu do ± 10 cm, v spodnjem delu pa ± 2 cm.

Na podlagi dobljenih točk smo izdelali 3D-model tipa nepravilne trikotniške mreže (TIN). Določili smo nagib ter površino klifa v tlorisu in pogledu.

Pri klifu Rokava-1, ki smo ga posneli v treh časovnih presekih, smo analizirali tudi

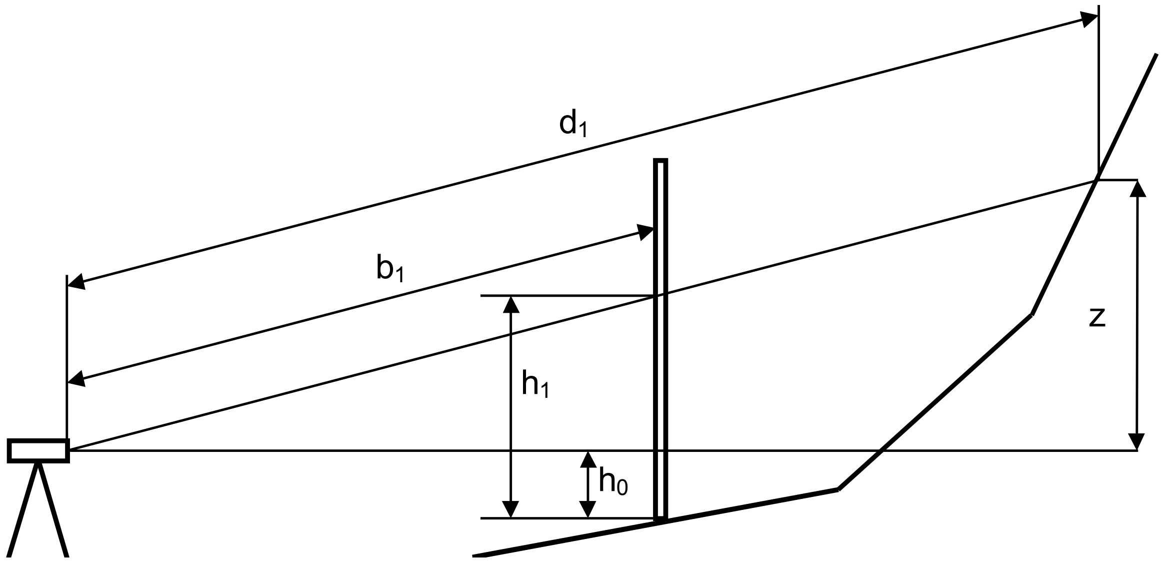
Photogrammetric survey of the biggest cliff Rokava-1 was carried out by the Geodetic institute of Slovenia (GI, 2001; 2002a; 2002b). The accuracy of the obtained 3D points was ± 10 cm in the upper part and ± 2 cm in the lower part.

From the measured points a 3D model of cliff surface was constructed as triangulated irregular network (TIN). Areas in plan and front view were calculated.

The change surface and volume was

spremembo površine in prostornine. Erozijo in odlaganje na tem klifu smo spremljali tudi s pomočjo erozijskih žebljičev. Postavili smo 28 žebljičev v žlebičih ter v medžlebičnem prostoru, in sicer tako na območju, ki je bilo deloma zaščiteno z vegetacijo (šopi trave), kot na nezaščitenem območju. Žebljiče smo razmestili v spodnjem delu klifa na njegovem skrajnem koncu v sotočni smeri (slika 4).

analysed for the cliff Rokava-1, where three time records of the cliff were available. Also, short-term erosion or sedimentation was monitored using erosion pins. A network of 28 pins was set up in three different areas of the cliff: in rills, in the bare interrill area and in the vegetated interrill area. Pins were placed in the lower part of the cliff at its downstream most corner (Figure 4).



Slika 5. Določitev višine merjene točke *z* s pomočjo razdaljemera.
Figure 5. Determination of elevation by distance meter.

2.3 MERITVE EROZIVNOSTI PADAVIN

Padavine smo merili z avtomatskimi dežemeri Siap WL-8100 z ločljivostjo 0,1 mm dežja. Dežemeri so bili postavljeni na izbranih lokacijah v Kocjančičih, Marezigah, ob Rokavi, ob Dragonji in na Koštaboni. Lokacije so podane na sliki 3.

Erozivnost smo izrazili z dejavnikom *R* (Renard *et al*., 1997). Padavinski podatki iz dežemerov so bili najprej razdeljeni na 15-minutne intervale. Nato so bili iz njih izločeni erozivni dogodki oziroma nalivi. Po Renard et al. (1997) je erozivni dogodek definiran kot dogodek, v katerem pade skupaj najmanj 12 mm padavin oziroma največja skupna količina padavin v pol ure preseže 6 mm. Dva dogodka sta ločena, če med njima obstaja šesturni interval, v katerem pade manj kot 1,2 mm padavin.

2.3 RAINFALL EROSIVITY

Rainfall was measured by automatic raingauges Siap WL-8100 with a resolution of 0.1 mm. Raingauges were placed in selected locations in Kocjančiči, Marezige, at Rokava, Dragonja and Koštabona. Locations are shown in Figure 3.

Rainfall erosivity was estimated with the *R* factor (Renard *et al*., 1997). Raw rainfall data was distributed in 15 minute time intervals. Then the erosive events were determined. Following Renard et al. (1997), an erosive event is defined as event, where total amount of precipitation is more than 12 mm or when the maximum amount of precipitation in 30 minutes exceeds 6 mm. Two events are separated if a six-hour time interval exists between them with less than 1.2 mm of precipitation.

Dejavnik R [MJ/ha mm/h] je za en naliv definiran kot produkt energije padavin E [MJ/ha] in največje 30-minutne intenzitete naliva I_{30} [mm/h]:

R factor [MJ/ha mm/h] for a single event is defined as a product of rainfall energy E [MJ/ha] and maximum 30 minute intensity I_{30} [mm/h]:

$$R = E \cdot I_{30} \tag{3}$$

Energija padavin E je odvisna od trenutne intenzitete naliva i^* [mm/h]. Enotsko energijo padavin e [MJ/ha·mm] na enoto površine (ha) in enoto padavin (mm) določimo po empirični enačbi:

The rainfall energy is a function of instantaneous intensity i^* [mm/h]. Unit rainfall energy e [MJ/ha·mm] per unit of area (ha) and unit of rainfall (mm) is calculated by the following equation:

$$e = 0.29 \cdot (1 - 0.72 \cdot \exp(-0.05 \cdot i^*)) \tag{4}$$

Letna erozivnost je seštevek erozivnosti vseh posameznih nalivov v izbranem letu.

Annual erosivity is the sum of erosivities of all events in the selected year.

3. REZULTATI IN RAZPRAVA

3.1 MERITVE PRETOKOV VODE, RINJENIH IN LEBDEČIH PLAVIN

Struga Rokave je del leta suha. Skupen čas, ko je v sezoni 2000/01 po strugi tekla voda, je bil 248 dni. Srednji letni pretok, če računamo samo obdobje, ko je bila v strugi voda, je 428 l/s. Če to preračunamo na celo leto (365 dni), dobimo srednji letni pretok 291 l/s. Največji zabeleženi pretok 19,7 m^3/s v omenjenem obdobju je nastopil 4. 11. 2000. Srednja letna visoka voda v merilnem prerezu znaša Q_2 = 16.3 m^3/s, visoka voda s petletno povratno dobo pa Q_5 = 25 m^3/s (Petkovšek, 2002).

Pri šestih poplavnih valovih v tem obdobju je bila merjena tudi koncentracija lebdečih plavin in izračunan njihov masni pretok (kalnost). Vrednosti so podane v preglednici 1. Pri nekaterih dogodkih so bile izmerjene koncentracije nekajkrat večje od povprečja.

Pri poplavnem valu 14. 9. 2001 je v naraščajoči veji, pri pretoku približno 10 m^3/s, vodomerna postaja prenehala pravilno delovati. Zato podatki o največjem pretoku temeljijo na oceni najvišje dosežene kote vode (sledi na obrežnem grmovju), prostornina poplavnega vala pa je bila ocenjena na podlagi trajanja poplavnega vala in ocene koeficienta odtoka.

3. RESULTS AND DISCUSSION

3.1 WATER DISCHARGE, SUSPENDED SEDIMENT AND BEDLOAD

During summer, there is no water flow in the Rokava stream. Total time with water flow in the season 2000/01 was 248 days with a mean discharge of 428 l/s. If this is averaged over the whole year (365 days), the mean value is 291 l/s. The maximum recorded discharge of 19.7 m^3/s in the period occurred on November 4, 2000. Discharges with characteristic return periods were estimated by Petkovšek (2002). The discharge with a return period of two years equals 16.3 m^3/s, and that of five years equals Q_5 = 25 m^3/s.

Concentration of suspended sediment and their discharges was measured for six events. Values are given in Table 1. At some events, the measured concentrations exceeded the average value by several times.

For the flood wave on September 14, 2001 the water level recorder stopped functioning properly in the rising limb at the discharge of approximately 10 m^3/s. Therefore, the data on peak discharge is based on the highest water level reached, which in turn was estimated by traces left on riparian vegetation. The runoff volume was estimated on the base of the flood wave duration and an estimate of the runoff coefficient.

Preglednica 1. Pregled poplavnih valov na vodomerni postaji Rokava, pri katerih so bile vzorčevane lebdeče plavine. Oznake: izmerjene koncentracije: C_m – srednja vrednost, C_{max} – največja vrednost; M_{SS} – skupna masa premeščenih lebdečih plavin, Q_{max} – največji pretok vode, V_q – prostornina površinskega odtoka, P – višina padavin.

Table 1. Overview of sampled flood events at Rokava sampling station. Explanation of symbols: concentrations: C_m – mean, C_{max} – maximum; M_{SS} – total mass of transported suspended sediment, Q_{max} – peak flow, V_q – volume of surface runoff, P – precipitation.

datum / *date*	C_m	C_{max}	M_{SS}	Q_{max}	V_q		P
d.m.yy	kg/m^3	kg/m^3	1000 kg	m^3/s	1000 m^3	mm	mm
10.10.00	0.72	2.72	61.3	5.6	92	4.7	51
4.11.00	2.72	3.33	759	19.7	275	14.0	79
25.11.00	1.04	5.98	96.5	5.0	89	4.5	29
14.9.01	4.73	14.91	1800*	20*	380*	19.5*	108
7.2.02	0.53	0.88	32.5	1.77	61.8	3.0	23
9.4.02	0.06	0.07	4.2	1.65	66.1	3.2	48

Na podlagi prikazanih rezultatov v preglednici 1 lahko zaključimo, da manjši poplavni valovi odplavijo do 100 ton lebdečih plavin, večji pa tudi 1000 in več ton. V obeh opazovanih sezonah se je pojavil en velik poplavni val in nekaj (5–10) manjših poplavnih valov, ki premeščajo lebdeče plavine. Tako lahko letno odplavljanje lebdečih plavin v opazovanem obdobju s povodja Rokave ocenimo na okrog 1500 ton letno, ta vrednost pa je najbolj odvisna od največjega dogodka v letu. Leto 2001 je bilo, glede na padavine, sicer nekoliko podpovprečno (na lokaciji klimatološke postaje Portorož – Letališče 978 mm v primerjavi z dolgoletnim povprečjem 1013 mm). Meseci oktober, november in december 2000 pa so bili nadpovprečno mokri (na lokaciji Portorož – Letališče 652 mm v primerjavi z dolgoletnim povprečjem v teh mesecih 318 mm).

Razmerje med koncentracijo lebdečih plavin C in pretokom Q niha, zlasti med različnimi poplavnimi valovi. Tako je bila pri dogodku dne 10. 10. 00 koncentracija lebdečih plavin pri pretoku Q = 3 m^3/s le okrog 0,5 g/l, medtem ko je bila pri dogodkih 4. 11. 2000 in 14. 9. 2001 okrog 2 g/l. Opazimo lahko tudi, da se koncentracija lebdečih plavin s pretokom včasih ne zvišuje, najvišje koncentracije se pojavljajo pri relativno nizkih pretokih. To

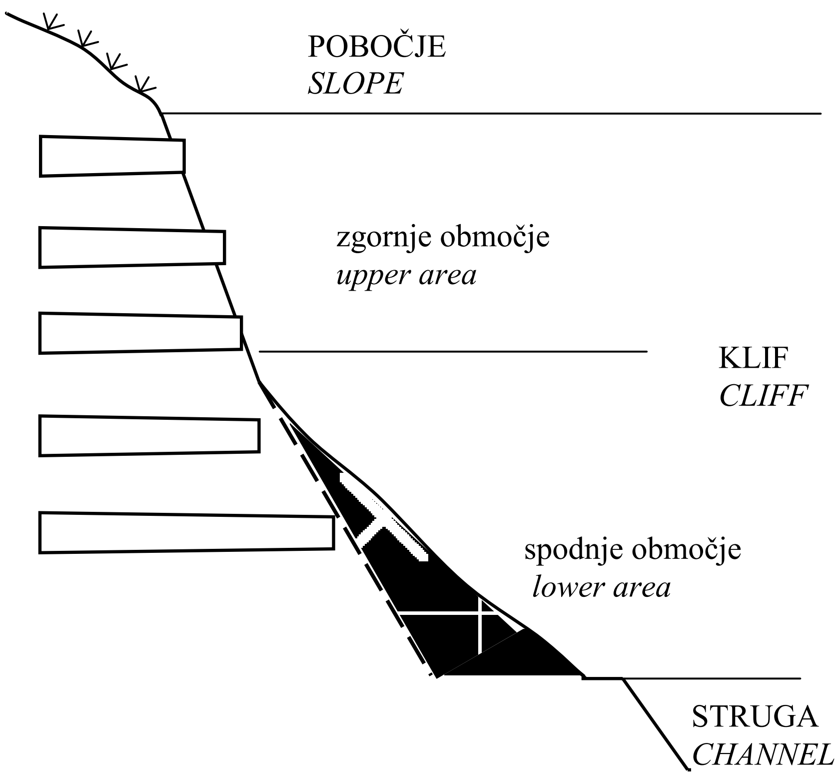
From Table 1 it can be concluded that the suspended sediment discharge at smaller events is approximately 100 tonnes, while at bigger events it is above 1000 tonnes. In both monitored seasons one big event and several (5–10) small events with ability to transport suspended sediment occurred. Therefore, the suspended sediment yield in the monitored period can be estimated to 1500 tonnes per year. Variation mostly depends on the biggest event in a year. The precipitation in the year 2001 was a bit below the mean value. At the location of the climatological station in Portorož Airport, the annual precipitation was 978 mm compared to the long-term average of 1013 mm. The months of October, November and December 2000 were above the long-term average (at Portorož Airport, 652 mm compared to the long-term average in the same months of 318 mm).

Relation between the concentration of suspended sediment C and the discharge Q varies between events. The concentration at the discharge Q = 3 m^3/s was around 0.5 g/l for the event of October 10, 2000, while it was around 2 g/l for events of November 4, 2000 and September 14, 2001. Often the concentration was not increasing with the discharge and the peak in concentration occurred at relatively low discharges. This is especially true for the event of November 4, velja npr. za dogodek 4. 11. 2000. Izmerjeni podatki torej kažejo, da omejitveni dejavnik premeščanja lebdečih plavin ni premestitvena zmogljivost, temveč dotok sedimentov. To potrjuje tudi dejstvo, da na dnu skoraj ni mogoče najti drobnih zrn plavin. Ravno tako lahko sklepamo, da erozija brežin, ki je odvisna predvsem od pretoka vode, ne prispeva bistvenega deleža lebdečih plavin.

Zaplavni prostor za pragom na lokaciji vodomerne postaje Rokava se je zapolnil v času dogodka 4. 11. 2000 (vrh poplavnega vala Q_{max} = 19,7 m^3/s). Prostornino plavin za pragom smo ocenili na 50 m^3. Približno enaka količina rinjenih plavin se je odložila na položnem delu med pragom in stopnjo, ki leži približno 50 m dolvodno. V času tega poplavnega vala se je po strugi skozi presek tik nad pragom torej premestilo najmanj 100 m^3 rinjenih plavin.

2000. The measured data show that the sediment discharge is not transport capacity limited, but supply limited. This can also be confirmed by the fact that there is very little fine sediment in the streambed. It can also be concluded that the bank erosion, which is mostly water discharge dependent, does not contribute a considerable amount of sediment.

The deposition volume behind the broad crested weir at the site of Rokava water level recorder was filled during the event of November 4, 2000 (peak flow Q_{max}= 19.7 m^3/s). Volume of deposited bedload was estimated at 50 m^3. Approximately the same volume was deposited between the broad crested weir and a step located approximately 50 m downstream. Therefore, we estimate that during that event at least 100 m^3 of bedload was transported.



Slika 6. Deli klifa glede na dinamiko sedimentov.
Figure 6. Parts of cliff regarding sediment dynamics.

Preglednica 2. Dimenzije in nagib klifa Rokava-1.
Table 2. Dimensions and slope of the Rokava-1 cliff.

	zgornje območje (erozija) *upper area (erosion)*	spodnje območje (odlaganje) *lower area (deposition)*	skupaj *total*
površina – tloris A_z *area – plan view A_z*	2682 m^2	878 m^2	3560 m^2
površina – pogled A_y *area – front view A_y*	3685 m^2	745 m^2	4430 m^2
nagib *slope*	1.48	0.87	1.32

3.2 EROZIJA S KLIFOV

Na povodju Rokave smo identificirali štiri erozijsko aktivne klife: Rokava-1, Rokava-2, Rokava-3 in Lopar (slika 3). Klifi so sestavljeni iz dveh območij (slika 6): zgornje območje se večinoma erodira, na spodnjem območju klifa se sedimenti začasno odlagajo.

Na podlagi terenskih opazovanj smo prišli do naslednjih ugotovitev o dinamiki sedimentov na klifih:

1. Na zgornjem delu klifa prihaja do erozije, predvsem zaradi preperevanja in zdrsov manjših zemljinskih mas.
2. Drobnejše frakcije se odložijo na spodnjem delu klifa, grobe frakcije pa zaradi večje vztrajnosti padejo neposredno v strugo.
3. Iz spodnjega dela sedimente v strugo odnaša predvsem površinska vodna erozija (medžlebična in žlebična erozija).

3.2.1 KLIF ROKAVA-1

Klif Rokava-1 je največji. Podatki o tem klifu so bili dobljeni s fotogrametričnim snemanjem. Klif je visok do 50 m, širina pa je 180 m. Pogled z značilnimi deli klifa je prikazan na sliki 4. Spodnji del klifa v protitočni smeri je precej zaraščen, tako da tam meritve nismo opravili. Preglednica 2 podaja nekatere značilnosti klifa.

Klif je spodaj zaraščen do x = 980 m (lokalne koordinate, območje 1E na sliki 4), zato lahko sklepamo, da je količina erodiranega materiala, ki doseže strugo, na tem

3.2 EROSION FROM CLIFFS

Four active cliffs were identified in the Rokava catchment: Rokava-1, Rokava-2, Roaka-3 and Lopar (Figure 3). Cliffs consist of two areas (Figure 6): the upper area, where the area is mainly eroded, and the lower area, where sediment is temporarily deposited.

Field observations helped us reach the following conclusion about sediment dynamics on cliffs:

1. In the upper part, the sediment is mostly eroded due to decay and small landslides.
2. Fine sediment is deposited in the lower part of the cliff, while bigger grains tend to fall directly into the streambed.
3. From the lower part, sediment is eroded into the stream mostly by soil erosion processes caused by rainfall (rill and inter-rill erosion).

3.2.1 CLIFF ROKAVA-1

Rokava-1 cliff is the biggest cliff in the catchment. Topography of the cliff was obtained by a photogrammetric survey. The cliff is up to 50 m high and 180 m wide. The front view with indicated characteristic parts is shown in Figure 4. In the upstream direction, the lower part is considerably vegetated and no survey of that part was performed. Table 2 gives some data about the cliff.

The cliff is vegetated up to x = 980 m (local coordinates, area 1E in Figure 4). It can be therefore assumed that the amount of sediment reaching the stream in this part is negligible.

delu majhna. Med x = 980 m in x = 1000 m je na višini z = 120 m klif precej položen in zaraščen, tako da se sedimenti, ki se morebiti sprostijo iz višje ležečih delov, tam ustavijo in prav tako ne dosežejo struge (območje 3E na sliki 4). Površine in nagibi posameznih delov klifa so podani v preglednici 3.

At elevation z = 120 m between x = 980 m and x = 1000 m the cliff surface is nearly flat. The sediment that is eroded from higher parts is deposited there without the possibility of being flushed to the stream (area 3E in Figure 4). Areas and slopes of individual parts of the cliff are given in Table 3.

Preglednica 3. Površine in nagibi območij klifa Rokava-1 (glej tudi sliko 4).
Table 3. Rokava-1 cliff: areas and slopes (see also Figure 4).

območje / *area*	A_z [m^2]	A_y [m^2]	nagib I [-]
1E	1096	1593	1.56
2E	978	1222	1.35
2N	390	370	0.97
3E	194	271	1.50
4E	414	600	1.56
4N	488	373	0.78

Preglednica 4. Prostornine erodiranega in nanesenega materiala na klifu Rokava-1 med 27. 9. 2001 in 5. 2. 2002.
Table 4. The volumes of eroded and deposited material. Cliff Rokava-1, time span September 27, 2001 to February 5, 2002.

V [m^3]	erodirajoči del *eroding area*	nasuti del *deposition area*	skupaj *total*
erodirani material *eroded material*	–10	–54	–73
odloženi material *deposited material*	3	175	178
skupaj *total*	–7	112	105

Razlike med časovnima presekoma 27. 9. 2001 in 5. 2. 2002 so podane v preglednici 4. Med tem časom ni bilo intenzivnih deževij in visokovodnih valov, zato lahko sklepamo, da so spremembe posledica preperevanja materiala oziroma drugih oblik erozije (zdrsi ipd.). Med časovnima presekoma 5. 2. 2002 in 27. 8. 2002 pa je zaradi površinske vodne erozije na nekaterih nasutih delih klifa prišlo tudi do odnašanja materiala.

Zaradi kratkih časovnih obdobij med snemanji in slabše natančnosti meritve v zgornjem delu klifa so rezultati za erodirajoči

The differences between time sections September 27, 2001 and February 5, 2002 are given in Table 4. During that time, there were no intensive rainfall and flood events. Therefore, it can be concluded that the differences are a consequence of material decay and small landslides. On the other hand, between February 5, 2002 and August 27, 2002 rainfall did cause some erosion from the deposition parts as well.

As the time span between surveys is short compared to the accuracy of the surveys in the upper part of the cliff, the results for erosion in del manj zanesljivi. Pri določanju specifičnega letnega sproščanja smo se zato oprli na rezultate odlaganja na spodnjem delu klifa v prvem polletnem obdobju (27. 9. 2001–5. 2. 2002), ko erozije na tem območju klifa skoraj ni bilo. Če predpostavimo, da se je ves sproščen material odložil na klifu, lahko izračunamo, da je specifično letno sproščanje na enoto tlorisne površine okrog 500 m^3/ha oziroma na enoto površine v pogledu okrog 400 m^3/ha.

3.2.2 DRUGI KLIFI

Poleg velikega klifa smo izmerili tudi druge manjše aktivne klife. Preglednica 6 podaja nekatere dimenzije in nagibe klifov. Pri klifu Rokava-3 območja nasipanja nismo zaznali v nobenem obdobju. Zato smo sklepali, da klif ne prispeva pomembnejše količine sedimentov v strugo.

Iz preglednice 6 vidimo, da so v primerjavi s klifom Rokava-1 drugi klifi mnogo manjši. Njihova skupna površina je približno petkrat manjša. Iz nagibov spodnjega dela klifa lahko izračunamo strižni kot erodiranega materiala. Ta znaša med 35° (Rokava-2) in 41° (Rokava-1). To so precej visoke vrednosti, ki pa so glede na obliko (ravnokar odlomljen oglat material) pričakovane.

3.2.3 PRIMERJAVA S PODOBNIMI MERITVAMI V HRVAŠKI ISTRI

O meritvah sproščanja s klifov poročajo iz hrvaškega dela Istre (Jurak et al., 2002), ki so od leta 1995 s fotogrametrično metodo merili sproščanje s klifa v Sv. Donatu (A_z = 2191 m^2, A_y = 3856 m^2) in erozijske eksperimentalne ploskve v Abramih (A_z = 8,9 m^2, A_y = 3,7 m^2).

Tam znaša specifično letno sproščanje med 393 in 497 m^3/ha v tlorisu oziroma med 200 in 269 m^3/ha v pogledu. Vrednosti so podobne, kot smo jih dobili na klifu Rokava-1. To je pričakovano, saj so klifi tako v topografskem kot geološkem pogledu podobni.

the upper part are less reliable. Therefore, the results from the lower part in first half-year (27 Sept. 2001–5 Feb. 2002) were chosen for calculation of specific (per year and area) sediment production from the cliff. There was hardly any erosion of sediment from this part. If we assume that all the sediment eroded from the upper part of the cliff was deposited in the lower part, the specific annual sediment production can be estimated at 500 m^3/ha of area in plan view or 400 m^3/ha in front view.

3.2.2 OTHER CLIFFS

In addition to the biggest cliff, other cliffs were also measured. Their sizes and slopes are given in Table 6. Cliff Rokava-3 had no deposition area and therefore it was concluded that the amount of the sediment contributed to the stream network is negligible.

From Table 6 it can be seen that the other cliffs are much smaller in comparison to the Rokava-1 cliff. Their total area is about five times smaller. From the slope of the lower part of a cliff angle of repose of the eroded material can be calculated. It is between 35° (Rokava-2) and 41° (Rokava-1). These values are high but considering the shape (freshly broken angular material) they are expected.

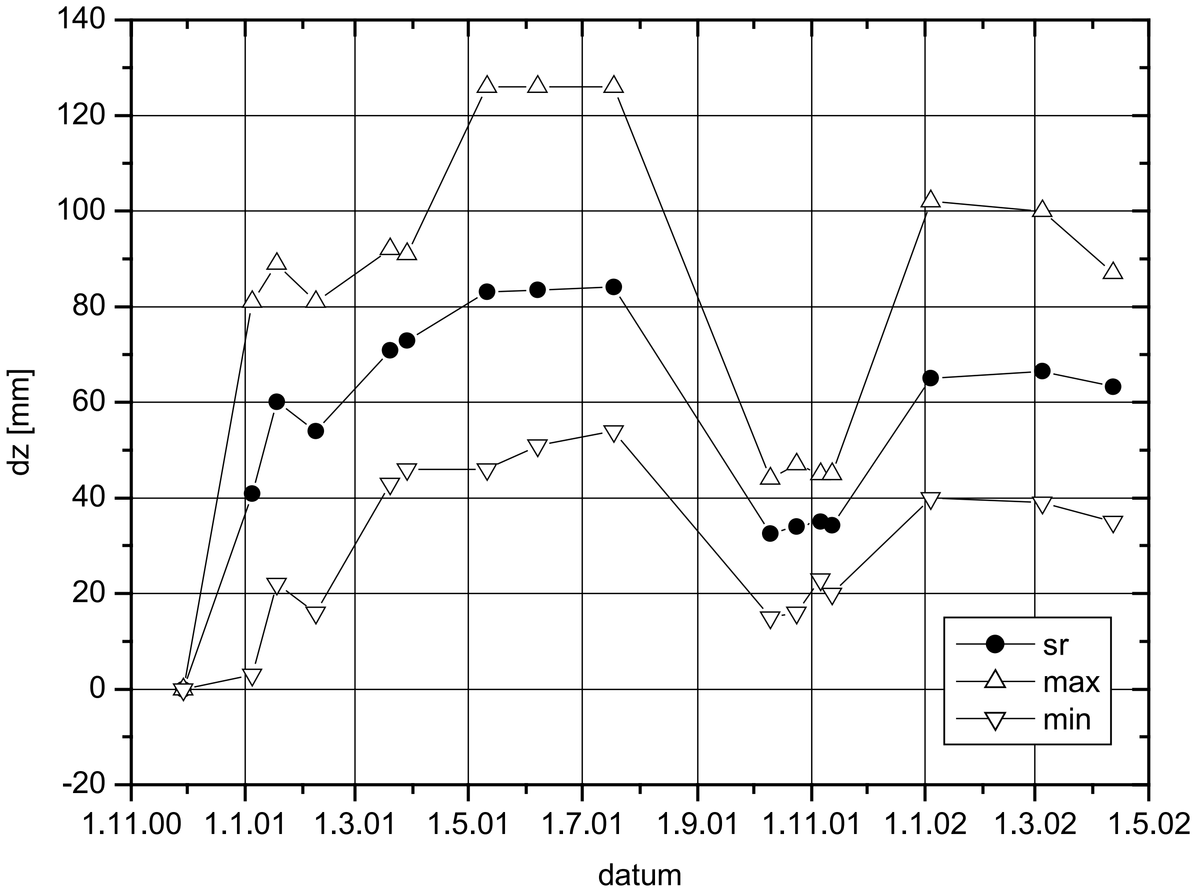
3.2.3 A COMPARISON TO SIMILAR MEASUREMENTS IN CROATIAN ISTRIA

Jurak et al. (2002) report about sediment production from cliffs in the Croatian Istria. From 1995, photogrammetrical surveys of the cliff in Sv. Donat (A_z = 2191 m^2, A_y = 3856 m^2) and experimental erosion plot in Abrami (A_z = 8.9 m^2, A_y = 3.7 m^2) were performed.

Specific annual sediment production from these cliffs is between 393 and 497 m^3/ha in plan view and between 200 and 269 m^3/ha in front view. These values are similar to the ones obtained from Rokava-1 cliff. Similarity could be expected since the cliffs are similar in topography and geology.

Preglednica 6. Dimenzije in nagibi manjših klifov.
Table 6. Size and slope of smaller cliffs.

klif *cliff*	A_z [m^2]	A_y [m^2]	nagib / *slope*	
			nasuti del *deposition area*	erodirajoči del *eroding area*
Rokava-2	320	310	0.7	1.5
Rokava-3	50	150	-	3.0
Lopar	360	310	0.75	1.8



Slika 6. Napredovanje sedimentacije v žlebičih (n = 8).
Figure 6. Dynamics of sedimentation in rill area (n = 8).

3.2.4 MERITVE Z ŽEBLJIČI NA KLIFU ROKAVA-1

Napredovanje sedimentacije v žlebičih je predstavljeno na sliki 6. Iz slike 6 vidimo, da je klif v obdobju od maja do julija tako rekoč neaktiven. Največja sprememba se zgodi z nastopom pozno poletnih oziroma zgodnje jesenskih nalivov z veliko erozivno močjo

3.2.4 MONITORING WITH EROSION PINS AT ROKAVA-1 CLIFF

The dynamics of the sedimentation in the rill area is shown in Figure 6. From Figure 6 it can be seen that the cliff is practically inactive in the months of May and June. Changes are fastest in late summer and early autumn and are caused by intensive rainfalls (Petkovšek,

(Petkovšek, 2002). Takrat se na novo pojavijo žlebiči, v katerih se nato zlasti v novembru in decembru, pa tudi še v pomladanskih mesecih, znova odlagajo sedimenti, dokler se žlebič ne izravna z okoliško površino. Na podlagi meritev smo ugotovili, da so žlebiči globoki do 10 cm, široki okrog 20 cm, dolžina pa je odvisna od velikosti nasutega dela klifa, kjer se pojavljajo. Tipična dolžina je med 5 in 10 m.

3.3 EROZIVNOST PADAVIN

V obravnavanem obdobju od se je na obravnavnem območju pojavilo sedemnajst velikih dogodkov, ki so na vsaj eni lokaciji presegli mejo R = 100 MJ/ha mm/h. Slika 7 za te dogodke prikazuje erozivnost padavin po lokacijah. Preglednica 8 podaja višino padavin P, največjo polurno intenziteto padavin I_{30} in erozivnost padavin R za deset največjih dogodkov.

Iz rezultatov vidimo, da so se nalivi z veliko erozivnostjo pojavljali pozno poleti in jeseni (julij–november). Zunaj tega obdobja, to je v desetih mesecih od decembra 2000 do junija 2001 in od decembra 2001 do februarja 2002, sta se pojavila le dva velika dogodka.

Poletni erozivni dogodki so prostorsko omejenega značaja, če upoštevamo, da je razdalja med dežemeri le nekaj kilometrov. Tako je bil dogodek 10. 7. 2001 eroziven tako rekoč le v Kocjančičih, 29. 7. 2001 pa predvsem v Koštaboni. Tudi pri ostalih dogodkih je opazno izrazito prostorsko spreminjanje erozivnosti padavin.

Posebno pozornost zasluži dogodek 31. 8. 2001, ko je največja polurna intenziteta padavin I_{30} presegla 100 mm/h. Podobne in večje vrednosti so sicer značilne za poletne in jesenske nalive na območju Sredozemlja. Martinez Casanovas et al. (2002) navajajo dogodek iz osrednje Katalonije (Španija) junija 2000, ko je največja polurna intenziteta padavin dosegla I_{30} = 170 mm/h, erozivnost dogodka pa kar R = 11.756 MJ/ha mm/h.

2002). Rills are formed at that period of year. From then on, the sediment is deposited in rills (especially in November, December) till they are filled and levelled with the rest of the cliff surface in spring. Measurements showed that the rills are up to 10 cm deep and 20 cm wide while the length depends on the size of the deposition area where a rill is formed. Typical lengths are between 5 and 10 m.

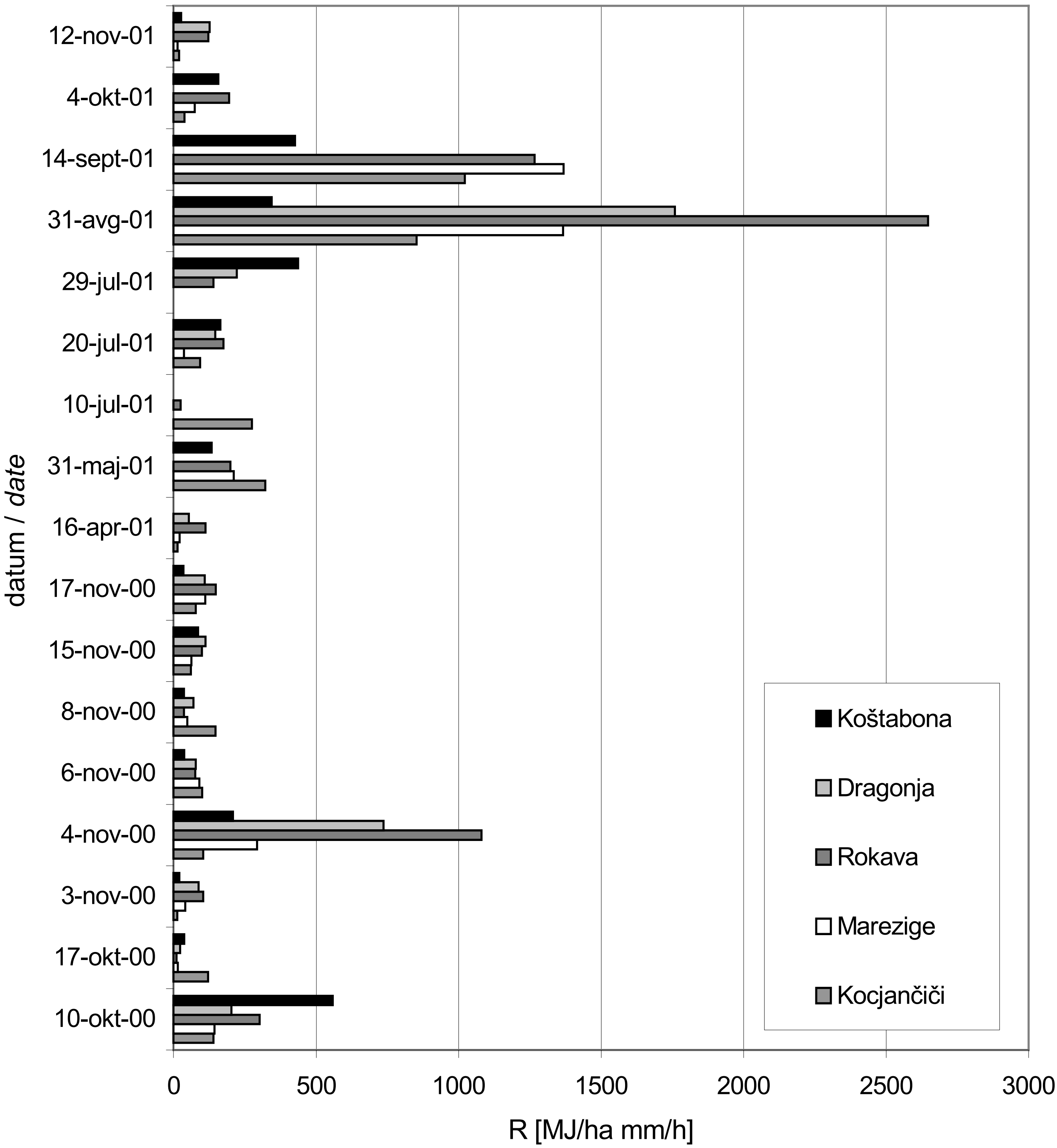
3.3 RAINFALL EROSIVITY

In the monitored area and the period of observation, seventeen big events occurred that exceeded the limit of R = 100 MJ/ha mm/h in at least one location. Figure 7 shows the value of R factor for these events for all locations. Table 8 gives precipitation P, maximum 30 minute intensity I_{30} and R factor for ten biggest events.

The results indicate that the storms with high erosivity occur in late summer and in autumn (July–November). Outside of that period, i.e. in ten months between December 2000 and June 2001 and December 2001 and February 2002, only two big events occurred.

During the summer, erosive events are of spatially limited character, considering that the distance between the raingauges is only a couple of kilometres. The event of July 10, 2001 was limited to Kocjančiči, while the event of July 29, 2001 was more or less limited to Koštabona. A similar pattern could be observed at other events.

A special attention must be paid to the event of August 31, 2001, when the maximum 30 minute intensity I_{30} exceeded 100 mm/h. Similar values are characteristic for summer storms in the Mediterranean. Martinez Casanovas et al. (2002) inform about an event from central Catalonia (Spain), where in June 2000 the following values were recorded: I_{30} = 170 mm/h and R = 11756 MJ/ha mm/h.



Slika 7. Pregled dogodkov z veliko erozivnostjo (R > 100 MJ/ha mm/h).
Lokacije so razvrščene v obratni smeri vodnega toka.
Figure 7. Overview of the events with high erosivity (R > 100 MJ/ha mm/h). Locations are ordered in the upstream direction.

Preglednica 8. Pregled desetih največjih erozivnih dogodkov.
Table 8. Overview of ten biggest erosive events.

Št. / *No*	datum / *date* d.m.yy	Lokacija *Location*	P mm	I_{30} mm/h	R MJ/ha mm/h
1	31.8.2001	Rokava	86.5	108.8	2647
2	31.8.2001	Dragonja	74.2	85.5	1759
3	14.9.2001	Marezige	105.2	54.4	1368
4	31.8.2001	Marezige	62.8	79.7	1366
5	14.9.2001	Rokava	115.6	44.8	1267
6	4.11.2000	Rokava	61.2	68.6	1081
7	14.9.2001	Kocjančiči	105.0	42.1	1022
8	31.8.2001	Kocjančiči	68.2	50.7	853
9	4.11.2000	Dragonja	54.4	54.7	736
10	10.10.2000	Koštabona	84.9	32.6	558

4. ZAKLJUČEK

Na podlagi opravljenih meritev od jeseni 2000 do pomladi 2002 lahko povprečni letni odtok lebdečih plavin s povodja Rokave ocenimo na okrog 1500 t (750 kg/ha), povprečni letni odtok rinjenih plavin pa na vsaj 10 % te vrednosti.

Ocenjujemo, da je premeščanje večjih zrn rinjenih plavin omejeno v povprečju na en dogodek letno. Rinjene plavine izvirajo predvsem iz klifov in morda bočne erozije že odloženega materiala.

Rezultati kažejo, da je vir večjega dela lebdečih plavin površinska erozija, manjšega pa klifi (nekaj 100 m^3 oz 100 ton letno). Za natančnejšo določitev deležev so potrebne dolgotrajnejše meritve.

Erozivni dogodki so zelo neenakomerno razporejeni, tako časovno kot prostorsko. Največji dogodki se pojavljajo pozno poleti in jeseni. V tem času je tudi erozijska aktivnost klifov največja.

Pri meritvah klifov se je za uspešno izkazala kombinacija fotogrametrične meritve in meritve z erozijskimi žebljiči.

4. CONCLUSION

The following conclusions apply to the measurements in Rokava catchment from autumn 2000 to spring 2002. The average annual suspended sediment yield is around 1500 t (750 kg/ha).

The average annual bedload transport is about one tenth of that value and on average occurs during one event per year. The source of bedload is rocks that originate from cliffs and possibly bed and bank material.

The results show that the source of suspended sediment is mostly surface erosion, while cliffs contribute a couple 100 m^3 or approximately 100 tonnes per year. Further measurements in a longer period are required to obtain more precise results.

Erosive events are highly variable both temporally and spatially. The biggest events usually occur in late summer and in autumn. During this time, the activity of the cliffs is also at its peak.

For monitoring of cliffs, the combination of photogrammetry and erosion pins proved to be successful.

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