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The gully of Potovošća on the Island of Krk – The effects of a short-term rainfall event

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ABSTRACT

The rainfall event during the night of 10th–11th September 2007 caused strong erosion in the gully of Potovošća on the Island of Krk. In the main fan, two new gullies and two fans were formed. Those morphological changes have been mapped, measured and explained, across the drainage basin in terms of topography and precipitation intensity. The drainage basin morphology was studied using GIS that allowed comparison of morphological and dynamic relationships within the study area. In order to obtain the relative potential erosion intensity between different points in the basin, as well as to differentiate areas with areal (diffuse) erosion from those with dominant linear erosion, the Stream Power Index (SPI) was calculated. The drainage basin specific properties were further related to the event specific properties, precipitation intensity and hydrologic estimations. The rainfall intensities obtained, allow the calculation of discharge at the gully mouth and the definition of recurrent periods using the rational method. The rainfall-runoff event studied was also influenced by the relatively high Antecedent Precipitation Index (API). This allows explanation of the morphological consequences of the short-term event. Consequently the interrelationship between short-term and long-term events has been discussed. In addition, the physiography of the gully has been recently modified by human interference, which has also influenced the morphological consequences of the aforementioned short-term rainfall event.

Keywords: gully erosion, precipitation intensity, rainfall-runoff relationship, beach dynamics, Krk Island, Croatia

1. INTRODUCTION

The shorelines of the Island of Krk are primarily rocky. Rocky coasts are predominantly erosional forms, while unconsolidated and poorly consolidated sediments like beaches are primarily depositional in nature, these being present to a much lesser extent. A beach is an accumulation on the shore of generally loose, unconsolidated sediment, ranging in size from very fine sand up to pebbles, cobbles and occasionally boulders (BIRD, 2008). Most of the beaches on the Island of Krk, as well as those along the whole Adriatic coast, are formed of sediments, which range between sand and pebble and, rarely, cobble in size. The majority of the beaches along the Croatian coast are formed from proluvial fan material of the drowned torrent karstic valleys similar to the gully of Potovošća (Fig. 1). Occasional flows bring pebbles and cobbles and form fans, in which gravely beaches formed in contact with the sea. Therefore, as is usual in temperate zones, the beach material is primarily composed of sediments of terrigenous origin (PIRAZZOLI, 1993). These are sands and pebbles that come from the hard fluvial drift (alluvium), or from the destruction of headlands. In the areas of less resistant rocky coasts, wave-cut notches are formed and cliffs evolve. The pebble beaches at the foot of the cliffs are relatively narrow, due to the quite short (less than 6 000 years) period of wave action on the coast. Such an example can be found near the studied area, the beach and the Pod Črnice cliff (Fig. 1) which is still an active cliff, 132 m long, with notches at its foot, and a beach up to 10 m wide (Faivre, unpublished).

The gully of Potovošća is 4.2 km long with a catchment area of 3.3 km^2. It is formed in the upper Cretaceous limestone, mainly reef and foraminiferal limestone (according to ŠUŠNJAR et al., 1970) (Fig. 2). This gully is episodically active, but some of the nearby gullies also lose their hydrological function. This can be observed in the bay of Kozica, near Vrbnik (Fig. 1), which is largely filled today with a thick cover of colluvial sediments (> 2 m), (Faivre, unpublished).

This study of the gully of Potovošća, is part of a larger work examining several gullies and beaches in this region, including the aforementioned Pod Črnice cliff and Kozica gully, together with the gully in Vrbnik (Luka Vrbnik), the gully of Prva draga near Senj and Uboka near Mošćenička draga (Fig. 1). The primary aim was to identify gullies with beaches showing different patterns of evolution.

The relationship between the recent morphology of these torrent valleys, morphology of the bays and present sea level indicates that the valleys and gullies had been formed earlier, when sea level was lower. The dynamic geomorphology of the Kvarner area coastline is regulated by interrelated changes in sea level, erosion and deposition of sediments along the coastal margins (JURAČIĆ et al., 1999; SURIĆ & JURAČIĆ, 2010). Under postglacial conditions or rapidly rising sea levels, the dominant geomorphic process shifts from erosion to deposition, with finer sediments deposited in bays or estuaries formed at the mouths of newly flooded coastal canyons rather than along the coastline. As sea-level rise slows, these estuarine and gully embayments fill with sediments (BENAC et al., 1991; FAIVRE et al., 2011). Following this culmination of sea-level rise, new bays were formed and actual beaches shaped in proluvial fans. In such a way numerous pocket-beaches have been formed along the eastern rocky coast of the island of Krk.

The dynamics of pocket beaches has not been studied to the same extent as the open sandy beaches. There are very few papers dealing with this kind of subject (e.g. STORLAZZI & FIELD, 2000), particularly those related to the Kvarner area (e.g. BENAC, 1996; JURAČIĆ et al., 2009; BENAC et al., 2010). Gullies on the island of Krk have been studied by BENAC (1992) explaining that most of them are not active any more, meaning there is no flow even in periods of intensive rainfall. Their bottoms are covered with humus and redeposited clay and are overgrown with vegetation. According to BENAC (1992) this is a clear indicator of relief energy decrease as a consequence of Holocene sea level rise. The latest paper of BENAC et al. (2010) deals precisely with the morphodynamics of the Kvarner area pocket beaches.

Observing the changes in beach morphology after a heavy rainfall event in the field, we try to examine this short event, as best as possible, studying morphometric relief parameters, climatic elements from the nearest stations and their morphological consequences. The aim is to determine how the pocket beaches react to such short-term events and to estimate climatologic and hydrological properties which can produce the changes observed. The new opened profile in the beach allows questions to be raised on the longer term evolution of the beach.

Sedimentary features such as beaches are perceived as having high social and economic value today. Therefore, human impact is more and more accentuated along the Croatian coast. The beach of Potovošća has just started to come under

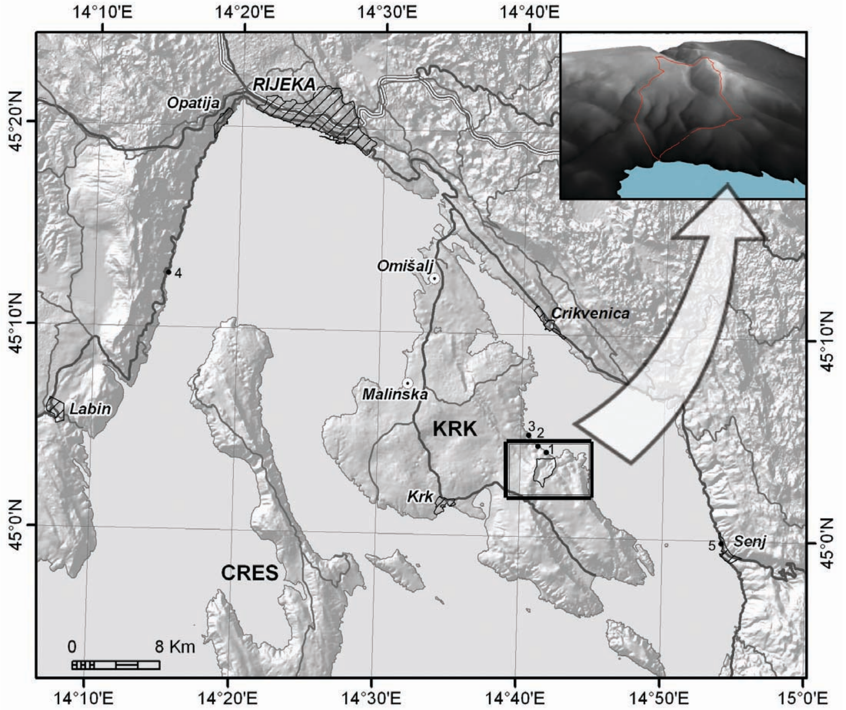

Figure 1: Study area with several other beaches mentioned in the text (1-Pod Črnice; 2-Kozica; 3-Luka Vrbnik; 4-Uboka; 5-Prva draga).

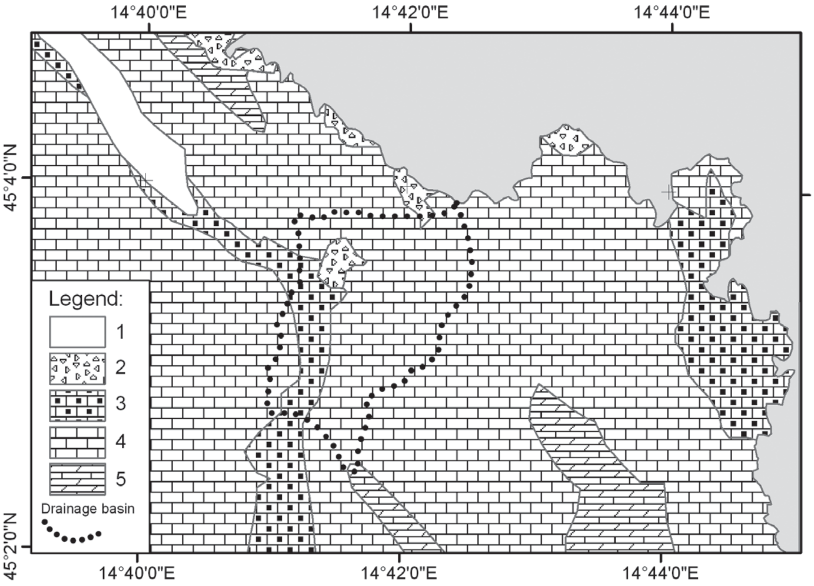

Figure 2: Lithological map of the studied area, (ŠUŠNJAR et al., 1970). Legend: 1-Quaternary sediments, 2-Limestone breccias, 3-Foraminiferal limestone, 4- Reef limestone, 5-Dolomites with limestone fragments.

the first direct human impact. Since 2006, the beach has been under concession and it is artificially levelled for tourism purposes every year in July. Consequently, we must take not only natural but also anthropogenic factors into account in this study.

2. MATERIALS AND METHODS

The first field investigation started a week after the event. All the morphological changes were mapped and measured using GPS Garmin eTrex Vista HCX. The results have been presented on the Main Croatian Map 1: 5000 from the State Geodetic Survey. The precise longitudinal profile across the fan of the gully was made using a Suunto clinometer, calculating inclinations at 20 points. The part submerged by the sea has also been mapped and measured, corrected for tide, pressure and wind. The coastline has been mapped several times since 2007. Further study of this event has been undertaken through the analysis of the drainage basin specific properties and event specific properties.

The drainage basin properties were analysed using GIS, whereby, the digital relief model was interpolated on the basis of altitudinal data, digitalized contour lines, elevation points and breaklines of slope from the topographical map on the scale of 1: 25000 (E=10 m). The TIN relief model of the investigated area was generated from these data, and later transformed into a raster grid structure with 10 × 10 m cells. The calculated digital relief model was the basis for the digital geomorphologic analyses of the drainage basin parameters. For these analyses and visualization of the obtained results, the ArcGIS Version 9.3 programme package was used, including Spatial Analyst and 3D Analyst extensions.

Morphometric characteristics of the drainage basin, that is, hypsometrical properties, the distribution, shape and the angle of slopes as well as the distribution and orientation of the ridges and valleys represent the basis for the analysis of derasion and erosion intensity. The calculation of quantitative indicators of dynamical geomorphologic processes inside the river basin, primarily using the digital relief model, is the basis for numerous methods inside the digital relief analyses (GALLANT & WILSON, 2000). As an indicator of the potential erosion intensity inside the whole investigated area, the values of the Stream Power Index were calculated at particular points of the drainage basin. The Stream Power Index is calculated according to the equation (MOORE et al., 1991):

$$\mathrm{SPI} = \ln(A_s \times \tan\beta),$$

where

A_s (m²/m) – is the specific catchment (catchment area draining across a unit width of contour), and

$\beta(°)$ – the slope angle in the studied point (cell of the GRID).

To analyse the event specific properties different methods have been used. Precipitation intensity was calculated in order to establish the volume of precipitation that falls on the studied area. The precipitation intensity is defined as the precipitation volume that falls over a particular area in a defined time-period (ŠEGOTA & FILIPČIĆ, 1996). As it is recommended to observe only periods with registered precipitation, precipitation intensity was calculated as a quotient of the precipitation volume and of the number of days with precipitation.

As there are no precipitation data for the researched location, the data from the nearest stations were used. Those are: the meteorological stations at Crikvenica, Senj, Omišalj (airport), Malinska and Krk (Fig. 1). In order to get a better overview of precipitation intensity at the stations mentioned, the precipitation amount was analysed for the 1981–2007 period. Since no continuous data-series exist for the meteorological stations of Malinska and Krk, shorter time series were analysed. With the aim of analysing precipitation amount on 11th September and its relationship to average precipitation, standard deviation is calculated. According to CON-

RAD & POLLAK (1950), the following are the groupings and nomenclature of precipitation deviation from averages:

above +3 σ	extremely above normal
between +2 σ and +3 σ	greatly above normal
between +σ and +2 σ	above normal
between + σ and – σ	normal
between –2σ and – σ	subnormal.

The Inverse Distance Weighted (IDW) interpolation method (Power 3.5) has been used to define the precipitation intensity for the studied area, with Root Mean Square Error (RMSE) = 38.7. This method was chosen because the calculated error was the smallest. The inverse distance weighted interpolation determines cell values using a linearly weighted combination of a set of sample points. The weight is a function of inverse distance. The *Power* option of IDW lets us control the significance of known points on the interpolated values, based on their distance from the output point. It is a positive, real number.

Furthermore, there are several other methods that could be used for precipitation analyses which can give more precise insights into the rainfall-runoff relationship in small drainage basins, like the Potovošća one. One of these is short-term precipitation analysis. In the research area and its surroundings, short-term precipitation is only continuously measured at the Senj and Rab meteorological stations, while on the Omišalj airport station the data are not continuous and could not be obtained from the Meteorological and Hydrological Service in Zagreb. Consequently due to the lack of data, it was not possible to conduct precise analyses of short-term heavy rainfalls.

As an alternative to short-term rainfall analyses the analyses of annual maximum daily precipitation are mostly used for small drainage basins (RUBINIĆ et al., 1995; GAJIĆ-ČAPKA & ČAPKA, 1997; GAJIĆ-ČAPKA, 2002). Analysis of annual maximum daily precipitation, using some of parameters methods, could be conducted if long-term data series are available. GAJIĆ-ČAPKA (1999) showed that in the Croatian Littoral the series of annual daily maximum precipitation values stabilizes during the time span of 80 years, consequently long-term data series are required. They are needed for short-term heavy rainfall analyses as well. RUBINIĆ (2003) suggests usage of data series of at least 50–60 years. Since the available data series are far too short for all the meteorological stations on Krk island (less than 30 years), the parameters methods couldn't be undertaken, to meet the requirements of this paper. Therefore, the results of RUBINIĆ (2006) were used, which provide an estimate of short-term heavy rainfall in the broader regional context that also allows us to give some hydrological estimation.

For the calculation of peak discharge (maximal stream flow) in the Potovošća drainage basin, the rational method was used. This is a simple technique for estimating a discharge from a small watershed. It was developed by MULVANEY (1851) and further advanced by KUICHLING (1889) for drainage basins in urban areas. The method is described in many textbooks (e.g. ŽUGAJ, 2000). It is based on a formula that relates the runoff-producing potential of the watershed, to the average intensity of rainfall for a particular length of time (the time of concentration), and the watershed drainage area. The formula is

$$Q = C * i * A * C_u,$$

where:

Q – maximal flow (peak) [m^3/s]
C – rational (runoff) coefficient
i – rainfall intensity [mm/s]
A – surface of the drainage basin [km^2]
C_u – units conversion coefficient (1000)

The rainfall or storm intensity, i, is a function of geographic location and design exceedence frequency or return interval. Consequently, the longer the return interval it is the greater the precipitation intensity for a given storm duration. Furthermore, the longer the length of the storm, the lower the storm average precipitation intensity (THOMPSON, 2006). The relationship between these three components, storm duration, storm intensity and storm return interval is represented by curves called intensity-duration-frequency curves (IDF curves). The climatological data for the creation of IDF curves of defined recurrent periods have been used from RUBINIĆ (2006) who calculated maximal short-term heavy rainfalls (mm) inside the defined periods (24h; 12h; 6h; 2h; 1h; 40'; 30'; 20' and 10') according to the recurrent periods (1.25; 2; 5; 10; 20; 50; 100 years) for the Punat area. As there is no available adequate data for Krk Island area at all, RUBINIĆ (2006) used data from the nearby stations of Pula, Rijeka and Senj obtaining data of larger regional significance. In this paper the rainfall intensity was calculated using the following formula:

$$i = H/t_o$$

where:

i – rainfall intensity (mm/s)
H – rainfall amount (mm)
t_o – length of the rainfall (period, interval) (min),

that is, the IDF curves have been obtained for defined recurrent periods. As the rainfall intensity (i) is a function of the concentration time t_c and the recurrent period P, where $i = f(t_c, P)$ the time of concentration t_c have been calculated to select the average rainfall intensity from IDF curve.

The time of concentration, t_c, of a watershed is the time required for runoff to travel from the hydraulically most distant point to the outlet of a watershed (KIRPICH, 1940; McCUEN et al., 1984). T_c is a time parameter widely used to estimate peak discharges in hydrologic designs. The concept of t_c is useful for describing the time response of a watershed to watershed runoff, that is at t_c the watershed is fully contributing. If the chosen storm duration is larger than t_c then the rainfall intensity will be less than that of t_c. Therefore, the peak discharge estimated using the rational method will be less than the optimal value. If the chosen storm duration is less than t_c, then the watershed is not fully contributing to runoff to the outlet for the storm length, and the optimal value will not be realised, therefore it is defined that the storm length is equal to t_c for use in estimating peak discharge using the rational method. As it is very small drainage basin, the KIRPICH (1940) formula has been used for calculation of the time of concentration of the Potovošća drainage basin as follows:

$$t_c \text{ [hours]} = 0.00032{*}L^{0.77}{*}I_{max}^{-0.385},$$

where:

L – Maximal length of the travel of water [m]
I_{max} – down drop of the drainage basin ($\Delta H/L_{max}$).

According to the standard tables (ŽUGAJ, 2000) for steep slopes, the runoff coefficient C was defined as C = 0.3. From the obtained parameters, the maximal stream flow, that is the peak discharge, Q (q_{peak} mm/s) for the Potovošća drainage basin according to defined recurrent periods has been calculated.

For the calculation of short-term rainfall intensity for the night of 10th–11th September 2007, only the hourly rainfall time series for Senj and Rab meteorological stations have been obtained, and according to which the discharge during the studied event has been estimated.

As the soil moisture condition prior to a rainfall event has a great influence on runoff generation process, higher moisture content, generally, leads to a higher runoff generation (CHOW, 1988; DESCROIX et al., 2002) and *vice versa.* Hence, the antecedent precipitation index (API) [mm] is often used as a measure of soil moisture condition. It is based on the assumption that soil moisture after a rainfall event decreases exponentially (PATIL, 2008). The more time elapsed after rainfall has ceased the less moisture remains in the soil due to evaporation and infiltration losses. So, the API has been calculated using the following equation:

$$API(t_0) = \sum_{i=1}^{n} P_{dly}(t_{0-1})\,\lambda^i$$

where:

P_{dly} – daily rainfall
λ – decay factor

The decay factor λ normally ranges between 0.85 and 0.98 (HEGGEN, 2001), depending on the catchment of the region, but most of the empirical investigations suggest λ=0.90 (PATIL, 2008). Therefore this value was used in the study. In API usage, i, is typically 5, 7, or 14 days (HEGGEN, 2001). In this study API time series have been calculated with 7 antecedent days (n=7 days).

3. RESULTS

3.1. Morphological consequences of the short-term event

After a long period of dry weather a strong storm with very intensive rainfall occurred during the night of 10th–11th September 2007. The gully became active and the beach responded almost instantaneously to the high volume of water flow. During the storm, two incised gullies were formed in the beach (Figs. 3 & 4a). The western one, 18 m long, does not have any visible torrent bed in the background today, while the eastern gully is a continuation of the main gully system. During the storm, water also came from fresh water sources located longitudinally to the beach near the dry walls. Two new fans, around 8 m long, were formed in the sea (Fig. 4a) mainly from beach sediments. They are positioned on the edges of the previous, older and larger fan (Fig. 3). The gullies in the beach were 7 and 9 m wide, respectively, at the mouth. Both of them were incised 80 cm into the beach sediments (Fig. 3). According to the morphology of the new gullies, the volume of the eroded beach sediments was calculated as ~130 m^3±10%; 58 m^3 for the eastern and 72 m^3 for the western gully. The accuracy of the calculated volume is limited because of the relatively small number of measured points. The layers of different size beach sediments are easily observed on the profiles of the gullies.

In the profile of the eastern gully, a succession of organic layers is observed, indicating the periodic torrential episodes. In the western profile, a layer of boulders is observed 60 cm below the upper beach surface. Their position and size point to the ancient torrent valley (Figs. 3 & 5). These relationships could also be related to a lower sea level of that period, as well as to the landward migration of the beach profile.

The same storm had much less visible impact on the hard rocky coast, but while changes to rocky coasts are long-lasting to permanent, beaches may quickly recover from storms. Most beaches are susceptible to raid morphological changes. Their topography and volume vary with wave-climatic re-

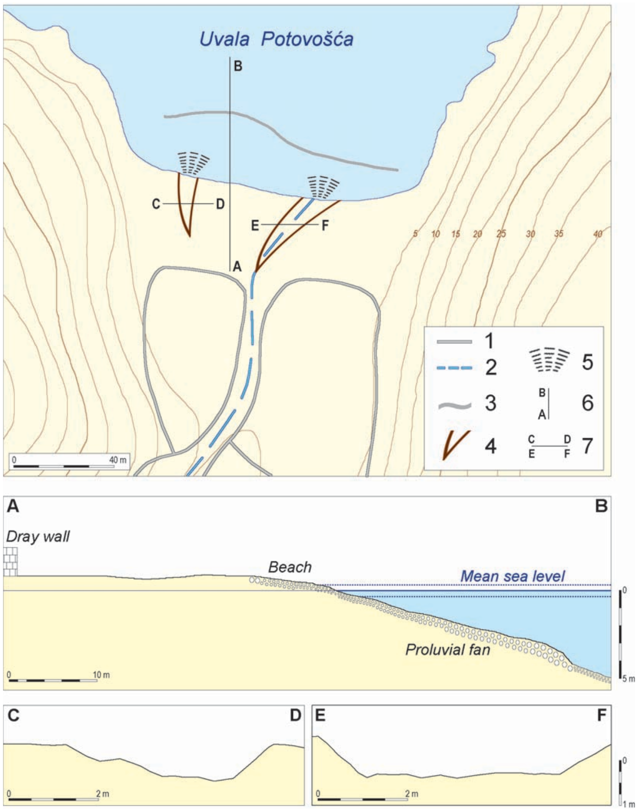

Figure 3: The ground plan of the Potovošća Bay with effects of the short-term event, with longitudinal (A-B) and transversal profiles (C-D; E-F). Legend: 1-Dray wall, 2-Gully bed. 3-Ground-plan of the main proluvial fan below the sea, 4-Gully formed during the rainfall event, 5-Proluvial fan formed during the rainfall event, 6-Profile across the main proluvial fan, 7-Gully cross section.

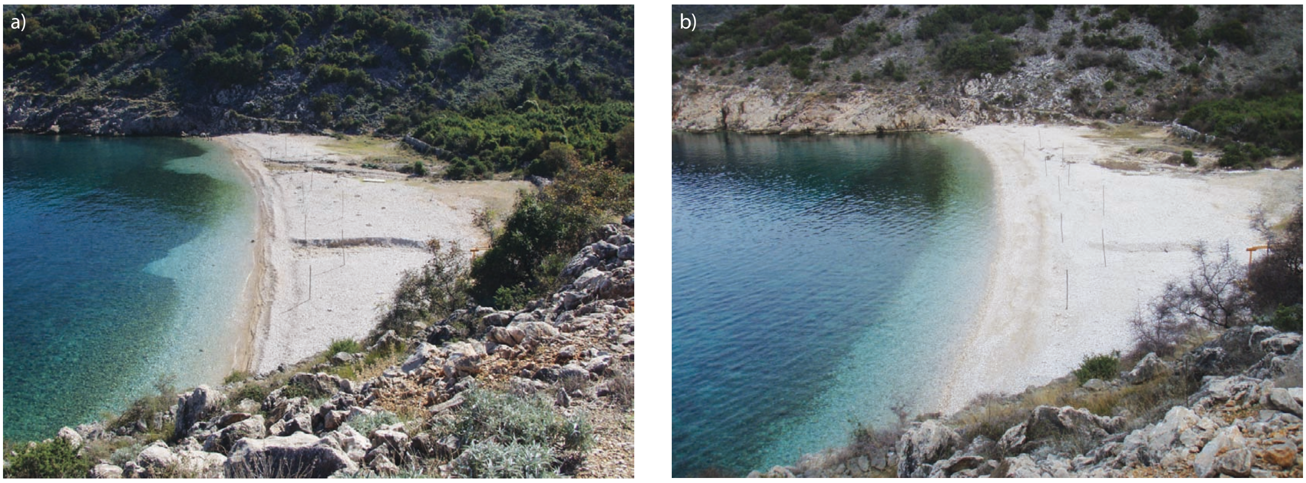

Figure 4: a) The beach of Potovošća after the short-term event (22.09.2007), b) The beach outlook six month after the short-term event (14.03.2008).

gimes (DUBOIS, 1988), which generally coincide with the winter and summer seasons. A very good example of a beach which responds to seasonal variations in the Kvarner area can be observed in the bay of Uboka, (Faivre, unpublished). Rapid changes of the Potovošća beach occur particularly in stormy weather. After the storm, a strong NE bora wind blew at Potovošća, with waves starting to reshape it immediately. The waves created a 60 cm high beach berm near the shoreline, behind which two small temporary ponds were created. These short repeating episodes can be observed on the eastern gully in the profile marked by organic material. The ponds were 3 m from the sea. The existence of lateral channels in the gully indicates the large volume of water flowing in a very short time. Therefore, we tried to establish rainfall intensity and the rainfall-runoff relationship that produces such incised gullies in unconsolidated sediments, displacing 130 m^3±10% of beach sediments, as well as to define the morphological characteristics of the drainage basin as a whole.

Figure 5: Profile along the western gully formed after the storm (22.09.2007).

As the surface was artificially levelled 2 months before the event, it was almost like a laboratory simulation experiment. In Fig. 4b, the naturally reshaped beach, is observed six months after the event. The beach tends again toward its equilibrium state.

The width and inclination of the beach is a function of the available amount of material, wave energy and strength of the currents that can transport this material. The waves sort the beach material and give a characteristic shape to the beach. The biggest pebbles or boulders are accumulated at the top of the beach, which moves only during extremely high sea-level events (during storms). The finer material is located at the seaward end of the beach. Therefore, the beaches are often sandy in contact with the sea. On Potovošća beach, the surface anthropogenic impact disables the study of surface sediment distribution but, fortunately, deeper layers are undisturbed.

The Potovošća beach is embayed and 121 m long. Under natural conditions it was up to 10 m wide. It is a low-tide beach with an average daily sea-level range of 48 cm (Archive of the Geophysical department, Faculty of Science, Zagreb; for 1930–2009). At the beginning of June 2008, before the beach was artificially levelled, a profile along the main fan was made (Fig. 3). The profile is 64 m long: 37 m on the shore and 27 m below sea level. It represents a punctual stage of the beach morphology. As can be observed, the beach has a gentle profile. The inclination varies between +0.5° in the back area, behind the beach berm, up to −14°, which is attained at contact of the beach with the sea, at the time of measurement. Generally, the beach profile does not show great seasonal variation. The submerged part of the fan shows granulometric regularity, from coarse sand to large boulders at the end of the fan, 4 m below MSL. The contact can be seen in Fig. 3. The Potovošća beach can be regarded as a relatively closed system where sedimentary exchanges are minimal. Even if embayed beaches have received more focused research, since they have been recognized as being morphologically distinct from open coasts (STEPHENSON & BRANDER, 2003), there is still a lot of work to do in order to better understand their functions.

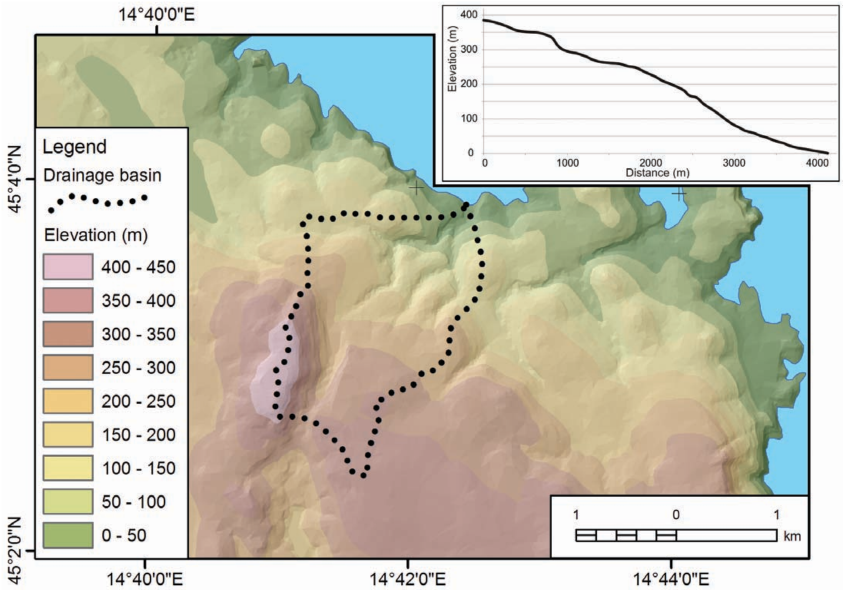

Figure 6: The drainage basin of Potvošća gully with longitudinal profile.

3.2. Drainage basin specific properties

Drainage basin specific properties are dependent on the particular location and include morphological properties, size, shape, and slope of the catchment, SPI, time of concentration, land use and vegetation. On the basis of the hypsometrical characteristics of the area and longitudinal profile of the gully, the basic morphological characteristics of the investigated area can be observed (Fig. 6). The drainage basin area includes the north-eastern edge of the larger karst plateau which is, in this section, inclined in a north-south direction. The Hlam elevation is located in the upper part of the basin, on its south-western edge, this being separated from the aforementioned plateau by the source part of the main gully. The lower part of the basin is characterized by an angle of 10° with a better developed system of gullies which are, on average, 1.8 km long. The main gully of the drainage basin is oriented southwest-northeast and is 4.2 km long (Fig. 6). A largegreat part of the drainage basin, 45.5%, belongs to the slope inclination class of 12−32° in which gullying processes usually take place. On the whole, 80.9% of the basin is included in two inclination classes, the aforementioned one, and that of 5−12° (Fig.7).

The gully system described is much better expressed on the map of the Stream Power Index (Fig. 7). The Stream Power Index was chosen to estimate terrain erosive power as according to TAGIL & JENNESS (2008) it is indicative of the potential energy available to transport sediments. Areas with high stream power indices have a great potential for erosion what allow the highlighting of areas with high potential for sediment removal and hence are prone to gullying (KAKEMBO et al., 2009). Higher values of the index (3.2–5.4) are found in the upper part of the basin, on the slopes of the Hlam elevation (M. Hlam, 446 m) and the source part of the gully, while it increases again on the developed system

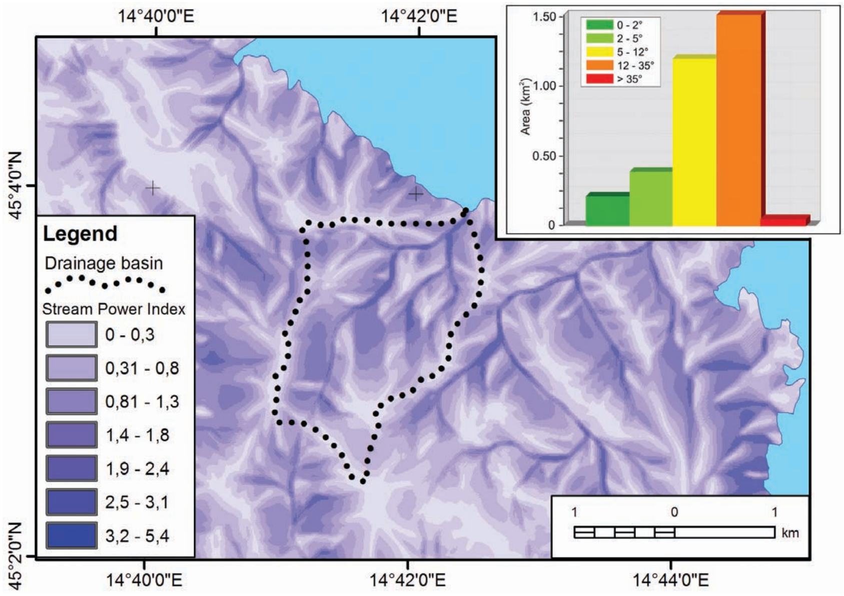

Figure 7: Stream Power Index map with histogram of slopes for the Potovošća drainage basin.

of the shorter gullies in the lower parts. Generally, the maximum values of the Stream Power Index inside the lower part of the basin are related to the linear spreading of the gullies, while in the upper part they are related to the areal slope distribution (Fig. 7). The system of well developed gullies in the lower part of the basin with concentrated linear erosion potential enables powerful runoff and transport of the eroded material from the upper parts of the basin till its deposition.

Exposed morphological properties of the catchment directly influence the time of concentration t_c, as one of the important parameters for the peak runoff estimation at the gully mouth, as well as for the estimation of runoff during the studied short-term event. The time of concentration has been calculated where: the length of the gully bad L= 4198 m and the total down drop of the gully bad I_{max}= (calculated as ΔH [m]/L [m], real length) 385/4198 = 0.09. The obtained t_c for the study area is 0.49 h, that is 29.7 min.

As it is a relatively small-size catchment area the periodic fluvial inputs do not importantly influence the sediment budget of the beach on the time scale of several hundred years due to the presence of a dry-walls system behind the beach, against which the sediments are banked up and recent vegetation recovering due to the change in land use after the World War II. Namely, the increase of infiltration and evapotranspiration was followed by the decrease of erosion and gullying, meaning a smaller sediment supply to the beach. Therefore, it is primarily precipitation intensity which influences changes of beach morphology during the rainfall event on the night of September 10–11th 2007.

3.3. Event specific properties

Event specific properties are those which are dependent on the rainfall-runoff event and the conditions prior to the event. The main event specific properties include total rainfall, event duration, and season and antecedent moisture conditions. The selected meteorological stations in the study are characterised by a similar average annual course of monthly-precipitation since they are situated close to one another. The data about the average annual course of monthly precipitation intensity (Table 1) show the influence of precipitation on erosion processes. The maximum precipitation intensity, for all stations except Malinska, is in September, which is therefore the optimal period for strong erosional (gullying) processes on the studied area. The precipitation intensity in July and August is, on average; two times lower than in September.

Table 2: Daily precipitation on September 11th 2007 (mm), standard deviation and precipitation deviation from averages.

Meteorological station	Daily precipitation (mm)	Standard deviation of daily precipitation	Precipitation deviation from average
Omišalj	38.8	5.2	4 SD
Senj	81.3	8.2	7 SD
Crkivenica	36.2	10.2	2 SD
Malinska	72.0	10.8	4 SD
Krk	16.7	14.1	0 SD

The amount of rainfall that caused gullying processes during the night of September 10–11th 2007 was measured on September 11th, according to precipitation data methodology. The observed stations, apart from the Krk station, had higher precipitation amounts on that day than the average of mean daily precipitation intensity in September (Table 2). Three meteorological stations (Omišalj, Senj and Malinska) had precipitation volume extremely above normal, one (Crikvenica) had greatly above normal, and one (Krk) station had deviation of precipitation amount within one standard deviation, that is, normal precipitation amount.

For the calculation of the interpolated values, daily precipitation volume at the 19 surrounding meteorological stations on September 11th 2007 has been used (Table 3). According to the IDW interpolation results (Fig. 8) the Potovošća area had 40 mm of precipitation on that day. As the precipitation intensity is particularly variable in space, and depends on numerous factors which are not taken into account, we assume that this is the minimum value, as the nearby stations Malinska and Senj had much larger amounts of precipitation on that day. Therefore, it is highly likely that the volume was higher.

Besides the precipitation volume on the event day, precipitation during the antecedent days is also very important, because the soil moisture content of small catchment areas may strongly influence rainfall-runoff processes (KOVÁŘ, 2004). According to the precipitation amount of the last 7 days before the heavy rainfall episode, that is, to the calculated API (Table 3) the saturation of the soil with water could be roughly estimated as relatively high on the Krk Island, which additionally emphasizes the runoff effect in the drainage basin that day. The equation parameters of IDF curves have been calculated based on the precipitation intensity ac-

Table 1: Average annual course of monthly precipitation intensity (mm) for 1981–2007 period.

Meteorological station	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Omišalj	8.5	9.8	9.7	7.3	8.6	8.3	7.6	11.3	14.4	13.6	11.8	10.4	10.2
Senj	7.8	9.0	8.3	7.7	9.4	8.8	5.9	12.3	16.4	12.5	12.3	10.2	10.1
Crkivenica	10.2	10.9	10.8	8.5	10.6	10.6	7.9	12.4	19.1	16.1	13.1	11.3	12.0
Malinska *	10.5	10.6	11.5	9.5	9.7	8.6	8.4	12.7	17.2	17.5	14.0	12.2	12.2
Krk**	12.0	12.8	11.4	10.9	12.3	8.4	7.3	12.1	19.2	16.7	13.8	12.6	12.9

*1992–2007 period
**1999–2007 period

Table 3: Daily precipitation at the 19 surrounding meteorological stations on September 11th 2007, precipitation amount in August and 10, 5 and 3 days before the event (mm) with the antecedent precipitation index in mm for the nearby meteorological stations.

Meteorological station	Latitude	Longitude	Altitude (m a.s.l.)	Daily precipitation on 11.09.2007 (mm)	Precipitation in August 2007 (mm)	10 days before the event (mm)	5 days before the event (mm)	3 days before the event (m)	API (mm)
Bakar	45°18′	14°32′	12	35.2	73.1	32.6	4.1	3.2	16.5
Brinje	45°00′	15°09′	483	205.8	104.6	59.4	14.2	7.6	–
Cres	44°57′	14°25′	5	0.1	61.7	60.2	2.3	0.6	28.7
Crikvenica	45°10′	14°42′	2	36.2	101.6	25.5	3.6	3.6	7.3
Drežnica	–	–	–	117.0	135.9	84.4	30.4	18.0	–
Krk	45°02′	14°35′	12	16.7	75.0	75.2	3.4	1.6	36.1
Kukuljanovo	45°20′	14°32′	355	50.0	77.7	35.5	2.7	1.2	–
Labin	45°05′	14°08′	320	23.0	40.0	39.0	1.1	0.0.	–
Lokve	45°21′	14°45′	721	64.4	119.3	52.0	11.0	3.1	–
Malinska	45°07′	14°32′	1	72.0	84.1	58.1	22.8	7.0	32.6
Omišalj airport	45°13′	14°35′	85	38.8	69.6	40.3	3.5	1.8	18.7
Pula	44°52′	13°51′	30	0.0	59.2	23.5	0.3	0.0	–
Pula airport	44°54′	13°55′	63	0.0	76.6	31.5	0.5	0.0	–
Rab	44°45′	14°46′	24	3.8	100.7	22.2	4.0	2.4	10.1
Rijeka	45°20′	14°27′	104	37.6	95.0	38.7	1.0	0.3	–
Senj	45°00′	14°54′	26	81.3	104.5	54.5	5.0	3.0	28.0
Volosko	45°06′	14°19′	46	45.0	98.0	32.7	0.7	0.3	–
Vrh Učke	45°17′	14°12′	1372	18.9	104.8	55.1	0.0	0.0	–
Zavižan	44°49′	14°59′	1594	1.9	193.9	94.3	20.0	10.2	–

cording to recurrent periods (Table 4). According to the IDF curves for determined recurrent periods the rainfall intensity has been calculated for the obtained t_c (Table 5).

From the coefficient C, defined as C=0.3 and the surface of the drainage basin which amounts A = 3347890 m^2 the calculation of the peak discharge (maximal stream flow) for the Potovošća drainage basin according to defined recurrent periods has been calculated (Table 5).

Once the maximum peak discharge for the Potovošća drainage basin was acquired for recurrent periods we aimed to calculate the discharge during the studied short-term heavy rainfall event, from the night of 10th to 11th September 2007. The aforementioned lack of short-term rainfall data for the Krk Island meteorological stations led us toward the available data for stations Senj and Rab. At Rab station there was almost no rainfall recorded, therefore only the Senj mete-

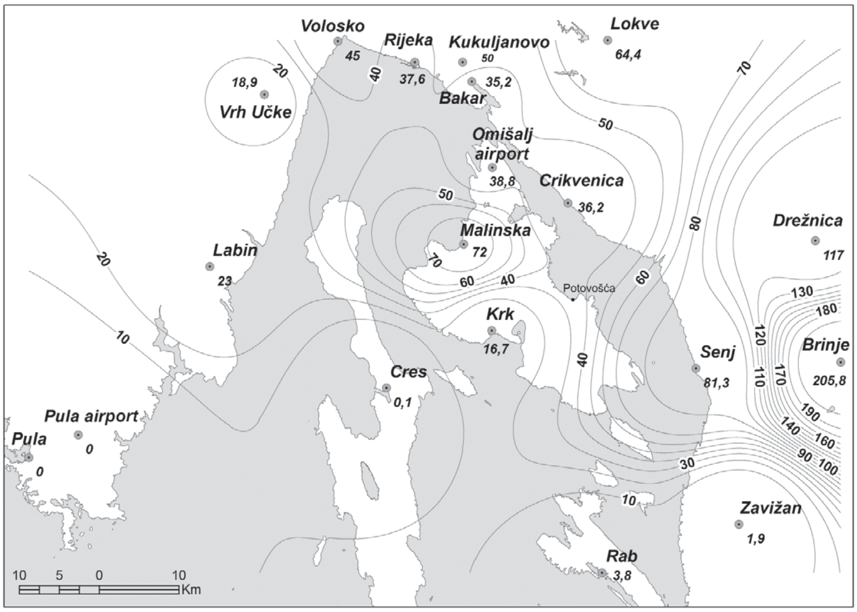

Figure 8: Isolines of the daily precipitation volume at the 19 surrounding meteorological stations on September 11th 2007.

Table 4: The rainfall intensity in mm/s calculated for the Potovošća drainage basin for recurrent periods P (in years).

min	P 1.25	P 2	P 5	P 10	P 20	P 50	P 100
10′	0.028	0.032	0.037	0.039	0.043	0.045	0.046
20′	0.018	0.021	0.025	0.027	0.031	0.034	0.037
30′	0.014	0.016	0.020	0.022	0.026	0.029	0.032
40′	0.012	0.014	0.016	0.019	0.023	0.026	0.029
1h	0.009	0.011	0.013	0.016	0.019	0.022	0.025
2h	0.006	0.007	0.009	0.011	0.014	0.017	0.020

Table 5: Rainfall intensity T_c and maximal (peak) discharge calculated for the Potovošća drainage basin according to the recurrent periods

Recurrent Interval (years)	1.25	2	5	10	20	50	100
Rainfall intensity (mm/s)	0.014	0.016	0.020	0.022	0.026	0.029	0.032
Stream discharge Q (m^3/s)	14	16	20	22	26	29	32

orological station data were used (Table 6). In our opinion those data are reliable for the studied area and are adequate for estimation of the real discharge during the event at the gully mouth of Potovošća.

Rainfall intensities have been calculated based on hourly rainfall intensities from 1–3am at the Senj meteorological station (Table 6) on September 11 (data obtained from the Meteorological and Hydrological Service in Zagreb, 2010). The obtained intensities of 0.009 mm/s for the period between 1 and 2 am, and 0.014 mm/s for the period between 2 and 3am (Table 6) indicates, that, in relation to the IDF curve, those values appear in the recurrent periods of 1.25 years and 5 years respectively (Table 4). The total amount of rainfall which fell between 1 and 3am give the intensity of 0.011 mm/s which corresponds to the 10 year recurrent period (Table 4). When those data were inserted into the rational formula with the parameters of the Potovošća drainage basin we obtained a discharge for the 2–3am observed period of 13.56 m^3/s which respectively corresponds to the maximum discharge for the recurrent period of 1.25 years. Even if the daily precipitation volume was smaller on Krk Island compared to the Senj area, the higher API for the Krk and Malinska stations, compared to the Senj station (Table 3) indicates significant saturation of the soil consequently leading to increased runoff in the studied drainage basin producing the exposed morphological changes.

4. DISCUSSION

Analysis of the short-term rainfall event exposed in the Potovošća gully reveals numerous factors which influence beach morphology and the beach sediment budget. Generally the physiographic properties of the particular region are the sum of tectonic activity, geomorphological activity, and both short-term and medium-term processes repeated through geologic time. In time, individual landforms recording short time-scale events are obliterated and/or preserved as sporadic relicts. Processes operating over longer time-scales are generally the sum of processes operating over shorter time-scales (KELLER & PINTER, 2002).

An important parameter of beach dynamics relates to the beach sediment budget. It is well known that fan morphology is generally a function of the size of the drainage basin contributing sediments to the fan, together with geological and geomorphological properties including, tectonic activity, climate and vegetation. As the Potovošća beach is formed of proluvial fan material the beach sediment budget is related to the aforementioned properties. One of these relationships has been recently studied by BENAC et al. (2010). On the basis of a clear correlation between the size of the drainage basin and the size of the beach formed in accumulated gully deposits, the authors concluded that the beach surfaces in the Kvarner area primarily depend on the size of their catchment areas. If the data from the Potovošća gully (surface of the drainage area – 334.789 × $10^4 m^2$ and surface of the beach 2374.1 m^2) is compared with the southwestern Krk pilot area of BENAC et al. (2010) our results show that the beach of Potovošća is 18% bigger, than expected according to the size of its drainage basin (expected size 1948 m^2 corresponding to the linear regression $y=4.650x + 391.6$). This is probably due to its sheltered position toward southern winds. This allows us to conclude that the surface of of the Potovošća gully beach is in correlation with the size of its drainage basin.

Recent sediment supply to the Potovošća beach is also influenced by different anthropogenic activities which can have short-term and also medium-term effects. Human impact on the natural shoreline is very strongly expressed to-

Table 6: Hourly rainfall time series for Senj meteorological station for the night from 10th to 11th September 2007

Hours	23–24	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11
Rainfall (mm)	–	–	32.2	48.6	0.1	0.3	0.1	–	19	5	1	0.1
Duration (min)	–	–	60	60	30	20	40	–	60	60	60	20
Rainfall intensity (mm/s)	–	–	0.009	0.014	0.000	0.000	0.000	–	0.005	0.001	0.000	0.000

day. Changes in the beach equilibrium induced by man are observed on numerous beaches. The beaches formed in the fan material of the drowned torrent karstic valleys could be affected due to interventions along the watercourses, which diminish the natural supply of beach material (JURAČIĆ et al., 2009). In such a way, many torrent valleys are completely dry today and their mouths are often filled with concrete (like the gully in the town of Vrbnik, Luka Vrbnik). On the other hand, man-made constructions along the coast have also provided extra material, which enlarges natural beaches (RAJČIĆ et al., 2010). For example, according to preliminary, and unpublished results, the beach of Prva Draga gully in the town of Senj has been enlarged by 12 m over the last 35 years as a result of human interventions along the nearby coast providing additional sediments, which then accumulated on the beach due to longshore drift (Faivre, unpublished).

The human impact encompasses not only the beach morphology. It is important for the larger area which evolved under the influence of the traditional agriculture that developed under the Mediterranean conditions (ANIČIĆ et al., 2004). The dry-walls are typical structures of the area. They were constructed at the end of the gully, on the proluvial fan, 37 m from the sea (Fig. 3). Those structures were used to prevent soil erosion as the proluvial fans generally represented areas with potentially fertile soils, which are rare in karst areas. In the last century, this area was used for cultivation of vineyards, while those structures are mainly used today as barriers for sheep. Consequently, such structures directly influence sediment supply, even if the straight central part of the gully between the dry walls is open. After a period of strong human impact on the karst area, the cessation of agricultural activities following World War II caused regernation of vegetation that is also reflected in a change in the runoff regime. Both facts (dry walls and vegetation regeneration) directly result in low sediment supply to the present beach. Therefore, torrential flow, together with fresh water sources, is the main morphological short-term influence on present beach morphology. As the beach has been under concession since 2006, and is artificially levelled for tourism purposes, this has surely additionally increased the explained short-term effect on the beach.

As shown in this study, short-term effects on the area can be induced principally by extreme weather conditions such as high precipitation intensity and wave climatic regimes which leave their mark on the beach. However, the rainfall-runoff relationship directly relates topography to event specific conditions.

Topography of the drainage basin is an important parameter in this study as according to YILMAZ (2009) the spatial variation of hydrological conditions is firstly controlled by topography. Primary topographical attributes, such as slope and aspect, are calculated from the directional derivatives of a topographic surface (GALLANT & WILSON, 2000). Alternatively, secondary topographical attributes are computed from two or more primary attributes. According to GALLANT & WILSON (2000), the majority of these secondary attributes come from the ability of describing patterns as a function of process. Catchments are dissipative systems in that energy is released as precipitation travels through the catchment and performs work on the landscape. Energy dissipation in river systems is equivalent to stream power (McNAMARA et al., 2006). The distribution of energy index produces distinct domains in slope-area space that partition the landscape according to erosion mechanisms (McNAMARA et al., 2006). Therefore, the topographical index considered in this study, the Stream Power Index is often used at present when studying the geomorphologic (topographic) thresholds in gully development (McNAMARA et al., 2006; KAKEMBO et al., 2009). KAKEMBO et al. (2009) separate out a specific threshold zone (of 2 to 6 SPI values) for gully development along the SPI continuum. Consequently the calculated SPI for the Potovošća drainage basin which range from (0−5.4) confirms the existence of the appropriate energy potential for gullying.

Due to the lack of precise meteorological data for the studied area, assessment of the event specific conditions was much harder. Although parameter analysis of the expected annual maximum daily precipitation wasn't conducted, results obtained for the nearby stations (176.9 mm for Crikvenica, 160.6 mm for Senj and 120.2 mm for Rab; GAJIĆ-ČAPKA & ČAPKA, 1997) for the shortest published return period of 20 years show that the precipitation amount that fell on 11th of September on the studied area was much lower. However, hourly rainfall data calculated for the Senj meteorological station indicate that 2 hours precipitation intensities (for 80.8 mm precipitation volume) correspond to the 10 years recurrent period (Table 6). The time of concentration of the Potovošća drainage basin has been calculated to 29.7 min which is significantly lower from the time interval of the available data on the registered short-term precipitations on the closest ombrograph station at Senj (horary data). Given that during this precipitation episode almost the total daily precipitation amount of 81.3 mm fell in two hours, together with the fact that the drainage basin of the Potovošća gully received a much smaller precipitation amount (Fig. 8), some correlations can be made concerning the occurrence of maximum discharges. The, two hourly precipitation of 40 mm (average 2 hours intensity of 0.0056 mm/s) has a characteristic return period of 1.25 years, that is, an 80% probability of occurrence. At the Senj station, the hourly intensity was already achieved during the second hour (counting from the onset of precipitation), therefore, under conditions of the greater water saturation of soil, it is to be expected that the peak discharge of the Potovošća gully in similar conditions was somewhat greater than calculated for the 1.25 yearly recurrent period (Table 5) but not significantly different from the order of magnitude of the 2 year recurrent period. Therefore, it deals with the runoff which had the character of an extreme event on the scale of 1 year but does not represent a particularly rare extreme event over a longer time scale.

But the calculated API for the Potovošća drainage basin which is relatively high (Malinska, 32.6 mm; Krk 36.1 mm) can be an additional factor contributing to the higher runoff during the exposed event and consequently was of sufficient intensity to cause the gulling processes described.

It is also important to emphasize the results of RUBINIĆ et al's, (2009) study concerning the nearby Rijeka meteorological station. It shows that the occurrences of short term heavy rainfall events (10 minutes – 1 hr) increase during the warm part of the year while the (6–24 hrs) rainfall events prevail mostly in the second half of the year with maximum values in August and September.

It is also known that the Potovošća beach has been affected by sea level rise as a long term process over a larger area (FOUACHE et al., 2000; FAIVRE & FOUACHE, 2003; BENAC et al., 2004; BENAC et al., 2008), to which the beach should have been responding over the last few centuries. The response of low coasts, formed in unconsolidated sediments, to sea-level rise has been the subject of considerable scientific research globally for over four decades, particularly on sandy shores. It is difficult to take account of the "sea-level rise" parameter in quantifying shoreline evolution (DUBOIS, 2002; BRUNEL & SABATIER, 2009). Therefore, many studies of coastal erosion with sea-level rise have centred on a well-known scientific model known as the "Bruun Rule". According to the Bruun Rule (BRUUN, 1962; BRUUN, 1988), if the beach profile has reached its equilibrium, this profile will change as a consequence of the sea-level rise. The erosion starts in its upper part and sedimentation in the infralittoral part. This process lasts until the new equilibrium profile is achieved. The current consensus of opinion is that, whilst probably essentially valid, the standard Bruun Rule is a greatly simplified model of coastal behaviour which needs to be supplemented with a variety of additional considerations before it can be used. BRUNEL & SABATIER (2009) adopt the principle of dynamic – active submersion for sandy beaches, assuming that the slope of the beach profile remains identical in time and migrates horizontally towards the land when sea level rises in the case of no major sediment input and if there is space available in the background. However, the response of dominantly pebble beaches to sea-level rise is even less clear than the response of sandy beaches.

The Potovošća beach has also been recently submitted to sea-level change and consequently, in our opinion, most likely to the landward migration of the beach profile. This short event showed that the former large fan is related to different formation conditions, that is, to long-term evolution. It was formed during lower sea level while the two fans that formed during the short-term event do not correspond to the morphology of the major older fan. As we know that during the last few centuries the beach has also experienced recent submergence and from the new profiles which revealed an older torrent bed, 60 cm below the recent beach surface, we assume the landward migration of the beach as a long-lasting process. We hope to determine more about the short- and long-term influences on evolution of the pocket beaches in the future by continuing to monitor the beach profile.

5. CONCLUSION

This research allows determination of the main geomorphological properties of the gully of Potovošća from which the high erodability potential is derived. Overall, 80.9% of the drainage basin is included in two slope inclination classes, 5–32° in which gullying processes are the most effective. The analysis of the Stream Power Index, provides more details on the potential energy distribution in the Potovošća drainage basin (vary from 0–5.4). The highest values (3.2–5.4) are obtained in the upper parts of the drainage basin as well as along the main gully and tributary gully beds. In these appropriate morphological conditions the influence of a short heavy rainfall event was examined.

The torrential flow together with the fresh water sources induces gullying in the beach, causing the formation of 80 cm deep gullies and results in two new submarine fans. During the night of the 10th–11th September 2007, the three meteorological stations (Omišalj, Senj and Malinska) had precipitation amount extremely above normal (above +3 σ). According to the interpolated values, the rainfall volume for the Potovošća area amounted to 40 mm. The precipitation intensity can be highly variable in space and depends on numerous factors, but, as the two nearby stations had much higher amounts of precipitation (Senj and Malinska) it is assumed that the volume of rainfall on the investigated area was also probably higher. Therefore it can be concluded that 40 mm of precipitation volume preceded with relatively high API value is the minimum value that can produce runoff estimated to be 14 m^3/s and displaced 130±10% m^3 of beach sediments. In addition, according to this study similar strong gullying events can be expected over a larger studied area principally in September. This gullying effect was also intensified due to human interference on the beach surface.

This example clearly shows the rapid changes of beach morphometry, which are primarily related to the precipitation and wave climatic conditions. That is, it was also observed that beaches with a predominance of pebbles respond to storms to some extent with an offshore movement of larger particles, followed by later return of smaller particles to the beach.

This study shows that coastal landforms illustrate well the relative role of time-scale in landscape evolution. The explained short event also revealed aspects of long-term beach evolution. The well known context of sea level rise at the eastern Adriatic coast implies that the beach has also experienced recent submergence and that the beach profile should have adjusted to those changes, e.g. probable landward migration of the beach.

As the expected sea level change during the 21 century amounts from 20 to 60 cm (ANTONIOLI & SILENCI, 2007), this trend will probably mark the future evolution of the beach. As we know, the most vulnerable areas in the Kvarner area are the beaches (BENAC et al., 2007; JURAČIĆ et al., 2009). According to the recent morphological situation the landward migration of the Potovošća shoreline is still possible because the beach narrowing due to the relative sea-level change won't be important by the end of this century.

As the episodic recurrence of similar gullying events in the past was well observed in the profile of the eastern gully, it is expected that, due to the climate change, the frequency of future short-term climate events will increase (SÁNCHEZ et al., 2004; SEMMLER & JACOB, 2004; PLANTON et al., 2008). Consequently, it can be assumed that the frequency of the events described here will also increase. The effects of the 10−11 September 2007 short-term event demonstrate the relative roles of natural processes and minimum human interference, which will surely increase in the future, in determining the evolution of the investigated area.

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