Regional methodologies to estimate the sediment transport rate in watersheds in Puglia

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***Abstract*—**Soil erosion is a natural physical phenomenon associated to changes in surface earth morphology. It usually develops quite slowly, even if it is often accelerated because of anthropic actions. Erosion depends on many different connected factors, such as climatic conditions, soil type, morphology, hydrology, vegetation, crops and agricultural techniques. Erosion processes can be described both in a qualitative and a quantitative way, and referring to many different spatial and temporal scales of analysis.

In this paper, an analysis of erosion and transport dynamics in watersheds in Puglia, Southern Italy, is proposed, with the aim of investigating the most influential parameters in the development of these phenomena on wider scales. Integrating a modeling activity with the analysis of field data, many different relationships are proposed, particularly to relate the solid transport with climate, morphology, hydrological and hydraulic characteristics of the sampling area. This could be particularly useful to evaluate quantitatively and qualitatively the entity of erosion processes in ungauged watersheds.

Moreover, the effects of erosion are also related to some parameters which are strictly connected with the characteristics of the investigated region, such as area and index flood. Furthermore, considering the fundamental mechanisms of flow generation, the relationship between sediment transport rate and areas contributing to runoff are analyzed. Finally, once detected the most influential parameters, some multiple regressions are performed and the results are here critically interpreted.

***Keywords*—**Erosion processes, regional analysis, sediment transport rate, watershed-scale erosion.

I. INTRODUCTION

Erosion processes can be interpreted both in qualitative and in quantitative terms, and investigated at different scale of analysis, from the single slope scale, to the mountainside, the watershed and the regional scale.

Morphological rill processes are more evident at a detailed scale. At a larger scale, vegetation and pedology become prevailing, while climate and lithology influence the phenomenon on a regional scale. Usually, the investigation of the entity of erosion processes on watershed and regional scale is carried out introducing intensity classes (low, medium, high), which are determined by means of qualitative considerations strictly connected with the relative weight of the factors considered, with particular attention to lithology [1], [2].

A quantitative evaluation of the erosion can be performed only by means of site measurements, which require the installation of particular gauges on slopes. Field data are necessary particularly to calibrate mathematical models used to relate the entity of erosion to one or more physical factors.

Surface erosion is a process constituted by two clearly separate phases: the detachment of solid particles from the soil surface is followed by the transport of the same particles by surface runoff. Erosive phenomena are limited by the detachment process where erosion factors are such that the transported particles are much more than those detached. On the other hand, erosive phenomena are limited by the transport where the detached material is more than the movable quantity.

A soil subjected to the action of rain is consequently exposed to three phenomena: detachment, transport and deposit. The difference between the net soil loss, in eroded areas, and the net deposit in each soil cell of the site, is referred to as the sediment production.

The study of erosion processes at the watershed scale has reached, in the last years, an increased interest as far as the management of soil-water system has a decisive role. Reference [3] first tried to find a mathematical relationship between the water discharge and the suspended soil flow (the specific maximum monthly turbidity is expressed in Kg/m^3) deeply investigating the behavior of some rivers, such as the Ofanto river in Puglia. Then, many different approaches have been proposed. Among them, an interesting regionalization methodology for the sediment transport rate has been developed in Italy by [4] and used in Emilia Romagna with the aim of estimating the entity of total and specific fluvial solid transport, on monthly and annual basis, also in ungauged sites. This regionalization technique allowed the detection of the most relevant parameters in the investigated phenomena (climate, rainfalls, flow, physiographic characteristics), and the definition of relationships between these parameters and the mean annual solid flow Q_s. The introduction of specific sediment transport rate (ratio between the total sediment flow and the watershed area) is certainly useful to avoid a scale problem due to the different areas of watersheds. Many different examples are present in Italian literature, but an analysis conducted by [5] on Tevere river is particularly significant. They found a linear relationship between the value of flow which is exceeded ten times in one year, Q_{10}, and the value of annual solid transport, expressed in tons. This result appears really important, despite being only locally employable, and without a general validity. An important contribution to the analysis of erosion and transport dynamics in Puglia region is due to [6], [7] who used continuous site measurements in Carapelle river area to study the characteristics of the phenomenon. A good relationship between sediment concentration and discharge, with particular attention to the influence of the specific rainfall of the area, whose characteristics are strictly connected with the semi-arid climate of the investigated area, was found.

A study by [8], [9] appears particularly relevant because it was conducted on a regional scale, to describe erosion processes in the United States. A dependency of long term solid transport on many different factors, such as rainfall, geology, soil use and channel stability was found. Particularly, the most significant parameter is assumed to be the discharge having a return period of 1.5 years ($Q_{1.5\ years}$, named "effective discharge"). This value of discharge can be calculated as a function of the watershed area, using regional estimating relationships.

The work here presented required a first step, based on sediment flow data collection, considering the available data in gauged stations located in the investigated area. Then, many different simple and multiple regressions have been performed, with the aim of relating the mean value of total and specific sediment transport rate with significant morphological, hydrological and hydraulic factors of the watersheds. To validate and compare the results, a Jack-knife resampling technique has been adopted to estimate the bias and the standard error (variance) of the investigated parameters.

II. CHARACTERIZATION OF THE INVESTIGATED AREA

The data series of torbiometric measurements available by "Servizio Idrografico e Mareografico della Regione Puglia" have been collected in gauged stations of Ofanto and Candelaro rivers, in the northern area of Puglia (Fig. 1). Particularly, data collected between 1932 and 1986 are available for the Ofanto river, and data collected between 1952 and 1986 are available for the Candelaro river.

These two watersheds can be considered part of a unique hydrogeological area (named "Tavoliere" area), even if they show peculiar characteristics in terms of geomorphology, hydrographic structure and climate.

The investigated area is characterized by a typical mediterranean climate, with temperate winters, and hot and dry summers. The mean annual temperature is 15°C, with peak values of even more than 40°C during July, and minimum values below 0°C in the mountain areas during winter months.

The hydraulic regime of the rivers is torrential, and the discharge mainly concentrated in the autumn-winter period. Specifically for Ofanto river, the branches, even if characterized by low discharges, play a fundamental role because they guarantee the development of the hydrogeological fluvial equilibrium, providing a constant fluid and solid flow during the whole year.

In Table I the main parameters used in the regression analyses, for each measurement station, are presented: watershed area (A), mean annual sediment transport rate E[t], index flood E[x], lag time (τ), De Smedt runoff coefficient (C, [10]), critical rainfall intensity (I[τ]), fraction of watershed area contributing to the development of surface flow (r).

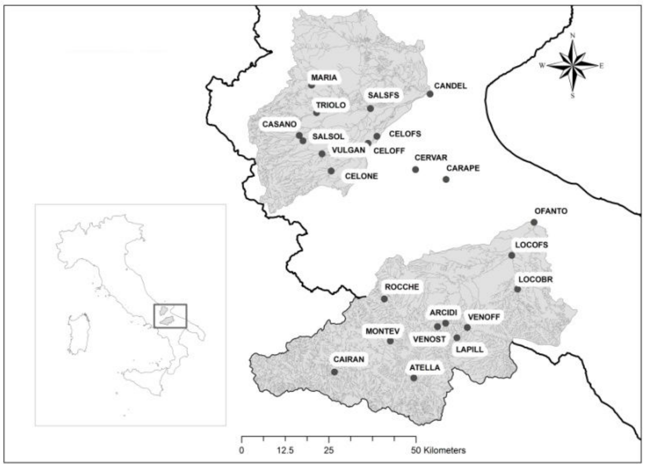


Fig. 1 Investigated watersheds and hydrometric and torbiometric measurement sites

Cod.	Measurement site	A [km²]	E[t] [ton]	E[x] [m³/s]	τ [hours]	C	I[τ] [mm/h]	r
1.0	Ofanto a S. Samuele di Cafiero	2702.800	901669.000	517.600	17.93	0.4354	14.32	
1.1	Ofanto a Cairano	266.400	47138.960	208.000	5.67	0.4541	20.29	
1.2	Atella a P.te sotto Atella	175.900	54386.310	61.300	4.32	0.499	17.13	0.16
1.4	Ofanto a Monteverde Scalo(Rocchetta S.Antonio)	1111.000	406191.600	436.700	11.52	0.4785	18.37	0.9
1.5	Arcidiaconata a P.te Rapolla Lavello	123.900	44196.910	44.900	3.83	0.4765	15.59	0.22
1.6	Lapilloso a P.te S.S. 168	28.500	993.614	10.400	1.87	0.513	13.60	
1.7	Venosa a P.te Ferroviario	204.000	8788.168	39.900	4.88	0.3296	13.40	
1.8	Venosa a P.te S. Angelo	263.000	39438.880	55.800	5.56	0.3489	13.36	0.14
1.9	Locone a P.te Brandi	219.400	30441.000	43.300	5.09	0.351	11.30	
4.0	Candelaro a Strada Bonifica N.24	1777.900	186301.600	140.700	14.55	0.4055	12.38	
4.1	Celone a S. Vincenzo	92.500	18175.370	31.800	3.19	0.3503	15.56	0.11
4.4	Vulgano a P.te Troia-Lucera	94.100	28341.370	74.700	3.34	0.4006	14.91	
4.5	Salsola a Casanova	44.100	2690.763	45.500	2.26	0.4343	13.92	
4.6	Casanova a P.te Lucera-Motta	57.300	8618.518	27.500	2.49	0.3906	12.52	0.18
4.8	Triolo a P.te Lucera-Torremaggiore	55.900	13038.360	36.500	2.52	0.3919	11.90	0.19
4.9	Canale S.Maria a P.te Lucera-Torremaggiore	58.100	10632.090	18.900	2.66	0.4204	10.96	0.13

Table I Watershed data and parameters used in regressions

III. TOTAL SEDIMENT TRANSPORT RATE ESTIMATE

Hydrological rainfall-runoff models, and particularly lumped models, are useful to interpret the hydrological response of a watershed to a rainfall, referring to some parameters characteristic of the watershed itself.

Generally, the mechanisms of surface flow generation are controlled by hydraulic properties of the soil and by its water content [11], [12]. The production of surface flow is usually strictly connected with rainfall which overcomes some thresholds that could be expressed in terms of intensity or depth. Sometimes different thresholds can be defined, especially connected to different losses, such as those due to infiltration when ordinary and extraordinary discharges happen.

However the flow production is concentrated in small watershed areas which, according to its own hydro-geologic characteristics, are mainly influenced by the presence and the location of the rivers or by pedologic characteristics of soils [13]. The concept of fraction of area contributing to surface flow has many literature confirmations with different studies oriented to the investigation of surface and hypodermic flow in saturated and unsaturated soils, associated to analyses on the variation of humidity conditions as a function of curves of flow release. Particularly, these investigations are connected with the development of 'variable source' or 'partial area' models, originally associated to a 'saturated overland flow' mechanism of surface flow. Reference [14], by means of a theoretically derived distribution for discharge peaks, introduces the use of area *a* contributing to a fraction of the discharge associated to the whole watershed area A, giving to the parameter *a* the role of a stochastic variable to whom a mixed probability function is associated, with a gamma type continuous part when a<A and a discrete part dependent on A, when the rainfall involves the entire watershed. This distribution is highly influenced by the mean value of contributing areas E[*a*] or, equivalently, by the fraction of contributing area r=E[a]/A whose dependency on geology, geomorphology and climate has been investigated in many works, and particularly in [15], [16], [17].

The variability of the mean annual sediment transport rate, that is detectable on a regional scale, can be explained by means of the regressions presented in Fig. 2 referring to watershed areas and in Fig. 3 referring to the areas contributing to the surface flow, expressed as a fraction of the area r·A.

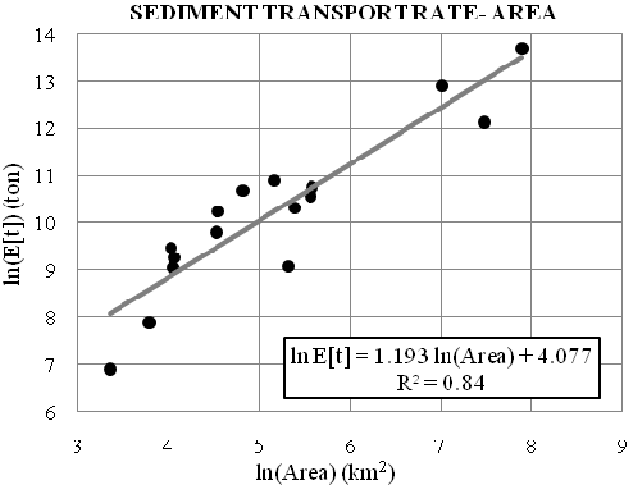


Fig. 2 Regressions conducted referring to the watershed area.

Even if the estimated values of this parameter are only available for a part of the investigated watersheds, the use of the parameter r·A instead of the simple area A guarantees a significant increase in the correlation coefficient, as it emerges clearly from the proposed diagrams. This conclusion is useful to endorse the existence of a strong dependency of the sediment transport rate on the geo-morphoclimatic characteristics of the watershed and particularly on the mechanisms interfering in the onset of surface flows.

Another possible alternative is based on the hypothesis of the existence of a link between the mean annual sediment transport rate and the index flood E[x], defined as the mean value of the peak discharges measured referring to the whole period of analysis [18]. It was therefore carried out a regression (Fig. 4) between the annual sediment transport rate E[t] and the index flood E[x], which gave a smaller correlation coefficient (R^2= 0.79), however sufficient to apply the relationship in approximate estimates.

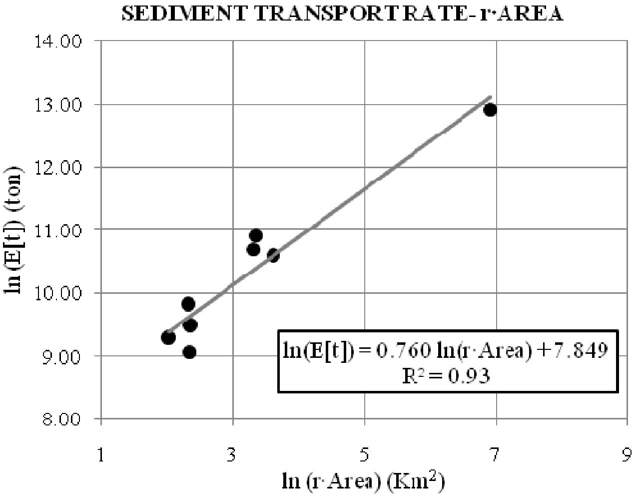


Fig. 3 Regressions conducted referring to the areas contributing to surface flow r·Area.

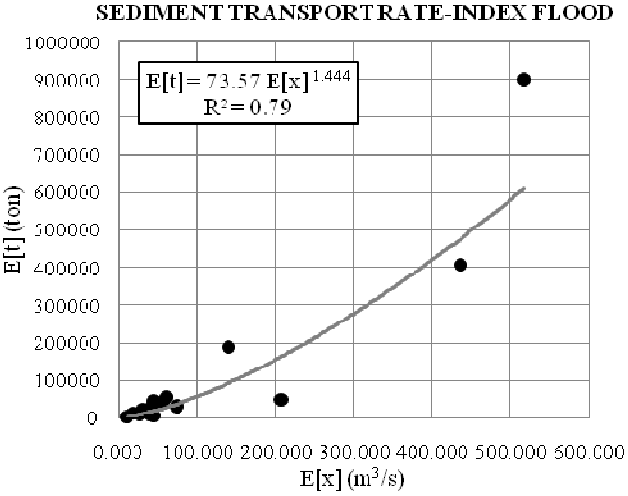


Fig. 4 Regressions conducted referring to the index flood.

The comparison of these results shows that, with the aim of performing quick estimates of the sediment transport rate in ungauged watersheds, the first relationship, based only on the dependency on the area A, is the most efficient one, because it is based on a parameter that is easily computable and characterized by a low level of uncertainty. In fact this is the main advantage with respect to the use of the index flood and the watershed fraction *r*, which are however regionally estimated. It is noticeable that better results are obtained introducing the product r·A which defines the portion of watershed contributing to surface flow in case of ordinary and extraordinary rainfall events.

Therefore, with the aim of investigating the study of erosion phenomena with specific reference to the generation of surface runoff, the mean runoff coefficient C introduced by De Smedt was used. The values of C can easily quantify the soil tendency to produce surface flow, according to specific conditions of slope, soil use and soil type. The coefficient C can be estimated by means of tables, which give its value as a function of slope, soil use and soil type. The correlation between mean annual sediment transport rate and area contributing to runoff (C·Area), presented in Fig. 5, gives a significant result (R^2=0.85) thus substantiating the fact that the parameters used in the evaluation of C are the same controlling the erosion processes at a watershed scale (slopes, soil use, pedology).

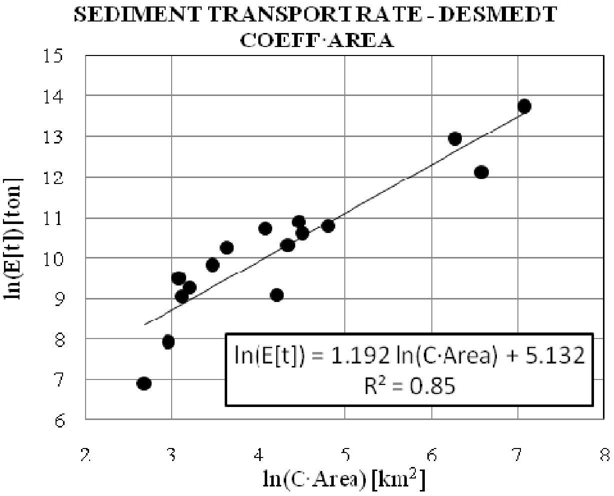


Fig. 5 Regressions conducted referring to the areas contributing to runoff.

Once detected the most influential parameters in the description of erosion processes, many different multiple regressions were performed. They did not provide meaningful achievements except the linear relationship (1) between C·A and E[x] which gives the highest correlation factor. In the presented formula the sediment transport rate E[t] is expressed in ton, the area A in km^2, the index flood E[x] in m^3/s and the rainfall H in mm.

$$E[t] = 541.19 \cdot E[x] + 400.44 \cdot (C \cdot A) \qquad R^2 = 0.91 \qquad (1)$$

With the aim of validating the multiple regression a Jack-Knife test was performed. This test, as previously described, is a resampling procedure used to estimate the standard error in the measurement of a parameter. The parameter is systematically recomputed leaving out one (or more) observations at a time from the sample set and an estimate of bias and variance is performed starting from this new data set.

Results not shown here suggest that such a multiparametric approach is not satisfactory in the regional framework probably due to the low number of gauged sites.

IV. UNIT SEDIMENT TRANSPORT RATE ESTIMATE

Starting from the observations before presented and from the selected parameters, many different regressions useful to estimate the mean annual unit sediment transport rate have been found. In fact this parameter, also taking into account the strong link between E[t] and A, appears to be highly representative of the watershed behavior, according to its climatic, pedologic and geomorphologic properties. However such an analysis did not produce significant results, so it was not possible to establish significant relationships to calculate the unit sediment transport rate (sediment yield per area unit).

So, referring to the results achieved in the former section, the unit sediment transport rate was computed as the ratio between the total mean annual value and the index flood. In Fig. 6 and Fig. 7, the results achieved considering the ratio E[t]/E[x] (ratio between the total mean annual sediment transport rate and the index flood) are presented. This quantity was particularly investigated with reference to the areas contributing to surface flow, calculated as C·A (Fig. 6). Another interesting correlation has been detected between E[t]/E[x] and the lag time of the watershed τ (Fig. 7).

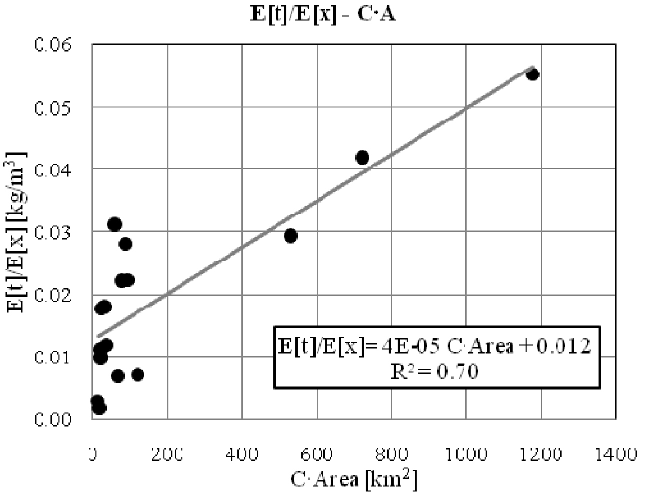


Fig. 6 Regressions conducted to estimate the unit sediment transport rate as a function of areas contributing to surface flow.

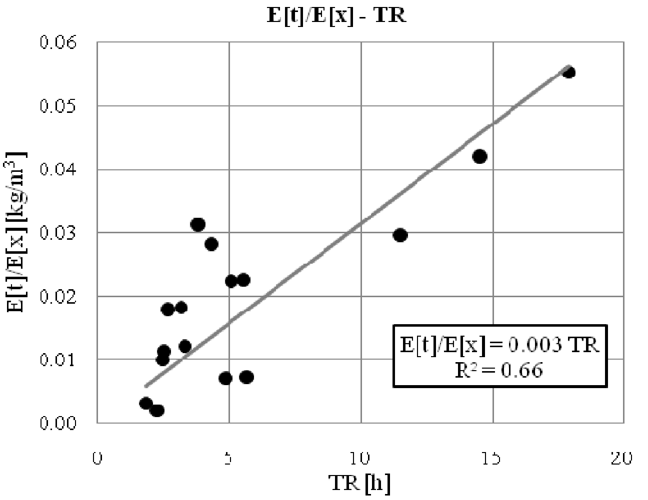


Fig. 7 Regressions conducted to estimate the unit sediment transport rate as a function of watershed lag time.

At last the ratio between the total sediment transport rate and the total mean annual rainfall has been studied. The rainfall was calculated as suggested in the CSEP methodology [1], as the sum of the products between the monthly rainy days

$N_{0,i}$ and the monthly mean rainfall $R_{0,i}$. In Fig. 8, it is presented the relationship between this quantity, expressed as $E[t]/N_0R_0$, and the rainfall H calculated, according to [18], as the critical rainfall for the analyzed watershed with 1 year of return period TR.

In Fig. 9 the relationship between $E[t]/N_0R_0$ and CA is shown.

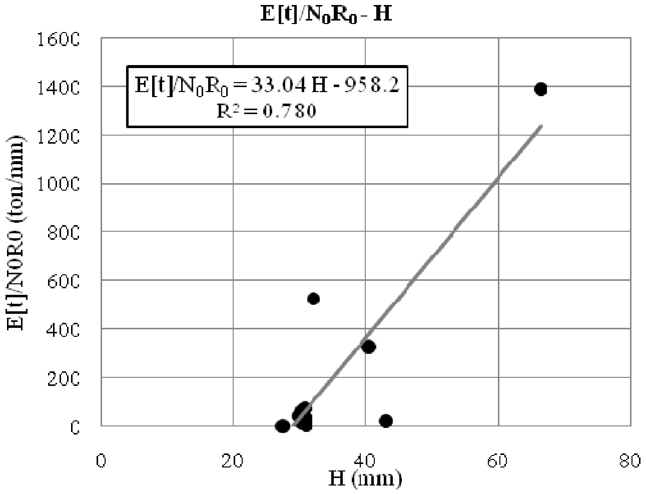


Fig. 8 Regressions conducted to estimate the unit sediment transport rate as a function of critical rainfall.

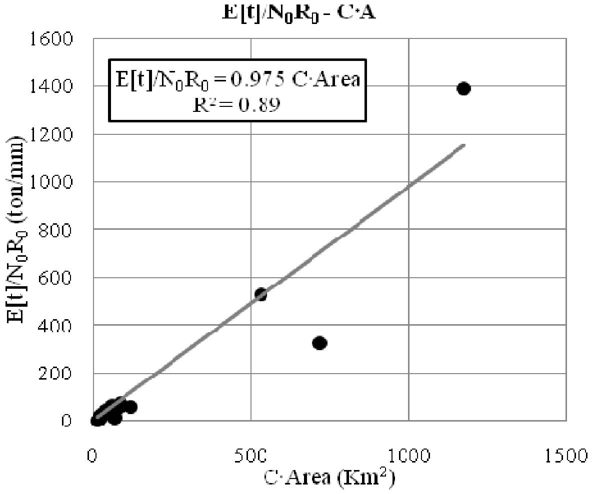


Fig. 9 Regressions conducted to estimate the unit sediment transport rate as a function of areas contributing to surface flow.

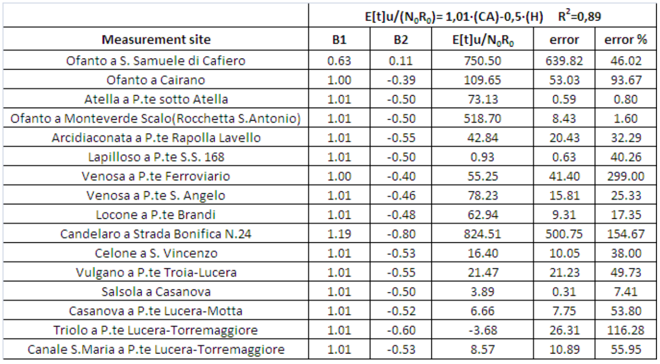
Once defined the most influential parameters, multiple regressions were carried out to evaluate the unit sediment transport rate. In the following relationships (2) and (3), area A is expressed in km^2, rainfall H in mm, lag time τ in hours, unit sediment transport rate E[t]/E[x] in kg/m^3 and unit sediment transport rate $E[t]/N_0R_0$ in ton/mm.

$$E[t]/E[x]=(1.13\cdot(C\cdot A)+183.2\cdot\tau+725.2)\cdot 10^{-5} \quad R^2=0.71 \qquad (2)$$

$$E[t]/N_0R_0=1.01\cdot(C\cdot A)-0.5H \quad R^2=0.89 \qquad (3)$$

Also in this case a Jack-knife test has been performed (Table II) to validate the relationships. From the considered correlations, also taking into account the results of the test, the proposed formulae can be considered adequately representative, both for the values obtained and for the possibility of performing an estimate of the unit sediment transport rate.

The following table contains the values of the parameters B1 and B2, which are the coefficients of the linear regressions performed excluding step by step one of the measurements, the term $E[t]u/N_0R_0$ represents the estimated value at each single step. At last the error is also introduced.



	$E[t]u/(N_0R_0)= 1,01\cdot(CA)-0,5\cdot(H)$ $R^2=0,89$				
Measurement site	**B1**	**B2**	**$E[t]u/N_0R_0$**	**error**	**error %**
Ofanto a S. Samuele di Cafiero	0.63	0.11	750.50	639.82	46.02
Ofanto a Cairano	1.00	-0.39	109.65	53.03	93.67
Atella a P.te sotto Atella	1.01	-0.50	73.13	0.59	0.80
Ofanto a Monteverde Scalo(Rocchetta S.Antonio)	1.01	-0.50	518.70	8.43	1.60
Arcidiaconata a P.te Rapolla Lavello	1.01	-0.55	42.84	20.43	32.29
Lapilloso a P.te S.S. 168	1.01	-0.50	0.93	0.63	40.26
Venosa a P.te Ferroviario	1.00	-0.40	55.25	41.40	299.00
Venosa a P.te S. Angelo	1.01	-0.46	78.23	15.81	25.33
Locone a P.te Brandi	1.01	-0.48	62.94	9.31	17.35
Candelaro a Strada Bonifica N.24	1.19	-0.80	824.51	500.75	154.67
Celone a S. Vincenzo	1.01	-0.53	16.40	10.05	38.00
Vulgano a P.te Troia-Lucera	1.01	-0.55	21.47	21.23	49.73
Salsola a Casanova	1.01	-0.50	3.89	0.31	7.41
Casanova a P.te Lucera-Motta	1.01	-0.52	6.66	7.75	53.80
Triolo a P.te Lucera-Torremaggiore	1.01	-0.60	-3.68	26.31	116.28
Canale S.Maria a P.te Lucera-Torremaggiore	1.01	-0.53	8.57	10.89	55.95

Table II Jack-knife test for the performed regression

From the analysis of the proposed regressions, it can be easily noticed that in the case of simple regression the parameter which better approximates the values of unit sediment transport rate is the lag time of the watershed. In this case, considering a relatively low value of R^2 = 0.66, the Jack-knife test provides a mean error of 64%.

In the case of multiple regression, the most significant parameters are the critical rainfall height and the area contributing to runoff C·Area; also in this case a mean error of 64% was found.

Nevertheless despite such a mean error such a mean error, results show that for the downstream station of the entire watersheds (San Samuele di Cafiero [Cod. 1.0] and Candelaro at Strada Bonifica [Cod. 4.0] stations), the estimation appears reliable. This certainly confirms that erosive processes, on a wider scale of analysis, are qualitatively described correctly. On the other hand, when sub-watersheds are considered, whose behavior is much more variable because of specific morphological, climatic and hydrological factors, the models may provide a strong underestimation or overestimation. This is also confirmed by Venosa case [19], whose behavior both in terms of liquid and sediment transport rate, is strongly influenced by lithological and pedological characteristics of the watershed.

V. CONCLUSIONS

By means of the presented activity, a strong dependency of erosive factors on climatic, hydrologic - hydraulic and geomorphological factors has been shown. Particularly, a strong dependency of sediment transport rate on the areas contributing to the surface flow (*r*·Area) was found, and a good agreement was shown also considering an approximate relationship (C·Area). The dependency on areas contributing to surface flow is also particularly interesting, because it provides, at least methodologically, a conceptual basis for erosion phenomena analysis, which is particularly fit to climatic and territorial characteristics of investigated areas.

Moreover referring to and confirming the approach proposed by [8], [9] with the objective of performing regional analyses of erosive phenomena, it is evident the relationship between solid transport and index flood. Nevertheless this estimate, even if effective, is strongly influenced by the availability of methodologies to calculate the index flood.

Finally, it is clear that the use of multiple regressions, also evaluating the relative weight of different factors, guarantees a significant improvement in the estimation, also quantitative, of the mean total and unit sediment transport rate. However the introduction of the sediment transport rate per unit of area, as traditionally referred to in literature, did not give a good result. Therefore, the unit flow has been expressed differently, as a function of the index flood (kg/m^3) and of the rainfall annual volume (ton/mm), to overcome a scale problem connected to the enormous variability in watersheds areas. While in the first case the underlined problem of the estimate of index flood is still present, in the second case it can be overcome, and consequently a relationship valid for a quantitative evaluation of erosion processes also in not instrumented sites is available.

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