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Nuclear techniques for measuring sediment transport in natural streams – examples from instrumented basins

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ABSTRACT Solid transport in torrential streams in many areas of Mediterranean and other semiarid environments usually occurs during flash floods of short duration with suspended sediment concentrations higher than 100 g l^{-1}. Under these conditions it is very difficult to gauge sediment transport, except by using nuclear gauges. These are the most suitable means available for such situations because they can be used over a wide range of sediment concentrations and because they are able to resist bed load transport consisting of boulder-size material. This paper presents the main characteristics of nuclear turbiometric gauges with artificial gamma sources, and the calibration and operation of such gauges are discussed. Two types of completely automatic gamma transmission gauges installed at fixed points in drainage basins in Italy are described. Finally radioactive tracer techniques for bed load transport in torrential regimes are discussed.

Les techniques nucléaires et la mesure du transport solide des cours d'eau - exemples de mesure dans des bassins versants équipés

RESUME Dans de nombreuses régions mediterranéennes et semiarides le transport solide des cours d'eau a lieu seulement pendant des crues brutales et de courte durée, atteignant des concentrations de sédiment en suspension souvant supérieures à 100 g l^{-1}. Dans ces conditions particulières les appareils de mesure nucléaires semblent les plus indiqués car ils peuvent mesurer des gammes de concentrations très étendues et, en même temps, résister au transport de sédiment très grossiers. Dans cette communication on présente une synthèse sur les appareils de mesure nucléaires ainsi que sur les méthodes d'étalonnage et on decrit deux types d'appareils à rayons gamma automatiques installés sur des bassins versants en Italie. On présente aussi quelques exemples d'application des traceurs radioactifs artificiels pour la mesure du transport des sédiments en régime torrentiel.

INTRODUCTION

A knowledge of sediment transport in natural streams provides the possibility of evaluating erosion phenomena and also gives basic information necessary for the planning of numerous engineering works such as the building of artificial reservoirs, bridges and viaducts, and the regulation of water courses, etc. It is therefore a factor of major importance in studies of soil conservation. Calculation of bed load transport, especially in water courses characterized by torrential regimes, still presents a number of problems which have not been fully resolved, and the methodologies used to date have produced only semi-quantitative data. On the other hand, the problems connected with the measurement of suspended sediment transport, particularly in cases of low sediment concentration, would appear to be more easily resolved. In these situations, gauges based on optical or ultrasonic systems may be successfully used, or alternatively automatic samplers can be installed, which make it possible to study the detailed variations of sediment concentration. However, it is much more difficult to measure the high sediment concentrations which frequently occur during floods in water courses characterized by torrential regimes.

In many areas of the Mediterranean, sediments are highly susceptible to erosion and floods, which often are very severe during the autumn-spring period, may produce suspended sediment concentrations sometimes in excess of 100 g l^{-1}. Collection of hydrological data, therefore, is difficult, and may be especially problematical when bed load includes boulder-size material which makes it almost impossible to maintain gauges permanently in the stream.

In these situations, gauges based on nuclear techniques can be successfully used. The nuclear method is generally preferable to optical and ultrasonic methods in cases where suspended sediment concentrations are higher than 5-10 g l^{-1} and, in the opinion of the author, it remains the only valid method when dealing with concentrations of hundreds of grams per litre. Moreover, if one uses a gamma radioactive source, such as ^{137}Cs, it is possible to manufacture gauges protected by a strong steel structure which are capable of withstanding flood events, even when large-sized sediment is being transported.

An important feature of the nuclear method is the fact that the measurements are based on the density of material and, therefore, are in practice independent of the colour and diameter of the suspended particles and, to a certain extent, are also independent of the chemical composition of the particles. Moreover, with nuclear gauges it is easy to measure concentration gradients vertically to within a few centimetres of the stream bed.

This paper deals with certain aspects of nuclear techniques applied to studies of sediment dynamics, and has special reference to water courses characterized by torrential regimes. Some of the results obtained using nuclear gauges installed in two hydrological basins in Italy will be introduced. The gauges are fully automatic and require little attention since power for each installation is derived from a photovoltaic solar panel.

The techniques used in measuring bed load transport with artificial radioactive tracers will also be discussed.

NUCLEAR GAUGES

The measurement of suspended sediment concentration is based on the absorption or diffusion of X or γ radiations by an artificial radioactive source, or alternatively on the measurement of natural gamma radioactivity emitted by the suspended sediment.

The use of gauges based on artificial radioisotopes offers many possibilities, and depending on the source-distance and on the energy of the radiations (X, soft γ or hard γ), quantitative measurements of suspended sediment concentration are feasible for a volume of influence which varies from a few litres to one hundred litres. All other factors being equal, the accuracy of the measurements is greater the lower the energy of the radiations emitted by the source. For example, gauges using ^{109}Cd sources permit measurements for volumes of influence with a diameter of 8-10 cm (Florkowski & Cameron, 1966; McHenry *et al.*, 1967; Papadopulos & Ziegler, 1966), those with ^{241}Am sources for volumes of influence with a diameter of 20-40 cm (Ciet & Tazioli, 1976; Courtois *et al.*, 1970; Florkowski, 1970; Martin, 1970), while those using sources of higher radiation energy (^{137}Cs, ^{60}Co) can allow measurements for volumes of influence with a diameter of 90 cm (Ciet & Tazioli, 1976; Florkowski, 1968).

One of the greatest advantages of the nuclear method is that measurements can be carried out without interruption and practically without disturbance to the fluid, thus giving more reliable data than can normally be obtained by other sampling techniques.

The turbiometric gauges based on the measurement of the natural radioactivity of sediments are much simpler than those equipped with artificial radioactive sources, in that they only have a gamma-ray detector and electronic counting and recording equipment. The volume of influence for these gauges is generally much greater than that for gauges based on artificial radioactive sources.

The measurements carried out using nuclear methods can easily be extended to concentration ranges between 1 and 200-300 g l^{-1}.

Principle of gamma-ray transmission gauges

It is well known that the attenuation of gamma-rays from material placed between an emitting source and a detector is due to the density or concentration of the material itself. In practice, a comparison is made between the number of impulses N_S, measured in a sediment-water mixture which has a turbidity C, and the number of impulses N_W, measured in a reference medium which is generally composed of pure water. All turbiometric data provided by the nuclear gauges derive from counts carried out over a period of 5-15 min, and thus represent a mean concentration value relating to several m^3 of turbid water.

This integrating system is highly suitable for flood events characterized by great variations in sediment concentration.

Principle of gamma-ray scattering gauges

In the case of gamma-ray scattering gauges, the radioactive source is separated from the detector by lead, and the radiations recorded are only those diffused into the volume of influence of the gauge. The principle is based on measurement of the scattered radiations attenuated by turbid water. Furthermore, the counting rate for these gauges is related to the density or to the concentration of the suspended sediment (Anguenot & Caiveau, 1980; Florkowski, 1970).

Principle of gauges based on natural radioactivity measurement
This principle is based on the relation between the counting rate, recorded in turbid water containing suspended clayey sediment, and the turbidity of the water itself. By means of a calibration curve (Fig. 1) it is possible to calculate the suspended sediment concentration from the values of gamma radioactivity recorded (Courtois *et al.*, 1970). However, this technique is limited to large water courses, or at least to depths of over 1 m, because of the influence on the detector of radiations coming from the sides and bottom of the stream channel.

In cases of high suspended sediment concentration, the precision and sensitivity of this method are comparable to those of nuclear gauges based on artificial radioactive sources (Tazioli & Caillot, 1981).

Calibration
Correct functioning of a nuclear gauge depends on calibrations undertaken both in the laboratory and *in situ*. In the first instance, calibrations are carried out in tanks using sediment sampled from the water course selected for turbiometric measurements. Turbidity levels associated with concentrations varying from 1 to 100 g l^{-1} are created in the tanks by means of pumps, and suspended sediment concentrations are controlled using the gravimetric method (Ciet & Tazioli, 1976).

A calibration curve is constructed by relating the counting rate N_s to the varying suspended sediment concentration values (Fig. 2). The validity of the curve is then verified *in situ* during flood events. *In situ* checks are normally carried out at least once a month using clear water and saline solutions which have a chemical composition similar to that of the sediments.

Factors influencing measurements
As regards the accuracy of the measurements, several factors undoubtedly play an important role, and not all of them can be easily defined. The effects of temperature, the chemical composition of the sediments and electronic drift are the major factors influencing the measurements.

Temperature obviously affects the measurements when the gauges operate at temperatures other than those for which they have been calibrated. Fluctuations in temperature cause variations in water density, modifications in the mechanical structure of the gauges, and changes in the response of the scintillation detectors. The latter effect is particularly important if measurements are carried out with a threshold higher than 10 keV (Courtois *et al.*, 1970; Martin, 1970), or at temperatures higher than 35°C (Fig. 3). It is therefore necessary to employ temperature recorders at the gauging stations.

Laboratory research into the influence of the chemical

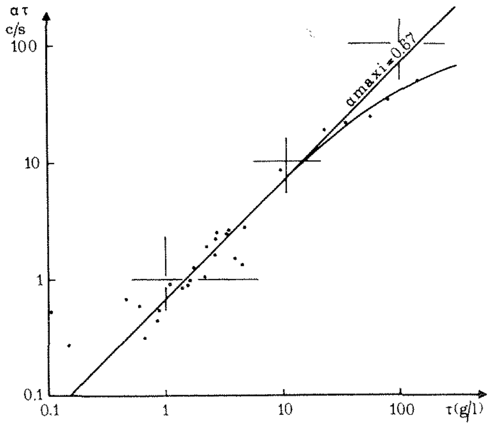

Fig. 1 Relation between counting rate (c/s) and suspended sediment concentration, after Courtois *et al.* (1970).

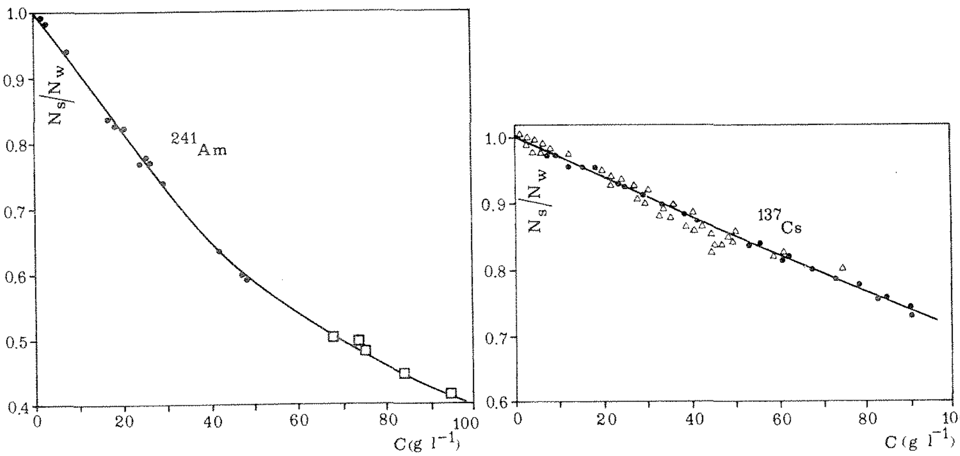

Fig. 2 Calibration curves obtained in the laboratory using silty clays (solid circles) and quartzose-feldspathic sands (triangles), and during flood events (squares). N_s/N_w = ratio between observed count and clear-water count.

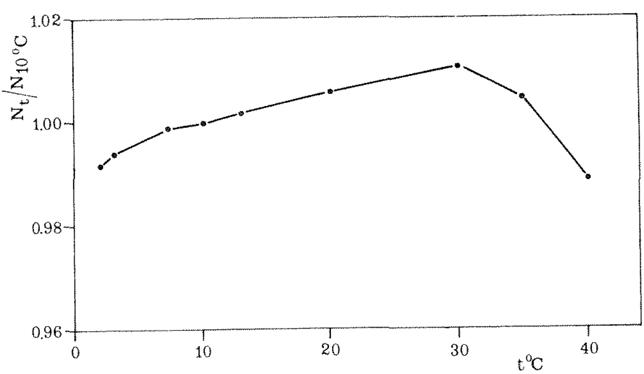

Fig. 3 Variation of counting *vs.* temperature with ^{241}Am gauge in a thermostatically controlled tank. $N_t/N_{10°C}$ = ratio between counting rate at temperature t and at 10°C.

composition of sediments, based on quartzose-feldspathic sands and clays, has shown distortion equal to about 2 g l^{-1} for concentrations of 10 g l^{-1} in the case of ^{241}Am gauges, but almost zero distortion under the same conditions for the ^{137}Cs gauges (Ciet & Tazioli, 1976). It is therefore necessary to check the chemical composition of sediments in the field by taking samples during flood events, and siphon-bottles are used for this purpose.

Another important factor is the variation in water salinity when working in estuaries (Courtois *et al.*, 1970). Laboratory research and some years of field work have indicated that measurements are not affected by electronic drift provided equipment is checked at 15-30 day intervals.

Taking into account all the effects mentioned above, it may be tentatively stated that measurements will be accurate to within 1 g l^{-1} for the ^{241}Am gauge, and within 2 g l^{-1} for the ^{137}Cs gauge, in the case of counts lasting for 10 min.

PRACTICAL APPLICATIONS

The possibilities of manufacturing nuclear gauges with different geometries and sensitivities are multifold. However, it should be remembered that one particular gauge geometry is unlikely to be considered applicable in all situations. The best results are obtained by manufacturing gauges suited to the characteristics of particular measurement locations, taking into account the expected concentration range, the chemical composition of the suspended sediments, and the size of the sediments constituting the bed load transport, etc.

Many different types of nuclear gauges have been experimented with in the last 15 years (Courtois *et al.*, 1970; Florkowski, 1970; Florkowski & Cameron, 1966; Martin, 1970; McHenry *et al.*, 1967; Papadopulos & Ziegler, 1966; Tazioli, 1980), but for the most part they have been used in laboratories or for occasional *in situ* measurements. A feature of nuclear gauges which is particularly interesting for the sedimentologist and the hydrologist is their potential for use in permanent installations.

The application of these gauges to the measurement of sediment transport in water courses of instrumented basins will now be described.

Measurements in instrumented basins

Monitoring techniques using nuclear gauges have been employed for over 5 years in two instrumented basins in southern Italy. These basins are characterized by torrential regimes of surface runoff and by high suspended sediment concentrations.

The area experiences a mediterranean climate, and the annual rainfall is concentrated into a short period so that resulting floods are often severe. One of the basins is located in Basilicata (Fig. 4) and covers an area of 63.5 km^2. Most of the basin is underlain by Quaternary marly clays of generally silty and/or sandy texture, and by quartzose-calcareous sands and by polygenic conglomerates. Recent alluvial deposits of varying

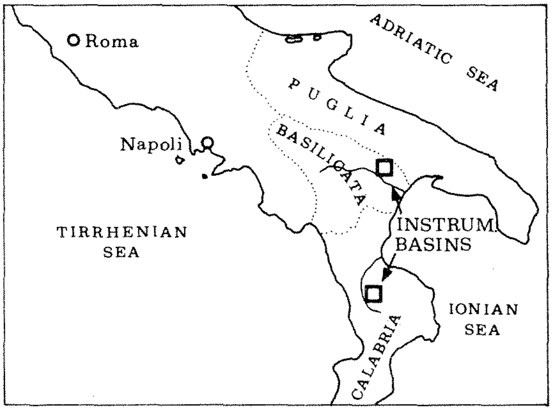

Fig. 4 Location of the instrumented basins.

thickness and silty-sand texture cover the valley floors of the main stream and its tributaries from the centre of the basin to the mouth. The mean elevation of the basin is 243 m above sea level and the mean slope is 31.8%. The mean slope of the main stream is 2.5% in the upper part of the basin and 0.6% in the lower part.

The other basin is situated in Calabria and has a surface area of 4.7 km^2. It is underlain by crystalline Palaeozoic rock and by Quaternary sand and conglomerates, which provide a large amount of suspended and bed material for transport (Frega *et al.*, 1976). The latter often comprise boulders 50 mm in diameter. The maximum and minimum elevations are 960 and 185 m a.s.l., and the mean slope of the main stream in 12.7%.

Two ^{241}Am gauges have been installed in the first basin, whereas one ^{137}Cs gauge has been installed in the second.

^{241}Am gauges The first gauge is equipped with a source of ^{241}Am (100 mCi) and a gamma scintillation detector with a NaI(Tl) crystal, 38 x 25 mm, contained inside a steel tube which is fixed to the stream bed by means of steel pipes and concrete (Fig. 5). The distance between source and detector is 32 cm. The geometry of the gauge is such that measurements can be carried out in a portion of the stream cross section between 0.20 and 0.60 m from the bed, in a volume which has a diameter of about 0.40 m.

A second ^{241}Am gauge, with a different geometry, has been installed to make measurements at a distance of 0.05-0.25 m from the stream bed. This gauge is equipped with a source of ^{241}Am (100 mCi), and the detector has been collimated with Pb in order to reduce the volume of influence. The minimum water depths for correct functioning of the gauges are 0.25 and 0.6 m (Fig. 6).

The counting and recording equipment is situated in a concrete hut 50 m away from the gauges. The equipment is powered by semi-stationary lead batteries which are recharged by a photovoltaic solar panel (Fig. 7).

Since runoff is torrential and generally of short duration, it is necessary that these gauges function fully automatically. This is achieved by means of a switch which activates them when

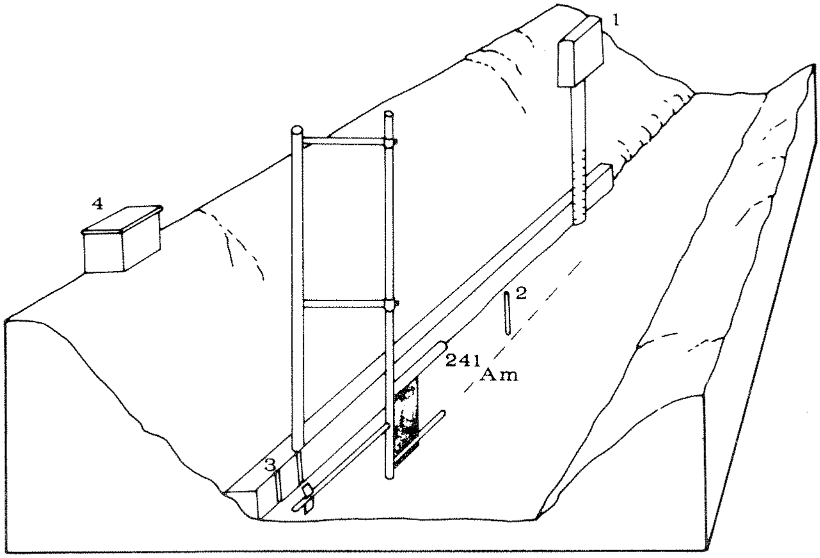

Fig. 5 Gauging station for water stage and suspended sediment concentration. 1 = water stage recorder, 2 = iron rod to divert trash; 3 = activating switch; 4 = box containing the counting and printing unit.

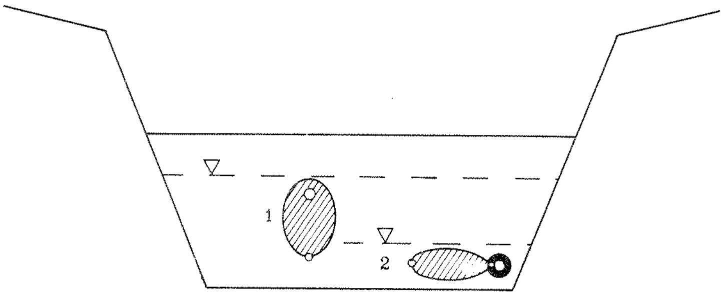

Fig. 6 Volumes of influence of ^{241}Am gauges and minimum water depths for correct measurements.

water depth exceeds 0.20 m and switches them off 40 min after the water depth drops below this level.

^{137}*Cs gauge* This gauge is a rigid steel structure into which two 9 mm thick tubes have been fixed at a distance of 0.90 m from each other. The tubes contain the detector and radioactive source. The gauge can be installed permanently in the water course and allows measurements of suspended sediment concentration in a volume of influence as large as 0.90 m by 0.30 m (Fig. 8).

The structure is situated in a 16 m long and 2.10 m deep concrete flume where it has been in operation for over 5 years. The gauge makes suspended sediment concentration measurements over the entire breadth of the stream and in a cross section between 0.20 and 0.50 m from the fixed bed. It is considered that the velocity of water and thus the suspended sediment concentration are uniformly distributed in the measuring cross section (Rosso, 1978). The gauge operates automatically, and the

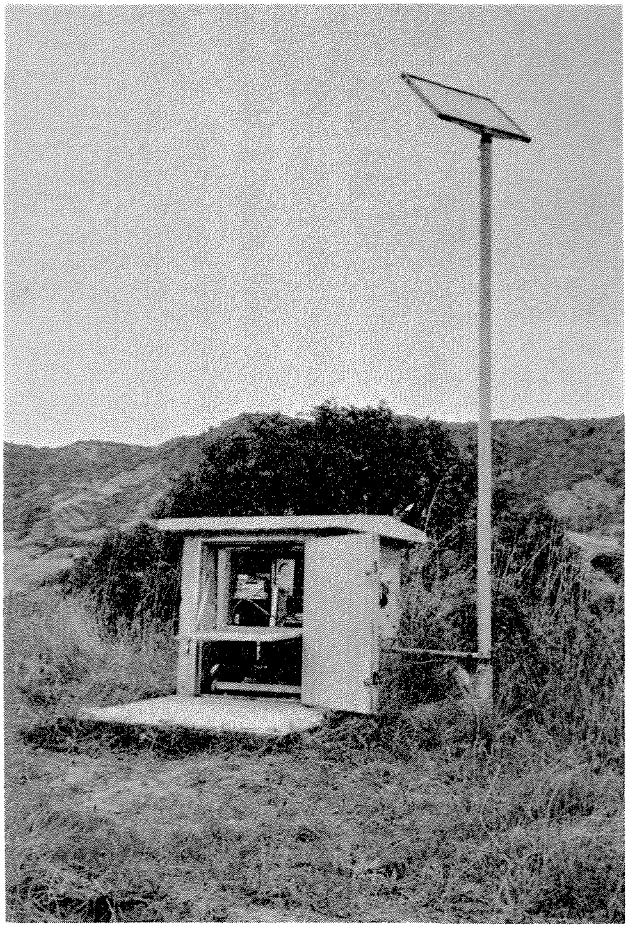

Fig. 7 Box containing ratemeter, scaler, interface, digital printer (SAPHYMO and NARDEUX), switching mechanism and batteries powered by a photovoltaic solar panel.

minimum water depth for correct functioning is 0.50 m. The counting and recording equipment is identical to that described for the ^{241}Am gauges.

Gamma-ray retrodiffusion gauge In the case of larger water courses characterized by transport of coarse sediment and by marked morphological variations in the stream bed, the use of ^{137}Cs sources makes it possible to manufacture gauges capable of operating under very difficult conditions, although measurements will be less accurate than those obtainable with the ^{241}Am gauges.

Figure 9 illustrates an example of a gamma-ray retrodiffusion gauge with a ^{137}Cs source which can be installed easily in large water courses. Moreover, by using this geometry it is possible to obtain vertical profiles of sediment concentration.

IN SITU MEASUREMENTS

Some examples will now be given of the suspended sediment

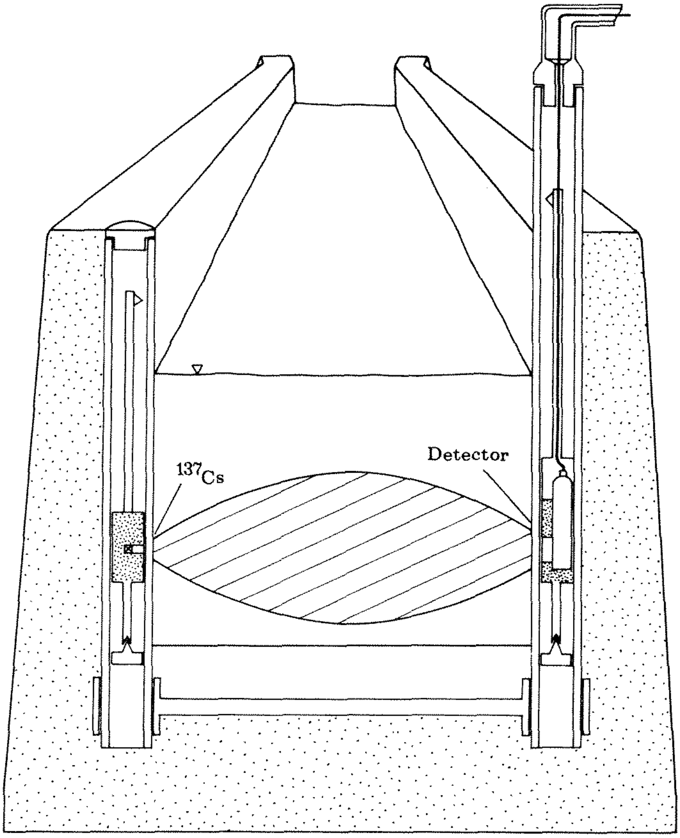

Fig. 8 Gauging station for suspended sediment concentration.

transport measurements carried out using the permanently installed nuclear gauges described above. Figures 10 and 11 show examples of high suspended sediment concentrations recorded during 1978 and 1980 in the Basilicatan basin. Figure 10 represents an example of recordings made by two gauges placed at different heights above the stream bed. An example of records from the ^{137}Cs gauge in the Calabrian basin is shown in Fig. 12.

The sediment discharge G_S was calculated as the product of water discharge Q and sediment concentration as follows:

$$G_S = C\,Q$$

where, C represents suspended sediment concentration (g l^{-1}) recorded by the nuclear gauges, and Q is the flow volume (m^3 s^{-1}), which is calculated from water stage, H, by application of the stage/discharge rating for the gauging station.

Data collected using the ^{241}Am gauges suggest during major flood events there are no appreciable vertical gradients of suspended sediment (Fig. 11). This finding was also verified by taking samples during a flood event with a depth of about 1 m (Ciet & Tazioli, 1978), and is explained by the nature of the sediment at this site which is predominantly clay or sandy-silt.

The same basin displays a reasonable degree of correlation

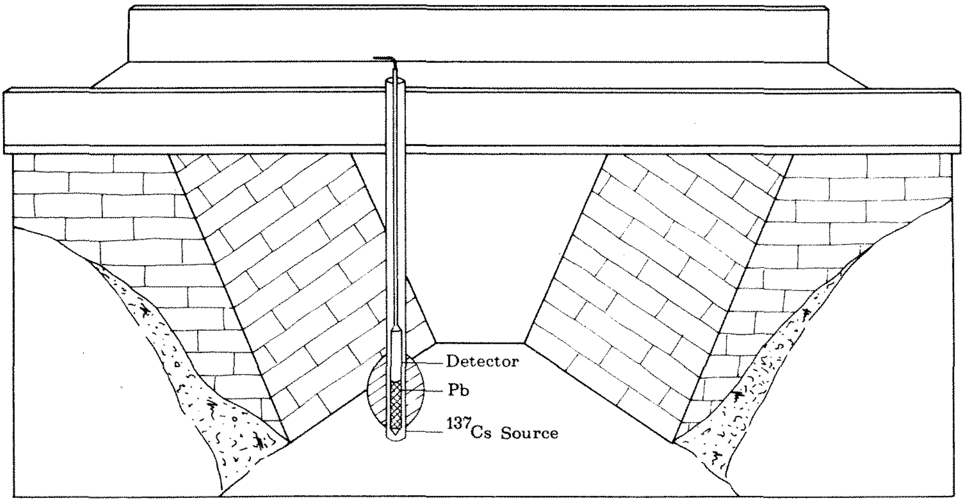

Fig. 9 Gauging station for suspended sediment concentration.

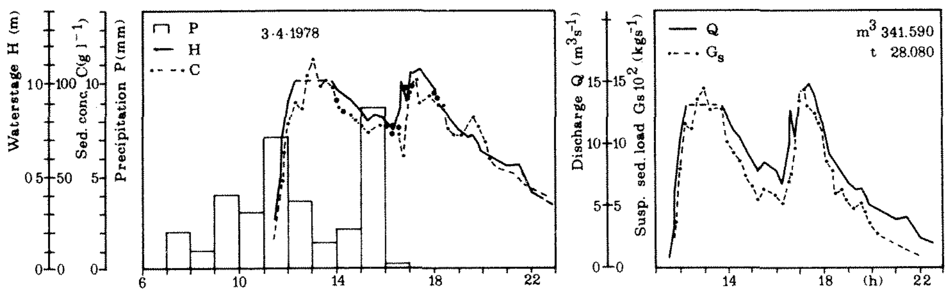

Fig. 10 Rainfall histogram, water stage (H) and suspended sediment concentration (C); water discharge (Q) and suspended sediment discharge (G_s). The solid circles indicate data obtained by independent sampling.

between discharge and suspended sediment concentration, and between total runoff volumes and total suspended sediment loads for some flood events (Fig. 13). Although observations have only been carried out for a few years, the mean annual suspended sediment load has been calculated and found to exceed 1000 t km^{-2}. The period October 1979-May 1980 was associated with particularly high rates of suspended sediment transport, and the record load of 1600 t km^{-2} in this period corresponds to a mean lowering of the basin by about 0.8 mm. Bed load transport at this site can be considered negligible.

TRACER TECHNIQUES FOR MEASUREMENT OF BED LOAD TRANSPORT

There are numerous tracers available for studies of sediment movement, but the most frequently used are fluorescent and artificial radioactive tracers.

Petrographic methods and techniques using the measurement of natural gamma radioactivity of sediments generally give very useful indications as to the origin of the sediments and the

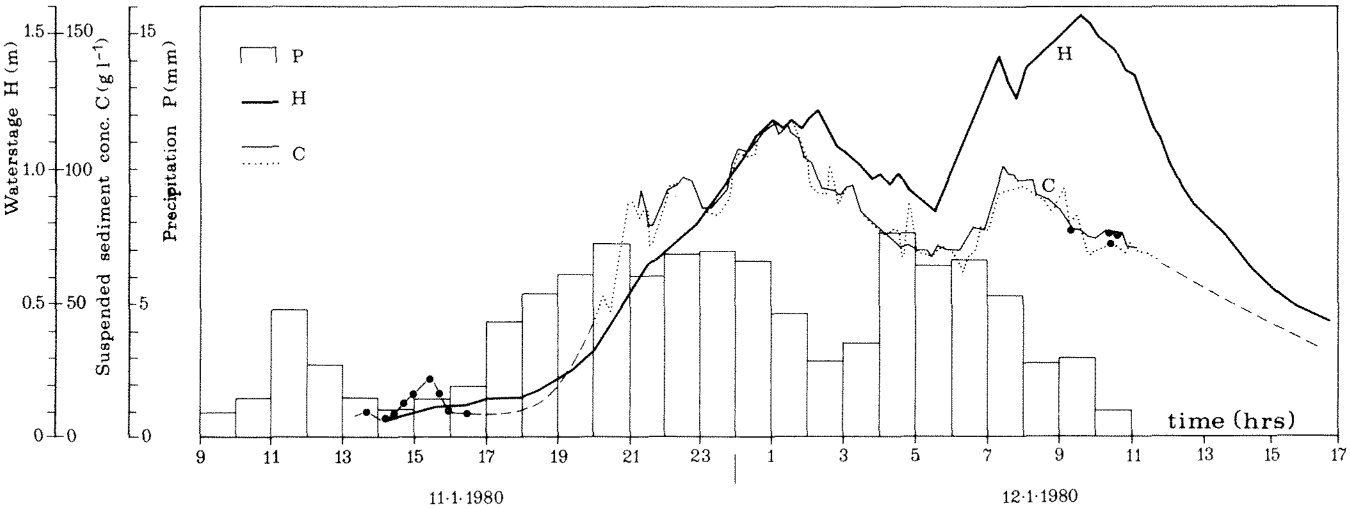

Fig. 11 Rainfall histogram, water stage (H) and suspended sediment concentration (C) registered by two ^{241}Am gauges at different depths. The dotted line indicates data obtained in a section 0.05–0.25 m from the river bed; the continuous line (C) indicates data obtained in a section between 0.20 and 0.60 m from the river bed. The solid circles indicate data obtained by independent sampling.

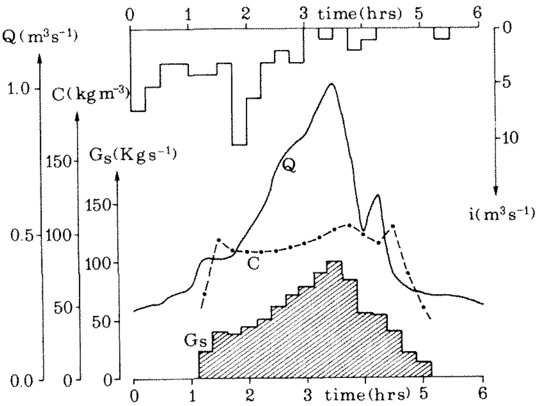

Fig. 12 Rainfall histogram, suspended sediment concentration (C), water discharge (Q) and suspended sediment discharge (G_s). After Rosso & Tazioli (1979).

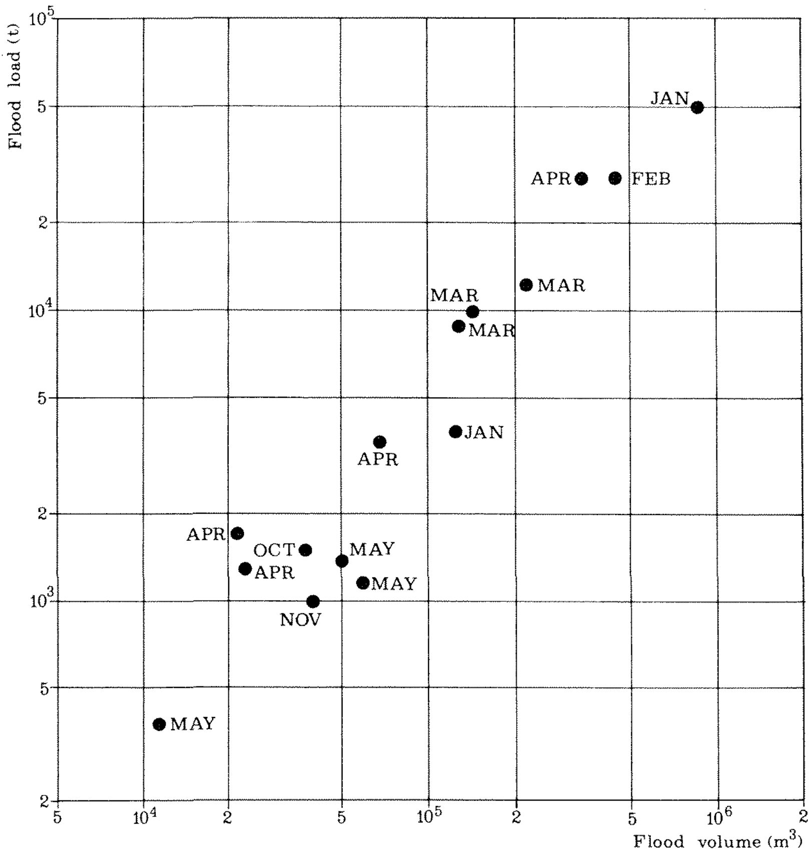

Fig. 13 Relation between suspended sediment load and runoff volume for 15 flood events.

direction of transport. Artificial radioactive tracers, unlike fluorescent tracers, can be detected *in situ*, and in some cases make it possible to check the sediment dynamics during transport. For example, they offer the possibility of determining the parameters which are needed to verify theoretical expressions of transport, and they enable the occurrence of erosion and sedimentation, and the direction, velocity and depth of transport to be directly established.

The measurement of bed load transport using an artificial radioactive tracer is carried out by emplacing in the river a quantity of radioactive sediment, with characteristics similar to those of natural sediments, and then following its movement by means of portable detectors.

The choice of radioactive tracers is made according to the half-life and the energy of their gamma-rays. The half-life must be suitable for the duration of the experiment and possible replication of surveys. The energy of the gamma radiation emitted should be sufficient to permit detection especially in cases where deep burying of the tracer is expected (Courtois, 1968).

In general, ^{198}Au is used for preliminary experiments, whereas radioisotopes with a longer half-life, such as ^{51}Cr, ^{192}Ir, ^{46}Sc, ^{182}Ta, are frequently employed in the later stages of a study.

The activities used depend on the type of experiment, but they vary in general from a few millicuries to 150 Ci (Courtois,

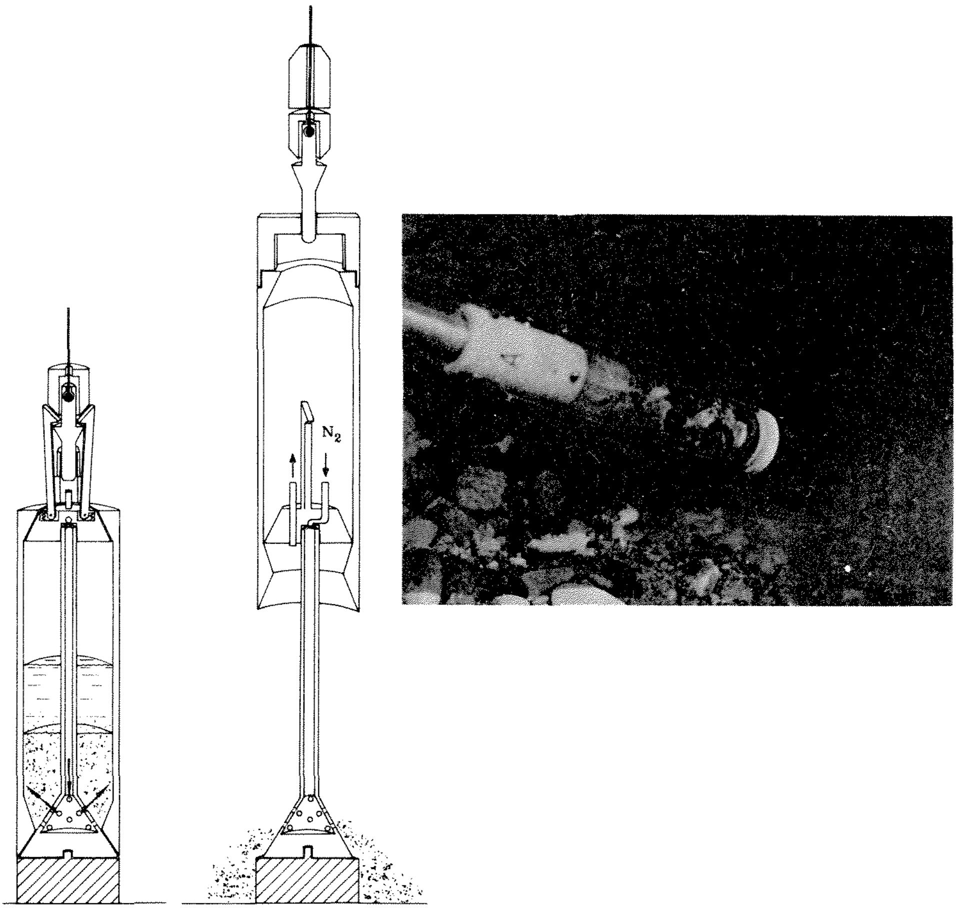

Fig. 14 Bottle for labelling and injecting sands, on the left, (after Carlin & Magri, CNEN, Casaccia & Tazioli, University of Bari). On the right, device for placing labelled pebbles in torrents.

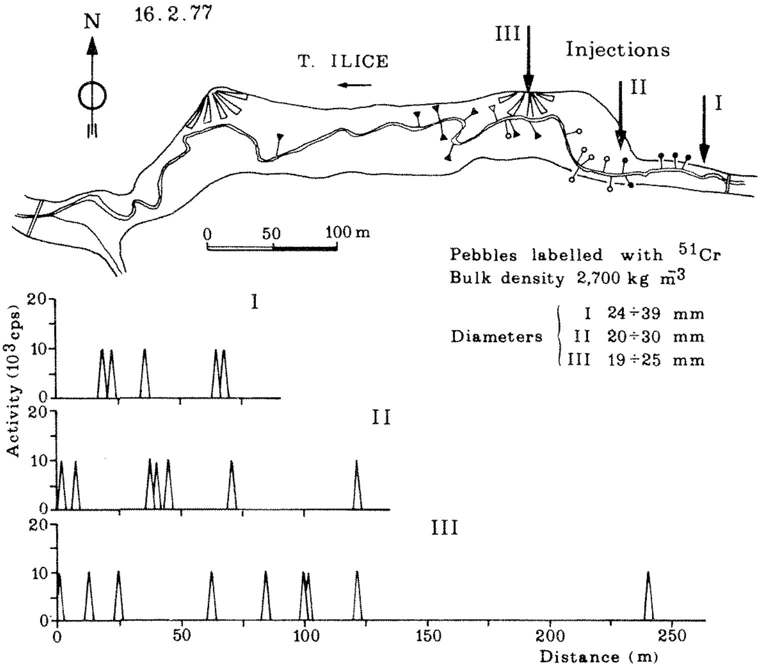

Fig. 15 Dispersion of pebbles after a flood event in a small stream in southern Italy.

1968). The mass of radioactive sediment emplaced varies between a few dozen grams and several kilograms for pelitic sediment and sand, whereas for pebbles the number used can vary from a few dozen to a maximum of 200. The radioactivity induced in each pebble is of the order of 100 µCi if ^{182}Ta is used, or 500 µCi for ^{51}Cr.

Labelling of natural sediment may be undertaken by depositing radioactive isotopes on the surface of the particles, or in the case of coarse sediment radioactive material may be inserted into the body of the particle. In the former case, it should be pointed out that the tracer activity is confined to the exposed surfaces of particles, which generally makes accurate calculations of transport impossible. For this reason, some sedimentologists now prefer to use artificial glass containing, as an impurity, an element which becomes radioactive after irradiations in reactors (Courtois, 1968). Labelling of pebbles and boulders is normally carried out individually by introducing radioactive sources or by depositing radioactive solutions in drilled holes which are subsequently sealed with cement or epoxy resin. Further details of the methods for labelling sediment are described by Bougault *et al.* (1967).

The emplacement of radioactive tracers is carried out using special devices which are controlled by long rods (2-3 m), or using bottles connected to a steel cable and controlled by a messenger (Fig. 14). The dispersion of labelled sediments is traced by dragging gamma scintillation detectors along the bed of a stream. However, a torrential regime prevents bed surveying during floods, and measurements have to be made at the end of a storm event.

Figure 15 illustrates the movements of pebbles labelled with ^{51}Cr in a small water course in southern Italy which were recorded during a joint research programme with the Soil Defence Department, University of Calabria, and the Cosenza Institute, National Research Council (IRPI).

Interpretation of results

All of the most industrialized countries already utilize radioactive tracer techniques for studying solid transport. In France, for example, between 1954 and 1980 approximately 200 experiments with radioactive tracers have been carried out (Caillot, 1981). In Italy tracer experiments in maritime environments (Carlin *et al.*, 1975) and in natural streams have been carried out since 1968.

It is well known that when flow conditions are stable, it is possible to follow the displacement of labelled sediments at a given time over specific reaches of the river system, and the bed load discharge q_s can be calculated from the equation:

$$q_s = q\ L\ V_m E_m$$

where, q represents the specific gravity of the sediment *in situ*, L and E_m the width and the thickness of the section of the moving layer and V_m the mean velocity of transport (Courtois & Sauzay, 1970; Caillot, 1981).

The mean velocity V_m is evaluated by analysing the progression over time of the centre of gravity of the isocount curves, whereas the thickness E can be determined by core sampling or by the use of the counting rate balance method proposed by Courtois & Sauzay (1970). In fact, the same authors found a relationship between

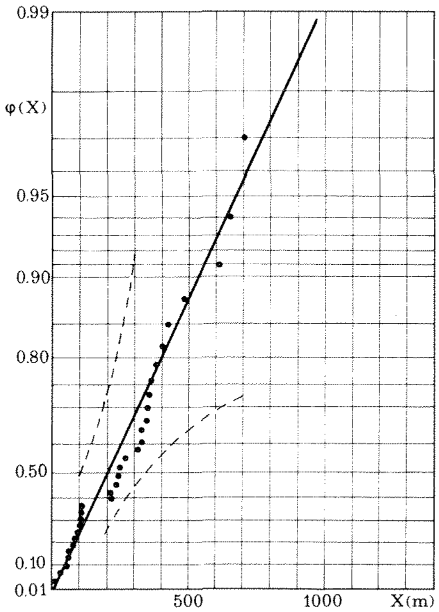

Fig. 16 Probability distribution of the distance travelled by sediments after a flood event, after Copertino *et al.* (1979).

the number of photons N received by a detector dragged along the bottom, the activity of the emplaced material and the burial of the tracer.

However the above expressions may not be applied to the case of unsteady flow which occurs, for example, during flash floods in small mountain streams, since the tracer dispersion cannot be monitored during such events.

Studies of bed load transport in natural streams have been carried out in Italy during the last 5 years (Copertino *et al.*, 1979; Caloiero *et al.*, 1979). In the particular case of pebble transport during flash floods, the approach taken has been to analyse the cumulative effect of a flood through an evaluation of the total displacement of the particles after the end of the event (Copertino *et al.*, 1979; Imperiale *et al.*, 1977). The displacement is considered to be a random variable whose probability density function, f(x), can be determined by tracer experiments. The data obtained from a small stream showed a good fit to a two-parameter gamma distribution function (Copertino *et al.*. 1979). Figure 16 illustrates results of a tracer experiment carried out in Italy during 1978. Using the same data, it is also possible to evaluate the probability that a number, N_o, of particles have passed through a given stream cross section (Shen & Cheong, 1973; Versace, 1979).

CONCLUSIONS

The use of automatic nuclear gauges for *in situ* measurements of suspended sediment concentration is advised wherever water courses are characterized by highly irregular regimes and by floods of short duration. However, it must be pointed out that monthly testing of the electronic equipment and independent sampling during flood events, in order to check the chemical composition of the sediments, are necessary for correct functioning of the gauges.

As regards bed load transport, it is evident that radioactive tracer techniques constitute a very useful means of investigation. These techniques are complementary to conventional methods, because unlike the latter they are capable of providing information on dispersion during the movement phase.

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REFERENCES

Anguenot, F. & Caiveau, G. (1980) Mesure de turbidité à l'aide de jauges radioéléments à absorption et à diffusion de photons γ.

Rapport interne CEA/SAR, S/80/2.
Bougault, H., Caillot, A., Courtois, G. & Janneau, B. (1967) Dépôts superficiels de radioéléments sur les sables et les vases. *Proc. Symp. Isotopes in Hydrology.* IAEA, Vienna.
Caillot, A. (1981) The use of tracers in dynamic sedimentology. In: *Guidebook on Nuclear Techniques in Hydrology.* IAEA Tech. Rep. Series, UNESCO-IAEA, Vienna (in press).
Caloiero, D., Militi, L., Rosso, R., Tazioli, G. S., Versace, P. & Zuffa, G. G. (1979) Problemi di misura del trasporto solido in un piccolo bacino (T. Ilice - Calabria) (Problems of measurement of solid transport in a small basin (T. Ilice - Calabria)). *Geol. Appl. e Idrogeol.* XIV part II, Bari.
Carlin, F., Dai Pra, G., Magri, G. & Tazioli, G. S. (1975) Ricerche sul trasporto solido litorale alla foce del Fiume Sinni (Golfo di Taranto) (Researches on littoral solid transport at the mouth of the Sinni River (Gulf of Taranto)). *Geol. Appl. e Idrogeol.* X, part I.
Ciet, P. & Tazioli, G. S. (1976) Metodologie radioisotopiche per la misura del trasporto solido in sospensione (Radioisotope methods for measurement of suspended sediment transport). *Geol. Appl. e Idrogeol.* XI, part I.
Ciet, P. & Tazioli, G. S. (1978) Sul trasporto torbido del T. la Canala (Basilicata) (On the suspended sediment transport of T. la Canala (Basilicata)). *Geol. Appl. e Idrogeol.* XIII.
Copertino, V. A., Tazioli, G. S. & Versace, P. (1979) The movement of bed-load during floods in natural stream channels: a Langragian global approach. *Proc. 18th Congr. IAHR* (Cagliari, 10-14 Sept. 1979).
Courtois, G. (1968) Sediment movement and transport. In: *Guidebook on Nuclear Techniques in Hydrology.* Tech. Rep. Series no. 91, IAEA, Vienna.
Courtois, G. & Sauzay, G. (1970) Les masses de sédiments marquées à injecter dans une expérience de traceurs radioactifs en sédimentologie dynamique. *La Houille Blanche* no. 7.
Courtois, G., Anguenot, F. & Magloire, C. (1970) Turbidimétrie: Absorptiométrie X-γ ou radioactivité naturelle? *Isotope Hydrology 1970.* IAEA, Vienna.
Florkowski, T. (1968) Sedimentology. In: *Guidebook on Nuclear Tech. in Hydrology.* Tech. Rep. Series no. 91, IAEA, Vienna.
Florkowski, T. (1970) Portable radioisotope gauges for suspended sediments. *Isotope Hydrology 1970.* IAEA, Vienna.
Florkowski, T. & Cameron, J. F. (1966) A simple radioisotope X-ray transmission gauge for measuring suspended sediment concentration in rivers. In: *Proc. on Radioisotope Instruments in Industry and Geophysics.* IAEA, Vienna.
Frega, G. A., Lanzafame, G., Marone, V., Tazioli, G. S. & Zuffa, G. G. (1976) Il bacino sperimentale del T. Ilice (Calabria) (The experimental basin of Torrent Ilice (Calabria)). *Geol. Appl. e Idrogeol.* X, part I.
Imperiale, G., Montano, F., Paoletti, A. & Piacentino, G. B. (1977) Ricerca sperimentale sul trasporto solido di fondo del T. Pora in Liguria (Experimental research on bed-load transport of T. Pora - Liguria). Atti Seminario su *Misura del Trasporto Solido al Fondo nei Corsi d'Acqua: Problemi per una Modellistica*

Matematica (Firenze).

McHenry, J. R., Coleman, N. L., Willis, J. C., Murphree, C. E., Bolton, G. C., Sanson, O. W. & Gill, A. C. (1967) Performance of nuclear sediment concentration gauges. *Proc. on Isotopes in Hydrology* (1966). IAEA, Vienna.

Martin, J. M. (1970) Les jauges radioactives de turbidimétrie. *La Houille Blanche* no. 8.

Papadopulos, Y. & Ziegler, C. A. (1966) Radioisotope technique for monitoring sediment concentration in rivers and streams. *Proc. on Radioistope Instruments in Industry and Geophysics.* IAEA, Vienna.

Rosso, R. (1978) Dispositivo per la misura di portata (canale Venturi) con sezione di rilevamento torbiometrico realizzato nel bacino del T. Ilice: I. Esame del processo idraulico (Gauging station for measurement of discharge (Venturi flume) and turbidity at the basin of T. Ilice: I. Examination of hydraulic process). *Int. Report no. 106, CNR-IRPI, Cosenza.*

Rosso, R. & Tazioli, G. S. (1979) Suspended sediment transport during flood flows from a small catchment. *Proc. 18th Congr. IAHR* (Cagliari, 10-14 Sept. 1979).

Shen, H. W. & Cheong, H. F. (1973) Dispersion of contaminated sediment bed load. *J. Hydraul. Div. ASCE* 99 (HY11).

Tazioli, G. S. (1980) The measurement of suspended sediment transport in natural streams using automatic radioisotope gauges. *J. Hydrol.* 47.

Tazioli, G. S. & Caillot, A. (1981) Measurement of suspended sediments by nuclear techniques. In: *Guidebook on Nuclear Techniques in Hydrology.* Tech Rep. Series, UNESCO-IAEA, Vienna (in press).

Versace, P. (1979) Un modello stocastico per la stima del trasporto di fondo durante le piene (A stochastic model for the evaluation of bed-load transport during floods). Seminario su *Moderne Vedute sulla Meccanica dei Fenomeni Fluviali* (Bressanone 8-12 ottobre 1979).