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Radiotracer and Sealed Source Applications in Sediment Transport Studies

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RADIOTRACER AND SEALED SOURCE APPLICATIONS IN SEDIMENT TRANSPORT STUDIES

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FOREWORD

The investigation of sediment transport in seas and rivers is crucial for civil engineering and littoral protection and management. Coastlines and seabeds are dynamic regions, with sediments undergoing periods of erosion, transport, sedimentation and consolidation. The main causes for erosion in beaches include storms and human actions such as the construction of seawalls, jetties and the dredging of stream mouths. Each of these human actions disrupts the natural flow of sand. Current policies and practices are accelerating the beach erosion process. However, there are viable options available to mitigate this damage and to provide for sustainable coastlines.

Radioactive methods can help in investigating sediment dynamics, providing important parameters for better designing, maintaining and optimizing civil engineering structures. Radioisotopes as tracers and sealed sources have been useful and often irreplaceable tools for sediment transport studies.

Radioactive tracers are the only unequivocal method of direct real time assessment of sediment transport pathways. Radiotracers are more sensitive and provide more accurate parameters than conventional tracers. In recent decades, many radiotracer studies for the investigation of sediment transport in natural systems have been conducted worldwide, and various techniques for tracing and monitoring sediment have been developed by individual tracer groups. In addition to radiotracers, sealed source techniques can provide information on the density of sediments deposited in a channel of navigation as well as on the concentration of sediments circulating in suspension.

There are some typical problems in which radiotracer and sealed source techniques can make a contribution. Littoral zones in many countries are subjected to erosion, and the shorelines undergo long term retreat, which often leads to beach loss. In addition, improper selection of dumping sites for dredging operations at harbours may cause the return of the dumped material to the dredged channel.

The environmental, economic and social benefits from the application of radiotracer and sealed source techniques can be enormous. However, the developed radioisotope techniques and methods for sediment tracing and monitoring have not yet been compiled as a technical document, which is essential for the preservation of the knowledge and transfer of the technology to developing countries. This training course material aims to compile all important theoretical and practical aspects of tracer and sealed source techniques for investigating bedload and suspended sediment transports. This publication will help the radiotracer groups in States to promote and apply radioisotope technologies for coastal engineering protection to better serve the environmental sector. It will also be useful reference material for engineers and managers of environmental and coastal engineering sectors to understand the potential of radioisotope techniques for investigating complex littoral sites and structures.

The training course material is based on lecture notes and practical works delivered by many experts in IAEA supported activities. Lectures and case studies were reviewed by a number of specialists in this field. The IAEA wishes to thank all the specialists for their valuable contributions. The IAEA officer responsible for this publication was P. Brisset of the Division of Physical and Chemical Sciences.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The training course material on "Radiotracer and sealed source applications in sediment transport study" is not a textbook of sedimentology and even less a book exposing the theory of mechanics of fluids devoted to sediment transport in water systems. It aims primarily to describe the radioactive techniques developed and applied to study the sediment transport.

More than half of the world population is living on maritime shores, estuaries and on banks of the rivers, where sediment transport problems are aggravated, the mean level of the oceans has not ceased increasing (approximately 15 cm for one century), and the forecast is alarming. The direct consequence is the acceleration of littoral erosion. Related is the creation of many problems, such as maintenance of the harbor works (basins, wet docks), circulation in navigation channels, monitoring the silting process in dams (more than 36.000 in the world), etc.

The economic consequences of the uncontrolled sediment transport in the natural environment are considerable. The protection of beaches, houses, roads and dams caused by littoral erosion is very expensive. Carrying out dredging of million cubic meters of sediments to maintain navigable depths in the access channels to ports costs a lot. For example, in France it is estimated that dredging services to maintain the access of the principal ports costs each year about 100 million Euro (40 million m^3).

Studies on sediment transport in rivers and coasts are of vital importance to many civil engineering projects such as dock construction, coastal reclamation, dredging and irrigation projects. Typical problems related to sediment movement in the natural systems are:

- Littoral zones in many countries are subjected to erosion. On sedimentary coasts, coastal erosion sometimes poses a serious danger to human settlements. Armoring structures are erected when coastal erosion threatens beachfront properties. The structures protect properties, but the shorelines undergo long-term retreat, which often leads to beach loss.
- For the management of sufficient water depth at ports and harbors to accommodate ship movements, dredging operations are carried out. The selection of suitable dumping site of dredged material is very important, as dumped material should not come back into the navigation channel.
- Municipal wastewater consists of a mixture of aqueous and particulate components. The effluent particles are complex mixtures of organic and inorganic solids. Information concerning the diffusion and settling behavior of the particles has important implication for understanding the impacts of effluent discharges on receiving water systems.

Radioisotope techniques are largely employed to monitor sediment (gravels, sands and silts), displacements in rivers and seas. Information necessary to build and maintain river and maritime works, such as dams, channels of navigation, harbor-basins, as well as to design and maintain barriers for beach and littoral protection from erosion can be obtained using radiotracers and sealed source techniques.

There are two kinds of radioisotope techniques used for sediment transport study:
- Radiotracers, to follow displacements of solid particles under the action of water currents and waves.
- Radioisotope sealed sources (nucleonic gauges or nuclear instruments) to measure the sediment densities or turbidities in rivers, estuaries, dams, channels of navigation, etc.

Since 1960s, radioisotopes as tracers and sealed sources have been useful and often irreplaceable tools for sediment transport studies. Radiotracer techniques are used to obtain quantitative information, such as the direction, velocity and thickness of sediment movement. Gamma scattering and transmission gauges are applied for sediment monitoring. They are used for either static or dynamic measurement of concentration of sediments deposited.

Computational fluid dynamics (hydrodynamic) modeling is now a common tool for the management of the natural systems and is increasingly used to study the fate and behavior of particulates and contaminants. Radiotracer techniques are often employed to validate hydrodynamic models to enhance confidence in the predictive value of the models. Experimental tracing and numerical modeling are complementary methods of studying complex systems. Tracer data are based on direct observation, but are limited to the labeled component of the system and to a restricted domain of space and time. Numerical models can in theory accommodate all the important parameters, but are limited by their underlying assumptions and accessible computing power. Individually both approaches have limitations, but together they offer a very powerful method of investigating complex systems. Over the past few years it has become clear that the synergistic modeling and tracer approach can make a significant contribution to addressing complex problems in natural systems.

During the last few decades, many radiotracer studies for the investigation of sediment transport in natural systems have been conducted worldwide, and various techniques for tracing and monitoring sediment have been developed by individual tracer groups. Recently, new technology, such as combined data acquisition systems or software that record radiation counts together with GPS position data, radiotracer injection systems for more convenient and safer handling, and radiation detection systems for more reliable data collection, as well as new software packages for more accurate tracer data treatment and interpretation, have been developed.

This technical document will help the radiotracer groups in Member States to promote and apply the radioisotope technologies for coastal engineering protection and better serving the environmental sector. It will help:

- Radiotracer groups to promote and provide services of radiotracers and sealed sources to coastal engineering, river management and dam maintenance,
- Graduate students of environmental and civil engineering faculties to expand their knowledge and to make use of radiotracer and sealed source techniques in research and development, in particular for their Master and PhD thesis,
- Engineers and managers of environmental and coastal engineering sectors to understand the potential of radiotracer techniques for investigating complex littoral sites and structures.

This introduction presents the importance of radiotracer and sealed source techniques for sediment transport studies. Principles and basic elements of the fluid mechanics applied to sediment transport are described in the first chapter. The radiotracer techniques as applied for sediment transport studies are presented in the second chapter; many case studies are provided to illustrate the tracer methodology and technology. The third chapter deals with radioisotope sealed source techniques as applied for monitoring solid transport concentration in sea, rivers and dams. Typical nuclear instruments and applications are described in details. Some economic benefits are described at the end.

The treated examples of radiotracer and sealed source techniques and applications are dealing with typical important problems related with the stability of the littorals, role and effect of structures for sandy beach protection, maintenance of channels of navigations and monitoring of navigable depth in harbors and estuaries, the extraction of the aggregates from the sea bottom, effects of dredging and discharge of products of dredging, dam monitoring and cleaning.

1.2. THE IMPORTANCE OF RADIOTRACER AND SEALED SOURCE TECHNIQUES FOR SEDIMENT MANAGEMENT

Sediment management is a key consideration for all countries around the world, developed or developing, whether protecting coastlines and populated areas from sea-level changes, storm waves and coastal erosion or the increasing frequency and intensity of rainfall events leading to widespread flooding, mudslides or loss of floodplains and agricultural land. Understanding the behavior, fate and impact of sediment movement is vital for ports and harbor development, dredging, engineering projects, pollution transport, flood and coastal protection, population protection, water quality, tourism, coastal zone management and environmental habitat protection.

For example a major cost of a new port development is the capital and then maintenance dredging costs; for medium size ports in India the annual maintenance dredge volume is estimated to be 60 million m^3 at a cost of US $125 million. It is therefore critical that the behavior and fate and disposal of such quantities is well understood and sediment does not simply return back to the port.

A balance has to be struck between the costs of transport for disposal and the cost of maintenance dredging costs and re-handling. In order to implement best management and environmental practice, to reduce or control maintenance dredging costs and avoid changes in hydraulics, risk to navigation, flooding, river and coastal erosion and contamination requires a detailed knowledge of sediment transport in order to formulate strategies, which will minimize capital and operational costs and environmental impact.

Accurate and conclusive field datasets detailing sediment movement and the conditions leading to disturbance, erosion and transport allow management strategies to be adopted preventing increased costs, doubling handling of sediment and environmental damage. Field data can be used in a standalone dataset, in straightforward studies. However in more complex study areas or sites where future changes are planned field data should always be used to carefully calibrate and/or validate numerical models.

Many developments, engineering activities and operations in rivers, reservoirs, lakes, estuaries and the coastal zone disturb sediment to a greater or lesser degree. This is particularly so in the case of dredging and sediment relocation, where impact can take place, both at point of extraction and discharge, leading to a potential impact on the environment and changes to the natural hydrography and morphology of a site. Therefore, all parties undertaking such activities and operations need to have a clear understanding of the aquatic environment in which they operate and need to be able to quantify transport of suspended and bedload sediment, particularly fine cohesive sediment and contaminated sediment.

Assessment of sediment transport can be performed in many ways including mathematical models, physical models, and bathymetric data by investigating sedimentology parameters, however the use of sediment tracers coupled with a standard suite of conventional hydrographic survey techniques provides the optimum way to measure sediment behavior, transport pathways, fate and deposition, in order to assess environmental impact. Sediment tracers can provide direct unequivocal measurement of these parameters in the field. Tracers offer a highly cost-effective and alternative method of determining sediment transport by assimilating tidal currents and wave dynamics and the sediment transport processes of erosion, re-suspension, transport, settling and deposition. Sediment tracers include both radioactive and non-radioactive (fluorescent) tracer particles used to simulate and measure the fate, behavior and re-distribution of fine and coarse sediment in the environment.

Since the mid-1960's it is estimated that hundreds of radiotracer sediment transport studies have been conducted during this time, mostly in Australia, Brazil, France, India, South Korea and United Kingdom. The radiotracer and sealed source techniques are still competitive and very useful; the trend is to integrate the radiotracer experiment with computer fluid dynamics (CFD) modeling for creation of more reliable models and their validation.

2. ABOUT SEDIMENT TRANSPORT

2.1. CONCEPT OF SEDIMENT DYNAMICS

In continents and islands the natural action of the rain and the winds, associated with the human intervention affects the morphology of the soil. The runoff produces soil erosion; water and sediments are then transported by the action of the gravitational force to lower regions and the sediments, depending on their grain size and the obstacles encountered, can reach the coastal area. The natural route for this flow of water and sediment is via rivers, which have different shapes and sizes. The transport of water and sediments is an important environmental phenomenon of very complex nature (three-dimensional and time dependent).

It poses the following question: what happens when boundaries of a water flow are constituted of sediments which can be set into motion by the flow? This comprises the erosion, transport and deposition of the sediment grains. The flow of water alters the boundaries of the flow and this change affects, in turn, the flow itself. It is an iterative process. The interdependence of the factors involved in practical hydraulic and sedimentological problems is so complex that a complete analytical solution does not exist.

The knowledge of the structural geology, hydrology and river sedimentology (the natural processes in rivers) are key for the understanding and forecasting of the changes that may occur in each particular system, due to natural causes or to artificial ones (soil management, construction of reservoir dams, dredging works and construction of training walls with navigational purposes, etc.). Erosion problems arising from either afforestation or deforestation schemes in lake catchments' basins can contribute to the reduction in the effective life of man-made lakes behind reservoir dams or power barrages. Due to the interception of sediments by these structures and the reduction of flow, channel degradation may develop downstream.

On the other hand, in marine environments, the natural processes affecting sediment transport are different and even more complicated compared with those occurring in rivers. Factors to be taken into account are: wave action, winds, currents of different origins actuating in various directions in open sea and bays, fluctuation of the sea level due to astronomical and meteorological tides, increasing the region of influence of waves and currents in the shore profile and causing the reversal of the current in estuaries, mixing of fresh and salt water in estuaries and its consequences to the behavior of fine sediments in suspension. Furthermore, it should be considered that all these hydrodynamic agents may act simultaneously in a given water body.

The progressive occupation of the coastal zones requires an increasing human intervention which has to be conducted by Coastal Zone Management (CZM) studies to well adapt the coastal region to this occupation. Several examples of human interventions and studies related to sediment transport in the marine environment can be mentioned:

- Capital or maintenance dredging of access channels to harbours, turning basins and berthing areas;
- Monitoring of the sedimentation in existing dredged areas or predicting the maintenance in future ones;
- Selection of spoil disposal areas for dredged material and study of the efficiency of the selected dumping sites;
    - Littoral movement of sediment along the coast (longshore and crosshore);
    - Behaviour of particulate contaminants discharged through outfalls or in water bodies;
    - Determining source of siltation;
- Construction of coastal structures such as: groins, jetties, detached breakwaters and sea walls;
- Artificial beach nourishment, harbor inlet by-passing schemes, location and dredging of sand traps;

- The associated sedimentological studies related to the response (accretion or erosion) of the shoreline to coastal structures and works mentioned, require a knowledge of the littoral-drift and the cross-shore sand transport in the nearshore region;
- Temporary excavation below natural depths for the burial of pipelines and cables, which can present various problems, mainly in the shoreline region;
- Reclamation works in estuaries and the influence of the loss of tidal volume on the sedimentary regime.

Nuclear techniques applied together with conventional techniques, hydraulic measurements and modeling to solve sediment problems in the coastal area, and also in river sedimentology, can be seen as a powerful tool, provided they are used with knowledge and caution.

2.2. SEDIMENT CHARACTERISTICS

It is interesting to highlight some definitions and properties of sediments, important for the comprehension of their behavior in different environments. The density of most sediments is about 2.65 g/cm^3, while their dimensions and forms are varied. Sediments under study can be classified by their grain size, from clay to gravel. Wentworth's classification (1922) is one of the most widely used in the field of sedimentology. It comprises four main classes of particles:

- Gravel: particles greater than 2 mm in diameter
- Sand: particles between 0.063 mm and 2 mm in diameter
- Silt: particles between 0.002 mm and 0.063 mm in diameter
- Clay: particles less than 0.002 mm in diameter.

Commonly sediment transport studies in seas, rivers and dams deal with sand and silt. There are different sub-classifications of sands according to their sizes:

- very coarse: ranging between 1 and 2 mm,
- coarse: ranging between 0.5 and 1 mm,
- medium: ranging between 0.25 and 0.5 mm,
- fine: ranging between 0.1 and 0.25 mm,
- very fine between 0.063 mm (63µm) and 0.1 mm (100 µm).

Silt particles are mainly made of silica and alumina (silico-aluminate) but contain also iron, manganese and potassium.

The size of the particle and its terminal fall velocity (fall velocity under steady state conditions, where the drag on the particle is equal to its submerged weight) are the most important parameters relating the sediment properties with the theories of grain motion.

Broadly speaking, sediments can be divided into cohesive and non-cohesive classes. Silt and clay are cohesive and sediments having grain size from sand to gravel are non-cohesive. There is a big difference in the behavior of these two classes of sediments when exposed to hydrodynamic actions. In case of cohesive sediments, the resistance to erosion relies on the strength of the cohesive bond between the particles. Once erosion has taken place, cohesive material may become non-cohesive relative to further transport, but it can flocculate when a region of saline water (e.g. estuary) is met.

According to the Wentworth sediment classification scale fine or pelitic sediments, known as mud, are those with dimensions under 63 µm. They are composed of silt ($2\mu m<\varphi<63\mu m$), clay ($0.2\mu m<\varphi<2\mu m$), and colloid ($\varphi<0.2\mu m$) fractions.

In general, these sediments contain mineral and organic components, the former being present in higher proportion. A particular mud is characterized by its different components and also by its grain size distribution or its sedimentation curve. The colloidal state is characterized by the equilibrium between the charged particles in suspension and the ions in solution. If the ionic concentration in the environment is changed, or if the sediment particles adsorb some materials, the equilibrium of the suspension may be lost or shifted, producing flocculation or de-flocculation (Bougault, 1970). These colloidal properties of the mud are responsible for its sensitivity to external agents and some physical properties of the suspension could be modified, such as its settling velocity as a function of the salt content of the environment.

2.3. GRAIN SIZE ANALYSIS

Sieving is the most traditional procedure to determine the granulometric distribution of the sand (particles bigger than 63 µm). The yield on each sieve is weighed. One calculates then the percentage of the sand obtained in each sieve compared to the initial mass of the sample. In practice, it is preferable to represent grain size distribution in terms of probability in order to highlight the various sedimentary families present in the sample. The representation called granulometric curve (or distribution) of the particles (Fig.1) consists in expressing the percentage cumulated of the mass according to the diameter of the particles. The transformation of the distribution of Gauss or Poisson of the diameters of particles into Henry line (cumulated percentage of the probabilities) is a very convenient mathematical handling to compare different samples.

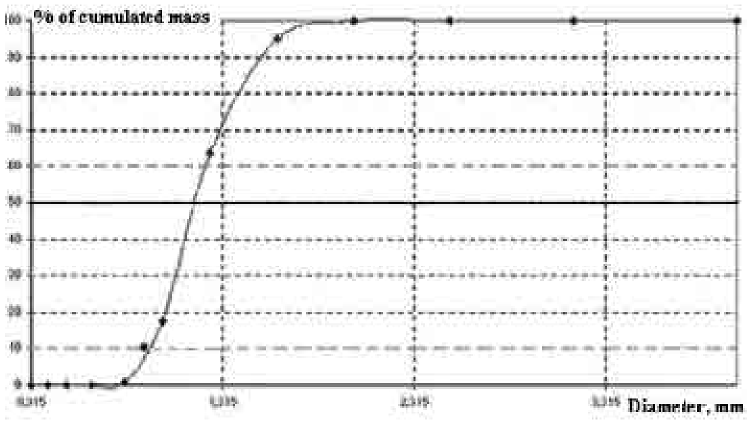


FIG. 1. Typical granulometric curve for sand.

For silts the size distribution is measured using sedimentation effect in the Andreasen pipette. Concentration of silts should be lower than 5 g/L. Stoke's law is used in this case:

$$W = 1/18\ (\rho_S - \rho_0) / (\rho_S)\ d^2\ g/\nu$$

where:

- W is the falling speed of the particles
- ρ_S and ρ_0 are respective specific masses of the solids and the liquid.
- ν is the kinematic viscosity of water (10^{-6} m^2/s with 20°C).
- d is the diameter of the particles.
- g is the gravity.

2.4. MODES OF SEDIMENT TRANSPORT

The dynamic mechanism of sediment transport depends on sediment size and water flow strength. Figure 2 (left) shows the main sediment dynamic mechanisms:

- Gravels and coarse sands move downstream by rolling or sliding along the bottom of the streambed.
- Medium size sand can bounce along the bottom in a series of jumps.
- Fine sand, silt, and clay particles are transported in suspension. The particles move downstream suspended in the turbulent water, giving the water a muddy appearance.
- Dissolved sediment materials (not visible) move downstream in solution.

Thus, the main different modes of sediment transport are (Fig. 2, right):

- *Rolling or sliding (Bedload)* of the particles along the bed; this sediment transport mode is applicable to coarser sediments (sand and gravel)
- *Saltation* is an intermediate situation between bedload and suspended sediment load where particles "bounce" along the bed.
- *Suspended:* when velocity of stream is higher in relation to the settling rate of particles the sediment retains in suspension.

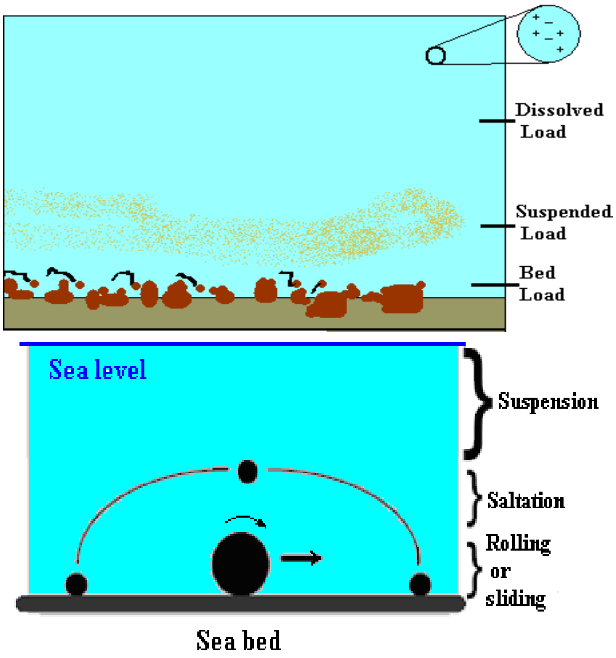


FIG. 2. Dynamic mechanisms (left) and sediment transport modes (right).

2.5. SEDIMENTARY PROCESSES AND MEASUREMENT OF SEDIMENT TRANSPORT

Sediment transport in rivers under unidirectional and quasi-steady flows is very complex. This complexity increases even more when dealing with sediment transport in coastal regions. The prediction of sediment behavior from flow parameters and the direct measurements of this behavior are normal tasks that have to be performed when dealing with environmental and engineering problems.

For the study of sediment behavior, use is made of physical models with movable bed and mathematical modeling. The latter have been more widely used for the last two decades because of the high construction and operational costs, doubts on the similitude and the inflexibility presented by physical models. These shortcomings of the physical models are more pronounced in river morphological or estuarine applications, where large areas to be represented demand a vertical distortion of the model. A vertically distorted mobile bed model does not scale bed roughness correctly, and the impossibility of scaling the threshold and settling velocities of the natural sediment has given more space for the use of numerical models. Moreover, it is hard to represent, in a physical model, the behavior of fine sediments submitted to aggregation processes: inorganic salts promoting salt flocculation; organic compounds producing organic aggregates and bio-flocculation; organisms such as copepods, mussels, tunicates, etc., transforming fine-grained suspended matter into pellets whose settling velocity is many times greater than that of the constituent particles.

Physical models using sand or light-weight mobile materials are still employed for wave-dominated coastal studies (e.g. shoreline region response to coastal structures; design of dredged access channel) and localized river engineering problems (e.g. morphological influence of training walls in their vicinity).

The use of mathematical modeling, without physical experiments to verify the model (because of costs), is the current trend. Mathematical models (Computer Fluid Dynamics - CFD - models) for sediment transport studies are more versatile and easily used because they are purely computer based, but these models are efficient and reliable only if the equations they use are representative of the reality.

Practically the lack in fundamental knowledge of complex sedimentary processes may lead to unrealistic model results. Ideally, CFD models should be validated in order to have confidence in their results. Tracer studies are a powerful tool for validation because they integrate all the hydrodynamic actions on the sediment and also because of the fast answer they give compared to conventional methods like differential bathymetry.

However, it is wrong to consider the bed-load transport as a layer of sediments moving with a thickness and a mean velocity. At sea, according to the grain sizes and wave amplitudes, sands are suspended by the swells, in particular in the surf zone, and then transferred over significant distances either towards the beach, or towards the deep water. It is thus not surprising to note that no method of calculation, even with the current capacities of calculation of the computers, is able to lead to reliable results if it is not confronted with checks, under known conditions, by tests on the ground or at the hydraulic research laboratory. Nevertheless, there are numerous theoretical formulas attempting to calculate or estimate the sediment transport in river or sea. They are satisfactory only when solid transport is of low importance.

Field measurement programs of hydraulic parameters and sediment movement are relevant for each particular site under study. They represent a first step in a predictive process that may subsequently make use of a physical or mathematical model if the complexity of the hydraulics cannot be treated by analytical tools.

Measurement of hydraulic parameters and physico-chemical site data is achieved by use of various instruments: water level, tide and wave recorders, recording current meters coupled with conductivity and temperature sensors and fixed or moored at convenient sites and depths, and also by manned instrumentation for profiling the water column. Measurement of sediment movement can be performed by direct observation and monitoring or with use of tracers. In the first case, the quantification of the suspended sediment movement requires a combination of simultaneous measurement of sediment concentration and current velocity at fixed stations (Eulerian approach).

For the determination of the concentration, samples are taken by the use of immersed bottles or by pumping and are subsequently analyzed in laboratory. Normally, hundreds of samples are necessary to quantify the suspended sediment transport in a cross section of a river or an estuary, due to the rapid variation in the concentration with time and with depth. In this way, it is interesting to perform "in-situ" measurement of the concentration using special gauges based on the scattering or transmission of light, sound or γ radiation. For the direct measurement of bed-load transport, devices to be filled, such as traps and baskets put in the bottom of the water courses are used, but they are normally not adequate because they interfere with the flow, cause local disturbance of the bed and are difficult to position. Nowadays, specialized hydraulic institutions offer relevant combinations of field measurements and physical and mathematical modeling facilities, utilizing the most recent techniques and scientific achievements, in order to solve environmental and engineering problems related to sediment transport.

2.6. MECHANICS OF FLUIDS APPLIED TO SEDIMENT TRANSPORT

2.6.1. Interaction of sediments with water

Under action of water, currents, wind and other natural actions, rocks and sedimentary formations are degraded. Sediments are transported by rivers to their estuaries, and after to the sea, along the littoral zones, where they will undergo the action of the currents generated by the tides, waves and the wind.

Sediment transport is developed under the action of major players of ocean forces generated by different hydrometeorological actions. The most important actors of ocean dynamic generating sediment transport are: tides, wave's currents and wind. Below some sediment dynamics considerations are provided mostly taken from internet sources (http://www.teara.govt.nz/en/coastal-erosion/,http://www.ozcoasts.gov.au/indicators/beach_erosion.jsp,http://deseagrant.org/outreach/coastal-processes-faq-difference-between-jetty-groin;
http://www.drbeach.org/physicaltherapy.html; http://www.thefullwiki.org/Longshore_drift.)

Coastal erosion is the retreat of the shoreline due to water currents, waves and wind. It is a natural process that can be influenced by human activities. Waves move sand offshore from the beach and back again in a continuous cycle. Fig. 3 shows the cross-section of a typical sandy beach.

FIG. 3. Cross-section of a typical sandy beach.

2.6.2. Acting forces

2.6.2.1. Sediment budgets

Any coast can be divided into natural segments within which the sediment budget is essentially self-contained, sediment transport in (sources) and out (sinks) are roughly in balance on average, and the component movements can be measured. These segments are *littoral cells*. Fig. 4 shows a typical littoral cell.

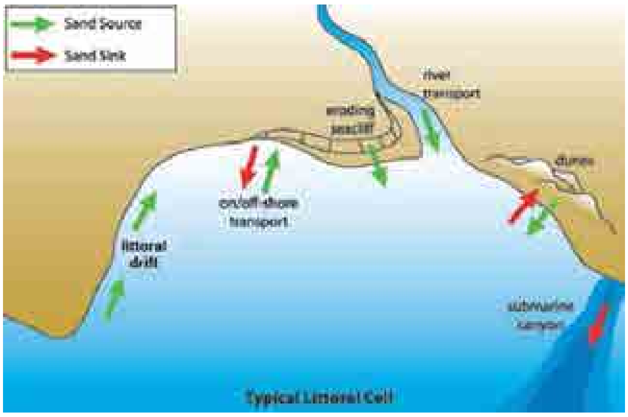


FIG. 4. Typical littoral cell.

Understanding the sediment budget for a given location on the coast is key to defining both, natural processes and the consequences of human interference, the budget measuring input of sediment versus removal, directions of transport, and volumes and variations with time of year. As with any budget, there are inputs and outlays: sand is added and removed. If there is a surplus, sand is deposited; if there is a deficit, erosion and land loss prevail.

2.6.2.2. Currents

Displacements of the solid particles in a fluid are caused by the currents. These currents have different origins. They are created by the slope in a river, by the tides in the oceans, the wind and the swells in particular along the littorals and in the zone of the surge.

The flow can be laminar: there are layers in which the molecules move quickly while others located close to the bottom of the river or sea bed move very slowly. In other words, there is a gradient speeds function of the viscosity of the medium. These fluids are called Newtonian.

But generally flow is turbulent: the local conditions are complex and change very quickly. They can be appreciated only by their average value integrated during a long time compared to the speed of occurrence of the events.

These two states, studied by Bernoulli and Reynolds, are distinguished one from the other by their Reynolds number:

$$R_e = v.d/\nu$$

Where v is the current velocity of a fluid having a kinematic viscosity $\nu = \mu/\rho$ in a tube of diameter d; ρ indicating the density of the liquid.

If R_e is lower than 2000, the medium is regarded as laminar, beyond 4000, it is turbulent; what is generally the case in natural environment.

2.6.2.3. Wind

Wind transport, in particular on the top of the beaches and the dunes, is particularly important by the distances covered and great volumes of transported dry sands, not fixed by the vegetation. The most important action of wind is the generation of waves.

2.6.2.4. Storms

A strict meteorological definition of a storm is a strong wind (a wind speed of 24.5 m/s - 89 km/h) or more.

2.6.2.5. Waves

A water wave is a disturbance that propagates through space and time, usually with transference of energy.Waves are the main causes of the coast erosion. They may be wind-generated surf, boat wakes, tsunamis or tidal currents. Waves are the result of water oscillating in a circular motion. Close to the beach, the circular water particle motion gets broken up as the cycling water hits the bottom.

This causes the wave to rise up (as the water piles up on it) and break. In fluid dynamics, wind waves or, more precisely, wind-generated waves are surface waves that occur on the free surface of oceans, seas, lakes, rivers, and canals or even on small puddles and ponds. They usually result from the wind blowing over a vast enough stretch of fluid surface.

A swell, in the context of an ocean, sea or lake, is a formation of long-wavelength surface waves. Swells are far more stable in their directions and frequency than normal wind waves, having often travelled long distances since their formation by tropical storms or other wind systems. Swells are often created by storms thousands of nautical miles away from the beach where they break.

Figure 5 shows the wave characteristics and the wave movement towards the beach. The wave amplitude and length are important regarding the sediment transport affection.

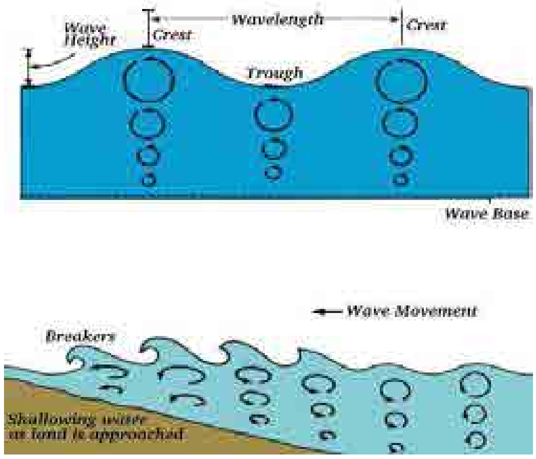


FIG. 5. Wave characteristics and movement toward the coast.

When waves travel into areas of shallow water, they begin to be affected by the sea bottom. The free orbital motion of the water is disrupted, and water particles in orbital motion no longer return to their original position. As the water becomes shallower, the swell becomes higher and steeper, ultimately assuming the familiar sharp-crested wave shape (Fig. 6). After the wave breaks, it becomes a wave of translation and erosion of the ocean bottom intensifies.

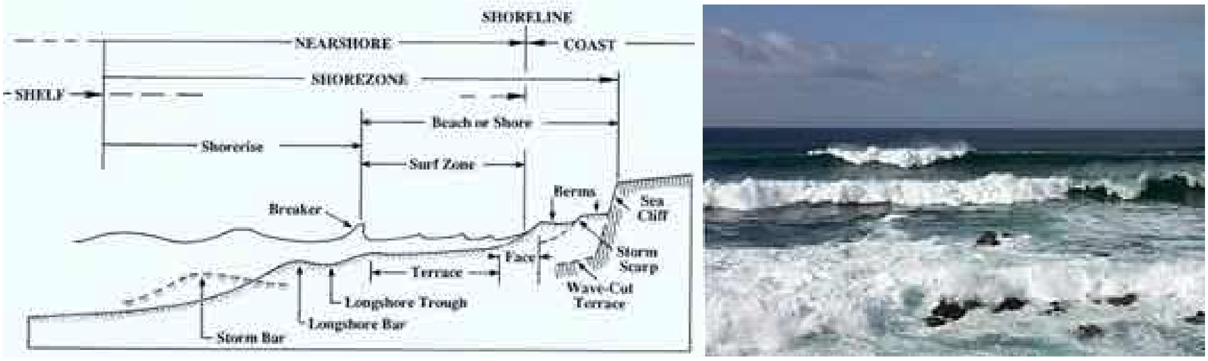


FIG. 6. Surf or breaking wave zone near the shallow water.

2.7. LONGSHORE TRANSPORT

Littoral transport is nearshore sediment transport driven by waves and currents. As shown in Fig. 7 this transport occurs both parallel to the shoreline (alongshore or longshore) and perpendicular to the shoreline (cross shore or on-off shore).

Movement of sediments along a beach is complex. When a wave breaks at an angle to the beach, sands or pebbles are carried up the beach in the direction of the wave (swash). The wave returns to the sea at right angles to the beach (backwash) because that is the steepest gradient, carrying some sands or pebbles with it. In this way, the sediment moves in a zigzag fashion along a beach. Longshore drift is responsible for the erosion of beaches and the formation of spits (ridges of sand or shingle projecting into the water). Attempts are often made to halt longshore drift by erecting barriers, or groins, at right angles to the shore.

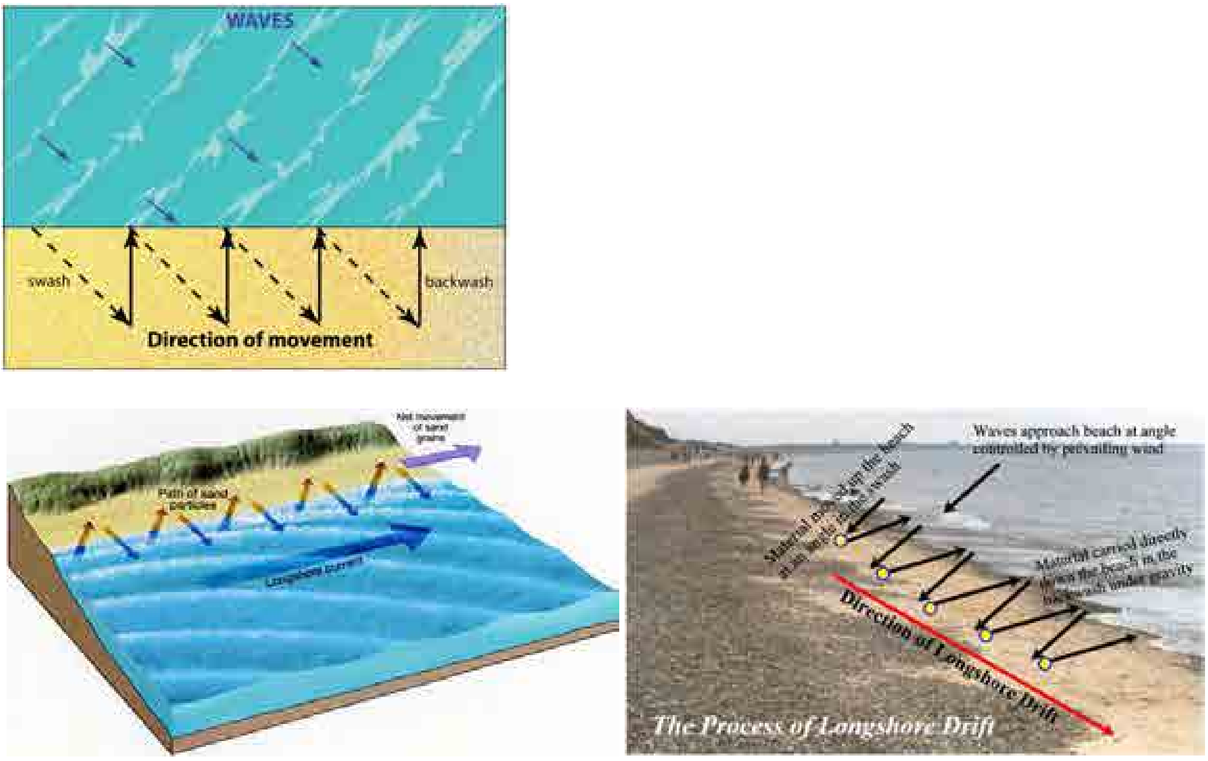


FIG. 7. Longshore drift.

Longshore drift is the movement of sediments, usually sand, along a coast parallel to the shoreline. It is also called longshore current or littoral drift. Longshore drift is where sediment is carried along the coastline by the waves. Waves often approach the coast at an angle. The sediment is carried up the beach by the swash. The sediment is dragged from the beach (to the sea) by the backwash, but this time it travels at a right angle to the beach; as it will roll own the steepest gradient. This movement will slowly transport sediment laterally along the coast.

Waves approaching the shore break in a region called the surf zone. They carry sediment up the shore in a white, frothy surge called the swash, and down again in the backwash. When the swash approaches the shore at an angle, it will carry and deposit sediment both up and along the beach, but the backwash, acting under gravity, will always carry and deposit its sediment perpendicular to the shoreline, following the line of the steepest gradient. This produces a zigzag movement of sediment along the beach known as alongshore drift.

Generally, the largest particles of beach sediment are found updrift, closer to the sediment source. The smallest sediment particles, those which are most easily picked up and suspended by wave action, are transported further downdrift before again being deposited.

Hydrometeorological stations for measuring wave, wind and currents

There are specific apparatuses for recording each hydraulic and meteorological parameter influencing the sediment transport in rivers, dams and seas.

The *current meters* allow to record speeds of water to various depths. The measurement of these currents can be carried out in two manners:

- *Eulerien measurement*, i.e. in fixed points according to time. This situation is most frequent. A current meter is immersed in fixed point, with a given depth, to record the variations of the currents and their directions.

- *Lagrangian measurements*, in this case one determines the speed of the water molecules or the solid particles in suspension, while following their trajectories, with various depths. The velocity vectors and directions are recorded according to time. These measurements are performed while following, in space and time, of the floats, or drifting buoys, positioned by GPS. The results are disturbed by the surface currents generated by the wind.

These two methods lead to identical results if the current is stable and uniform in space and time. It is generally not the case in kind.

Seawave recorder monitors the evolution heights of water of the seas according to the amplitude of the tides.

Sampling tools for bottom sea sediments. The Berthois' cones trailed on the bottom to sample sandy beds are simple tools used in many cases. The majority of sampling tools collects sediments more or less easily but is not strictly representing the bottom sediments because of water washing during the collection.

2.8. DYNAMICS OF THE LITTORAL ZONE AND ITS PROBLEMS

2.8.1. Geological background

Beach deposits predominantly consist of sand particles that can be easily eroded by waves. These deposits comprise terrestrial sediment delivered to the coast by rivers, sediment produced by the erosion of coastal landforms by waves, and marine sediment that has been reworked from offshore deposits onto the coast. Sand derived from a terrestrial source is usually dominated by resistant minerals such as quartz. Marine sediments, however, comprise resistant minerals and biogenically-produced calcium carbonate.

The sand in many beach systems normally is partially sourced from the continental shelf as well. Large volumes of this inner shelf sand have been pushed up the continental shelf as sea level rose following the end of the last glacial period (18000 years ago), and has been accumulating on the present coast during the last 6500 years of high and relatively stable sea level.

The rate of supply of sediment derived from the inner continental shelf varies between coastal regions, and in some has declined over the last few thousand years because over this period the volume of sediment available for reworking to the coast by wave-induced currents has gradually been reduced. Beaches may also be linked to offshore sources of biogenic sediment such as coral and algal reefs in the tropics and subtropics, and molluscan and bryozoan banks in temperate regions. The long-term supply of sediment to these beaches can be relatively constant.

Many beach systems can be supplied with sediment from rivers. This fluvial sediment is often transported in an alongshore pathway away from the mouth of the river. The supply of this sediment to beaches may be constant in the long term but can be affected by climate change and catchment modification by humans. The volume of fluvial sediment supplied to beaches, however, may be quite small compared to the volume being moved to the coast because sediment is often trapped in tide-dominated and wave-dominated estuaries, which act as sediment sinks.

On coasts where the shoreline configuration is highly irregular, long headlands and reefs can trap sediment delivered to the shore by rivers within an embayment. As a consequence, sediment is not moved along the coast by waves and currents but remains within the embayment, forming a compartmentalized beach sediment system. In contrast, in regions with a more regular coastline, sand can be transported many hundreds of kilometers along the coast by oblique waves and shore parallel currents, forming a corridor of sediment transportation.

There are beaches that erode rapidly, while it may take several decades for material to be deposited. If a series of storms occur within a short period (a few weeks to a couple of years), their cumulative effect can be severe, even if the individual storms are minor.

Erosive conditions vary as storms pass:

- Before the storm, waves are small, and the beach accretes as sediment moves onshore.
- As the storm approaches, waves become higher and the beach erodes.
- During the storm, as waves get higher and more frequent, erosion increases.
- After the storm, waves become flatter and less frequent, and the beach accretes once more.

A sandy beach that has undergone a long period of accretion is quite steep, and much of the wave energy hitting it is reflected back to sea; this is called a reflective beach. By contrast, an eroded beach is flat, and most of the incoming wave energy transports sediment and generates currents (a dissipative beach). Between these extremes there are a number of complex beach shapes that typically have currents running along the shore (intermediate beaches).

2.8.2. Beach erosion

Coastlines and seabeds are dynamic regions with sediments undergoing periods of erosion, transport, sedimentation and consolidation. The driving forces for these processes are primarily tidal currents, and surface waves. Transportation of sediments, in particular fine-grained silts and clays which are often contaminated, creates a variety of environmental impacts, including silting of harbor areas and docks, reduction in water transparency, affecting marine life, and alongshore drift. An understanding of the fundamental sediment transport processes is essential to address these issues and provide genuine, scientifically sound solutions.

While sea level rise sets the conditions for landward displacement of the shore, coastal storms supply the energy to do the "geologic work" by moving the sand off and along the beach. Therefore, beaches are greatly influenced by the frequency and magnitude of storms along a particular shoreline.

Beach erosion can occur because of simple inundation of the land; the relative rate of sea-level rise along most coasts has been approximately 30 cm in the last century. A unit vertical rise in sea level translates into 150 to 200 units of horizontal retreat of sandy shorelines. The rate of sea-level rise is expected to accelerate in the coming decades in response to global warming, which would exacerbate existing erosion problems.

There are two types of coastal erosion:

- Cut and fill erosion occurs on coasts made of loose sediment such as sand or gravel, which are freely exchanged by water action between land and sea. Known as soft coasts, these are mainly beaches. Eroded material may be replaced over time.
- Permanent erosion occurs on rocky or hard coasts. Eroded material cannot be replaced.

The public perception of coastal erosion is of a sandy beach being washed away, threatening nearby houses with the same fate. This is just one effect, caused by natural processes that move sediment on- and offshore. The coast is a dynamic environment; the flow of water and wind constantly shifts sediment from one place and deposits it somewhere else.

Figures 8&9 show some typical visually observed eroded beaches.

FIG. 8. Long-term erosion of the beach: left is a WWII gun bunker originally built behind the beach on the foredune, which now sits behind the bunker, while right is a bunker built on the top of dunes in 1943 which since years dismantled by the sea.

FIG. 9. Typical natural signs of eroded beaches(trees near the water).

Sandy beaches are dynamic sedimentary systems that naturally experience phases of erosion and accretion that operate over a range of time intervals. Frequent short-term changes are seasonal - erosion mostly occurs in seasons when storms that generate erosion wave regimes are more frequent.

Rapid erosion episodes may also be produced by high-magnitude storms, such as tropical cyclones or intense low pressure systems in temperate regions. The degree of erosion that occurs within a particular erosion phase can be highly variable, and this likewise is linked to the magnitude and frequency of storms that impact on the coast.

For example, during a 1 in 100 year high magnitude storm, waves may erode several meters into the foredune that sits well behind the normally active zone of accretion and erosion. Also, several lower-magnitude storms that occur in quick succession can produce a similar degree of erosion because the intervening periods are too short for constructive swell waves to push a significant amount of sediment back to the shoreline.

The accretion of sand on beaches occurs during the more quiescent seasons when average swell waves deliver sediment back to the shoreline. Beach accretion, however, is generally a much slower process than beach erosion. For example, it may take several years for a beach to return to its pre-storm condition after one major storm or several smaller storms in quick succession.

2.8.3. Human activities that accelerate beach erosion

Coastal development

The main pressures on beaches and dunes are urbanization and developments associated with coastal tourism. Major erosion problems have occurred where buildings have been erected on parts of a sandy beach system that are subject to natural phases of erosion, especially where the variations in beach morphology are linked to the longer cyclical changes in climate. Also, on many developed coasts modifications to the shoreline configuration, such as breakwaters, groins and retaining walls have disrupted the natural sediment transport pathways and created problems by starving sections of coast of sand. These sections then become more susceptible to erosion as the rate of sediment delivery falls short of the rate of loss. Likewise, the damming of rivers has also likely reduced the volume of sediment they deliver to the coast and, therefore, the rate of sediment delivered to beaches linked to terrestrial sources of sediment.

Climate change related to global warming

An increase in the frequency of major coastal storms or a rise in relative sea level can accelerate shoreline erosion and also trigger the erosion of dunes immediately behind the beach.

Removal of dune vegetation

The loss of protective vegetation is a major trigger for dune erosion. This can be induced by grazing, fires, tracks (four-wheel drives, motor bikes, horses) and even foot traffic, and can exacerbate beach erosion.

Relevant indicators

Changes in the following parameters may indicate that a beach is being eroded or is at risk for erosion:

- a reduction in beach and dune areas (measured by remote sensing techniques);
- a reduction in protective vegetation on dunes;

2.8.4. Protection of sandy costs using solid and soft solutions

The management options available to control coastal erosion and protect beachfront properties include shore hardening, and beach nourishment. Shore hardening refers to the construction of a range of structures built to retain sand, interfere with waves and currents in order to reduce their damaging effects, or protect beach from direct wave attack and hold back tidal waters. These structures built of wood, stone, concrete, or steel include bulkheads, seawalls, revetments, groins, jetties, and breakwaters. Bulkheads and seawalls can protect upland property from damaging storm waves, but they do nothing to abate the erosion of the beach fronting the structure. In fact, such hard shore-parallel structures such as bulkheads and seawalls may accelerate beach erosion by reflecting wave energy off the facing wall, impacting adjacent property owners as well. Building such structures along retreating shorelines eventually result in diminished beach width and even loss.

Groins and jetties intercept the alongshore movement of sand, building wide beaches on the updrift side and causing accelerated erosion of downdrift beaches. These shore-perpendicular structures do not create any new sand, but merely rearrange the sand that is on the beach. Groins are most effective and not detrimental when built as a cluster or "field" along a stretch of shoreline at the terminus of the alongshore movement of sand, such as at a harbor mouth. Offshore breakwaters have had mixed success.

Beach nourishment is the process of adding new sand to the beach profile in order to restore it to some former width. This is usually accomplished by dredge and fill operations with sand pumped onto the beach from an offshore source, such as sand bars or shoals.

Beach nourishment is only feasible at the community level as large sectors (e.g., miles of the shore) must be nourished to be economical viable. In the early 1980s, Miami Beach was restored at the cost of US$ 65 million along this 15 km strand of shore. While the cost was high, South Beach was rejuvenated, and today it is the "hottest" beach in the country; this beach nourishment project has paid for itself many times over.

Where the rate of erosion is high or there are nearby sand sinks, beach nourishment projects have been much less successful-it is not a panacea for all coastal communities. Beach nourishment does not stop the erosion trend--it simply "resets the clock." But beach fills achieve both goals of providing a wide recreational beach and reasonable storm protection for beachfront development.

A coastal engineering project that is successful in one area may not be well suited for another shore. Beaches are a part and parcel of the quality of life in coastal communities, and efforts should be made to preserve these vital resources.

The cost of beach rehabilitation can be estimated from:

- the number and dollar costs of beach nourishment programs,
- the number and dollar costs of stabilization works (*e.g.* walls, groins and ramparts).

2.8.4.1. Solid defenses (hard solutions)

To protect the sandy beach from erosion, solid defenses were often constructed in the past: groins, jetties, breakwaters, revetments and seawalls. Groin and jetty are often used interchangeably to refer to the short, shore-perpendicular structures that are built along a shoreline to hold sand in place. However, technically speaking, groins and jetties are not the same thing. Groins are the smaller shore-perpendicular structures, built to trap sand and stabilize a sandy beach. Jetties are large structures typically used to stabilize inlet channels.

Groins
A groin is constructed across the beach, perpendicular to the shoreline, and is designed to trap sand moving in the longshore transport system (Fig. 10).

Sometimes, the term jetty (a structure used to stabilize an inlet) is misused to refer to a groin. Jetties are larger structures used to maintain the opening to a navigational channel such as a tidal inlet.

As sand accumulates on the updrift side of the groin, the beach at that location becomes wider. However, this is often accompanied by accelerated erosion of the downdrift beach, which receives little or no sand via longshore transport. It is important to realize that groins do not add any new sand to the beach, but merely retain some of the existing sand on the updrift side of the groin.

Groins are usually constructed from materials including steel, timber, or stone. The length, elevation, and spacing between groins should be designated on the basis of local wave energy and beach slope. Groins that are too long or too high tend to accelerate downdrift erosion because they trap too much sand. Groins that are too short, too low, or too permeable are ineffective because they trap too little sand. Groins are generally constructed in groups called groin fields. Since the net direction of longshore transport is northward there, sand accumulates on the south side of the groins, and erosion occurs on the north side.

Groin is:

- *A fingerlike structure that extends from the shore*. Usually with more groins, intended to trap littoral drift (alongshore transport) and/or slow down erosion.
- *Perpendicular to the shore*. Can be built using shore-based equipment (less expensive than breakwater), from various materials. Does not change wave height.
- *Does not prevent offshore erosion*. Rip currents can develop around groins and thus even increase offshore losses. May prevent accretion downdrift.

FIG. 10. Groin defence against alongshore drift.

Jetties

Jetties are structures built at tidal inlets to stabilize the locations of the inlets (Fig. 11). Because jetties interrupt longshore sand transport, the effect of jetties on adjacent beaches is similar to the effect of groins: accretion occurs on the updrift side, and erosion occurs downdrift.

FIG. 11. Jetty harbours: The access channel to some ports situated on sandy coasts is guided and protected across the beach by jetties.

The offset is generally more extreme at jetties inlets, due to the length and relative impermeability of the jetties and the presence of strong tidal flow in the inlet channel. Long, impermeable jetties, combined with tidal currents in the inlet, allow very little sand to flow across the inlet. Material that does pass through or around the jetties contributes to shoaling either in the interior of the inlet or offshore, depending upon the direction of tidal flow.

Jetties are:

- A structure that projects into a body of water to influence the current or to protect a harbor.
- Difference between jetty and groin: jetties are found at the entrances of harbors and small bays.
- Similarities: accretion on updrift side and possible erosion on downdrift side.

Breakwater

Breakwaters reduce the intensity of wave action in inshore waters and thereby reduce coastal erosion. Breakwater is a defense against coastal erosion mostly caused by cross-shift sand transport. It is a barrier that protects a shore from the full impact of waves. It is constructed some distance away from the coast or built with one end linked to the coast.

Breakwaters have the following characteristics:

- More or less parallel to the shore,
- Effective,
- Can reduce wave height significantly,
- Can alter the surf zone,
- Can be a navigational hazard,
- Can become connected to the shore and interfere with longshore.

The breakwaters may be small structures, placed less than one hundred meters offshore in relatively shallow water, designed to protect a gently sloping beach. Figure 12 shows the schematic of a typical breakwater (left) and the effect of the breakwater on the beach in front of it (right). When oncoming waves hit these breakwaters, their erosive power is concentrated on these structures some distance away from the coast. In this way, there is an area of slack water behind the breakwaters. Deposition occurring in these waters and beaches can be built up or extended in these waters. However, nearby unprotected sections of the beaches do not receive fresh supplies of eroded sediments and may gradually shrink due to erosion.

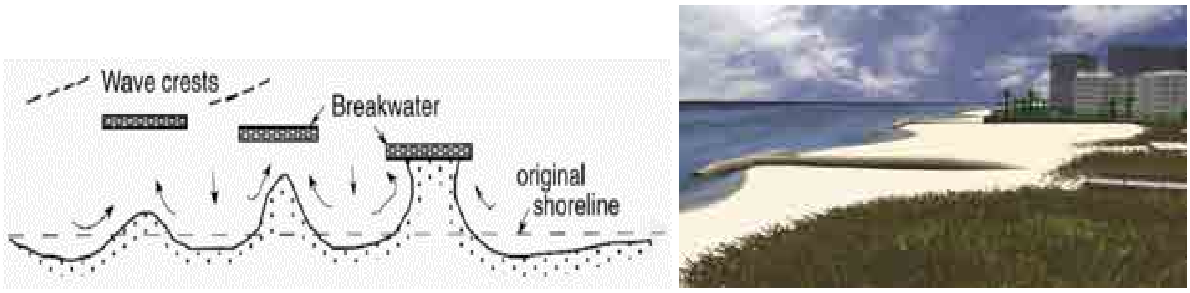


FIG. 12. Schematic of a breakwater: a barrier that protects a shore from impact of waves.

Figure 13 shows a coast line protected by a series of breakwaters.

FIG. 13. Series of breakwaters to protect coast line in front of them; left side is eroded coast line, when right is sand beach created under effect of breakwaters.

Breakwaters are subject to damage, and overtopping by big storms can lead to problems of drainage of water that gets behind them. The wall also serves to encourage erosion of beach deposits from the foot of the wall and can increase longshore sediment transport.

Revetment

- A protective cover (armor) placed on a bank or bluff to protect against erosion by waves or currents. Such a cover can be porous or watertight (and covering the entire slope).
- Revetments usually have little or no effect on littoral drift; they merely absorb energy. Beach erosion may be accelerated right in front of revetments. A groin or breakwater can help in such a case. The construction of revetments may result in a decrease of accretion elsewhere.

Seawall

It is a structure between land and water. It prevents erosion and other wave action damage. It may cause enhanced erosion in front of it and hence cause its own collapse.

2.8.4.2. Soft solutions

The past few decades brought new insights. "Soft" solutions such as beach nourishments turned out to be generally more effective. Artificial beach nourishment (beach fill) means that sand is dredged at one location and redeposited on a beach (Fig. 14). This may disturb the ecology at both locations and may lead to increased erosion at other locations.

Winning sands from ebb-tidal shoals as a source for artificial beach nourishment is often avoided but recent research shows that it does necessarily have a large impact on the stability of ebb-deltas.

Soft solutions are temporary solutions that need to be repeated regularly. Each year, several beach nourishments are carried out in The Netherlands. Artificial nourishment with grain size distributions close to the natural distribution work best. They last longer than nourishments with a different distribution.

FIG. 14. Artificial beach nourishment: sand is dredged at one location and redeposited on a beach.

3. RADIOTRACER TECHNIQUES TO STUDY SEDIMENT TRANSPORT

3.1. CONVENTIONAL AND RADIOACTIVE TRACERS

Conventional and radioactive tracers are available options among which one can select a tracer for sediment transport investigations. Conventional tracers include fluorescent and colored materials employed to coat sediment particles for sediment transport studies. Magnetic tracers are also in development for sediment tracing but will not be discussed here.

3.1.1. Fluorescent and color tracers

Fluorescent tracer is a non-toxic chemical used to mimic sediments. Different sediment granulometric classes are color coded with daylight and ultraviolet fluorescent coating material. Sediment cores are obtained from locations on the study, dyed in laboratory, and returned to their original positions in sea bed, beach or river bed.

Commercially available, daylight and near-ultraviolet fluorescent, colored dyes can be used in long- or short-lived surface coatings on coarse sediments. Such tracer coatings make possible day- or nighttime visual and quantitative determination of river or beach sediment transport. A wide selection of dye colors is available for use in four coating mixtures. All coatings are insoluble in fresh or saline water.

The Fluorescent Tracer (FT) Technique was developed and applied for sediment transport studies in some countries. Fluorescent tracers are chosen because they are considered harmless by regulators and public. They are relatively easily and accurately measured on-site with a portable, field-ready fluorometer.

Advantages of fluorescent tracers:

- Environmental friendly and considered harmless by regulators and public, therefore can be used on beaches, in rivers, lakes, reservoirs, water treatment systems.
- Multiple fluorescent codes allowing various sand sizes to be monitored simultaneously for the same or nearby sources during the same hydrodynamical & meteorological condition.
- Suitable for medium and high energy environments with measurement over months or years.
- No limit on the number of tracer particles that can be released allowing studies over mid- to far-field study areas of 50-250 km^2.

Disadvantages of fluorescent tracers:

- No real-time in-situ detection for bedload transport studies so sampling is ‘blind’; detection is achieved by collection of samples and subsequent analysis either at the project site or in the laboratory. This requires a lot of field sampling compared with in-situ detection offered by radioactive tracer detection. Also, there is no capacity to detect buried tracer material.
- Reduced ability (compared with radioactive tracers) to measure real-time for suspended sediment plume monitoring.
- Particles are artificial not native; however tests indicate very similar characteristics and behavior to native sediment.

3.1.2. Radioactive tracers

Radioactive tracers (radiotracers) have many advantages compared to non-radioactive tracers such as:

- easy to detect in-situ at very low levels (open-eyes detection) without any sampling;
- smaller tracer mass or less material is required to label compared to fluorescent or other conventional tracers (some hundred grams instead of some hundreds of kg for bed-load transport);
- no sampling required, except in some particular cases (large scale experiments – some hundred km);
- radioactive bedload tracers can still be detected when buried and mixed through the sediment profile;
- radiotracers are short lived, allowing for repeat studies in the same location;
- radiation detectors are easy to install, allowing the use of many detectors in suspended sediment studies;

The main disadvantages are:
- the public concerns;
- the strict regulation which impose a clearance from the national nuclear safety Authority.

The drawbacks of conventional tracers include low detection sensitivity, thus requiring large amount of tracer to be injected, and the need to collect samples for measurements in laboratory. High detection sensitivity, *in situ* measurements, physico-chemical compatibility, wide range of choice, ability to withstand at harsh conditions make radiotracers a preferred choice for many applications including sediment transport investigations.

Radiotracers were first employed to investigate sediment transport in 1954 simultaneously and apparently without acting in concert, in the UK, Netherlands, Portugal and France. The first radiotracer experiments provided mostly qualitative results about the resultant direction of sand transport in sea and river bottoms. French team further developed the radiotracer methodology by applying the so called "the count rate balance method" (G. Sauzay, 1967), which quantified the action of various metrological and oceanographic factors in addition to obtaining qualitative data about sand transport, employing only a limited quantity of radiotracer of a few hundred grams. This relatively small quantity of radiotracer generates radiation levels often lower than the authorized limits and reduce to a minimum the risk of contamination, making radiotracers a tool of choice for many sediment transport problems.

The modern radiotracer investigations highlight not only the direction of the movement and the speed of displacement but also the average thickness of the layer in transit (transport thickness), thus the sediment transport rate, which is very important parameter for correlation with action of individual hydraulic or weather factors like tide amplitudes, storms, currents and wind. Meteorological and hydraulic parameters are recorded continuously during a radiotracer experiment.

The radiotracer technique for sediment transport investigation involves preparation of a radioactive particulate tracer having similar physicochemical properties as the bed material, injection of the tracer at the desired point, tracking of the tracer with underwater nuclear detectors and finally interpretation of iso-activity contours to evaluate the parameters mentioned above. The details of the radiotracer methodology and technology as applied to sediment transport study are discussed below.

3.1.3. Activatable tracers

There is another group of activatable tracers, which are between conventional and radioactive tracers. Activatable tracers (more feasible for mud) have more or less the same operational advantages and disadvantages as fluorescent tracers. From a physical point of view, one important advantage, specifically for mud, is that one labels the real natural sediment. A specific disadvantage is that the analysis of samples through neutron activation analysis (NAA) requires nuclear facilities and produces radioactive materials to be treated in an adequate procedure. One can label mud with up to 20 different activatable elements using small mass of each one which allows potentially unlimited material to be labeled and therefore perform sediment transport for mid to far - field studies.

3.2. RADIOTRACER PREPARATION

Radiotracers in the form of radioactive sediment particles were prepared according to three procedures:

- By irradiation of natural sediments with neutrons produced in a nuclear reactor;
- By surface deposit of a radioactive chemical on the sediment surface;
- By artificial sands made of glass particles of the same density and granulometry labeled integrally with a special trace element \which becomes radioactive by reaction (n, gamma) in a nuclear reactor.

The last two procedures appeared most powerful. The surface deposit of a radioactive compound is used for labeling cohesive sediments, silts and clay, while the artificial radioactive sand is employed to simulate the sand transport.

The dynamic sedimentology required the development of specific radioactive tracers, in particular of activatable glasses, i.e. containing an element (gold, iridium, chromium, scandium, tantalum) with very low content (0.3 to 0.5%) suitable to be transformed into radioactive isotope after irradiation by neutrons in a nuclear reactor. These glasses, when they are still inactive, are crushed and sorted into the grain size distribution of the sand which one wants to measure the movements. Of course the density of these products is adjusted with that of the natural sediments, generally 2.65- 2.7 g/cm^3.

3.2.1. Selection of a radioisotope

A variety of radioisotopes have been used in sediment transport investigations (Table I).

TABLE 1. COMMONLY USED RADIOISOTOPES IN SEDIMENT TRANSPORT INVESTIGATIONS AND THEIR NUCLEAR PROPERTIES

Radionuclide	Half-life	Gamma energies, MeV (abundance)	Tracing of
Gold-198 (^{198}Au)	2.7 d	0.41 (100%)	mud and sand
Chromium-51(^{51}Cr)	27.8 d	0.32 (9%)	mud and sand
Hafnium-181 + 175 ($^{181+175}$Hf)	45 d	Complex spectrum	mud
Iridium-192 (^{192}Ir)	74 d	0.30 (100%) 0.32 (80%) 0.57 (48%) 0.60 (9.3%) 0.61 (6.3%)	sand
Scandium-46 (^{46}Sc)	84 d	0.89 (100%) 1.12 (100%)	mud and sand
Tantalum-182 (^{182}Ta)	115 d	0.07 (42%) 1.10 (34%) 1.20 (56%)	sand
Silver-110 (^{110}Ag)	253 d	0.66 (94%) 0.88 (72.5%) 0.94 (34%) 1.40 (24%)	pebbles
Technetium- 99m (^{99m}Tc)	6.02 hours	0.140	mud
Indium -113m (^{113m}In)	1.7 hours	0.39 (65%) 0.24 (20%)	mud

The selection of a suitable radioisotope for a particular investigation depends upon half-life, ability to be produced in a suitable physical form, type of radiation emitted and its energy, neutron absorption cross-section, radiotoxicity. The half-life of the radioisotope should be comparable to the duration of the study. It should be long enough for detection till the end of the experiment and at the same time short enough not to interfere with further experimentation and pose environmental hazards.

For *'in situ'* measurements, gamma emitting radioisotopes are used. The energy of the gamma radiation should be sufficiently high to penetrate through the water. The neutron absorption cross-section of the selected isotope should be reasonably high to produce the desired amount of activity.

Based on the above consideration, the most commonly used radioisotopes used in sediment transport investigations are:

- ^{192}Ir, ^{46}Sc, ^{198}Au and ^{51}Cr for sand transport studies,
- ^{198}Au and ^{51}Cr for mud transport studies.

3.2.2. Labelling techniques

3.2.2.1. Surface labeling

The surface deposit of a radioactive chemical on sediment surface is applied mostly for qualitative sediment transport of mud. The process more employed consists in depositing spontaneously, or by a chemical treatment, the radioelement on the matter studied: muds, spoils dredge, limestone. The selected radioisotope is allowed to get adsorbed onto the surface of the sediment grains after a suitable treatment. Sediment with particle size less than 0.04 mm should be labeled under careful conditions in order not to modify the surface properties and thus their hydrodynamic behavior. Care should be taken to ensure that the radioactivity does not get released under the severest field conditions. This surface deposit method is simple and can be carried out in countries that have not nuclear reactor. It can in fact be used for both mud and sand sediments. The experience of labeling of mud and sand has shown that:

- The labeling for mud particles is proportional to the mass of the particle.
- The labeling for sand particles is superficial and hence the activity labeled will be proportional to the surface area of the grains.

^{198}Au and ^{46}Sc are the two commonly used radioisotopes used for labeling particulate material and apply the labeled material as a tracer. The half-life of ^{198}Au is 2.7 days and thus is used for short term studies (mud and sand), whereas the half-life of ^{46}Sc is 84 days and thus is used for long term investigations (sand).

The particulate material is directly labeled with the desired radioisotope at the site. The labeling efficiency is a function of various parameters such as concentration of radioisotope to be labeled, pH, amount of particulate material and its size, equilibrium time etc. and needs to be investigated before preparing radiotracer for a particular study. In addition to this, the uniformity of labeling and leaching of the radioisotope is also investigated at the simulated experimental conditions. After optimizing labeling conditions, one knows the amount of activity require for prepare the tracer. Generally the labeling efficiency is from 80 % (sand) to 99% (mud).

This operation requires preliminary checks in laboratory. It is imperative to examine:

- The output of the operation (it must be close to 100%);
- The solidity of the deposit obtained (the radioactive isotope must remain fixed at the matter under the conditions of the study: abrasion, temperature etc);
- The similarity of the hydrodynamic behaviors of natural and radiolabeled material. A very detailed attention is paid in the conditions of flocculation of the two batches.

The chemical reactions of oxydoreduction are particularly favorable. For example:

- Gold in the form of acid aurochlorhydric ($HAuCl_4$) is reduced spontaneously out of metal gold in contact with very many products in powder form in suspension by respecting the criteria enumerated above.
- The oxydoreduction of technetium can be caused by a pretreatment of the particles by a diluted solution of chloride tin or money.
- Precipitation, spontaneous, of indium or hafnium chloride, in slightly acid solution, occurs within the mud suspensions (dredge spoils, station of purification etc.), it is an effective method of fixing of radioactive isotopes on the materials studied.

Evaluation of surface labeling techniques for sands using ^{198}Au.

Briefly, sand transport studies using radiotracers consist in labeling sand, placing the radioactive sand in the area to be studied, and surveying the area to measure the movement parameters. A number of techniques for sands have been developed. These techniques provide for: surface labeling and mass labeling. Surface labeling means the activity of sand particle is proportional to the particle surface, while mass labeling gives sand particles where activity is proportional to its mass.

^{198}Au is mostly used for sand labeling using surface deposit technique. A search of the literature showed that many sand studies have been carried out with ^{198}Au; however, the labeled-sand characteristics and the labeling procedures are not detailed. Several procedures for labeling sands with ^{198}Au for sediment transport study have been reported, but not in sufficient detail to permit their use in obtaining reproducible results or to provide information concerning the characteristics of the labeled sand. Two techniques mostly performed, one using direct reduction by stannous chloride and the other using displacement of silver with gold, are described.

Direct gold reduction by stannous chloride

A 30-g sample of sand was treated with an excess of stannous chloride ($SnCl_2$) solution. The mixture was slurried and allowed to stand for 5 to 10 min. The excess solution was then decanted, and the sand was washed three times with 10 to 15 ml of water. The sand was dried and ^{198}Au chloride solution was added with stirring. The mixture was allowed to stand for about 30 min and was stirred occasionally. The gold solution was counted before it was added to the sand. After standing, the solution was decanted from the sand. Both the sand and decantate were counted at this point. The sand was dried and divided into three parts. One part underwent leaching tests before any further treatment, one part was heated in a furnace to 500^0C before leach testing, and the third portion was heated to 1000°C before any testing.

Displacement of silver by gold

A 30-g sample of sand was treated with $SnC1_2$ as described above. Silver nitrate solution was added to the sand with stirring. After the $AgNO_3$ treatment the sand was washed once with 10 to 15 ml of water and dried. The dried sand was then treated with ^{198}Au chloride solution and divided as described above.

Comparison of these two techniques

- The technique of direct gold reduction by $SnCl_2$ gives better result. The mount of gold used was varied from 10 mg of gold per 1.45 g of sand to 1.2 g of gold per 145 g of sand.
- The reduction of silver by $SnCl_2$ followed by the displacement of Ag by Au was unsatisfactory. The Ag was not reduced when it came into contact with $SnCl_2$-treated sand, but instead reacted with the Cl- ions to form AgCl.
- Heating the sand to 500^0C for about 30 min after labeling has increased the retention of gold on the sand, which was found during abrasion and leach tests. Heating to 1000°C further increased the retention of the gold on the sand. After the sand was labeled and heated to 1000°C it appeared that all the gold was in the elemental state, and washing the sand with dilate HC1 removed only a negligible amount of activity.

3.2.2.2. Volume labeling

This method is used only for sands. A completely artificial tracer having the same physical characteristics as the sediment is prepared. It is usually a glass containing about 1% or less of an activatable element like iridium or scandium. This glass having the same density as that of the sediment is ground and mixed in suitable proportions to have the same grain-size distribution as the natural sediment and irradiated in a nuclear reactor to obtain the radioactive tracer. Since the activatable element has been incorporated in the volume of the tracer, the activity of the radiotracer is proportional to that of the mass of the tracer helps in a quantitative interpretation of the data obtained in a tracer experiment. The specific gravity of the sediment is 2.71 g/cm^3, so it is desirable to prepare the glass that has the specific gravity as close to this value as possible.

The preparation of glass incorporating activatable element involves judicious mixing of several oxides such as Na_2O, SiO_2, CaO etc., along with the activatable element in a suitable form and firing the well-mixed composition at a high temperature to produce the glass. The most important aspect of the procedure is that the activatable element should be uniformly distributed within the glass matrix.

In case of scandium, the element is added in the form of Sc_2O_3 and is well mixed with the other oxides before fusing them into glass. The composition of glass normally used in India is as follows:
SiO_2: 64%
Na_2O: 18.6%
CaO: 15.9%
Sc_2O_3: 1.5%

Another activatable element incorporated in glass matrix is iridium. Problems do arise with the production of iridium glass as it does not get uniformly distributed in the glass matrix due to its high density. The composition of the iridium glass normally used is as follows:
SiO_2: 48%
Al_2O_3: 19%
TiO_2: 5%
CaO: 17%
MgO: 5.72%
K_2O: 5%
Ir: 0.28%

It is understood that the addition of iridium in the form of an aqueous solution of potassium-chloro irridate at a certain stage of production process results in a uniform distribution of iridium in the glass (Vance et al, 1997). Table II shows common composition of glasses used to simulate the sand transport.

TABLE 2. COMMON COMPOSITION OF GLASSES USED TO SIMULATE SAND TRANSPORT

	Glass with Iridium	Glass with Gold	Glass with Chromium	Glass with Tantalum
SiO_2	48%	50.5%	48%	40%
Al_2O_3	19%	20%	22%	12%
CAD	17%	18%	14%	13%
TiO_2	5%	5.25%	5%	3%
K2O	5%			5%
MgO		6.25%	6%	5.5%
BaO			5%	6.5%
Element activatable	Ir 0.3%	Au 0.5%	Cr 3%	Ta_2O_5 15%

3.2.2.3. ^{99m}Tc adsorbed tracer for hydrodynamic studies of fine sediments in suspension

In the aquatic environment, heavy metals and many organic compounds are usually associated with fine sediments (silt and clay). The fate of these contaminants will be associated with the dynamic behavior of either suspended or bottom sediments in polluted streams. The study of suspended sediment behavior is required for many environmental studies. Of special interest is the study of individual discharges of contaminants associated with suspended sediments, the short-term dispersion of contaminated material dredged from harbors and reservoirs and dumped into water bodies, and the behavior of natural sediment in suspension in rivers, bays, estuaries or reservoirs. Tracking the contaminated suspended sediments introduced into streams by individual discharges over a few hours could allow, in some cases, the "in situ" quantitative determination of their advection, dispersion, dilution and sedimentation rates.

^{99m}Tc ($T_{1/2}$=6.02 h) in a reduced chemical form can be employed to label fine sediments. ^{99m}Tc, widely used in nuclear medicine, is eluted from ^{99}Mo generators as the pertechnetate (TcO_4^-) species. Since the mud flocs are generally electronegative (Migniot, 1968), the TcO_4^- must be reduced to an electropositive chemical species in order to be adsorbed by the fine sediment. For this reduction, $SnCl_2.2H_2O$ dissolved in an HCl (0.3%) solution was used.

When labeling fine sediments by adsorption of a radioactive element, two aspects should be taken into account: the chemical treatment should be as gentle and simple as possible, and the similarity of the behavior of the labeled sediment and the actual sediment must be ascertained (Bougault, 1970).

The study of the labeling of mud with ^{99m}Tc reported here has been divided in two parts: (a) development of the labeling technique; and (b) comparison of the hydrodynamic behavior of the labeled and unlabelled sediment. Simply labeling the fine sediment with a radioactive tracer is not enough for its correct application in field studies. It is first necessary to prove that the labeled sediment behavior is hydrodynamically equivalent to the actual sediment. Thus, the settling behavior of both sediments (labeled and not labeled) in water at rest was compared in sedimentation tests relating the cumulative percentage of mass to the fall velocity of the particles.

^{99m}Tc labeling and testing example from Brazil

Bottom sediment obtained from the Pampulha Reservoir in Belo Horizonte, Brazil, was used as dynamic studies of fine sediments in suspension in its hydrographic basin are to be undertaken. A mix of silt and clay samples obtained at five different positions, covering a region near the reservoir dam, where the occurrence of sand in the bottom is negligible, made up the material. The material was wet-sieved and then air-dried. The fraction with φ<63 µm was used in all the experiments, which were performed at ambient conditions.

The sedimentation tests were performed using a test tube and an Andreasen pipette, and suspensions with a concentration of sediment equal to 5 g/L. According to Migniot (1968) and Bougault (1970), settling of the suspension is not hampered at concentrations of this magnitude or lower. An activity of 4 x 10^8 Bq of ^{99m}Tc was employed to label 5g of sediment. Fifty milliliter of this solution was poured directly into an Erlenmeyer flask already containing the fine sediment in 960 ml of distilled water.

Results and discussion

The main results obtained from the development of the labeling technique, as described in Bandeira (Bandeira J.V. et al., IAEA Proceedins May 1999) were: (a) it is possible to easily label fine sediment with ^{99m}Tc with yields higher than 99%, using stannous chloride as the reducing agent; (b) the adsorption yield can be optimized by increasing the amount of sediment in the labeling solution, while maintaining its concentration; (c) in practical applications, the pH of the labeling solution must be above 5, i.e. in the range found in most natural waters, because at lower pH values the yield decreases;

(d) increasing the concentration of suspended sediment to be labeled increases the adsorption yield, the highest yields obtained with sediment concentrations being >15 g/L; (e) adsorption of the reduced species of ^{99m}Tc is not instantaneous but is rather fast. In laboratory tests to evaluate the influence of contact time, yields above 95% were obtained after stirring the suspended sediment with the Tc(IV) solution for 5 min; (f) labeling is only slowly reversible: significant desorption was not observed after 2 h of agitation, of sediment at three different concentrations typical of natural streams (50, 200 and 1000 g/L). The increase of activity in the supernatant with time was measured and indicated a release of radioactivity of <10% after the indicated agitation time.

Conclusions
Labeling of fine sediment (φ<63 µm) with ^{99m}Tc was achieved. Labeling without flocculation, which promotes the same sedimentation behavior of the labeled and the natural sediment was only achieved using small quantities of $SnCl_2$ dissolved in proportionately small volumes of HCl (0.3%), in the reduction of a $^{99m}TcO_4^-$ eluted from a ^{99}Mo generator.

The labeling of fine sediment with ^{99m}Tc has been successfully accomplished in situations with flocculation and without flocculation. The labeling yield of the fine sediment was quite high (over 90%) and relatively irreversible without significant desorption for at least two hours.

3.2.3. Radiotracer activities and masses used

For reasons of safety and cost price the activities as well as the masses of tracers implemented at the time of a study must be lowest possible. In addition to this, the tracer should have statistically significant number of particles to represent the movement of sediment on seabed. This problem can be formulated differently: Does one have to use a restricted number (a few thousands) of particles having an important individual activity or must one immerse a great number of particles (a few million) having a very weak individual activity, however sufficient to be detected correctly under the experimental conditions? Important theoretical and experimental developments were devoted to these problems as of the first studies calling upon these methods (Courteous G. 1964; Courteous G. and Sauzay G. 1970).

The amount of radiotracer activity strongly depends upon the efficiency of the detection system, the mode of detection, the expected spread of the tracer, the level of natural radiation on the sea bed and duration of the study. A 1.5” x 1” NaI(Tl) scintillation detector has an efficiency of about 70 counts per second (cps) per microcurie of ^{46}Sc per square meter. For example, if the natural background radiation level in the experimental site is about 30 cps and the tracer is expected to spread over an area of about 4 km x 2 km, then the activity required will be about 5 Curie. To have this much activity even after 4 months of monitoring, about 13.5 Ci (500 GBq) activity would be required for the investigation.

The theoretical estimation and the experience have shown that it is preferable that there are at least 25 to 50 particles per square meter of tracer measured by the detector of radioactivity. However the density of tracer must deliver with the radiation detector a signal at least equal to the double of the background (natural radioactivity) of the site.

The very small activities by particle are required to satisfy the most severe conditions of safety. Thus, if, by not very probable assumption, one or some radioactive particles penetrate and thus contaminate a living organism and in particular a human body, they will deliver a radiation dose lower than the dose delivered by a medical radiography (approximately 0.2 mSv).

Examples of activities and quantities used:

For sands:
^{192}Ir:

- Activity: $3.7\ 10^{10}$ Bq (1 Ci)
- Quantity: 250 grams
- Number of particles: $2.5\ 10^{7}$

For mud:
^{198}Au:

- Activity: 37 10^{10} (10 Ci)
- Quantity: 1 kilogramme
- Number of particles: Approx. 10^{12}
- Mud is in suspension with a concentration from 200 to 250 g/L.

3.3. RADIOTRACER INJECTION

Two types of tracer immersions are carried out:

- Specific deposit of a small mass (100 to 250 g) of crushed glass on the river or sea bed.
- Introduction of a fluid volume of silt (10 to 50 L with concentration of 200 g/L) into the well of a dredger containing of dredge spoils. This operation (using peristaltic pumps) is carried out few minutes before the discharge on the site.

3.3.1. Radiotracer injection in bed-load transport studies

After estimating the activity and mass of the radiotracer to be injected, the glass powder is irradiated and brought back to the hot cell. In hot cell the aluminum irradiation containers are cut open and the irradiated glass is transferred to a transport container. In some countries (Republic of Korea) the transport container itself is designed and used to inject the tracer onto the seabed. This avoids the unnecessary exposure during injection procedure. All the safety measures are followed during the transport of the tracer from reactors to the hot cell and subsequently from hot cell to the experimental site. The transport/injection systems used in Republic of Korea, India, Brazil and France are shown in Figs. 15-18. The dose rate at the surface of the transport container should not exceed more than 2 mSv/hr and the transport container must have an agreement as a Type A container or must be accepted by the national regulation.

Out of the above mentioned systems, it was found that the system used in Korea is simpler and safer from the radiological safety point of view, especially because there is no manipulation of the tracer out of the shielding on site.

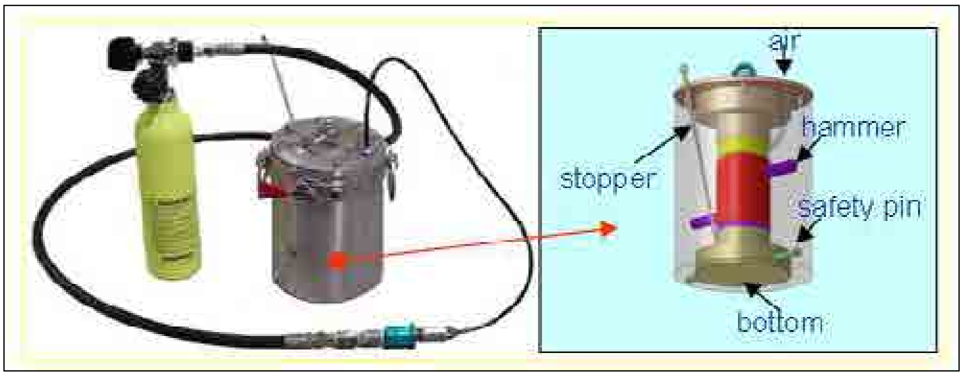


FIG. 15. Transport and injection system used in Republic of Korea.

FIG. 16. Tracer injection system used in India.

FIG. 17. Turning model tracer injection system used in Brazil (left before and right after injection).

FIG. 18. Tracer injection system used in France.

3.3.2. Radiotracer injection in into the well of a dredger containing of dredge spoils

Surface labeling of mud for sediment transport studies in suspension is carried out in the field, just before the injection. Figure 19 shows the preparation of the radiotracer (labeling mud) for injection into the well of a dredger, while Figs. 20&21 show the radiotracer injection process.

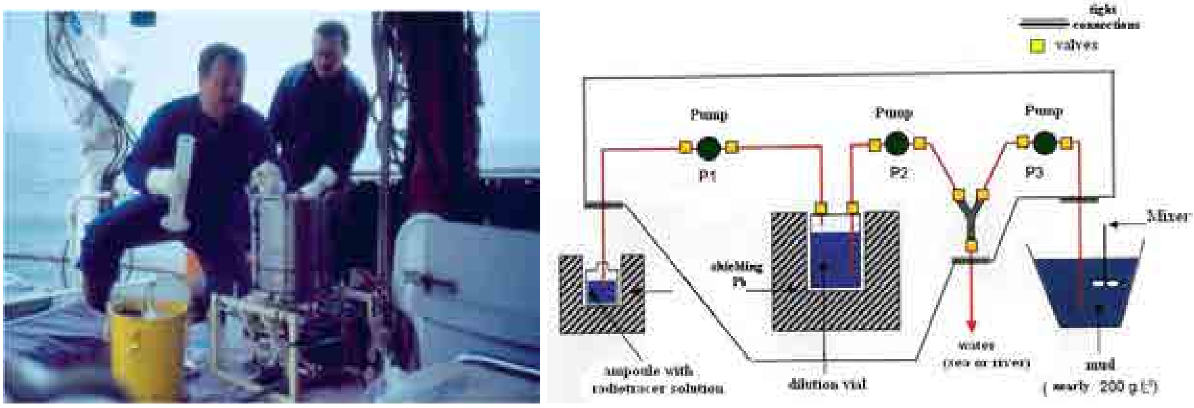


FIG. 19. Preparation of the radiotracer for injection in dredging study.

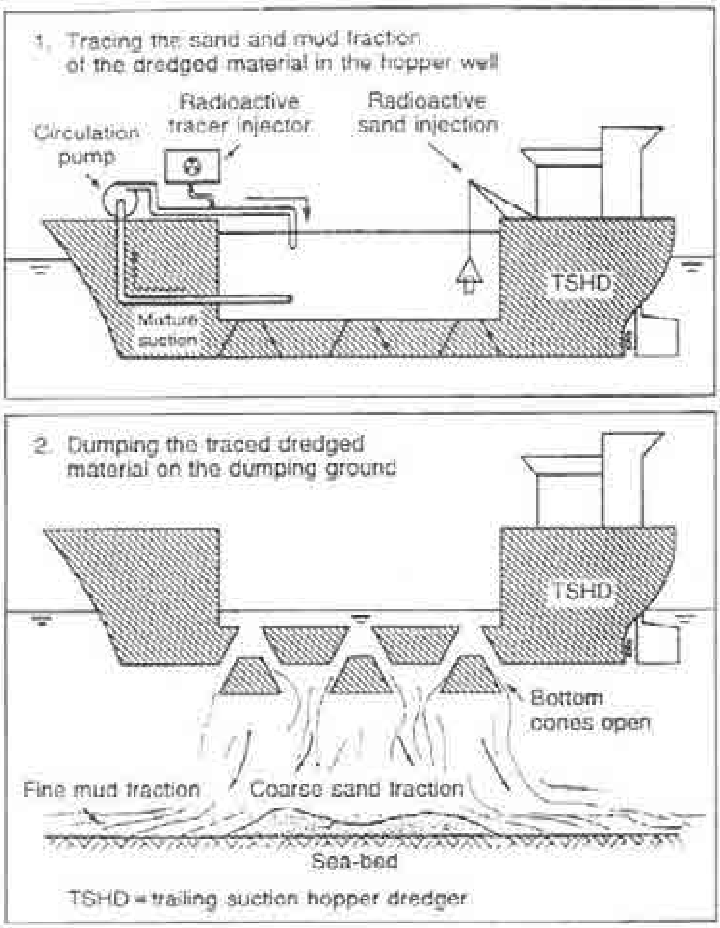


FIG. 20. Injection of tracer in dumping test.

FIG. 21. Example of release of sediments by a dredger.

3.4. MEASUREMENT OF THE RADIOACTIVITY

3.4.1. Radiation detectors

Geiger-Muller gamma detectors were used at the first studies (1954), now more sensitive NaI(Tl) scintillator detectors are employed. This has made possible to greatly reduce the quantity of radioactivity injected and to make use of average energy gamma emitters. Thus ^{46}Sc, the first radioelement historically implemented, has been systematically replaced by ^{192}Ir, for better protection against radiation.

The choice of gamma ray detector depends on a number of factors including their efficiency (determined in part by their density and size) and their peak resolution (determined in part by their light output). In addition, other detector material properties are important to consider such as whether the detector is rugged to thermal and mechanical shock and whether it is hygroscopic (absorbs water). Of course, price may also be a consideration in selecting a detector type.

For gross counting applications only, the 25 mm and 50 mm thick NaI(Tl) detectors are commonly used. NaI is an alkali halide inorganic scintillator with a relatively high Z from iodine. This results in high efficiency for gamma ray detection. Energy resolution of about 6% for the 662 keV gamma ray from ^{137}Cs is achievable for a 3" diameter by 3" long crystal and slightly worse for smaller or larger sizes. The light decay time constant in NaI is about 0.23 µs.

The signals are recorded permanently; formerly they were stored on analogical diagram recorders, today progress of data processing simplifies these operations and facilitates the data processing.

3.4.1.1. Calibration of the detectors for sand bed load transport

In the case of sand bed-load transport using radiotracer, the radiotracer is penetrating under the bottom surface under the action of currents generated by strong waves. The radiation absorption low is: $f = f_0 \cdot e^{-\alpha z}$, where α is sand absorption coefficient (cm^{-1}), z (cm) the penetration (burying) thickness of radiotracer, and f_0 represents the count rate (cps) when the tracer is uniformly distributed in 1 m^2 on the bottom surface.

The first of the steps is to carry out the calibration of the detector, i.e. to establish the relationship which makes it possible to convert the count rate in count per second (cps) to the activity of tracer expressed in Bq/m^2 (for bed-load transport).

The calibration of the detector is carried out in laboratory condition in a large tank filled with sand and water with radioactive sources to simulate the field conditions; the detector is placed in the water at the same distance above the bottom surface as it will be in the field (say 5-10 cm) (Fig. 22).

The typical values obtained for radiotracer Ir-192, and 1.5” x 1” NaI scintillator detectors are:

- f_0 = 50 cps for 37,000 Bq/m^2; this count rate is approximately 2 -3 times the natural radioactivity of a sand bed in marine environment,
- $\alpha = 0.170\ cm^{-1}$.

The laboratory calibration has to respect the geometry of the measurement condition on site, in particular a sufficiently large experimental volume regarded as infinite for the gamma radiation emitted by the isotope should be arranged.

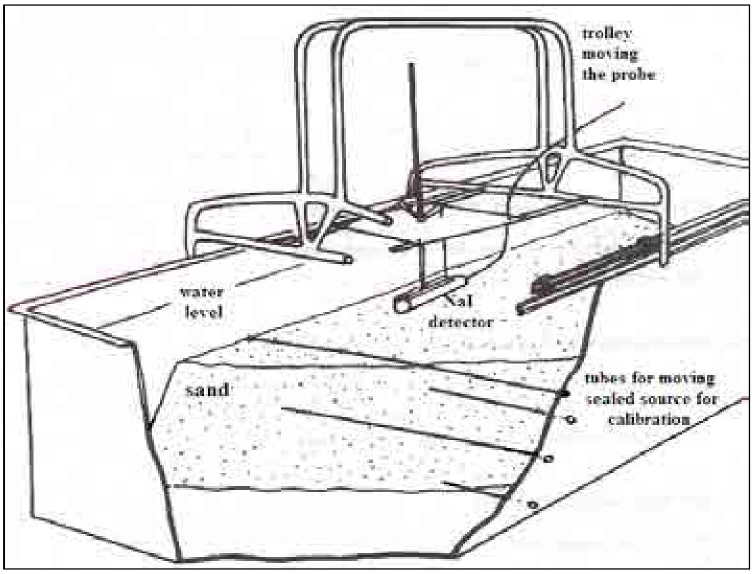


FIG. 22. Calibration tank.

In the case of sediment transport in suspension, it is necessary to measure the count rate (cps) for 37.000 Bq/m^3. For the same detector and Au-198 the f_0= 12 cps.

3.4.2. Data acquisiton systems

In accordance with the purpose of the experiment, radiotracer concentration is recorded along with the position of the radiation sensor lowered on bedload. A stand-alone data acquisition system (DAS) or computer with data acquisition software receives data from GPS system, radiation counter and other data sources such as depth or water quality sensors concurrently. The counts rate recorded by a nuclear counter and the position of the boat recorded by a GPS can be integrated and stored in a DAS or computer. Figure 23 shows a common used DAS for field radiotracer work in sea and rivers and Labview based data acquisition software used in Australia.

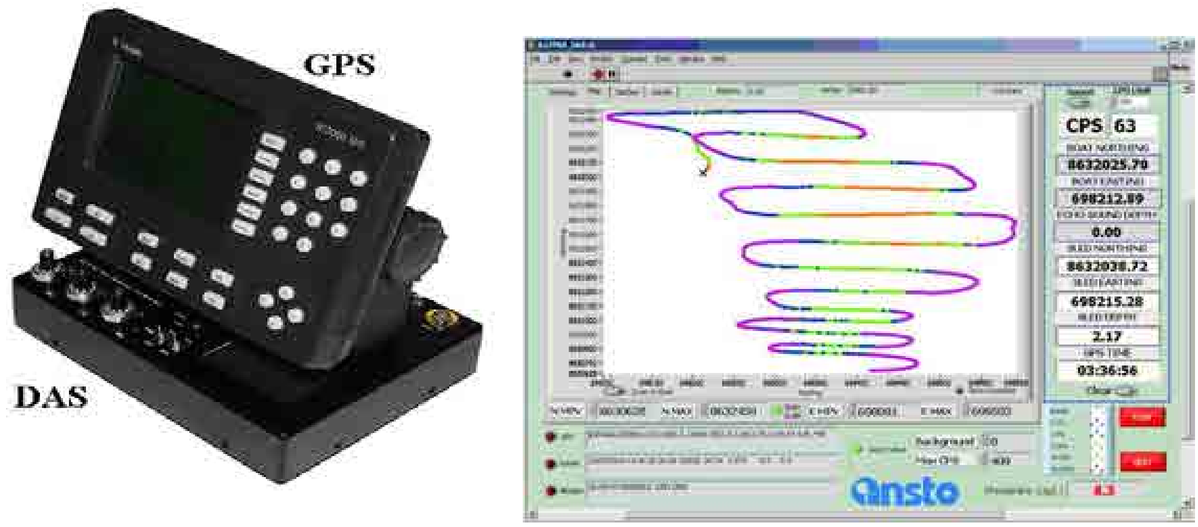


FIG. 23. (a) Combined GPS/Radiation integrated data acquisition system(DAS); (b) ANSTO Labview-based data acquisition and visualisation software.

3.4.3. Modes of detection of radiotracer for bedload transport: Post injection trackings

The common technique for studying the bed-load transport of send is to perform measurements on the bottom surface (Figs. 24- 27). The detector is fixed on a heavy sledge towed by a boat. In short term studies the tracking is carried out immediately after injection of radiotracer depending upon the tidal, wave and current conditions. The detection system should be waterproof and able to absorb the shocks during tracking. Care should be taken to protect the detector and cable from any physical damage as in many cases the cable supplies high voltage to the detector.

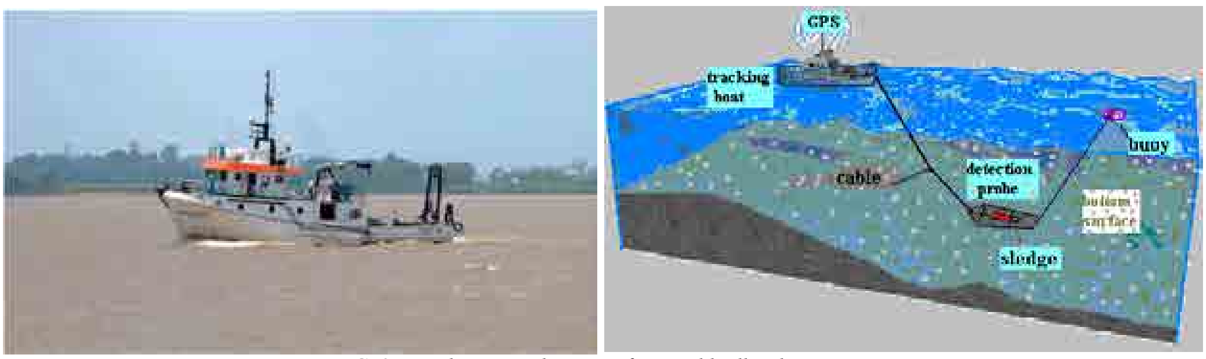


FIG. 24. Radiotracer detection for sand bedload transport.

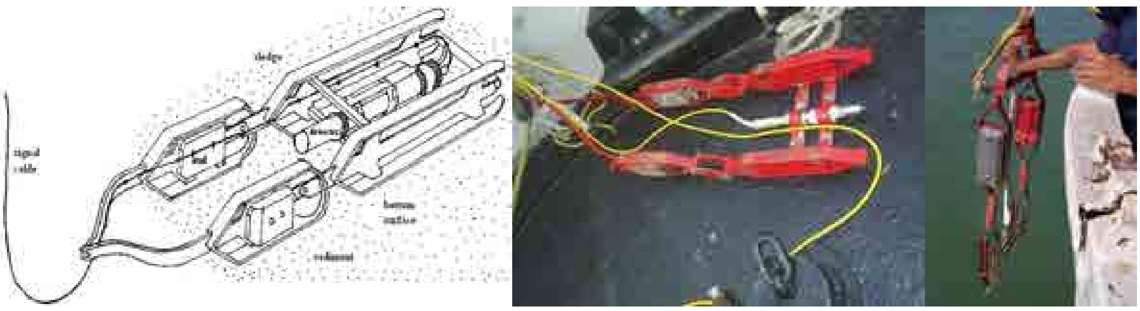


FIG. 25. Typical sledge for radiotracer detection on bottom surface used in France, India and Albania.

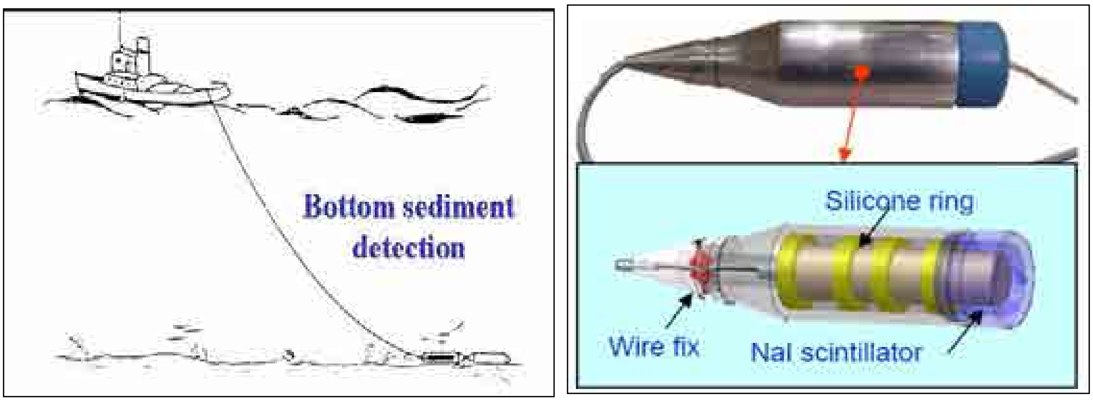


FIG. 26. Detection principle used in Korea (detector on bottom surface).

FIG. 27. Detector and sled used in Australia. Detector suspended by springs and triangular design minimizes risk of detector damage and keeps detector equidistant from bottom.

For long-term studies, a detailed post injection-tracking programme is chalked out depending upon the tidal and wave conditions and half-life of the tracer. The duration of the tracking depends upon the extent of spread. Normally, 4-5 post injection tracking surveys are carried out. The first post injection tracking is carried out after a few hours or days of tracer injection allowing the tracer to spread sufficiently with the current and settle. For monitoring the labeled sediment, the scintillation detector is mounted on a sledge and dragged on the seabed. The concentrations at different spatial locations are measured. The track of the survey vessel is fixed using a Differential Global Positioning System (DGPS) available onboard. The obtained radiotracer concentrations are corrected for natural background radiation and radioactive decay and isocount contour maps are prepared.

The positioning of the boat is obtained, also permanently, by the system of radiolocation GPS. The chart, drawing the shape of the tracer cloud distribution, is obtained in real time. *At early time, before employing location by satellites, the positioning of boat was done by manual and tiresome technique of using hydrographic theodolites giving, each minute, the position of the boat.*

3.4.4. Determining the detector position

Accurate positioning of the detector is important in many surveys. Only when the movement is very large can this be neglected. Bedload transport surveys have the least movement over time and in some cases the ability to measure subtle changes in plume location can make the difference between success or failure of the experiment. The position of the sled with respect to the boat (also known as layback) can be calculated using a "follow the dog" routine. Imagine you have a dog on a lead, and the dog is weaving about in front of you pulling you behind. You don't weave as much as the dog but you are always being pulled slightly in the dog's direction. The same thing happens when the sled is being towed by the boat (Fig. 28).

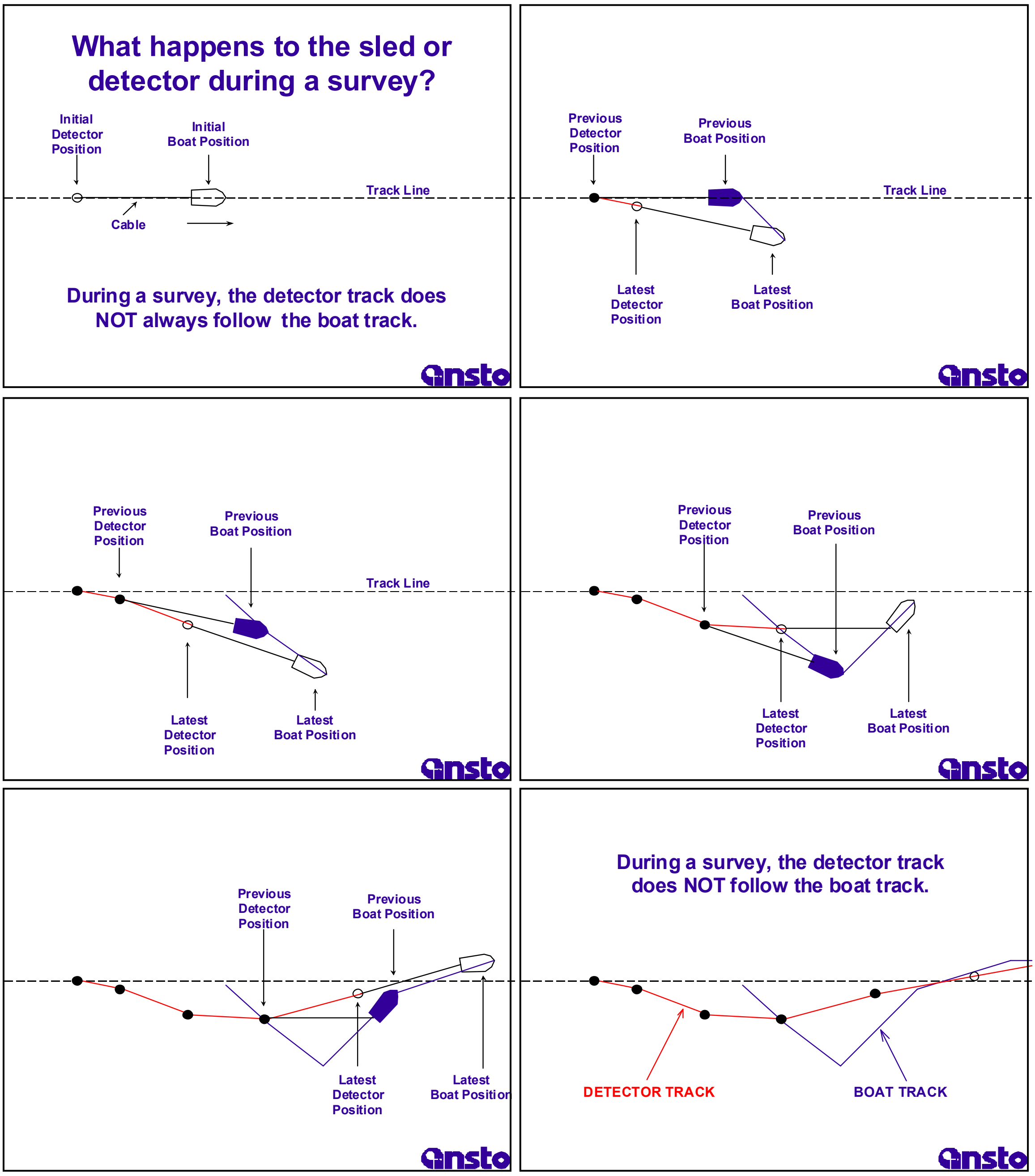


FIG. 28. Towed detector track.

Layback calculations are very reliable and the sled is less sensitive to random GPS error than the boat. If the vessel is large or the vessel "crabs" this can increase the error. Biggest likely error is lateral offset due to currents - this increases with cable length and is worst in rough weather. Catenary effects due to cable drag in the water are very small if sled is well weighted and can generally be neglected. This is not the case in water column surveys where positioning may not need to be so accurate. If the edges of the tracer plume at the beginning and end of a track appear to have a zig zag pattern this may be evidence of incorrect layback correction.

For accurate sled position the sled depth must be known and the exact location of the GPS antenna with respect to the anchor position of the cable must be recorded (Fig. 29). The sled depth can be measured using a pressure sensor installed on the sled or with the detector, or an echo sounder installed on the boat.

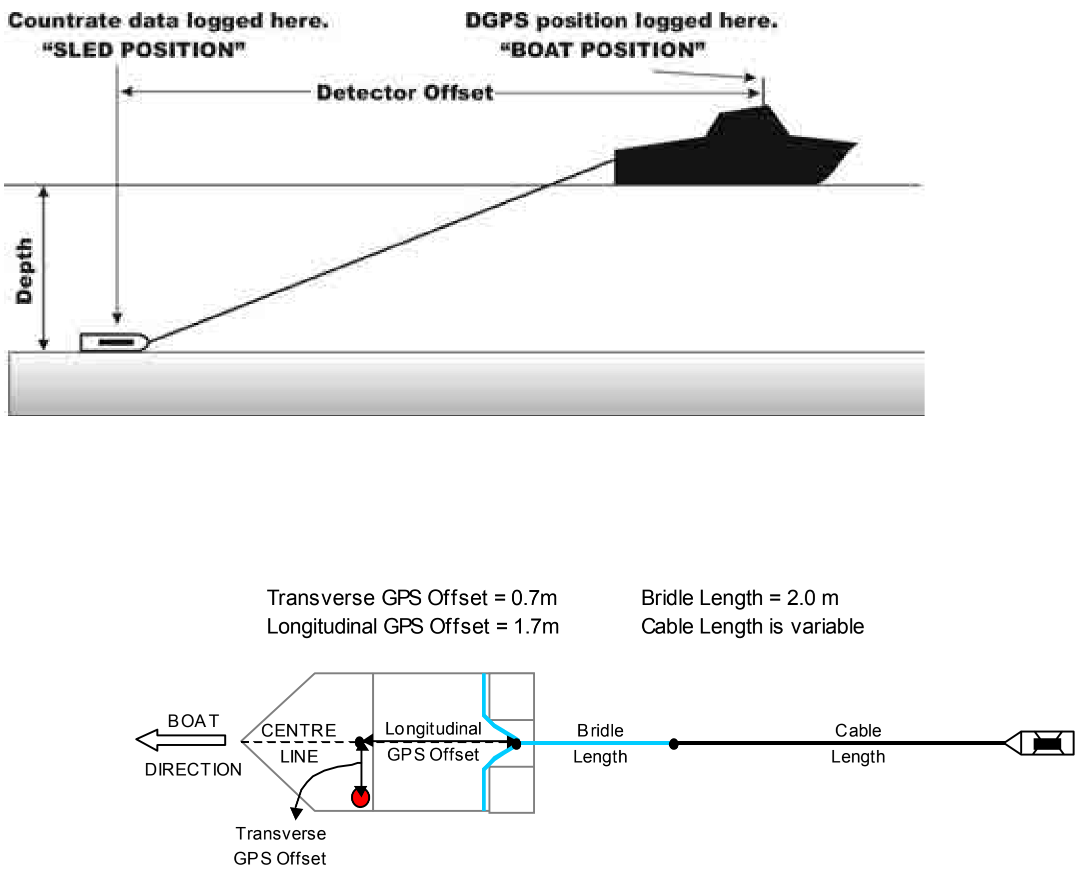


FIG. 29. Position calculation for bedload transport surveys.

An example of the difference between the boat track and the sled track is shown in Fig. 30. In this case the boat position is being affected by lateral wave action. This illustrates the importance of detector position correction.

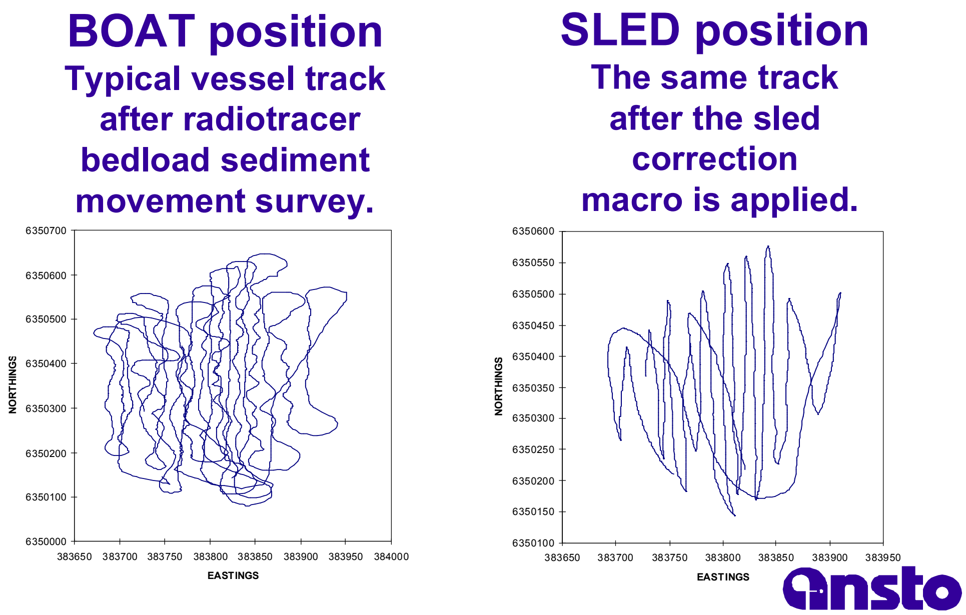


FIG. 30. Illustration of the difference between boat and sled track in a bedload tracer survey.

3.4.5. Calculation of mass flow rate of bedload transport

In 1967, G. Sauzay developed the count rate balance method to estimate the mass flow rate of bedload sediment transport. The mass flow rate Q of bedload sediment transport on bottom surface is expressed simply:

$$Q = \rho.l.V_m.E$$

Where:

- ρ unit weight of the sediment in water
- l width of transport often taken equal to 1 m perpendicular to the transport direction
- V_m mean velocity of the solid transport, expressed in m/d
- E average thickness of solid transport in m.

The radiotracer measurement provide l, V_m and E. V_m is easily estimated by the evolution of the centre of gravity of the tracer cloud between two detections spaced in the time of several days.

3.4.5.1. Determination of the mobile layer thickness (transport thickness) in bed-load transport study

The determination of transport thickness is based on the count rate balance. As bed-load moves, the tracer gets mixed within the thickness of the moving bed. This depth of tracer burial is called "transport-thickness".

E, the average thickness of transport, is calculated using the total number of counts N (corrected for background) of the whole tracer cloud. N will be smaller as bed-load transport is thicker (Fig. 31).

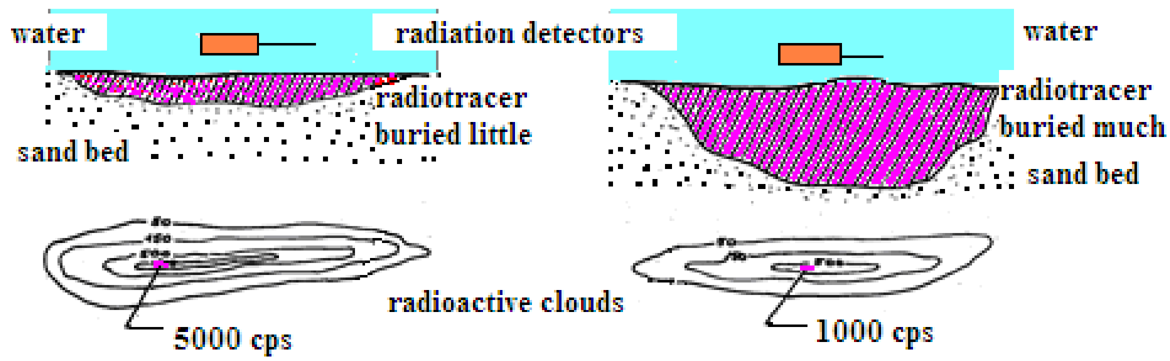


FIG. 31. Principle of the count rate balance method.

There is thus a relation between N and E, which was established by G. Sauzay. The total integrated count rate N (cpm x m^2) over the whole surface area of tracer patch for each tracking is related to the transport thickness by:

$$(1/\beta).(\alpha/f_0).(N/A).E = 1-e^{-\alpha E}$$

Where:

- β represents the vertical distribution of the radioactive grains in the thickness E; experimentally is found β=1,15 (sometimes the value of β is taken as unity, assuming that the distribution of tracer within the moving bed is uniform),
- A is the activity of the injected radiotracer in the day of measurement (corrected for decay),
- f_0 and α are known by the calibration of the detector in laboratory.

Calculating the total count N the estimation of bed-load thickness E can be achieved.

Another technique to determine E (the direct technique) is to take cores from the bottom and subsequent counting of the slices obtained in order to establish the distribution of the radioactive grains in the thickness E. It is clear that this technique is time consuming and asks for a large number of radioactive particles that increase substantially the injected activity.

3.4.5.2. Data treatment

Background radiation survey

Prior to the injection of the radiotracer onto seabed, an extensive background survey is carried out to monitor the natural radiation levels in the area of expected spread using a waterproof scintillation detector mounted a sled connected to ratemeter/scaler on board the ship. The background radiation levels may vary from site to site. However, the levels in a particular site are expected to be constant.

Mapping the radiotracer distribution on surface bottom

The count rates (counts/second) recorded are corrected for natural background and decay. The net counts are plotted as a function of latitude and longitude on a survey chart of the respective sites and iso-activity contours are drawn. An example of this is shown in Fig. 32.

From the plotted isocount contours, the general direction of movement of tracer is drawn and maximum longitudinal land lateral dispersion is estimated. From the results, following qualitative parameters are estimated.

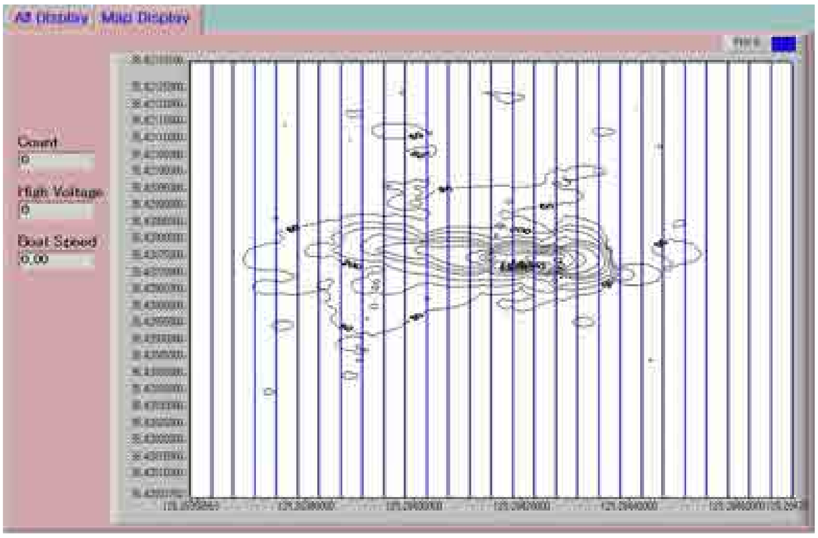


FIG. 32. Isocount countours.

3.4.5.3. Transport velocity: Spatial distribution of radiotracer- quantitative analysis for mean transport distance of tracer

For estimating the transport velocity, the cumulative of counts multiplied by the lateral distance of spread (cps x m), at regular interval perpendicular to the general axis of transport is plotted for each tracking. These diagrams are called transport diagrams (Figs. 33-34), and each is characterized by its center of gravity. Center of gravity is determined by the following formula:

$$\overline{X} = \frac{\int Cxdx}{\int Cdx}$$

From the shift in centers of gravity of consecutive trackings, the mean velocity of transport is calculated.

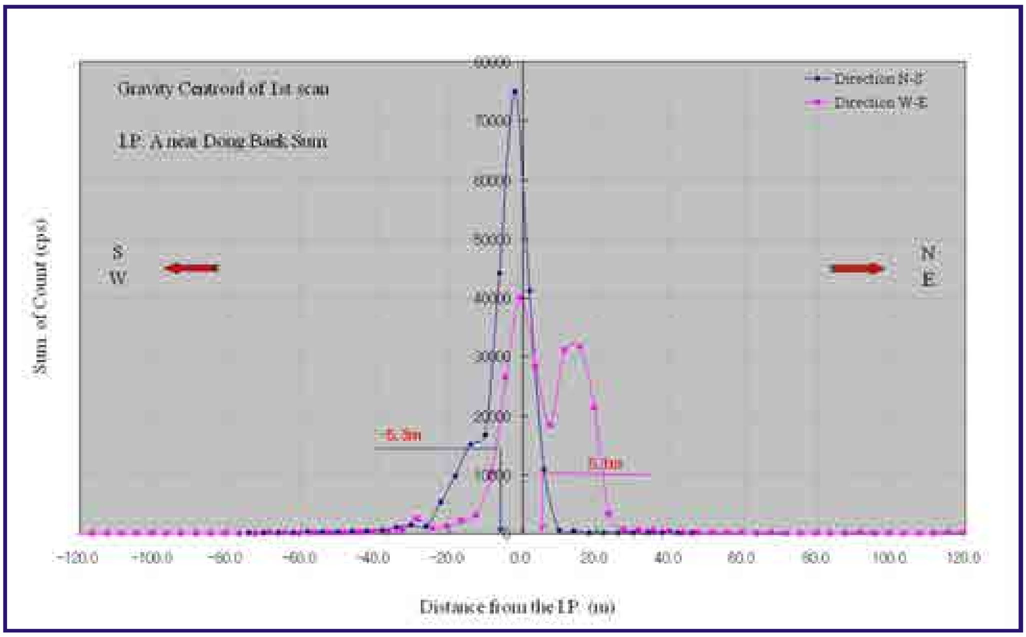


FIG. 33. Typical transport diagram.

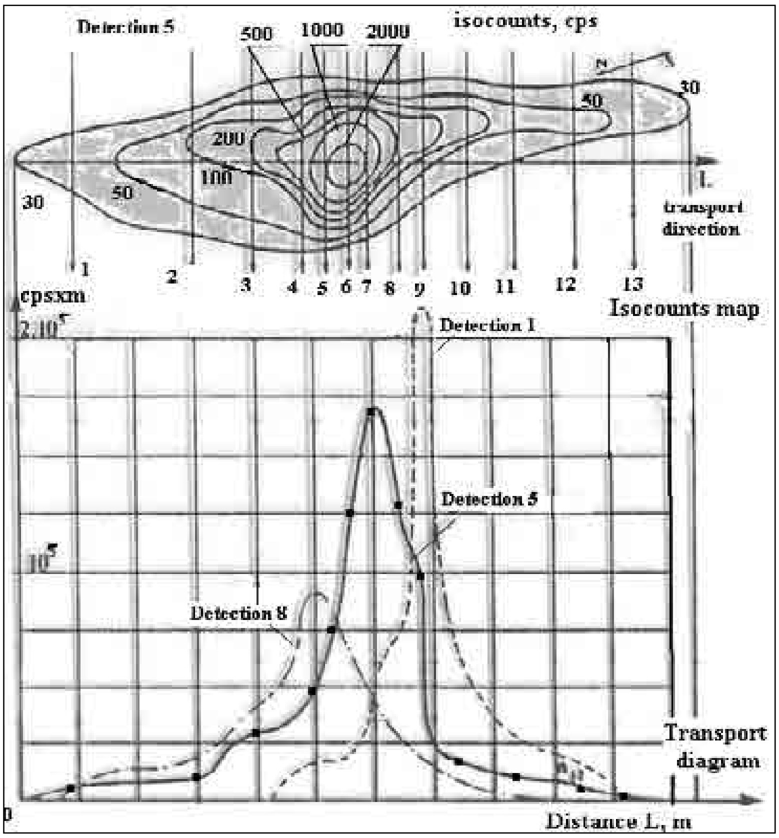


FIG. 34. Obtaining transport diagram from isocounts map.

3.4.6. Detection of radiotracer in suspension: Post injection trackings

If one labels fine sediment with radioactive tracer in the well of a trailing suction hopper dredger or of a barge, and also in the outfall of a hydraulic dredger it is possible to study the fate of dredging dumping. According the half-life ($^{181+175}$Hf, ^{160}Tb, ^{192}Ir, ^{198}Au) of the injected tracer, it is also possible to study the behavior of sediment in large scale systems (some hundred km). If one label fine sediment and dump it sub-superficially through a light pumping system, it is possible to simulate and study the behavior of natural fine sediment in suspension. Fig. 35 shows the detection principle for investigation of sediment transport in suspension.

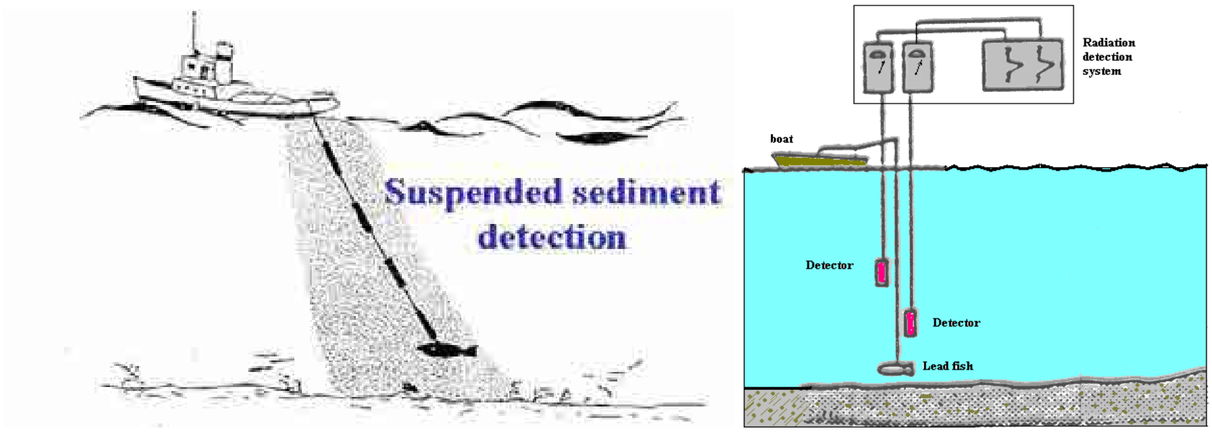


FIG. 35. Detection principle of sediment transport in suspension.

After injection, one proceeds to the detection which could be Eulerian (in narrow rivers) or Lagrangian (large rivers or sea). In this case the number of suspended detectors relies on the site conditions and objective of the work (typically 5 to 20 m water depth). At least 1 boat is used to criss-cross the cloud mainly perpendicularly to the direction of transport (transversal profiles). Preferably one uses 2 boats, the second doing longitudinal profiles (Fig. 36). Detection orientation floata are released together with tracer in order to guide better the relatively fast tracking process in the sea.

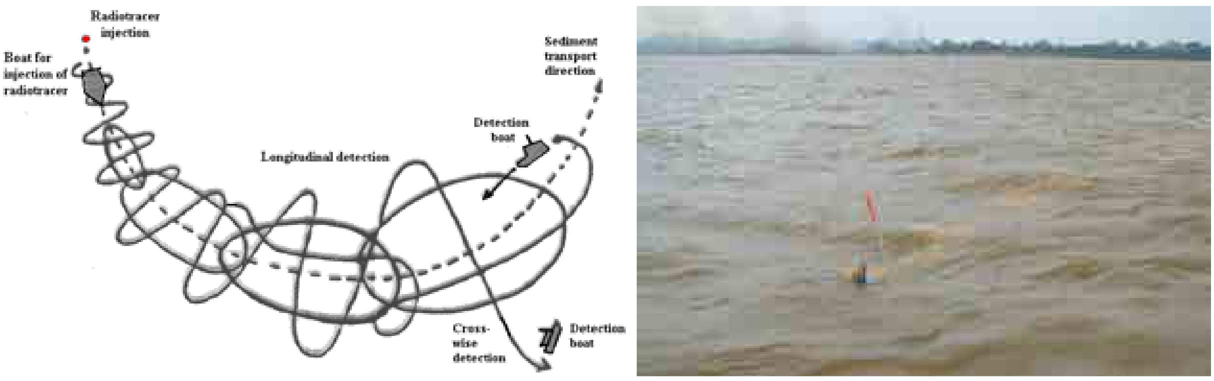


FIG. 36. Principle of detection for sediment transport in suspension(left) and detection orientation float to guide the fast tracking.

The depth of the tracer plume is also important to determine the settling characteristics, to ensure fixed depth detectors are suspended at the most suitable depth, and to allow layback correction to determine the detector position behind the boat. Vertical profiles using a detector equipped or co-located with a pressor sensor can be taken by the boat that is doing the longitudinal profiles (Fig. 37).

In addition data on water quality parameters such as conductivity, temperature and turbidity may be collected at the detector location. These may assist in modeling hydrodynamics particularly in coastal zones where freshwater inflows from rivers, groundwater or effluent discharge are significant.

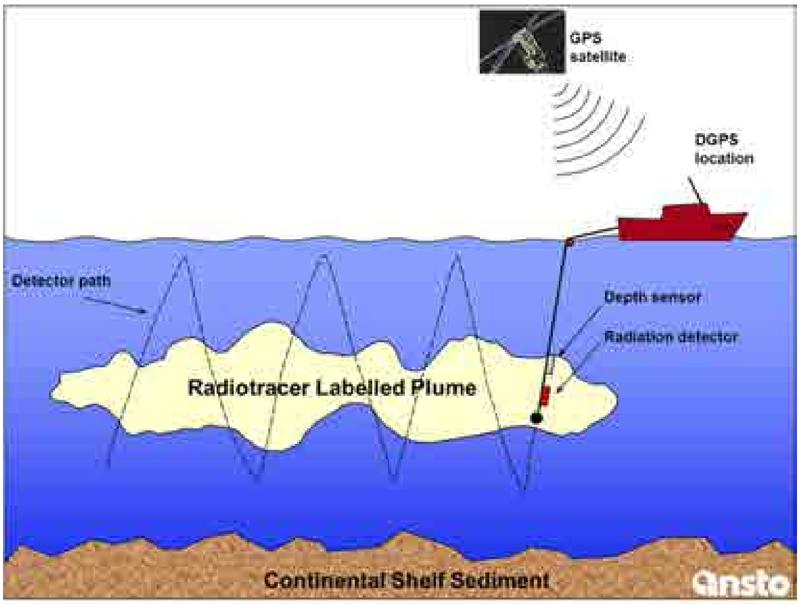


FIG. 37. Method for determining the vertical distribution of a sediment tracer in suspension.

In many cases, after suspension detection a boat equipped as described for bed-load detection explore the bottom of the experimental area to map the (potential) deposit.

In accordance with the purpose of the experiment, radioisotope concentration is recorded along with the position of the radiation sensor fixed at specific depth in the water column. Data acquisition system receives data from DGPS system and radiation counters concurrently. The counts rate recorded by a nuclear counter and the position of the detector recorded by a DGPS can be integrated and stored in a DAS in order to make it easy to install and operate them on board. The counts (counts/second) recorded are corrected for natural background and decay. The net counts are plotted as a function of latitude and longitude on a survey chart of the respective sites.

After data treatment the main results obtained are the following:
- Trajectory and advection velocity of the suspended cloud;
- Horizontal dispersion coefficients;
- Dilution along the cloud trajectory (vs. space and time);
- Settling velocity;
- Map of the potential deposit (in the case of dumping of dredged materials experiments for ex.).
-

3.5. NATURAL RADIOACTIVITY OF COASTAL SEDIMENTS AS "TRACER" IN DYNAMIC SEDIMENTOLOGY

3.5.1. Natural radioactivity of sediments

Radiometric measurement of natural gamma radiation is another simple and fast technique for lithological mapping of the sea bottom that could provide useful information about the origin and transport of sediments. Careful interpretation of gamma natural radioactivity of sea bottom sediments can provide:

- Lithology, which is the description of rock composition (what it is made of),
- Sediment transport trends
    - granulometric selection of sediments,
    - depth limit of wave effect on sea bottom sediments,

- direction and distance of distribution of fluvial sediments,
- accretion and erosion zones along the coast line.

Natural radioisotopes distributed in sediments are ^{238}U (and its family), ^{232}Th (and its family) and ^{40}K. Based on their concentrations in sediments and radioactive decay, it can be calculated that the major contributor of natural gamma radioactivity of sediments is ^{232}Th (over 55%), thus ^{232}Th is the "natural tracer" of sediment dynamics. ^{232}Th is always in equilibrium and is very resistant against chemical and mechanical agents.

3.5.2. Online mapping and data treatment

The gamma measurements are performed dynamically (on-line) from a moving boat with average speed of 1.5 m/s, commonly along profiles perpendicular with the coast line. The detection probe (NaI (Tl) scintillator 2"x2") is mounted in a special support, which keeps it a constant distance from the sea bottom of 5-10 cm.

The plot of radiometric data is treated according to following methods.

a).Treatment with Gauss chart.
For each lithology the distribution of count rates is normal; that means its graph in a Gauss chart is linear, with a mean value characteristic for that kind of sediment. Two count rate distributions are considered significantly different when $I_1^* + s_1 < I_2^* - s_2$, where I_1^*, I_2^*, - are the mean values of two successive distributions ($I_2^* > I_1^*$) and s_1, s_2 – are their standard deviations. Each count rate data distribution corresponds to particular sediment (lithology). To correspond a lithology to a class of count rate distribution several sediment samples have to be taken from the sea bottom and analysed in laboratory (granulometric analysis).

Thus, using radiometric data the sediments can be classified by their grain size, in two groups silt (<0.06 mm) and sand (0.06-2 mm); moreover what is the most important from sediment transport point of view, the very fine sand (0.06-0.1 mm) can be distinguished from fine, medium and large size sands, giving the classified sand map of the bottom that provides an insight into sediment transport mechanisms.

b) Treatment with regressive analysis (trend surface analysis)
Trend surface analysis is in most respects similar to normal regression analysis. "Trend" means the least squares trend. Given a set of data, and the desire to produce some kind of "model" of that data (model, in this case, meaning a function fitted through the data) there are a variety of functions that can be chosen for the fit. The trend surface analysis methods can be used to e.g., derive a continuous smooth surface from irregular data or isolating regional trends from local variations. Trend surface for natural radiation values are approached with a polynomial (mostly of the third degree):

$$X (ui, vj) == P (ui, vj) + aij,$$

where: X (ui, vj) – count rate I measured at bottom point (ui, vj); P (ui, vj) – most probable value; aij – error.

The trend surface map can provide an insight into the sediment transport resultant.

4. CASE STUDIES: RADIOTRACER APPLICATIONS FOR INVESTIGATION OF BEDLOAD TRANSPORT OF SEDIMENTS

4.1. SEDIMENT TRANSPORT INVESTIGATIONS IN INDIAN PORTS USING RADIOTRACER TECHNIQUE

4.1.1. Introduction

India has a long coastline of about 7640 km, out of which 2650 km is on the East Coast and 3360 km on the West Coast and the remaining is in different islands such as Andaman, Nicobar etc. As compared to the West Coast, the East Coast faces severe wave climate and has a relatively shallow seabed. The major rivers of India i.e. Ganga, Brahmaputra, Mahanadi, etc. discharge into the Bay of Bengal and bring along with them a large quantities of sediments. The sediments are carried along the coast by the alongshore currents generated by the waves breaking obliquely to the coastline. There are twelve major ports, six on the West Coast and six on the East Coast of India. In addition to this, there are over one hundred and forty intermediate/minor ports and other marine engineering projects along the coastline. The locations of the major and intermediate ports of India are shown in Fig. 38.

FIG. 38. Locations of the major and intermediate ports of India.

The existing ports and marine engineering projects are faced with the problem of continuous maintenance dredging and dumping operations for maintaining the depth of the navigation channels. In addition to this, capital dredging is also carried out during the construction of the new projects and expansion of the existing projects. The dredging operations constitute major expenditure in existing and new projects. The average annual maintenance-dredging requirement in various major ports in India ranges approximately 20-70 million cubic meters. This huge quantity of the dredge material is to be disposed off at suitable locations either inshore or offshore. In case of major Indian ports, disposing off at inshore locations is not economically and technically feasible option. Hence it becomes imperative that the dredged materials be disposed off at suitable offshore locations, from where it does not find its way back to the channel. In addition to this, the selected site should be such that the turn around time of the dredger is kept minimal to economize the dredging operation. A balance has to be struck between the cost of transport of the dredged material and the eventual return of the disposed material to the dredged areas. The cost of transport of the dredged material is known precisely. However, the assessment of the suitability of the disposal area is rather difficult.

Mathematical models, bathymetric data, hydraulic model studies and sediment accumulation in silt traps etc. are used to estimate the direction and transport parameters of sediments. All these methods provide approximate information and have their own limitations. In such situations, radiotracer techniques are used to evaluate the transport parameters such as transport velocity, transport thickness and rate of bedload movement. Most of the radiotracer investigations carried out are aimed at one or more than one of the followings:

- Examining the suitability of the existing dumping ground for dredged silt
- Selection of a suitable dumping ground for new projects
- Examining the suitability of alignments of proposed navigation channels
- Optimization of the dredging and dumping operation
- Implementation of the River Regulatory Measures and environmental regulations
- Littoral movement of sediment along the coast
- Movement of fly-ash discharged from thermal power projects
- Movement of particulate pollutants in water bodies

4.1.2. Case studies carried in India

In India the application of radiotracer techniques to study the movement of sediment on the sea bed started way back in 1959. Scandium-46 as scandium glass powder produced at AERE, Harwell, England was used as a tracer for investigating movement of sediment on seabed in Mumbai Harbor, Mumbai. In subsequent studies, indigenously produced radioisotopes were used in sediment transport investigations in various ports in India. Since 1959, Isotope Applications Division of Bhabha Atomic Research Centre has conducted 67 sediment transport investigations in various Ports in India. Some of the recently carried out investigations are described below.

4.1.2.1. Kandla Port (2004)

The Kandla Port is located on the west coast of India (Fig. 38). The exact location of the port is on the west bank of Kandla Creek and the creek is part of a complex network of creek system connected to the eastern end of the Gulf of Kutch. The Kandla Port is exclusively a tidal port and the ship movements in the approach area from the Gulf take place during high tides only due to very shallow depths. The tidal range at Kandla varies from 4.0 m during neap tides to 7.0 m during spring tides. The large tidal range generates strong currents of magnitude varying from 1.0 to 1.8 m/s resulting in high concentration (1000 to 3000 ppm) of sediments in the flow. Thus the strong currents cause large flux of sediments predominantly as suspended load. The bed material mainly comprises fine sand mixed with silt. The presence of large tidal range and strong currents results in a very dynamic morphology in the approach area with frequently shifting shoals (sand bars) and channels. The network of creeks and the approach area are flanked by vast reaches of inter-tidal flats, which get inundated during high water springs. Another very important feature is the total absence of any fresh water flow, even during the monsoon season, leading to absence of density stratification or gravitational circulation.

From the pilot station of Kandla Port, the total length of navigation channel is about 27.7 km. Out of which, a critical section of only about 2.3 km length was having very low depths (3.7 m). The present approach channel called the Sogal Channel including the critical section is dredged throughout the year for maintenance. A minimum navigable depth of about 6.0 m was achieved, in stages, by September 2004 when the Sogal channel was commissioned for navigation of ships. The Kandla Port has now achieved a draft of 13.5 m by carrying out required maintenance as well as capital dredging carried out during 2000-2007.

The maintenance dredging in the navigation channel, at Kandla Port, is a continuous activity and is inevitable due to the very dynamic nature of the morphology of the region under the influence of very strong tidal currents and high concentration of sediments in the flow. The annual maintenance dredging in the Port is of the order of 3.5 to 4.0 million cubic meters and is carried out continuously using a dredger of 4500 cubic meter capacity.

The knowledge about the likely spread of the disposed material is important not only to avoid re-entry of sediments in to the navigation channel but also to take advantage of beneficial use of the dredged material for utilizing the same to close the adjoining channels. This would help in concentrating the tidal flow along the navigation channel for natural maintenance and flushing of sediments.

Based on hydraulic parameters, two alternative sites one near inshore channel (Site 1) and another west of buoy no. 3 (Site 2) were proposed by Central Water and Power Research Station (CWPRS) Pune, India for dumping the dredged material. Therefore, radiotracer investigations were carried out at these sites to know the spread of the sediments at different tidal conditions. During November 2001, an radiotracer investigation was carried out at inshore channel site at ebb tide condition (injection at high water) to study the spread pattern of sediment and investigate the suitability of the dumping site. In addition to this, two investigations were carried out during 2004, one at inshore channel site at flood tide conditions (injection at low water) and another at site west of buoy no. 3 at ebb tide conditions (injection at high water). The Kandla-Hansthal Creek System and the two experimental sites are shown in Fig. 39.

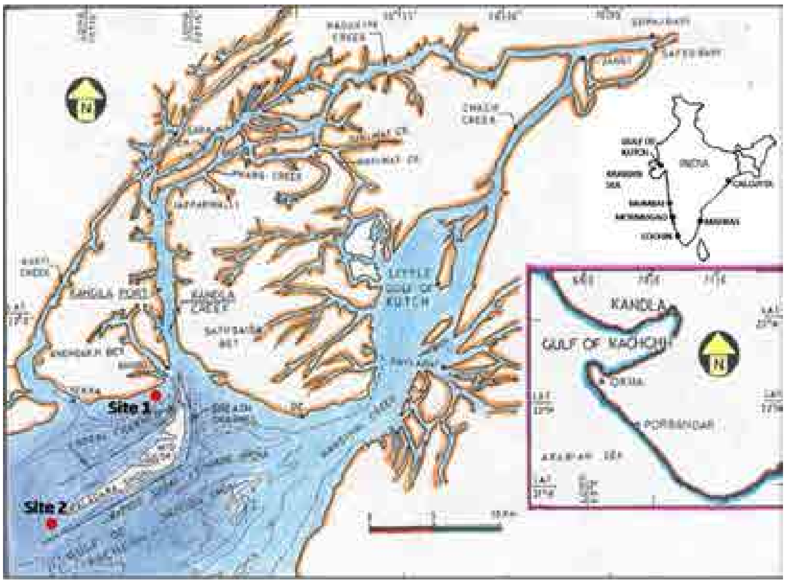


FIG. 39. Kandla-Hansthal Creek System and study area.

^{46}Sc as glass having particle size distribution of 60-300 µm was used as a radiotracer. About 3 Ci (110 GBq) activity was used in each experiment. The tracking schedule is given below in Table 3. The isocount contours and transport diagram plotted for three different trackings for Site 1 (Inshore Channel) are shown in Figs. 40 and 41 respectively. Similarly, isocount contours and transport diagram plotted for three different trackings for Site 2 (West of Buoy No. 3) are shown in Figs. 42 and 43, respectively. Transport velocity, thickness of moving bed and bedload transport rate etc. for both injection points are given in Table 4.

TABLE 3. SCHEDULE OF POST INJECTION TRACKINGS AT KANDLA PORT

Tracking No.	Site 1: Inshore Channel	Site 2: West of Buoy No. 3
1st Tracking	7-9 October 2004	8-9 October 2004
2nd Tracking	18-19 October 2004	19 October 2004
3rd Tracking	8 December 2004	9 December 2004

TABLE 4. RESULTS OF SEDIMENT TRANSPORT INVESTIGATIONS AT KANDLA PORT

Tracking No.	Days after injection	Location of cg (Km)	Activity spread N (cpm.m^2)	%Activity recovered	V_m (m/d)	E (cm)	Q (t/d/m)
Site 1: Inshore Channel							
1	1	0.650	2561 X 10^6	24	650	10.13	98
2	10	2.6	6549 X 10^6	60	222	5.33	17.7
3	30	1.27	7773 X 10^6	72	67	3.73	3.7
Site 2: West of Buoy No. 3							
Tracking No.	Days after injection	Location of cg (Km)	Activity spread N (cpm.m^2)	%Activity recovered	V_m (m/d)	E (cm)	Q (t/d/m)
1	1	0.625	14900 X 10^6	100	625	0	0
2	10	1.99	3461 X 10^6	25	152	10	22.8
3	30	1.39	3200 X 10^6	21	30	10.53	4.7

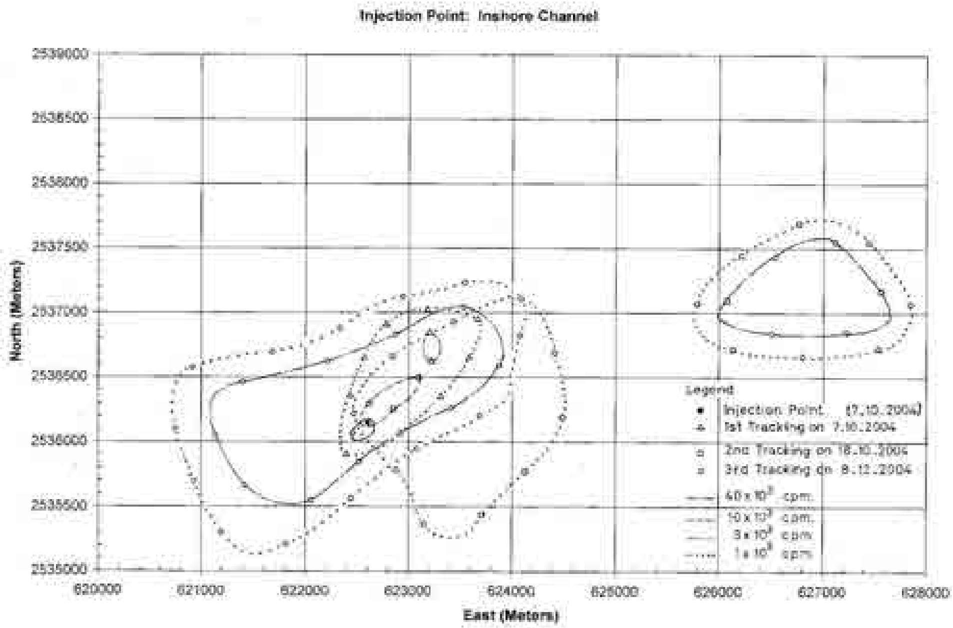


FIG. 40. Isocount contours for Inshore channel site at Kandla Port.

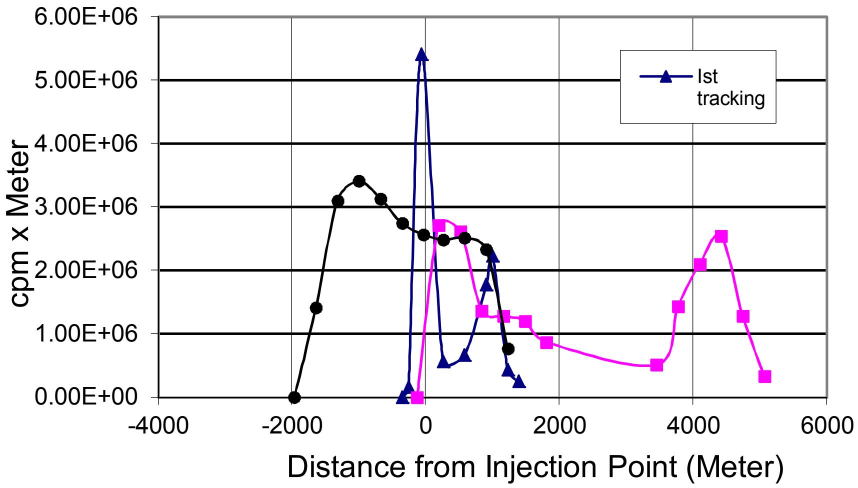


FIG. 41. Transport Diagram for Site No. 1 (Inshore Channel).

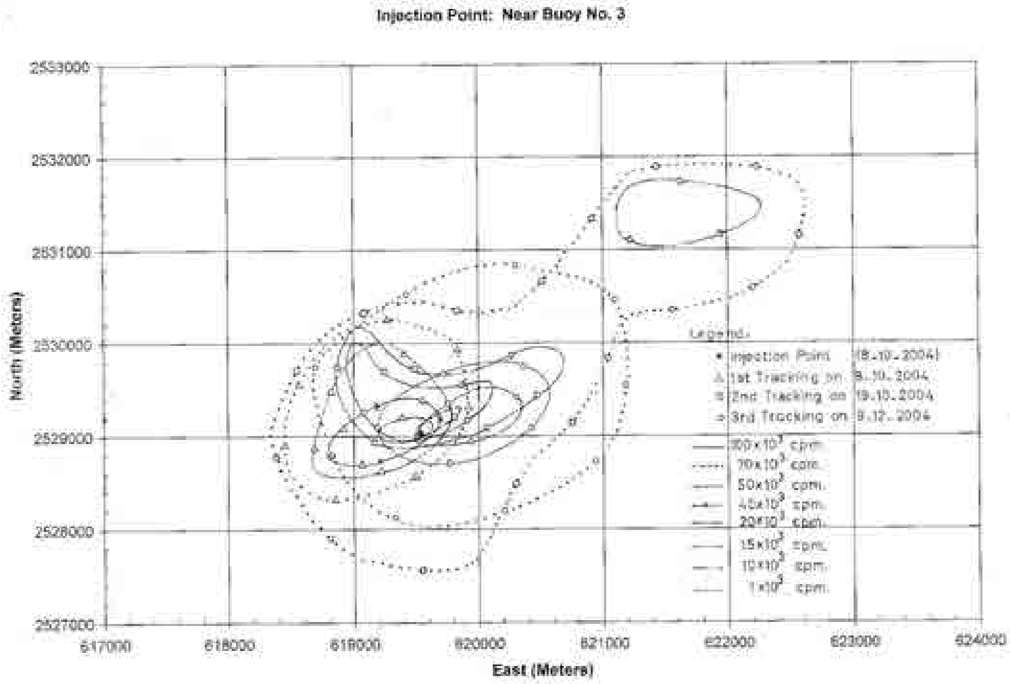


FIG. 42. Isocount contours for Buoy No. 3 site at Kandla Port.

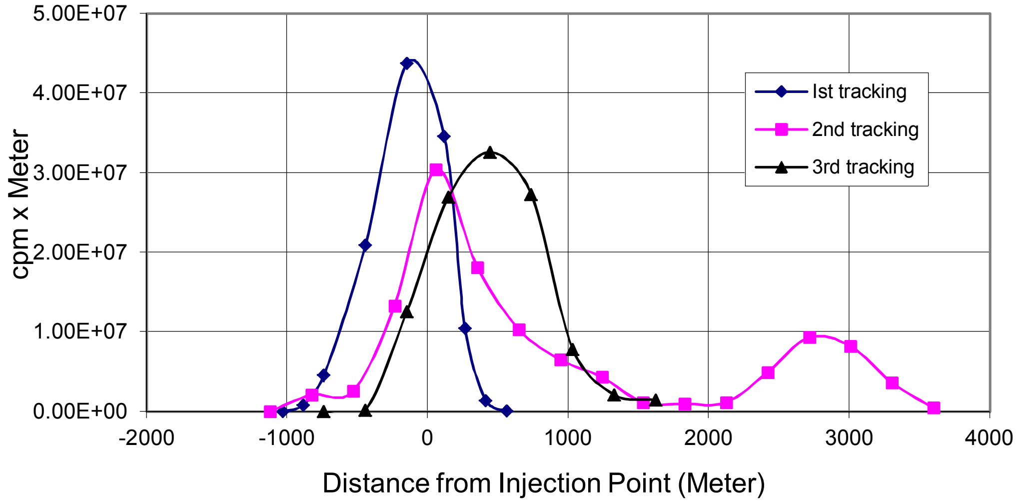


FIG. 43. Transport Diagram for Site No. 2 (West of Buoy No.3).

From the investigation, following conclusions were drawn.

- At site No. 1 (inshore channel), the movement of tracer during first two tracking was towards North-East direction with a maximum longitudinal spread of 6 km and transverse spread of 1.3 km. However, during the third tracking, the sediment movement was towards South-West direction with a maximum longitudinal spread of 5 km.
- At site No. 2 (west of buoy no. 3), the tracking carried out immediately after the injection indicated that sediment moved towards S-W direction as expected. The bedload was movement was predominantly towards N-E direction. However during the second and third tracking the material has also moved towards S-W direction.

4.1.2.2. *New Mangalore Port (2007)*

New Mangalore Port is one of the major ports of India and is located on the west coast, between Mormugoa and Cochin port. It is an artificially developed lagoon type of Port situated 10 km north of combined outfall of Gurupur and Netravati rivers. The Port facilities were developed over the past four decades at the New Mangalore Port, due to limitation of old Mangalore Port to provide deep draft. At the New Mangalore Port basin, the required wave tranquility has been achieved by constructing 2 breakwaters in stages, which presently have a length of 770 m each flanking the harbor entrance with centre-to-centre distance of 1362 m near the roots and 975 m at the outer tips.

The approach channel is almost perpendicular to the coastline in order to have minimum length and thus requiring minimum capital dredging. The length of channel is 7200m, depth 15.4m and width 245 m with side slopes of 1:20. Even though the approach channel is facing the critical westerly direction, due to the phenomenon of wave attenuation along the approach channel, most of the wave energy passes out of field after refraction along the slope of the channel and thus the tranquility in the harbor is achieved. The radiotracer experiments were carried out to examine suitability of a new dumping or alternative site. Sketch of New Mangalore port and experimental site are shown in Fig.44.

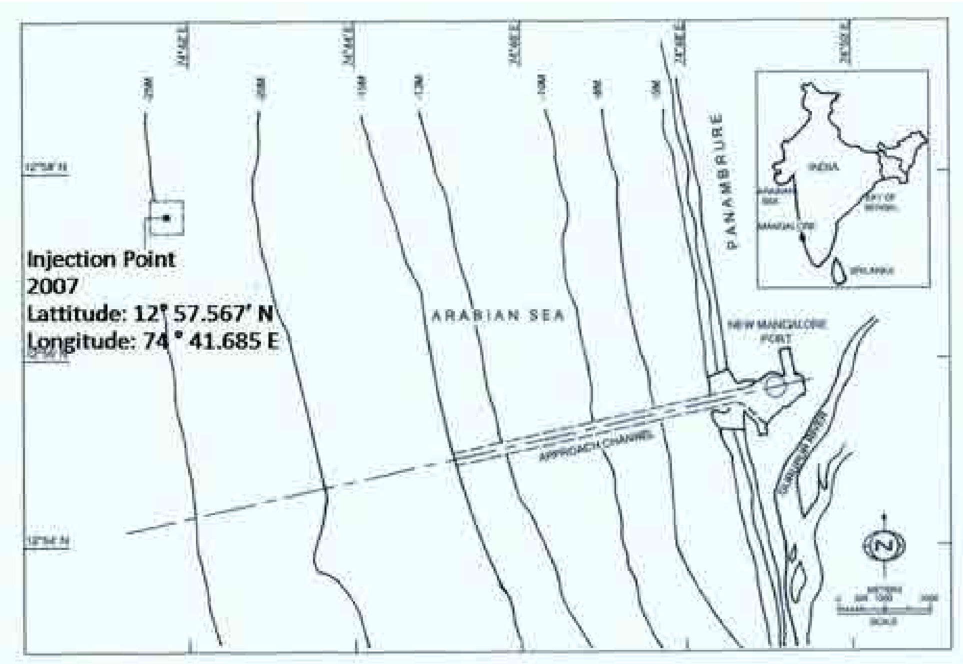


FIG. 44. Schematic diagram of Mangalore Port and study area.

Scandium-46 (activity 8 Ci) as scandium glass powder was used as a tracer. The isocount contours and transport diagram for four different trackings are shown in Fig. 45 and Fig. 46, respectively.

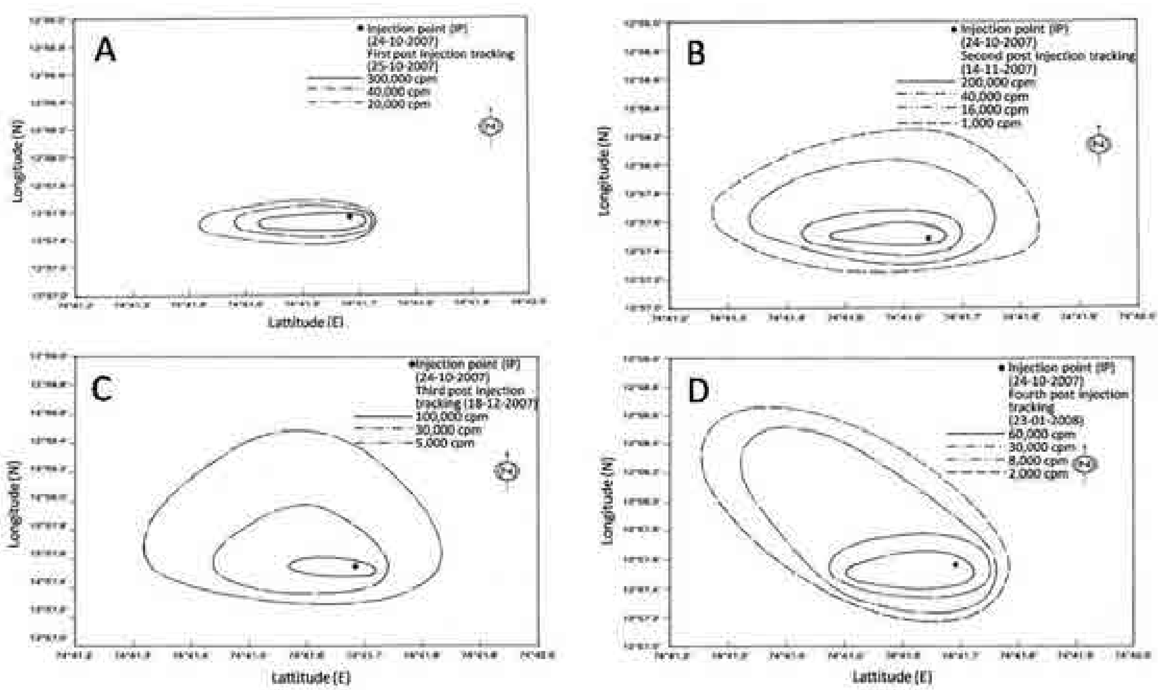


FIG. 45. Isocount contours of post injection trackings.

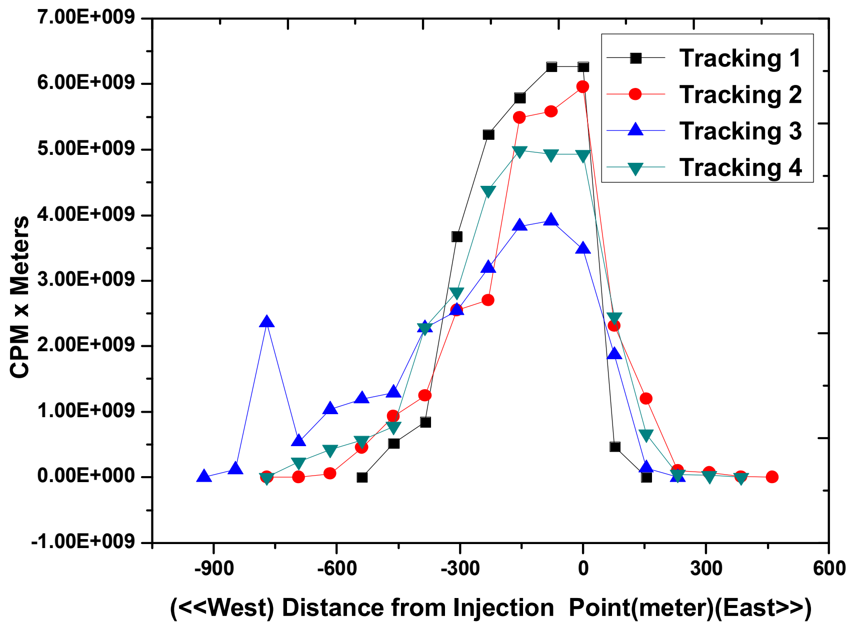


FIG. 46. Transport diagrams for post injection trackings.

Based on hydraulic studies carried out in the physical model, it was initially suggested a dumping ground south of the navigation channel and has been used since last two decades. However, with the increasing expansion of the Port, a need was felt to have a new dumping ground for the dredged material. The quantity of dredged material ranges about 6-10 million m^3 per annum in New Mangalore Port. On the basis of the studies carried out in model and analysis of current and bathymetry data obtained from field, a new dumping ground north of the channel was proposed. The results of the investigation are given in Table 5.

TABLE 5. RESULTS OF SEDIMENT TRANSPORT PARAMETERS INVESTIGATION AT MANGALORE PORT

Tracking No.	Days after injection	Location of C.G. (m)	Activity spread N (cpm. m^2)	% Activity recovered	V_m (m/d)	E (cm)	Q (T/d/m)
1	1	-146	2.88×10^{10}	90 (7.2 Ci)	-	-	-
2	20	-120	3.2×10^{10}	98 (7.9 Ci)	1.4	0.27	0.005
3	53	-254	2.8×10^{10}	87 (7.0 Ci)	4.0	0.86	0.052
4	90	-149	2.6×10^{10}	83 (6.7 Ci)	2.8	1.30	0.056

From the results of the investigation, following conclusions were drawn:

•The sediment predominantly moves towards north-west direction during all the four trackings. The movement towards south and east direction was relatively much less.
•After a period of 90 days the maximum longitudinal distance moved by sediment along west-east direction was about 1000 meters. Similarly maximum transverse movement along north-south direction was about 2600 meters.
•The average velocity of sediment transport over a period of 3 months (90 days) was found to be 2.7 meters/day during the last three trackings.
•The radiotracer investigation was successfully carried out to know the spread pattern of sediment and the results will be used to decide the suitability of the proposed dumping site.

Based on the investigations, it is found that the proposed site is suitable for dumping the dredged material, as the movement of sediment is away from the shipping channel.

4.1.2.3. Vishakhapatnam Port (2010)

Visakhapatnam Port is located on east cost of India and consists of two different harbours i.e. an inner and an outer harbour. This coast is affected by two monsoons i.e. South-West (S-W) and North-East (N-E) monsoon and is prone to high rates of a long-shore drift. The two major rivers namely Godavari and Krishna flowing from west to east act as major sources of sediments and cause the sedimentation and morphological problems linked with the development of Visakhapatnam Port on this coast. The development of port on open coast requires the construction of breakwaters which cause hindrance to the natural long shore sediment transport affecting the morphology of the adjacent coast lines with probable accretion on updrift side and erosion on down drift side. This problem needs to be addressed with appropriate design of port layout along with suitable provision of sand trap and sand bypassing methods.

Though S-W and N-E monsoons invoke littoral drift in two different directions northwards and southwards respectively, the impact of SW monsoon is high in view of its higher intensity and duration, thus resulting the net littoral drift towards the north. Theoretical computations for the littoral drift revealed that the coast line at Visakhapatnam is prone for SW monsoon drift of 0.88 million cum from south to north whereas the drift during NE monsoon would be around 0.18 M cum with its direction from north to south. These estimated rates are in agreement with the dredging requirements of the region.

Visakhapatnam Port Trust (VPT) proposed to develop three new berths in the Northern Arm of the Inner Harbour of the port and proposed to dump the generated dredged sediments at a location within the existing dumping ground. Ministry of Environment and Forests (MOEF) for Environmental approved the proposed development of the new berths and suggested to conduct a radiotracer investigation to evaluate the suitability of the proposed dumping location and movement of dumped sediments and its likely effect on environment.

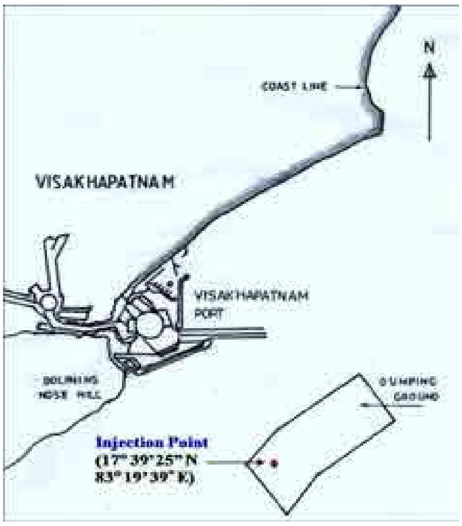


FIG. 47. Schematic diagram of Vishakhapatnam Port and dumping ground.

The location of the dumping ground is shown in Fig. 47. Scandium-46 (weight: 100 gm, activity: 7 Ci (260 GBq)) as glass powder of grain size distribution ranging from 60-100 µm was used as a tracer. Prior to conducting the radiotracer experiment, an extensive background survey was carried out around the proposed injection point using a waterproof scintillation detector (1 inch x 1.5 inch) connected to a scaler/ratemeter and mounted on a sledge. Natural background radiation level in the experimental area was observed to be in the range of 1500-2000 cpm (counts/minute). The position of the detector at any time was fixed by a Differential Global Positioning System (DGPS) available on board. The radiotracer mixed with 2 kg of native sand was injected at the experimental site (17^o 39' 25" N and 83^o 19' 39" E) on January 6, 2010 using a vessel equipped with a crane and derrick facility.

Three post injection trackings over a period of 74 days were carried out using the same sled-detector arraignment as used for background measurements. First post injection tracking was carried out after 2 hours of tracer injection, whereas the second and third trackings were carried out after 33 and 74 days respectively. The boat dragging the sledge-detector was navigated along pre-defined tracks and radiation intensity on seabed was manually noted at an interval of every 50-100 meters corresponding to each latitude and longitude position noted from the DGPS. The tracking on a particular track was continued till the background radiation levels were reached. Tracking was continued till the entire area around injection point was covered. The recorded tracer concentration during each tracking was corrected for natural background level and radiation decay and isocount contours were plotted.

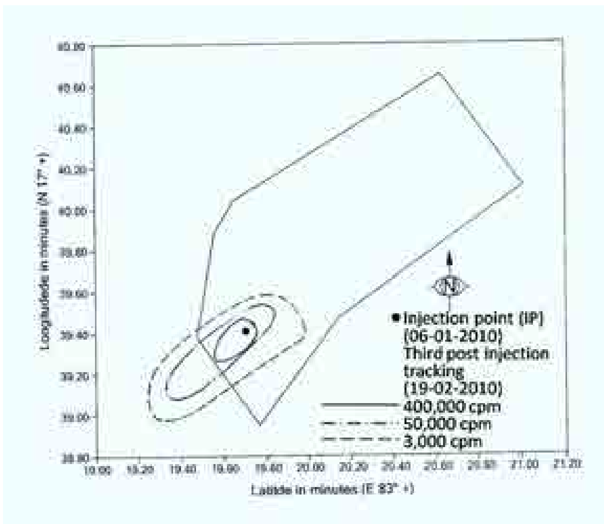


FIG. 48. Isocount contours for first tracking.

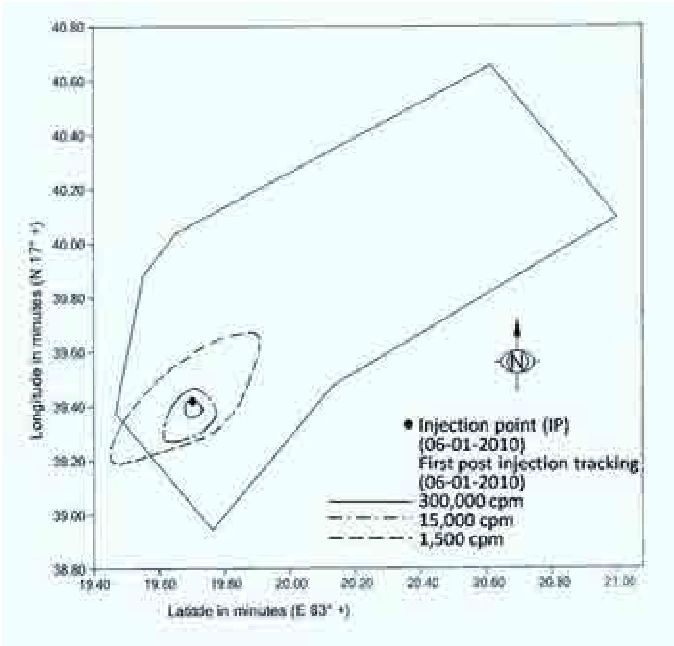


FIG. 49. Isocount contours for second tracking.

The isocount contours of first tracking carried out after two hours of tracer injection are shown in Fig. 48. During the first tracking only about 32% of injected activity was recovered. The low recovery of tracer was due to saturation of detector as most of the activity was concentrated around injection point. The isocount contours of second post injection tracking carried out after 33 days of tracer injection are shown in Fig. 49. During second tracking almost entire injected activity was recovered (99%) thus indicating negligible loss of radiotracer due to burial. The contours indicate that the movement of tracer is towards North-East and South-West directions and the maximum longitudinal spread is about 1800 meters. However, the maximum concentration of tracer was confined around injection point with a predominant movement of about 800 meters towards South-West direction of injection point. The isocount contours of the third post injection tracking carried out after a period of 74 days is shown in Fig. 50.

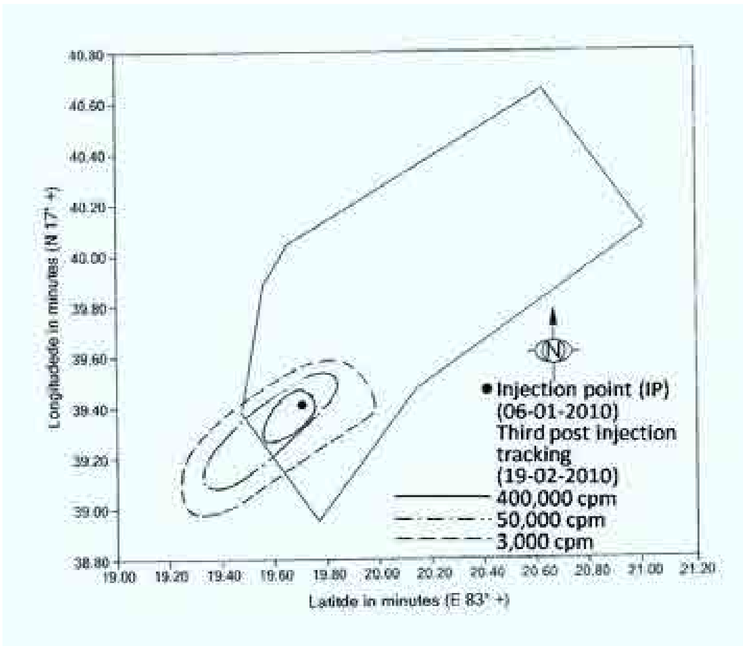


FIG. 50. Isocount contours for third tracking.

During third tracking about 87% activity was recovered indicating burial of radiotracer. Unlike first and second trackings, the third tracking shows that the tracer predominantly moves towards South-West direction only. The tracer moved 300 meters towards North-East and 900 meters towards South-West direction from the injection point. The velocity of transport was found to be the same as in second tracking.

The investigation showed that the general direction of movement of sediment was predominantly towards South-West direction of injection point over a period of 74 days of tracking. The maximum longitudinal distance travelled by tracer was about 1000 meters towards the east and 800 m towards west of the injection point. However, the maximum concentration of tracer was confined between 200 m east to 600 m west of injection point. Similarly maximum transverse movement of tracer was about 340 meters. The average velocity of sediment transport over a period of 74 days was found to be about 4 meters/day.

Based on the investigation, it was concluded that the general direction of movement of sediment was away from the shipping channel and may not find its way into the shipping channel. Therefore, the present dumping site was found suitable for dumping of dredged sediment. The investigation helped the Port authorities to plan their dredging and dumping operation during the expansion plan.

4.1.2.4. Kolkata Port (2012)

Kolkata Port is the oldest, the only riverine and most promising major port in India. Despite being 200 km away from the sea, Kolkata port is the best choice for eastern gateway to India. In order to facilitate shipping, the bars and other locations in the shipping channels are dredged throughout the year to maintain navigable depth. Dumping and disposal of huge quantities of dredged materials to the tune of around 20 million cubic meters per annum has become a problem. The dredged material is dumped at suitable offshore locations selected based on inputs from various studies. The locations are selected in such a way that the turn around time of dredger is kept to a minimum. The previous practice of dumping the material in deep pockets inside the estuary could no longer be continued due to shoaling of all such pockets. Presently the dumping is done at sea-face to allow the dumped material to be taken into the deep bay. Since such dumping is done during flood tide as well as ebb tide some apprehension regarding dredged material returning back to the estuary during flood tide was felt.

The Kolkata Port comprises two major dock systems i.e. Kolkata Dock System (KDS) and Haldia Dock Complex (HDC). Both the Dock Complexes are equipped with all the major and modern facilities and offer good services to its customers. The location map showing the two experimental sites is given in Fig. 51.

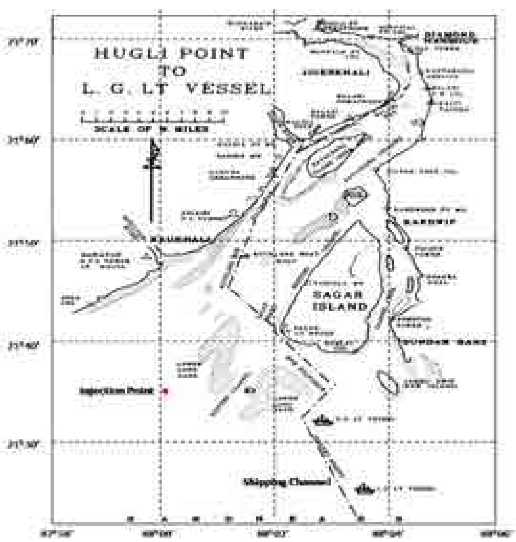


FIG. 51. Study area at Kolkata port.

A radiotracer investigation carried out to study the dynamics of sediments dumped at one of the newly selected locations in Hooghly Estuary near Sagar Island, to evaluate its suitability for dumping of the dredged sediments produced during maintenance dreading. The investigation was carried out using Scandium-46 (8 Ci(300 GBq)) as scandium glass powder having the particle size distribution ranging from 40-100 microns as radiotracer. The tracer was injected onto the seabed at the site using a remotely operated injection system and its movement was tracked using waterproof scintillation detector over a period of 62 days and schedule of each tracking is given in Table 6. The isocount contours and transport diagrams of these investigations are shown in Figs. 52-57.The results of the investigations are given in Table 7.

TABLE 6. SCHEDULE FOR POST INJECTION TRACKINGS

Sr.No.	Tracking no.	Tracking period	Days after injection
1.	Tracer injection	January 9, 2012	---
2.	1st Tracking	January 10, 2012	0.6
3.	2nd Tracking	January 22-24, 2012	13
4.	3rd Tracking	February 13-15, 2012	35
5.	4th Tracking	February 28-29, 2012	50
6.	5th Tracking	March 12-13, 2012	62

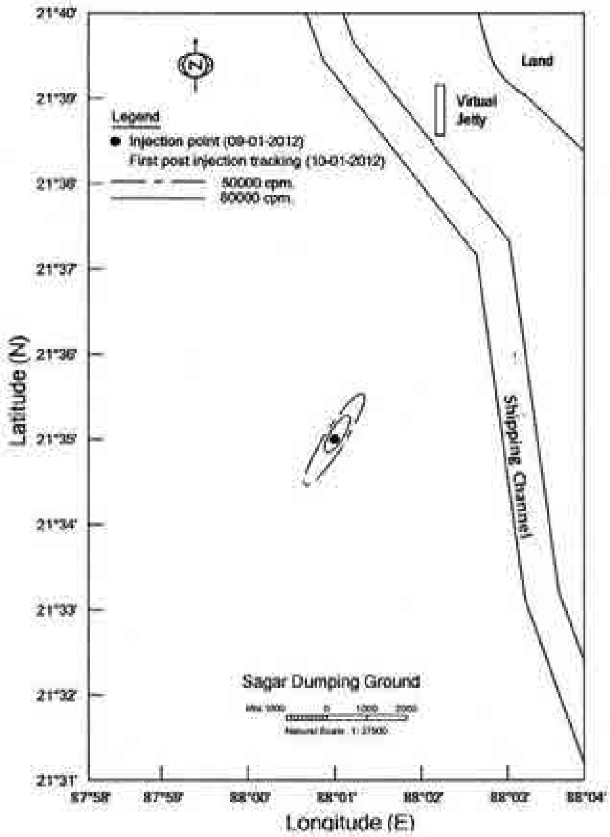


FIG. 52. Isocount contour of 1st tracking.

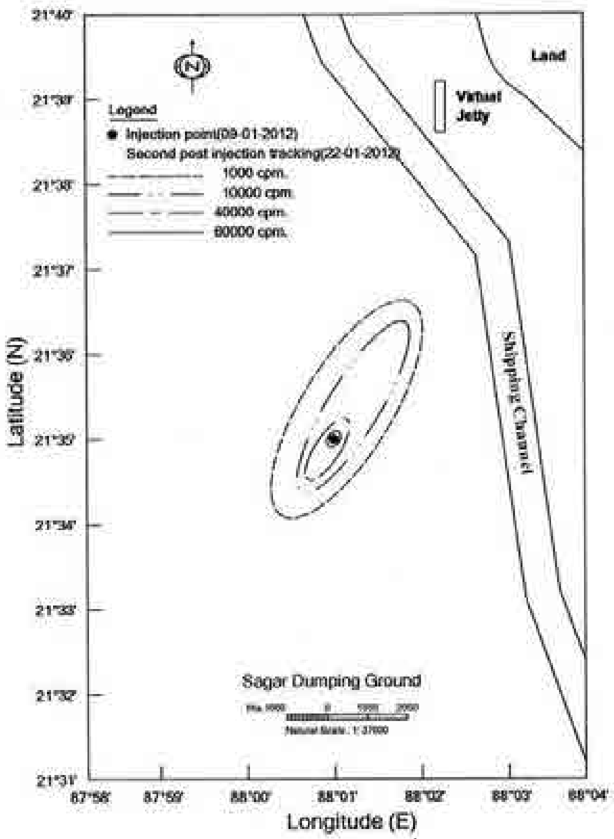


FIG. 53. Isocount contour of 2nd tracking.

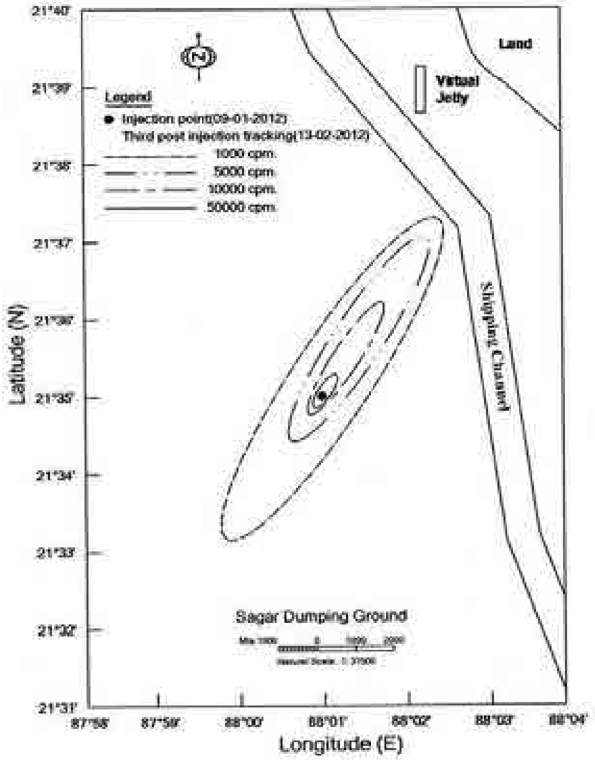


FIG. 54. Isocount contour of 3^{rd} tracking.

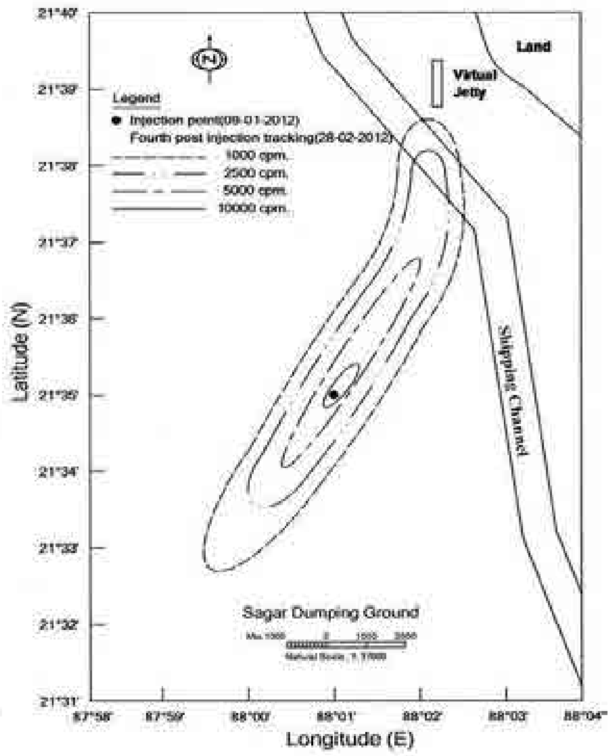


FIG. 55. Isocount contour of 4^{th} tracking.

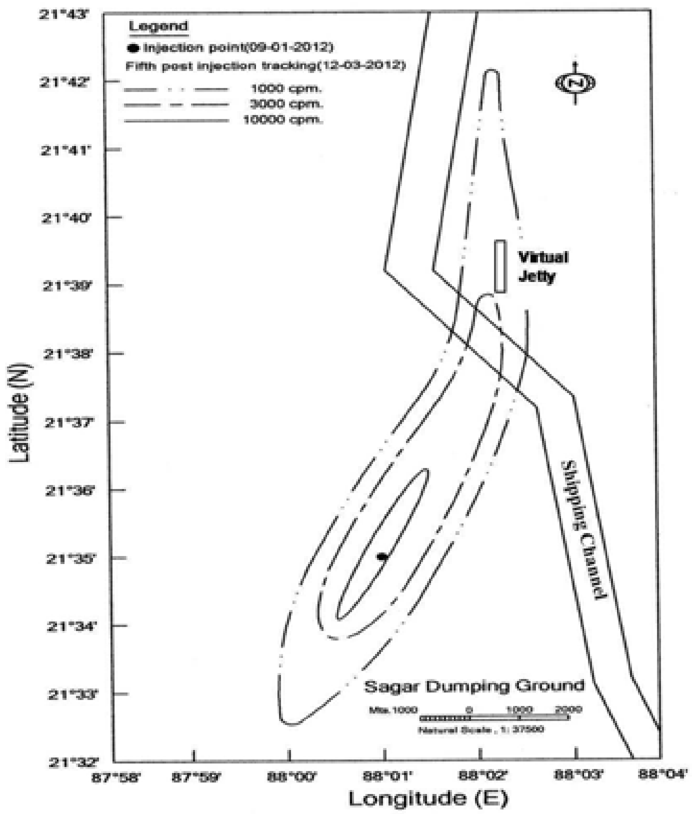


FIG. 56. Isocount contour of fifth post-injection tracking.

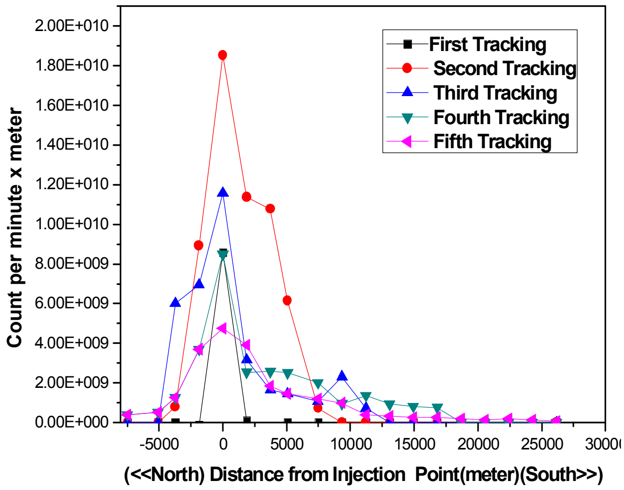


FIG. 57. Transport diagram of post injection trackings.

TABLE 7. RESULTS OF SEDIMENT TRANSPORT INVESTIGATION

Sr. No.	Days after injection	Location of C.G (m)	Activity spread N(cpm.m^2)	% Activity recovered	Vm (m/d)	E (cm)	Q (T/d/m)
1	1	1870	2.05x10^{10}	51.2	--	--	--
2	13	5218	4.4 x 10^{10}	97.5	279	0.3	0.6
3	35	8181	3.78x10^{10}	93.75	135	0.8	1.7
4	50	9028	2.9 x 10^{10}	72.0	56	3.6	3.0
5	62	10160	2.57x10^{10}	64.2	95	4.7	6.7

Based on the results of the radiotracer investigation carried out, following conclusions were drawn about the movement of sediments:

• The sediments predominantly moved towards North-East direction during all the five post injection trackings as compared to the South-West direction.

• The sediments moved into the shipping channel after 50 days of injection of radiotracer and subsequently has tendency to move towards North direction parallel to the channel.

• The sediments dispersed about 13000 meters (13 km) in longitudinal direction and about 4.500 meters (4.5 km) along transverse direction after 62 days.

• The mean velocity of sediment transport, transport thickness and quantity of sediment transported over a period of 62 days from time of injection were found to be 141 meters/day, 2.35 cm and 3 tons/day/meter.

• Based on the radiotracer investigation conducted, it is concluded that the proposed dumping site is not suitable for dumping of the dredged material produced during maintenance dreading during season January-March as the dumped material will its way into the shipping channel.

• Radiotracer investigation was successfully conducted to validate the suitability of the proposed dumping site leading to substantial economic benefit to the port.

4.1.3. Conclusions

India has fairly advanced infrastructure/facilities and good expertise for applications of radiotracer in industry. A large number of radiotracer investigations have been carried out in India mainly for investigating suitability of dumping sites for dredged material and alignment of navigation channels. About 67 large-scale sediment transport investigation have been carried out in different Ports in India on commercial basis. The investigations helped in optimizing the dredging operations leading to huge economical benefits to the Ports. The immediate economic benefits better than 1:150 have been achieved.

4.2. INVESTIGATION OF SEDIMENT TRANSPORT MECHANISMS IN THE DURRES GULF – ALBANIA USING RADIOTRACERS

4.2.1. Introduction

Radiotracers were applied to study the sediment transport in the gulf of Durres (Albania) in the framework of the maintenance of existing Durres harbor. Figure 58 shows the map of Albania where the gulf of Durres is located, as well as the Durres harbor view seen from the sandy beach in the middle of the gulf.

FIG. 58. Gulf of Durres.

4.2.2. Oceanometric and meteorological data of Gulf of Durres.

The port of Durres is located in the north side of the Durres gulf. The gulf of Durres is open to maritime actions from the south.

4.2.2.1. Tide

Mean amplitude of tide is of 0.4 m. Under the action of wind coming from south the variation of water level arrives 0.9 m.

4.2.2.2. Currents

All current measurements (with current meters as well as with flotation sticks) performed during good weather (wind velocity less than 10 m/s) indicated that the currents are weak, with velocity less than 0.10 cm/s. There is an irregular vertical profile of current velocities. Stronger winds are generating surface water currents which also generate short waves with high amplitudes that could affect the sediments on shallow waters.

4.2.2.3. Wind

The wind is coming mostly from west and south; from statistics it results that winds of south sector are stronger and more frequent, thus it is supposed that the south sector wind should have greater influence in the sediment transport of gulf of Durres

4.2.2.4. Waves

The waves were measured by the hydrometeorology station near the Durres port. The high amplitude wave (> 1.5 m) is considered as storm. The storm is defined for a wind superior to 15 m/s that corresponds to a frequency of 20, 4 ± 6.4 days per year for waves coming from south sector.

4.2.2.5. Sediment characteristics

There were analyzed hundred of samples taken from the sea bottom. The sediment of sea bottom consists of a mixing of fine sands with mean size of 70 µm (60-70%) with 30-40% of silt of sizes less than 40 µm (mean size 2-3 µm). This mixage of very fine sand with silt creates cohesive sediment on sea bottom. There is not any significative difference between the sediments of gulf and sediments of the access channel that is normal because the channel does not exist any more (is silted up). The samples from the south of Gulf have shown that the proportion of sand in the mixture is only 20%.

4.2.2.6. Conclusion of conventional hydrometeorology measurements in the gulf of Durres

Based on the conventional measurement and analysis of natural factors in the gulf of Durres, the engineers have already concluded that:

- Sea water currents circulating in normal weather conditions are very weak, they can not move the compact sediment from the bottom surface, thus the normal currents have not influence in sediment transport,
- Strong waves, mostly coming from south, but from west as well, are capable to move the sediments from the bottom surface and transport it further in their direction.
- There is a south –north transport orientation (resultant) of sediments in the gulf of Durres under the action of strong waves.

Based on hydrometeorological data registered in the gulf of Durres is not possible to calculate theoretically the sediment transport. It could be assumed only that the sediment transport is probable developed in suspension or by saltation of cohesive sediment that could be carried under the action of high amplitude waves coming from south sector, that means that the resultant of sediment transport in the gulf of Durres is from South to North, apparently in the direction of the harbor.

4.2.3. Data about the silting process of the access channel

The bathymetric data of several measurements taken during many years, showed that:
- silting up of the access channel is higher at the entry of the port in comparison to the part of the channel in open sea.
- silting up process of the channel was not proportional in time; the high silting process happened at the beginning just after the dredging due to the collapse of sides and due to the favorable settling conditions.
- the channel (4 km long) does not exist any more in the time of study.

4.2.4. Conclusion of conventional sediment transport study

-The gulf of Durres appears as an autonomous sedimentary zone.
- The normal water current can not generate a bed load transport of sea bottom sediments, because of their weakness, and because of the cohesive nature of sediments.
- High amplitude waves coming from south with amplitude over 1.5 m are capable of carrying up the sediments in suspension. These sediments are transported in suspension by currents generated from high amplitude waves in the direction of waves.
- The silting up of the access channel with 1.5 x 10^6 m^3 happened in less than 10 years, and the silting up is not proportional in time and space.

4.2.5. The objectives of radiotracer study

The radiotracer study had the following objectives:

- to clarify the mechanism and to obtain quantitative results regarding the sediment transport in the gulf of Durres.
- to find the sediment transport direction and quantity in the vicinity of the access channel of Durres port,
- to determine the sediment quantity deposed every year in the channel.

These results will serve port engineers to maintain normal operation of the access channel saving time and money for reducing dredging.

4.2.6. Selection and preparation of radiotracer

The main goal was to study the transport of the sand on the sea bottom on gulf of Durres. The radiotracer selected was Ir-192, which has a half life of 74 days. Iridium was incorporated in an activatable glass with density of 2.65 g/cm^3. The characteristics of this radioisotope make it an ideal tracer for sand sediment transport study lasting several months. Because the sand characteristics of the sediments on the sea bottom surface were almost the same, for practical reason the tracer was selected from 40 to 100 μm. Figure 59 presents the granulometry of the glass particles imitating the natural sand.

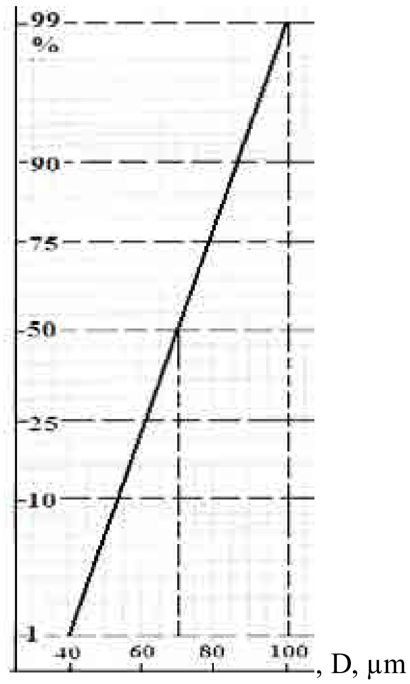


FIG. 59. Granulometric curve of radiotracers injected.

4.2.7. Injection of radiotracers

There were selected four injection places; all of them were around the access channel, in order to cover all potential movements of sediment to/from channel. Immersion of tracer was intentionally done in 2 m above the surface and non in a spot, in order to spread the tracer cloud and facilitate the detection. A small spot injection provides for tracer balance deficit because of detector saturation (crossing the very concentrated tracer) or because of missing the high tracer concentration that is localized in only few square meters difficult to cross in open sea.

Figure 60 shows the radiotracer injection points and supposed resultant direction of sediment transport (from conventional measurements).

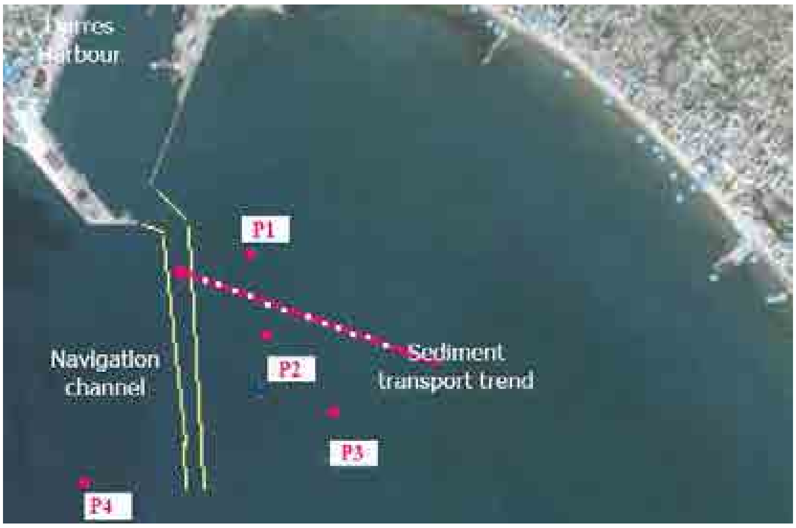


FIG. 60. Four locations around the channel where the radiotracers were released for study.

Points P1, P2 and P3 serve to quantify the sediment transport rate from centre golf to access channel, because according to all hydrometeorological data the main sediment movement direction is from south-east to north-west. Point P4 located at the other side of the end of channel was used to investigate the dredging material movement.

The activity of each injection was 1 Ci and the mass 0.25 kg glass. The glass tracer had 5.8 x 10^8 grains of 70 µm and each grain had an activity of 1.7 x 10^3 µCi. From laboratory calibration is known that a specific activity of 1 µCi/m^2 gives 50 cps in the detection system used for field test. This means that the zones that will have a count rate of 50 cps will have in average 580 grains of 70 µm in 1m^2. In the field the radiotracer cloud disperses and normally the isocount map is limited to 2 times the background. The background of sediments on the sea bottom surface in gulf of Durres is 20-25 cps; thus the limit of 50 cps is reasonably index of the boundary of the radiotracer dispersion. The zones with 50 cps represent statistically significant number of radioactive grains that represent the particle dynamics.

4.2.8. Online radiometric mapping of the sea bottom

The gamma measurements were performed in dynamic that means from moving boat with average speed of 1.5 m/s, according to profiles perpendicular to coastal line. The detection probe (NaI (Tl) scintillator 2"x2") was mounted in a special support, which kept constant distance probe-sea bottom of 5 cm. Figure 61 presents the detection probe and the boat used for tracking radiotracer.

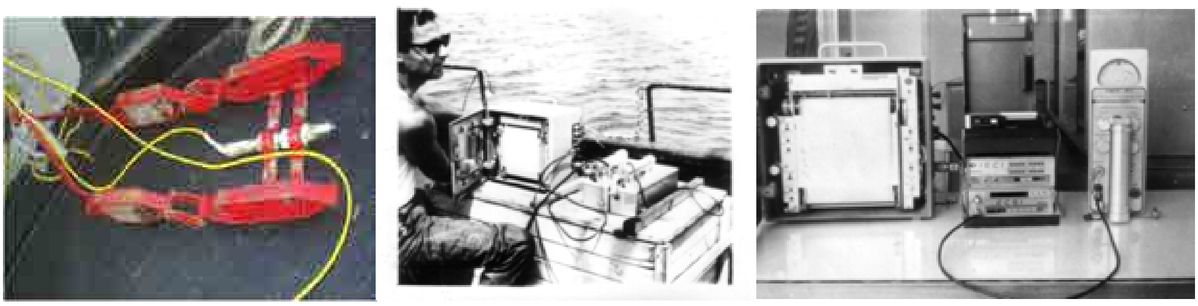


FIG. 61. Tracking and detecting the radiotracer.

Each profile had a length of several kilometers. It was proved that for rather homogeneous zones the count rate obtained in dynamic is the same with that in static. Taking into account the boat speed of 1.5 m/s and the measuring interval of 10 seconds, it results that each measured value represents around 15 m length. Radiometric profiles (250 m from each other) were performed in the map scale of 1: 25000, with a position error of 1 mm (equivalent of 25 m in the field) that is acceptable.

4.2.9. Chronology of radiotracer experiments

The radiotracers were released at early October and the measurements were performed till end of February. The same day (or the next day) of radiotracer release, the detection zero was performed, which was considered time zero (t= 0). The chronology of radiotracer experiments is given in the table below; days are after respective injections.

TABLE 9. POST-INJECTION TRACKINGS

Injection point (water depth)	Activity (Ci)	Detection 1 (days)	Detection 2 (days)	Detection 3 (days)	Detection 4 (days)	Detection 5 (days)
P1 (-7m)	1.17	6	13	52	92	120
P2 (-8.5 m)	1.21	5	13	41	71	115
P3 (-8.5 m)	1.07	4	11	50	117	
P4 (- 10m)	0.92	12	39	83	90	

During the winter (October – February) eight storms have happened, with wave amplitude of 1.5 m - 2.5 m.

4.2.10. Data treatment

There were performed enough detections to extract the required information. There have been found qualitative and quantitative results. Figure 62 show the radiotracer clouds for injection point P1 developed with time under the action of hydrometerological agents.

4.2.10.1. Qualitative results

Orientation of sediment displacement.
The axe of tracer distribution is towards NW direction that means the resultant of hydrometerological action is towards the access channel and port structure.

4.2.10.2. Quantitative results

Radioactivity balance.
Knowing the immerged activity A (μCi) in each point, the calibration coefficient f_0 (cps for $\mu Ci/m^2$) and calculating the measured radioactivity N (cps x m^2) supposed on the surface, it is possible to calculate the recovered activity.

$$A_{rec}\,(\%) = (N \times 100) / (A \times f_0)$$

The activities found at the detection zero are almost the same (100%) of the injected activity. The activities found at the first detection have shown that:

- P1: 55-60 % of activity was disappeared,
- P2: 50% of activity was disappeared,
- P3: 35% of activity was disappeared.

Observing the hydrometeorolocial conditions during the detections zero and first, it was found that a storm (wave higher than 1.5 m amplitude) has happened during this period. This storm has carried sediment in suspension and moved them away. The higher effect of the storm was found in point P1 which is shallower than other points. After first detection, the other detections showed that the radiotracer activity is almost constant (with light decreasing with time). It seems that the fine sand particles are not removed in suspension because are already trapped by cohesive sediment of sea bottom surface.

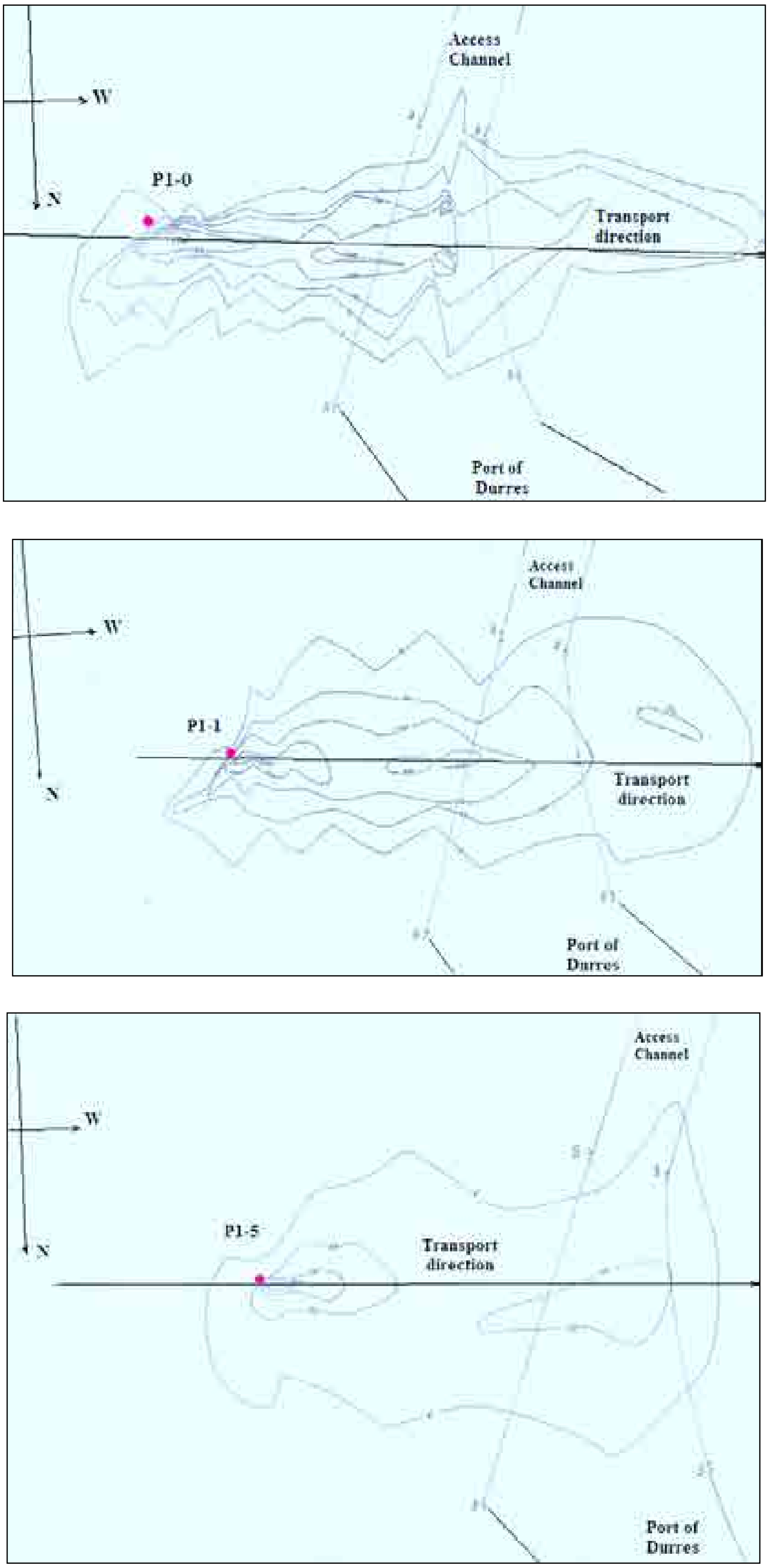


FIG. 62. Radiotracer cloud (isocount rates) distributions for point P1.

Diagrams of radioactivity transport are shown in Fig. 63. These diagrams of radioactivity indicate that there is a decreasing of their surfaces (that means loss of radioactivity) but not much evolution of their forms. In addition, the positions of gravity centers are almost not displaced from one detection to another. This fact indicates that there is not bed load transport in the gulf of Durres. This conclusion is very clear in point P1. Similar transport diagrams are obtained for other injection points. These transport diagrams suggest that there is a limited movement by saltation that means, sand particles are lifted and shortly settle again.

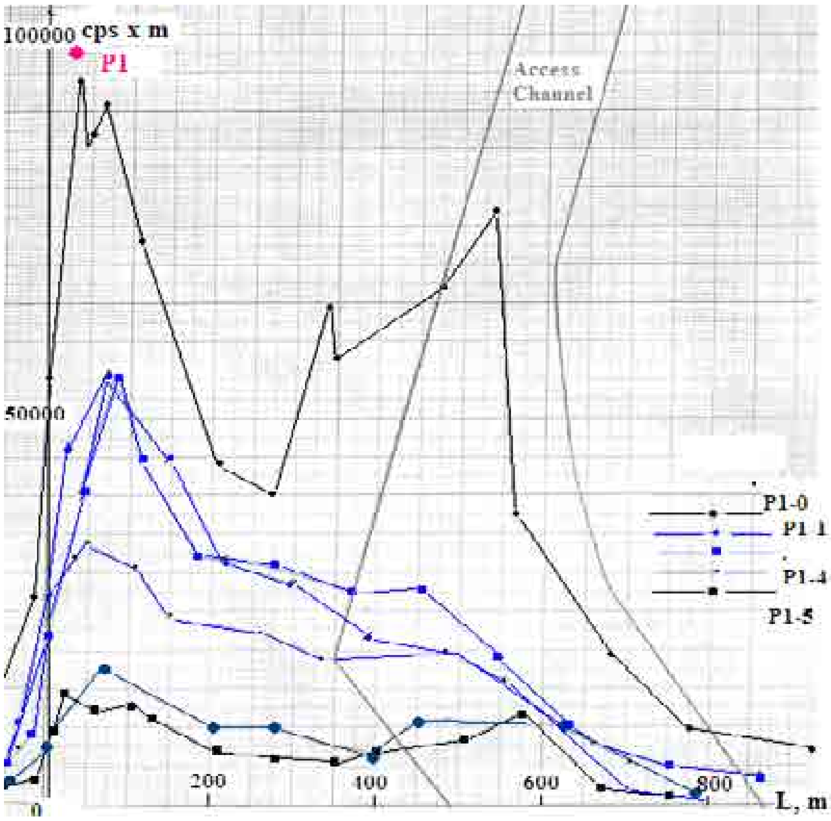


FIG. 63. Transport diagrams for P1.

Some partial conclusions deducted from the observation of isocounts contours distribution and transport diagram comparison are as follows:

- Waves of amplitudes less than 1.8 m can not remove the sediment in suspension and transport it further. These waves are dispersing the sediment through saltations, this is because the material is cohesive.
- The waves of amplitudes of 1.8 – 2.4 m remove in suspension the fine sand particles. The fine sand particles less than 70 µm are carried in suspension from depths 7-8.5 m under the action of wave's 2-2.4 m amplitude.
- The sand particles 70-100 µm are less sensitive to wave action once they are settled in cohesive sediment of surface.

4.2.10.3. Dispersion of the radioactivity

It is observed that during second, third, fourth and fifth detections, the radioactivity was disappeared without any evident bed load transport. The assumptions to explain the tracer disappearance could be the followings:

- during injection at 2 m above the bottom surface, a part of tracer in suspension was carried out and displaced away with currents,
- burying; the tracer (sand) was buried in the sediments of sea bottom mixing up with them under the actions of strong waves; in fact burying is characteristic of bedload transport that is not so evident and typical in this zone,
- get covered from other sediment deposit.

All these three mechanisms are acting in different proportions. The maximal thickness of tracer burying or tracer covering could be estimated in the following way.

a. Burying hypothesis
The assumption is that there is bedload transport only; this is an extreme hypothetical case. The thickness of bottom surface layer where tracer has been penetrated mixing up with sediments can be calculated from the count rate balance method, solving the transcendental equation:

$$(1/\beta).(\alpha/f_0).(N/A).E = 1-e^{-\alpha E}$$

To finding solution to this transcendental equation the graphical method was used. For a graphical solution, one method is to set each side of a single variable transcendental equation equal to a dependent variable (for example, y) and plot the two graphs, using their intersecting points to find solutions.

The main assumption was that the radiotracer undergoes burying after first detection only. This assumption is justified because between the detection zero and the first detection a storm (wave of 1.7 m, on 17 October) was generated, which has carried away and displaced parts of radiotracers injected in points P1, P2 and P3. Radiotracer injected in the P4 was not affected apparently from this storm because of the higher water depth.

The radiotracer balance between the first and last detections was calculated as follows:

P1: 78% of radiotracer underwent burying, which is the ratio of the activity found at the last detection (31% of injected activity) to the activity found at the first detection (40% of injected activity).
P2: 50% of radiotracer underwent burying, which is the ratio of the activity found at the last detection (25% of injected activity) to the activity found at the first detection (50% of injected activity).
P3: 38% of radiotracer underwent burying, which is the ratio of the activity found at the last detection (35% of injected activity) to the activity found at the first detection (65% of injected activity).

P4: 50% of radiotracer underwent burying, which is the ratio of the activity found at the last detection (50% of injected activity) to the activity found at the first detection (100% of injected activity).

The graphical solution of the count rate balance equation gave the following burying (mixing) layers: P1: 10 cm, P2: 11 cm, P3: 12 cm, P4: 11 cm.

Conclusion: Assuming only the bedload transport of sediments that causes the mixing up of radiotracer sand with sediments of bottom surface under the storm wave action, the burying thickness (or mixing layer, or sediment transport layer) was estimated around 10-12 cm. This is very rough and maximal estimation of sediment transport layer taking in consideration the bedload transport only, which in fact is not the pure case in this zone.

b. Hypothesis of covering

According to the count rate balance estimations for points P1 and P2, is seems that the total activities recovered after the second detection follow the exponential decrease (Fig. 64). Assuming that the decrease of the radiotracer activities is coming from the sediment deposit on top of radiotracer cloud (that is not moving any more) than the thickness x of the deposit (covering) layer is calculated by exponential absorption low:

$$f = f_0 \exp(-\alpha x), \text{ where } \alpha = 0.160 \text{ cm}^{-1}.$$

Figure 64 presents the graphic (in semilogaritmic scale) of the percentage of the activities recovered in different trackings in P1 and P2.

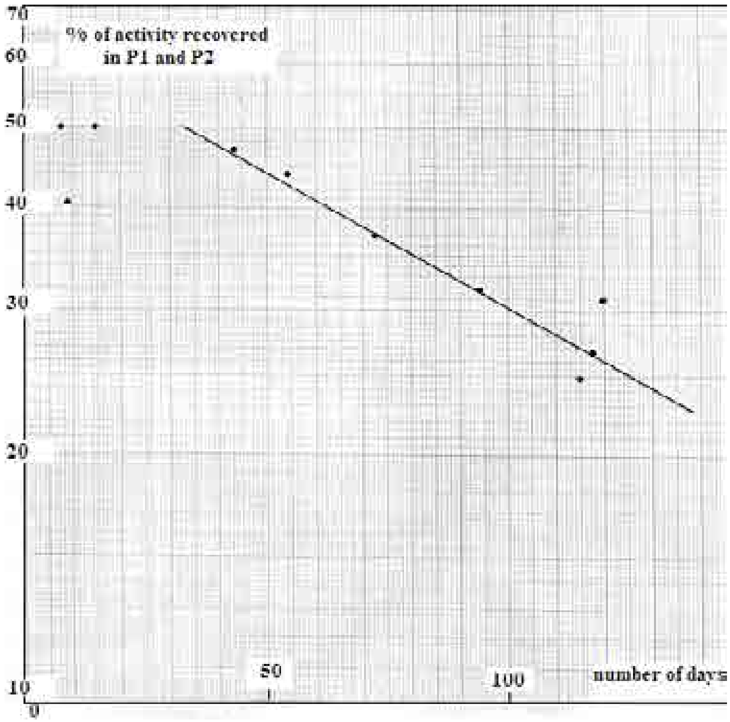


FIG. 64. Percentage of the activities recovered in different trackings in P1 and P2.

Figure 64 shows that the recovered activity became half in 70 days. This means that the deposit thickness x = (log2)/ 0.160 = 4.3 cm. During these 70 days, there were registered 3 storms (with wave amplitudes higher than 1.5 m), on 18 November, 17 December and 15 January.

Note: There is a difference between the burying (or mixing) layer of tracer (found 10-12 cm) and covering layer of tracer (found 4.3 cm). Burying or mixing layer indicates the bottom depth till where the surface sediments are affected by the action of high amplitude waves (storm), while the covering layer is related with quantity of sediments that are deposited during good weather as the results of storms.

4.2.11. Conclusion

The sediments of the sea bottom in the gulf of Durres are cohesive; there is not any evident sediment transport along or cross littoral during the normal hydrometeorological conditions. The storm waves (with amplitude higher than 1.5 m, with frequency of 24 days a year) affect the sediments of the bottom surface in a layer of nearly 10 -12 cm. Sediments of this layer are sensitive against storm waves and generated currents; storm waves shake and lift sediment in suspension, and currents generated by these waves transport them away. The sediments transported mostly in suspension during storm weather are settled and deposited on the bottom during the normal weather.

4.2.12. Interpretation of results

- The normal sea currents are weak in the gulf of Durres; they are not able to cause bed load transport of sands, even they cannot carry up cohesive surface sediments in suspension.
- Sediment transport is generated under the influence of stormy waves (waves with amplitude higher than 1.5 m). Only the storm coming from south sector can create problems for the port and its access channel. The hydrometerological records showed that the storm is caused by wind with velocity higher than 15 m/s, and there are 20.4 ± 6.4 storm days a year from south sector.
- Each storm causes a deposit layer of nearly 4.3/3 cm in the zone of access channel; extrapolated for the dredged access channel (where deposited sediment is trapped and not moved again) it is estimated a silting annual rate of nearly 30 cm.

Taking account these data, the rough estimation of silting volume per year of the access channel is:

$$V = 4000 \text{ m} \times 100 \text{ m} \times 0.3 \text{ m} = 120\,000 \text{ m}^3.$$

In fact, experimental results obtained in P1&P2 (characterizing the 2/3 of channel length) has indicated that the sediment dynamic is more intensive than in point P4 (representing 1/3 of channel length). The silting rate is more intensive in the first part of the access channel near the harbor, while its 1/3 part towards the open sea is silted less.

The total silting of the access channel (dredged till – 11 m) was estimated of 1500000 m^3 in 10 years. The radiotracer experiment provided more or less similar data. The difference between the radiotracer data and bathymetric records of dredging could come from the additional bank sliding effect of non appropriate bank slopes.

The dredging material can be discharged in the NW part of the port of Durres (near the point P4, after -10 m water depth); there is very small risk that the dredged material will return to the access channel.

Because the sediment transport occurs mostly in suspension (or saltation), there is not any appropriate protection structure of solution against the silting process taking place in the access channel zone. Thus, the dredging process should continue for maintaining the access channel once fully opened; in fact, compared to other similar situations worldwide the silting rate of this channel is not exceptional but rather an acceptable and affordable rate.

4.3. SEDIMENT TRANSPORT STUDY AT HAEUNDAE BEACH – REPUBLIC OF KOREA USING ^{192}Ir GLASS

4.3.1. Introduction

Haeundae beach is one of the most famous resorts in Korea and plays an important role as a special tourism district. However, the length and width of the beach are being reduced continuously (Fig. 65), which would have bad influence on the regional economy and be the financial burden to the local authority considering that a large amount of budget is spent in the beach nourishment annually. Hence, it was necessary to understand the dynamic behavior of sediments in the coast for the systematic preservation plan of coastal environment. Lately a monitoring system using radioactive isotope as tracers was considered as a novel technique in understanding the dynamic transport of sediments. The objective of this study was to investigate the possible variations in sedimentary distribution and quantify the characteristics of sediments using radiotracer.

FIG. 65. Haeundae beach before (left) and after (right) erosion.

4.3.2. Preparation of radiotracer

Sand was imitated with iridium glass, which was prepared according to the prescription of Table 10.

TABLE 10. COMPOSITION OF IRIDIUM GLASS

Chemical form	Wt (%)	Chemicals	Weight
SiO_2	48%	SiO_2	50.5g
Al_2O_3	19%	Al_2O_3	20.0g
CaO	17%	CaO_3	32.0g
MgO	6%	MgO	6.3g
TiO_2	5%	TiO_2	5.3g
Ir	0.3%	$(NH_4)_2IrCl_6$	0.66g

With an effort to delineate the behavior of field sediments, the preliminary sieving test was performed on the sediments in the seabed. The radiotracer should have identical physico-chemical properties and hydro dynamic behavior as of natural sediment. The radiotracer labeled with ^{192}Ir in the form of 0.3wt% iridium glass having the same specific gravity (2.6 g/cm^3) and particle size distribution (D_{50}= 0.25 mm) similar to that of natural sediment was prepared. 60 g iridium glass with 500 mCi each was injected in two places.

4.3.3. Experiment

The experiments of radiotracer were performed at two areas. One is near Dongbaek Island (IP.A) and the other is near Mipo port (IP.B). The experimental areas are shown below in Fig.66.

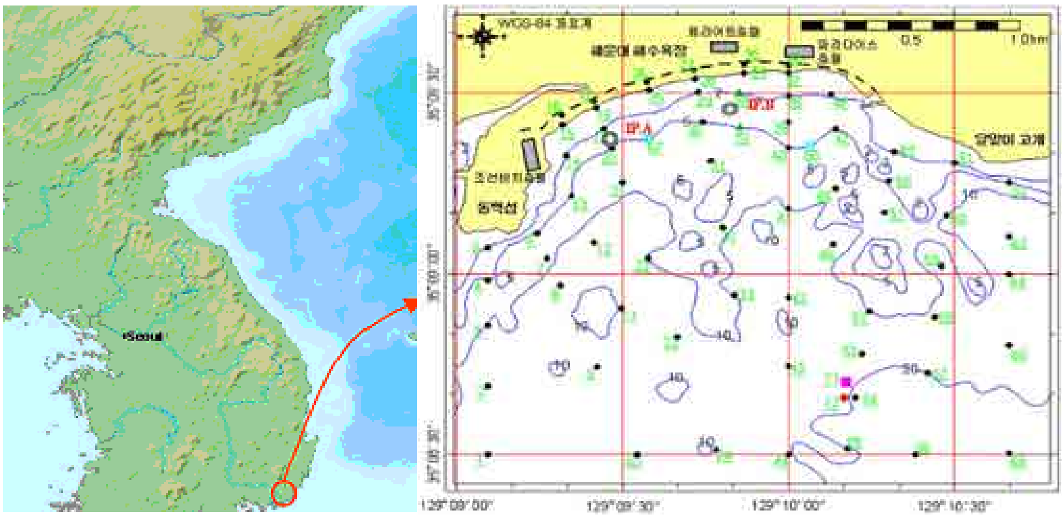


FIG. 66. Map showing study areas and the location of injection points; A and B.

A radioisotope container was specially designed to inject the radiotracer from 1m above the seabed without radioactive contamination during the conveyance from the nuclear reactor at KAERI. The position data from a DGPS and the radiation measurement data were collected concurrently and stored by means of the application software programmed with the LabVIEW of the National Instrument.

The time dependency of the spatial distribution of the sediment was studied in the area through the tracking measurements after the iridium glass was injected. After subtraction of natural radiation counts from the results, decay correction was performed.

4.3.4. Result and discussions

The radiotracer experiments were carried out during period May-August 2005. The distribution patterns of radiotracer presented in the form of isocount contour maps of the 1st and 3rd scans are shown below in Figs. 67 and 68 respectively. On the site IP.A, the initial behavior of radiotracer migration did not show any remarkable direction. However, the main direction showed a tendency of moving northeastwardly after the 2nd scan. The initial migration direction on the site IP.B was to the east and west, and then changed to the north predominantly that was towards the seashore. These directions confirm the know fact that seabed sediments move onshore in summer whereas moves offshore in winter.

The tracer transport diagrams (counts multiplied by transport distance) are presented in Figs. 69&70. The center of the gravity was calculated by equation:

$$\bar{x} = \frac{\int c \cdot x\, dx}{\int c\, dx}$$

Where, $\bar{x}$ is the center of gravity, c is the measured count and x is the dispersive length of lateral spread (grid space of 20 m).

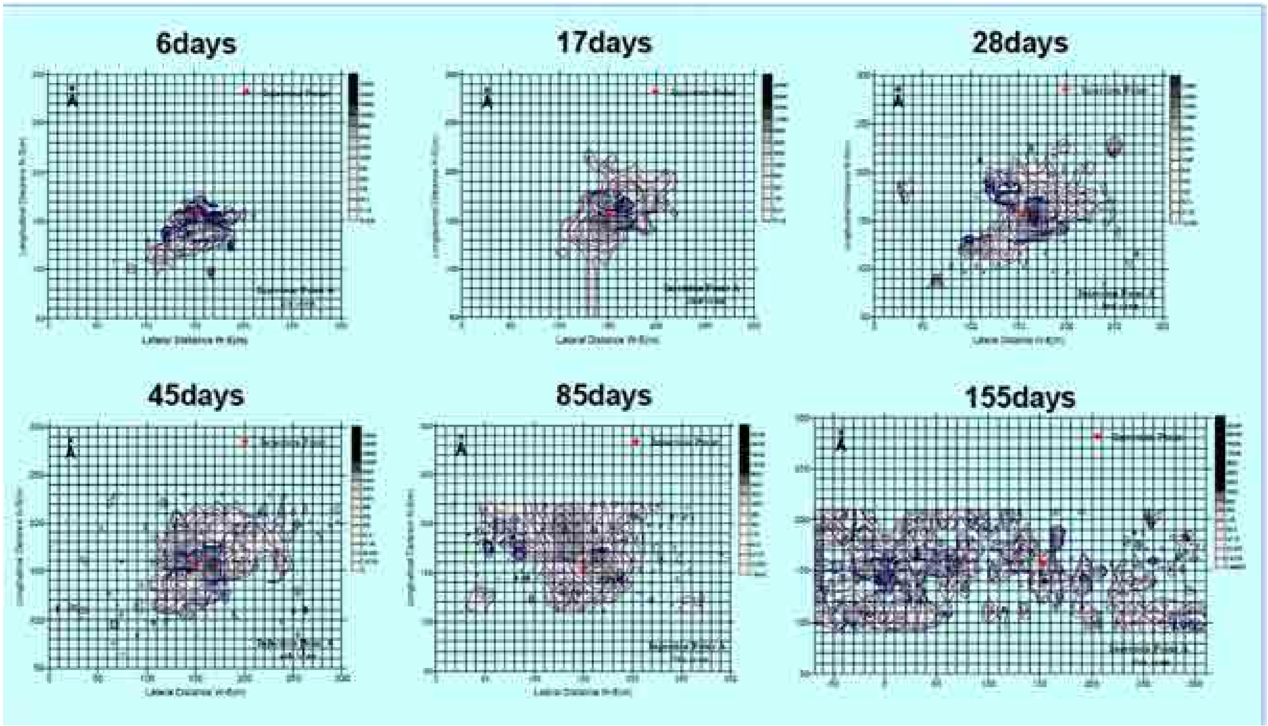


FIG. 67. Isocount contour map in IP.A.

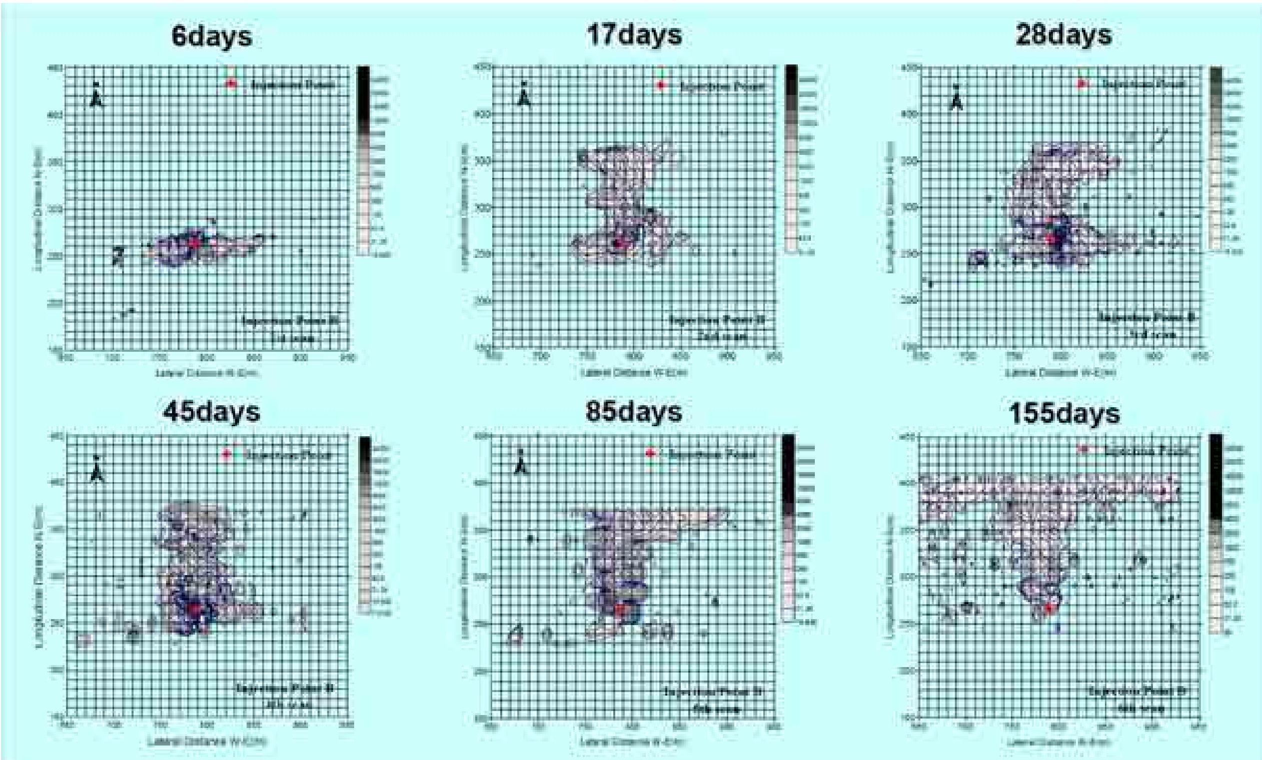


FIG. 68. Isocount contour map in IP.B.

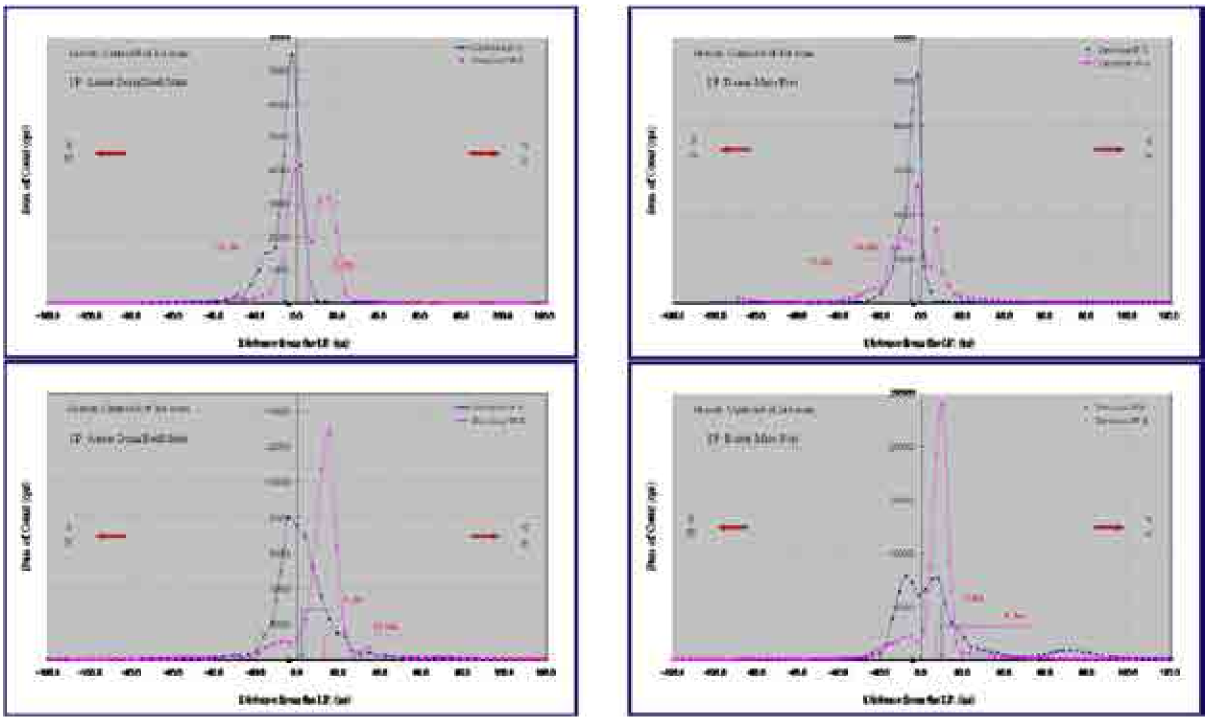


FIG. 69. Transport diagram of radiotracer in 3rd scan(IP.A and IP.B).

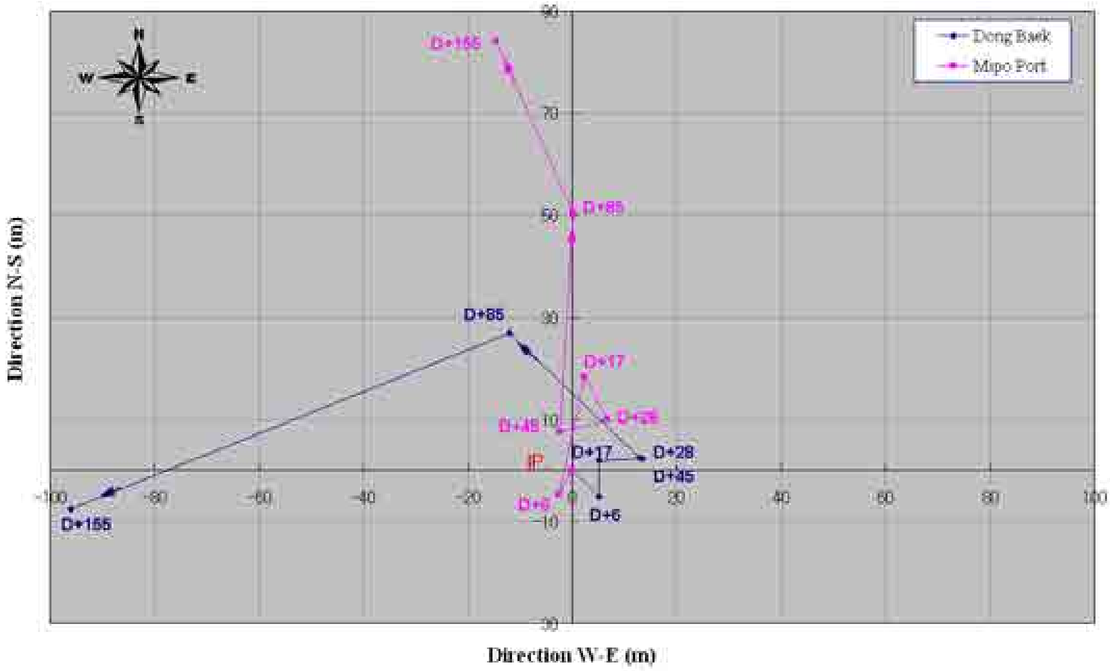


FIG. 70. Migration of the centroid of tracer.

Sediment transport is mainly influenced by wind, wave and current (weather condition). Tracer moved to the Northward towards the beach in counterclockwise direction. From the results of transport diagrams, the directional mean transport distances and velocities of tracer are extracted and listed in Table 11.

TABLE 11. THE MEAN TRANSPORT DISTANCE AND VELOCITY OF TRACER

Tracking No.	Elapsed days	IP. A				IP. B			
		Distance(m)		Velocity(m/d)		Distance(m)		Velocity(m/d)	
		W-E	S-N	W-E	S-N	W-E	S-N	W-E	S-N
1st	D+6	5.1	-5.3	0.9	-0.9	-2.5	-4.8	-0.4	-0.8
2nd	D+17	5.1	1.9	0.3	0.1	2.3	18.2	0.1	1.1
3rd	D+28	13.5	2.3	0.5	0.1	6.7	9.8	0.2	0.4
4th	D+45	12.9	2.4	0.3	0.1	-2.3	7.4	-0.1	0.2
5th	D+85	-12.1	26.9	-0.1	0.3	0.2	50.5	0.0	0.6

Regarding the IP.A, it was found that the initial transport velocity of tracer was relatively fast as 0.9 m/d in W-E and -0.9 m/d in S-N direction compared to the others results. Radiotracer in IP.B moved relatively fast at the beginning with a velocity of -0.4m/d in W-E and -0.8m/d in N-S. However the transport velocities of tracer were decreased gradually after the 1st tracking. This phenomenon was resulted from the fact that tracer particles with small grain size move far away preferentially at the beginning of the experiment and dispersed away below the detection limit eventually. Later on, the transport velocity of residual tracers with large particle size decreased with time, which resulted in the reduced velocity of the gravity center of tracer.

In the 5th tracking, the mean transport distance of IP.A displaced 25 m further to the west compared to that of 4th tracking, and 24.5 m to the north. The mean transport distance of IP.B moves 2.5 m further to the east and 43.1 m to the north markedly. The main hydrodynamic parameters influencing on the sediment transport were wind, wave and current.

From this point of view, the exceptional transport distances in the 5th tracking were considered to be derived from a couple of storms that have passed in between. The sedimentary distribution pattern of tracer is varied continuously with time. Therefore, it should be examined over the subsequent seasons by additional experiments.

4.3.5. Conclusion

After the injection of radiotracer, five trackings were performed for 85 days. The main patterns of distribution of tracer near Dongbaek Island and Mipo port were identical to each other at the beginning. After, under the influence of storms the characteristics of distribution patterns were changed continuously with time. Therefore, additional investigations using radiotracers have to be carried out to follow sediment transport for long periods and quantify actions of individual hydrometeorological factors.

4.4. RADIOTRACER INVESTIGATION OF THE EFFECT OF EXTRACTION OF THE SEABED AGGREGATES ON LITORAL SEDIMENT DYNAMICS (FRANCE)

4.4.1. Problem

Due to the enormous need for construction materials (sands and gravels) and because most terrestrial sand and gravel pits have become exhausted, the exploitation of sea bottom has been investigated. The coast of the Moors in France was investigated using radiotracer sand.

4.4.2. Studies

Injections of 250 grams crushed glass, simulating the granulometric distribution of natural sands, whose each grain contained a low radioactivity (about 3.700 Bq) of ^{192}Ir were carried out at various depths between -5 m and -15 m. Radioactivity detections were performed periodically using detectors dragged on sea bottom, for six months. At the same time, throughout all study, the hydrometeorological parameters were measured.

4.4.3. Results

Two data types emerge from these studies:

- The first, qualitative, described the sedimentary movements observed. It confirms the deductions of the sedimentologists essentially. The action of the swell causes a transfer of materials in direction of the sea. Under the action of waves the sands are moving towards the sea during the storms or brought back towards the beaches when the waves lost part of their energy (after storms). For this reason in summer the beaches find a fraction of materials lost in winter. The balance is generally negative: there is erosion of the coast. The littoral transit from north to south along this coast (between the beach and the zone of surge) occurs in periods of good weather, when the waves have low amplitude.

- The second, quantitative, shows the true contribution of the radiotracer and the method of the assessment of the counting rates.

Volumes of transported sediments are presented in the table below:

TABLE 12. RESULTS MEASURED WITH TRACERS AFTER A VERY STRONG STORM

Depth in m	-15	-12	-8	-6	-5
Thickness E in cm	1	1 to 2	5 to 10	15	15
Volume in m^3/m	1	2	Approx. 5	35	250

The differences between the quantities measured by the tracers and those which are calculated by the theoretical equations are very important as shows it the following table.

TABLE 13. VOLUMES OF TRANSPORTED SEDIMENTS: COMPARISON BETWEEN CALCULATED AND MEASURED VALUES FOR ONE WINTER

Depth in m	-7	-8	-10	-15	-20	-22
Einstein, in m^3/m	180	150	65	20	10	5
Meyer Peter, in m^3/m	380	100	38	13	5.5	4.5
Tracers, in m^3/m	700	300	90	14	2.5	1.5

With an extreme prudence it is possible to generalize (on the Atlantic littoral) the results of these studies; the volume of transported sediments V (m^3/m) is related with wave characteristics with the following empirical relation:

$$V\ (m^3/m) = f(d)\ \Sigma H^2 Tt$$

Where:

- H amplitude of the waves in m

- T period of the wave in sec
- t duration of the storm in sec

The coefficient: f(d) is different for different seabed depths:
- at the -8 m: f(d) $=2x10^{-7}$
- at the -10 m f(d) = $2x10^{-8}$
- at the -15 m f(d) = $7,5x10^{-9}$

The radiotracer results showed that it is necessary to go beyond -25 m to take sands without causing a material deficit on the beaches. While approaching the beach (trying to reduce the cost of dredging), the risk that extracting sand will cause a loss of sands from the beaches towards the deep sea, and thus a destabilization and erosion of the coast, is large.

These results are specific for this site, and they are not valuable a priori for other sites, in particular in such a different seas as the Mediterranean, the English Channel or the North Sea.

4.5. APPLICATION OF TRACER TECHNIQUES IN STUDIES OF SEDIMENT TRANSPORT IN VIETNAM

4.5.1. Introduction

Vietnam suffers greatly from sedimentation. Though a large amount of money is spent annually on dredging, 10.000 draught weight vessels can not enter or leave the ports. For these vessels or heavier ones a part of their cargo must be transferred at the open sea before they can enter the port. Efforts have been made by both national and foreign organizations to understand the sedimentation processes in estuarine areas under hydrometeorological conditions, but information given by mathematical models was not good enough, especially in the case of lack of a reliable database that would result from a systematic hydraulic and sedimentary survey. In order to obtain reliable data on the dynamic of sediment transport and to verify the modeling approach in the areas with such a complicated hydraulic conditions, the radiotracer techniques have been developed and employed since 1991. The qualitative and quantitative information on suspended sediment movement and bedload transport in Haiphong harbor area under the effect of northeast monsoon and southeast monsoon was obtained by using Sc-46 and Ir-192 labelled glasses as radioactive tracers. The influence of dredging materials on sedimentation rate in Haiphong access channel at two dumping sites was estimated by radioactive tracer technique.

Using the case of the Haiphong port, this work describes technical aspects in the use of tracer techniques to study sediment transport, both suspension and bedload, in the coastal and estuarine environment. Some results are then briefly presented.

4.5.2. Study of bed load transport

In sediment transport studies using tracer technology, sedimentation dynamics can be investigated by observing the movement of tracer materials. Therefore, the tracer material should behave in the same way with respect to hydrodynamic effects as natural sediments when both are exposed to the same sedimentary or hydraulic transport conditions. Scandium and Iridium-labeled glasses have been used as tracers in the studies of bed load transport. For easier interpretation of the measurement data, the granulometric distribution of the tracer was selected so that it could lay in the range of 30% either side of the median mass of the natural sediment. In tracer experiments carried out at Haiphong area, the selected size fraction in average is from 10 μm to 100 μm with the median mass (D_{50}) of 30 μm.

The mass and activity of the tracer were calculated relying on the equation put forward by Sauzay and Courtois, and on data of hydrodynamics in the region of interest. Generally, for the Haiphong harbor area, an amount of at least 80g tracer, which contains about 2.5×10^8 particles with grain-size distribution the same as natural sediment, with the activity of 2 Ci is required by most of bedload transport studies.

After irradiation, quartz ampoules containing radioactive tracer were put in injection devices with 5 cm thickness of lead. The injectors then were placed into the transport container with 10 cm thickness of lead.

By rotating a stainless steel disk mounted in the injector, quartz ampoules were pressed and broken. This operation took place on the boat deck while the injection device was in the transport container. To release the tracer material onto the sea bed, the injection device was winched off the transport container, immersed in water and then the bottom of the injector was opened pneumatically at the distance of 1 m above sea bed. The detection was carried out by dragging a sledge mounted the detector NaI(Tl) 2” x 2”. The boat was positioned by Global Positioning System 5000 DX. The detection frequency is about once a week.

The bed load discharge q across a section perpendicular to the resultant transport direction of sediments was estimated by the following equation:

$$q = \rho \, L \, V_m \, E_m,$$

where
q is given in t/d,
ρ is the specific gravity of sediment in situ,
L is the transport width,
V_m is the mean transport velocity,
E_m is the transport thickness.

The parameters to be determined are V_m and E_m. The mean velocity V_m of the bedload transport was determined by the ratio of the distance between centroids of the spatial tracer distributions to the time interval between the detections.

The mean transport thickness E_m was estimated in two ways: the direct technique was to take cores and subsequent counting of the slices obtained. The second method, employed by the Dalat Tracer Group was to use the ratio of the photoelectric peak to the Compton region in the gamma spectrum recorded in the field. The transport layer could then be determined after a previous calibration at laboratory.

4.5.3. Tracer investigation of silting process in the access channel of the Haiphong Harbor

Located 100 km east of Hanoi, on the coast and with a number of nearby navigable estuaries and waterways, Haiphong is a major port and important industrial harbor in the northern part of the country (Fig. 71). The Red River, flowing in the south of Haiphong, discharges a large amount of alluvium into the sea in the form of red mud (about 200 million tons a year). Under the influence of the south-east monsoon prevailing in summer and autumn, the river-transported red mud continues moving along the coast towards the Haiphong area. The port authority and Vietnam Maritime Safety Agency (VMS) wanted to know reliable information on sedimentary processes in the region in order to make a decision either they should continue maintaining the navigation channel or construct a new one.

FIG. 71. Haiphong Harbour.

A number of engineering schemes were proposed to reduce the sedimentation rate along the access channel. Hydraulic and sedimentary surveys carried out in the past by different groups of researchers resulted in quite contradictory conclusions about the pathway of the sediment being deposited along the channel.

In order to verify the accuracy of data given by mathematical models and to estimate the bedload discharge in a navigation channel section where the sedimentation was thought to be the most serious, some investigations using Sc-46 glass were carried out on both sides of the channel between buoys number 10 and 12.

The first experiment:
- period: 17 December 1992 – 7 March 1993
- activity: about 4 Ci of Sc-46 were injected at point DT1, 800m far from the buoy 10

The second experiment:
- period 10 October 1993 – 30 December 1993
- activity: nearly 4 Ci Sc-46 was released at point DT2, 900 m distant from buoy 10

These two experiments were under the influence of the northeast monsoon. In order to study the bedload transport under the effect of southeast monsoon prevailing from April to August another tracer experiment was performed.

The third experiment:
- period: 29 May 1995 – 5 July 1995.
- activity: nearly 4 Ci of Sc-46 glass was injected at point DT3.

The results of three experiments (bedload transport rate and resultant transport direction) are presented in the Table 14.

TABLE 14. MAIN RESULTS OBTAINED WITH BOTTOM SEDIMENT TRANSPORT STUDIES

Injection points	Time interval considered	Bedload transport rate (kg.m^{-1}.d^{-1})	Azimuth of sediment transport axis	Angle between the sediment transport axis and the alignment of the channel
DT1, Winter	19/12/1992 to 07/03/1993	459	350^o	45^o
DT2, Winter	10/10/1993 to 21/11/1993	380	340^o	35^o
DT3, Summer	23/05/1995 to 05/07/1995	276	330^o	25^o
A1, Winter	20/11/1996 to 20/01/1997	173	345^o	40^o
A2, Winter	26/11/1996 to 20/01/1997	238	357^o	52^o
B1, Winter	29/11/1996 to 20/01/1997	204	335^o	30^o
B2, Winter	01/12/1996 to 20/01/1997	272	40^o	95^o

The results proved that the bedload discharge varies from site to site and depends on monsoon season. However, the movement direction of bed material is of a little bit of difference.

4.6. RADIOTRACER STUDY OF BEDLOAD TRANSPORT AT THE PORT OF SONGKHLA, THAILAND (MODIFIED AFTER NIELSON ET AL, 2001)

4.6.1. Background

Radiotracers may be used to validate models of bed load transport with a range of applications in coastal engineering including: optimisation of the alignment of dredging channels and the location of dredge spoil grounds; the development of ports and harbours and the fate and behaviour of contaminants associated with particulates.

The Port of Songkhla lies at the entrance to Songkhla Lake, a brackish tidal lake covering 1040 km^2. Sedimentation of the dredged shipping channel at the Port of Songkhla in the Gulf of Thailand, poses a significant economic problem affecting Thai shipping.

Large tidal flows pass through the 380 m wide channel to the Gulf of Thailand but long-shore transport supplies sand which is deposited in the channel. Engineering structures such as breakwaters and jetties result in severe coastal erosion problems along the coastline, but in contrast the beach south of the port experiences rapid accretion.

To assist in addressing this problem a numerical model of the port entrance was developed and validated using radiotracer studies of actual sand transport in the area under an IAEA/RCA funded project involving Australia and Thailand. The principal aim of the investigation was to validate the model prediction of the bedload transport in the vicinity of the Port of Songkhla using tracer techniques so the model could be used to evaluate engineering options for port redesign.

4.6.2. Location and timing

The design of a successful tracer study required careful consideration of where to place the tracer, when to place the tracer and what tracer material would best be used. The analytical studies (*i.e.*, the hydrodynamic wave and tidal current modelling) were crucial in developing a successful tracer study design.

Given that the main current forcing was tidal, the current was reversing over much of the domain. In these parts of the domain, the tracer study was unlikely to be effective. This was because the net sediment transport, as determined by the movement of the tracer material, would be the result of a relatively tiny difference between the two very much larger reversing gross transport components. Therefore, the chances of achieving a good agreement between the tracer movement and the analytical assessment would be very low.

The two-dimensional tidal hydrodynamic model (RMA-2) was used to model flow patterns around the port entrance and used to select radiotracer injection sites (Fig. 66). This predicted that, on the ebb tide, current separation occurred on both sides of the inlet (Fig. 66). This induced an inlet-directed current close to shore that had a similar direction to that on the flood tide. Therefore, there were locations where the gross and net sediment transport was likely to be much the same. For this reason, Sites 1 & 2 (Fig. 72) were chosen as injection sites for the tracer study.

The sediment transport model indicated clearly the enhancement of transport occurring under wave action. A 12-month period of Waverider Buoy records indicated that the best time to undertake the field tracer study was from early November to the end of March. This was during the period of the northeast monsoon when *significant* wave heights commonly reached 1.5 to 2.0 m with periods of around 6 s. At other times, the wave climate was benign, with wave heights rarely exceeding 1 m and with wave periods generally less than 4 s. The tracer study commenced on 25 November and was completed on 7 January, a period of 6 weeks.

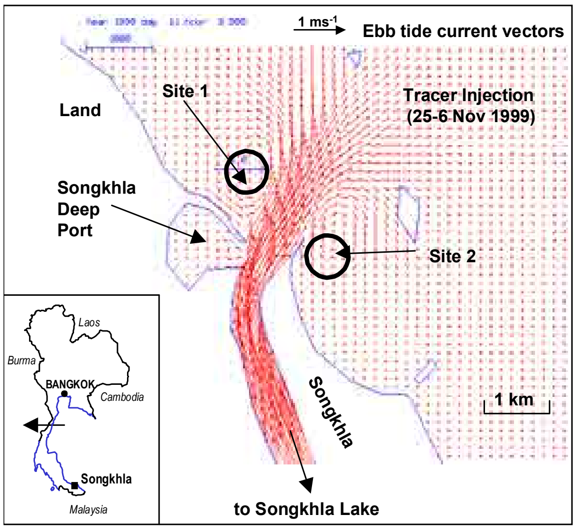


FIG. 72. Superimposed on the ebb tide current vectors in the vicinity of the Port of Songkhla are the locations of the two tracer injections made on 25 November 1999.

4.6.3. Tracer characteristics

To validate sediment transport modelling using tracer material, the tracer must have similar hydrodynamic properties to that of the native sediment. The physical property most relevant to the transport of sand-sized particles is the fall velocity; that is, the speed at which the particles fall through the water under gravitational force alone (see van Rijn, 1989).

The fall velocity of the native material was established from samples taken from the two injection sites shown in Fig.72. The mean grain size of the sediment off Samila Beach (near Site 1) was about 170 microns whereas off the northern breakwater (Site 2) the mean grain size was coarser at about 300 microns. Further, however, it was noted that the grading of sediment at Site 2 portrayed a bimodality, indicating a mix of two separate sediments. It was found that the coarser fraction of this sediment comprised a large fraction of carbonate material; that is, coarse shell, which explained the grading characteristics observed.

The grading of the tracer material used at each site was designed to match the native sediments based on their fall velocities. This was done through the testing of a range of fractions of the glass tracer material and matching the fall velocity characteristics of each of the sand samples based on the fall velocity grading obtained from the settling tube. Each designed mix was then tested in the settling tube and the results compared with the sand sample results. A good match was established in each case and the so-designed glass sediment mixes were submitted to ANSTO for the preparation of the tracer experiment.

The radioisotope tracer used was ^{192}Ir labelled synthetic sand made from a manufactured glass containing 0.03% iridium (Vance et al., 1997).

4.6.4. Radiotracer experiment

Tracer injections at Sites 1 & 2 were conducted in approximately 3 m of water. Bottom sediments at Site 1 were unconsolidated muddy sands with high background radioactivity levels averaging 103 counts per second, which was fourfold greater than that expected for clean sands. This radioactivity is hypothesised to have been caused by elevated thorium levels commonly associated with tin mining, which has been carried out in the Songkhla Lake catchment. Lower background radioactivity levels averaging 43 counts per second were found at the sandier Site 2. In both cases, these levels were significantly higher than would normally be expected. The radioisotope tracer injection at each site involved the transfer of two vials containing ^{192}Ir labelled sand to a steel bottle breaking apparatus. The vial was then broken in the water at an elevation of approximately 1 m above the seabed.
Tracer surveys were conducted on four occasions including the injection dates. A sled mounted scintillation detector was dragged along the bed on a 30 m cable behind the survey vessel. Radioactivity data was obtained using a Minekin digital ratemeter logged and monitored at 1 s intervals. Position-fixing of the survey vessel was by differential GPS. The sled location was then estimated using simple trigonometry.

Over the 6 weeks following the tracer injections, the activity surveys (Fig. 73) detected little movement of the centre of activity at each site. At Site 1, the centroid of the tracer translated 76 m along the bearing 333°. At Site 2, the centroid of the tracer translated 5 m along the bearing 168°. The translation of the centroid of the tracer (X) can be converted to the mass of sediment transport (Q) based on the depth of movement (D) and the in-situ dry density of the material (γ_d) as follows: $Q = X{\cdot}D{\cdot}\gamma_d$.

The stratigraphy of cores taken on the seabed indicated clearly that, at each site, the depth of movement was 0.19 m. For an in-situ dry density of 1,550 kg/m^3, over the period of the tracer study the mass rate of sediment transport is given in Table 15.

TABLE 15. ^{192}IR SEDIMENT TRACER CHARACTERISTICS, TRACER STUDY AND MODELLING RESULTS

Site	Total mass of tracer	Total activity	Injection date	Transport (kg/m)		Bearing	
				Model	Tracer	Model	Tracer
1	150 g	10.75 GBq	25 11/1999	16,560	22,400	321°	333°
2	180 g	12.68 GBq	26/11/1999	4,337	1,470	162°	168°

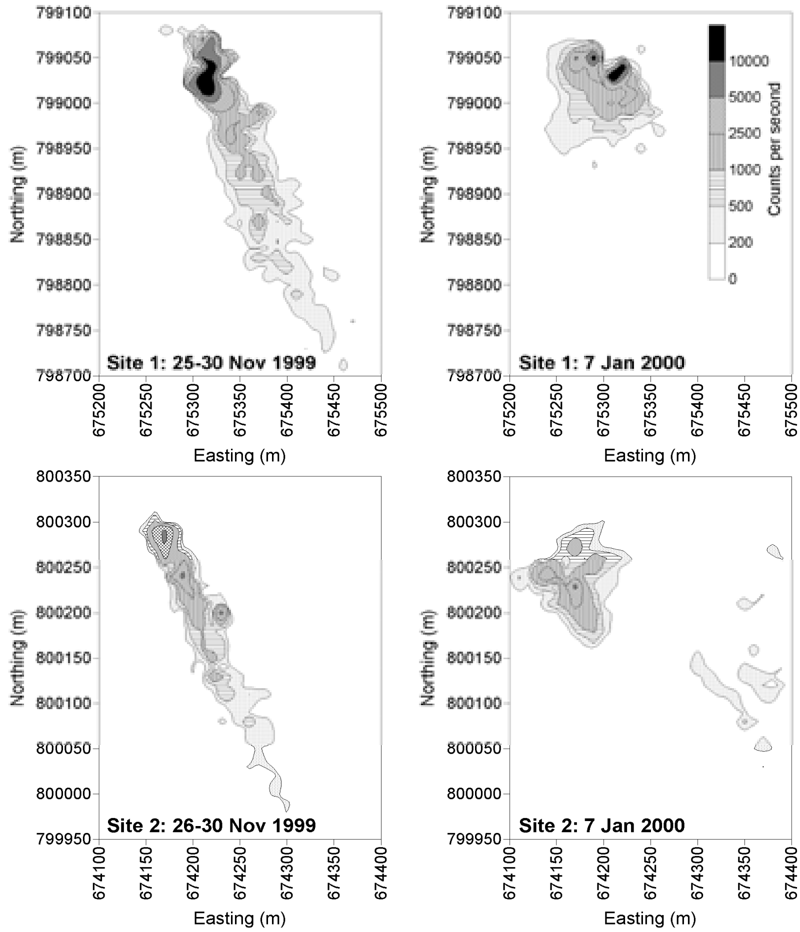


FIG. 73. Decay and background corrected tracer distribution immediately following injection and six weeks later (from Nielsen et al, 2001).

4.6.5. Modelling

A finite element numerical hydrodynamic model describing the tidal discharge characteristics of the Songkhla estuary, with particular attention to the inlet, was developed using RMA2 and based on detailed hydrographic survey data. The model comprised some 3323 nodes and 1531 elements. Although the tidal range was only in the order of a few decimetres, the tidal currents that it generated at the inlet were considerable. Tidal speeds peaked in excess of 1 m/s because the inlet serviced a very large estuary that had the potential to generate a significant tidal prism. The model was tuned for several variables against measured tidal stage and discharge data and the model was verified adequately against two independent sets of tidal discharge data.

For the period covering the tracer surveys, the tidal currents at the tracer injection sites were generated using the RMA hydrodynamic model with the time series of recorded tidal stage variation. The waves at the tracer injection sites were generated using the time series of recorded wind speeds and directions. Using these generated time series of currents and waves, a time series of sediment transport was computed for each site. Model results showed that during periods of higher wave activity, the rates of transport increase by several orders of magnitude.

The time series of computed sediment transport rates were integrated to provide gross and nett sediment transport data. For each site the nett transport is given in Table X.

4.6.6. Outcome and conclusions

The validated sediment transport model was used by the Thai Harbour Department to evaluate breakwater placement. The original breakwater was only on the southern side of the port which allowed northward migrating sands to deposit in the channel as the ebb tide flows were dissipated and failed to flush the channel. The model was used to evaluate the effect of constructing a parallel breakwater on the northern side of the channel to reduce sedimentation and predicted that sand transport rates on the ebb tide would be an order of magnitude greater with the additional breakwater. This breakwater has now been constructed.

5. CASE STUDIES: RADIOTRACER APPLICATIONS FOR INVESTIGATION OF SUSPENDED SEDIMENT TRANSPORT

5.1. SEPETIBA HARBOUR DREDGING STUDIES USING ^{198}Au - BRAZIL

Sepetiba Bay is situated in the southeastern region of Brazil, at 100 km west from Rio de Janeiro, with approximate dimensions of 25 km (E-W) and 12.5 km (N-S). It is well protected from wave action from open sea by a barrier beach with about 40 km in a E-W direction, ending in Marambaia Hill (Fig. 74).

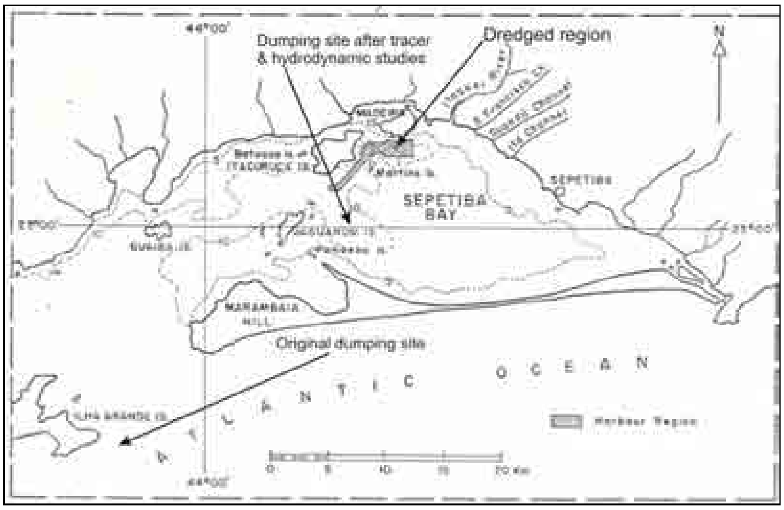


FIG. 74. Sepetiba Bay, Brazil, with new dredged region and the dumping sites.

The main entrance is located in its western side through passageways and channels between the mainland and several islands. In terms of water circulation the shallow eastern entrance is unimportant. Local tides are semi-diurnal, with maximum spring tidal range of 1.5 m.

Sea waves generated by local winds do not exceed 0.8 m, having short periods (2 to 3 s). Maximum wind velocities amount to 10 m/s and occur in the winter months when it blows from southerly directions. In general, mean wind velocities ranges from 3 to 5 m/s. There is no stratification in the water column inside the bay and the tide is the main hydrodynamic agent governing the weak currents (< 0.5 m/s) occurring inside the bay, which have a predominant W-E direction in the flood tide phase, and E-W during the ebb tide. Silt is the dominant material on the bottom of Sepetiba Bay.

An iron-ore and coal terminal was built in the 70's in Sepetiba Bay and it was necessary to dredge $10x10^6$ m^3 of fine material for the establishment of an approach channel, turning basin and dock site (dredged region – Fig. 74). For the dredging works, trailing suction hopper dredgers (TSHD) with carrying capacity of 4000 m^3 were employed. The Navy Authority determined that the dumping site should be situated outside Sepetiba Bay, at E of Ilha Grande (Fig. 74). For dumping at that place it was necessary around 5 hours for a round trip of the dredge, only to transport the dredged material, not taking into account the dredging time.

In order to save time & money in the dredging operations, it was clear the interest of studying a dumping site nearer the dredged region. In this way, hydrodynamic measurements and water circulations studies were performed inside the bay, followed by five experiments labeling the full load of a trailing suction hopper dredger (TSHD) with ^{198}Au performed by the Centre for the Development of Nuclear Technology (CDTN) from Belo Horizonte, Brazil.

Activities between 1 to 3 Ci (37 to 111 GBq) were employed in the moment of the injection, and the mass of thin foils of gold irradiated was 3 g for each injection. In order not to lose tracer during the filling of the well of the dredger, the dredging stopped before the start of the overflow.

The studies were performed in June/July 1977 (Fig. 75) and the dumping covered distinct situations of currents: spring and neap tide; ebb and flood phase and slack water; dredge anchored or in movement during the dumping. The depths in the studied area varied between 11 and 13 m. The radioactive clouds formed after the dumping were followed through Lagrangian detections of the material in suspension, employing two boats with scintillation detectors placed at 2m and 8m depth. For all the injections, very little material was detected in suspension. Due to the weak currents of the studied area and the vertical descendent momentum of the denser mixture of dredged material inside the well of the dredger (even without the overflow dredging), in relation to the density of the receiving water, most of the material reached the bottom in the dumping region. After the suspended sediment detections, bottom sediment detections were performed up to 6 days after the injections in each place.

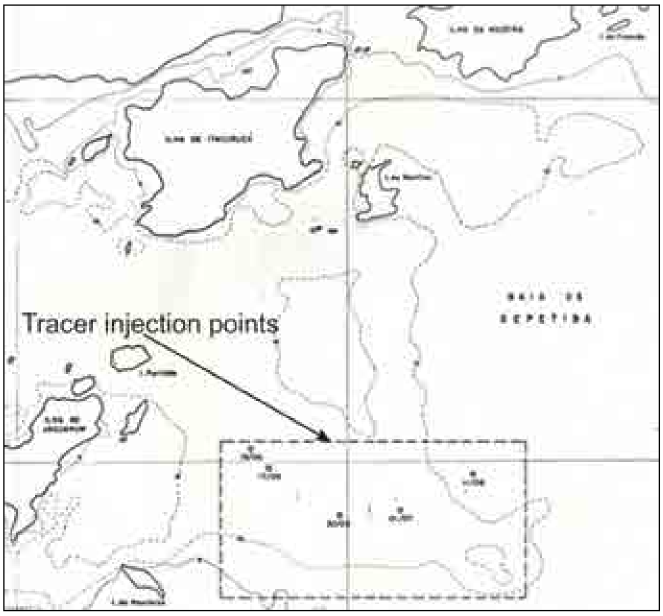


FIG. 75. Sepetiba Bay, Brazil, Tracer injection points in the dumping studied area.

The main results of this series of studies were:

- Soon after the dumping the fine material reached the bottom because very little material was detected in suspension;
- Between 80% and 100% of the dumped material were found in the bottom of the dumping area just after the dumping, and the tide conditions and the state of movement of the dredge during the dumping did not influence these values; only the deposition form is influenced: more concentrated if the dredge was anchored and the tide was near slack water;
- Around 60% to 70% of the dumped material stayed in the bottom of the dumped area (also constituted of fine material – Fig. 69) taking into account detections performed up to 6 days after the dumping (limited by the half-life of ^{198}Au);
- Probably part of the dumped material, weakly consolidated, re-entered in suspension, but as there were not transversal currents (N-S) between the dredged and the dumping area (10 km to the S of the former) it was unlikely that this material reached the harbor area;
- As studies with longer half-life tracer than ^{198}Au were not performed to survey the long term behavior of the dredged material dumped in the bottom, it was recommended to follow the bottom depths evolution due to the dumping of the dredged silt, with bathymetric surveys.

Based on the results of the hydrodynamic studies and tracer experiments the Navy Authority allowed the changing of the dumping area from outside Sepetiba Bay to the studied area. Taking into account that the capital dredging was $10x10^6$ m^3 and the capacity of the TSHD's employed were 4000 m^3, at least 2500 dredging cycles were necessary to complete the work. As the shortening in a round trip of the dredge was about 40 km, a total distance of 100,000 km (2.5 times the circle of the earth in the equator region) was saved. This implied that the dredging works finished 6 months ahead of the scheduled time, with an economy of millions of US$.

5.2. PAMPULHA RESERVOIR DREDGING STUDIES USING ^{99m}Tc - BRAZIL

The main motivation of the study was to decide weather to dredge the fine sediment that accretes (400000 m^3/year) the Pampulha reservoir, in Belo Horizonte, Brazil, which is in an accelerated process of decrease of its liquid volume and water surface (Fig. 76). With this tendency, the reservoir could lose, in a near future, two of the main purposes for which it was built: flood damping and leisure region, with its water surface indubitably attached to the Niemeyer buildings, forming the Architectonic Complex which is the landmark of the modern Brazilian Architecture.

1964 2001

FIG. 76. Pampulha Reservoir Accretion, Belo Horizonte, Brazil.

There is no available area inland to dump the dredged material from the reservoir. The watercourses downstream the dam are the natural way for the sediment that accretes the reservoir if the dam were not constructed.

In this way, field experiments, with simultaneous and instantaneous injections of sediment and water, labelled, respectively, with ^{99m}Tc and Rhodamine WT, were performed, in dry season, in 2000 and 2001, to measure the hydrotransport capability downstream the dam, in a stretch of 25 km. A recent mathematical model was applied and calibrated to the data obtained and, through convolution, the sediment dumping in suspension using hydraulic dredging system was simulated, calculating also, the physical environmental impacts: increase of sediment concentration and the possibility of deposition. Through the measurement of physical-chemical parameters of the water, the possibility of desorption of the metals adsorbed in the sediment to be dredged, was evaluated.

It was concluded that there is no impediment for the dumping of the dredged fine sediment in the watercourses downstream.

5.3. ORINOCO RIVER SUSPENDED SEDIMENT STUDIES USING ^{99m}Tc - VENEZUELA

In April 2006, under the IAEA TC project VEN/8/019: "Management of Sediments throughout the Navigation Channel of the Orinoco River" radiotracer studies were performed in Orinoco River, Venezuela, in the stretch Guarguapo-Barrancas-Ya Ya (Fig. 77), in order to evaluate bottom and suspended sediment transport. The objective of the former study was related to the choice of dumping site for the dredged material in the ship channels. The main objective of the latter was to study the behavior of fine sediment in suspension: advection velocity, dispersion coefficient, sedimentation rate (S_R) and dilution, taking into account that the fine sediment is the main carrier of heavy metals and other pollutants in the water environment. The Orinoco River basin is, nowadays, experiencing a fast industrial development with many industries being installed in the river margins and having outfalls discharging into the watercourse.

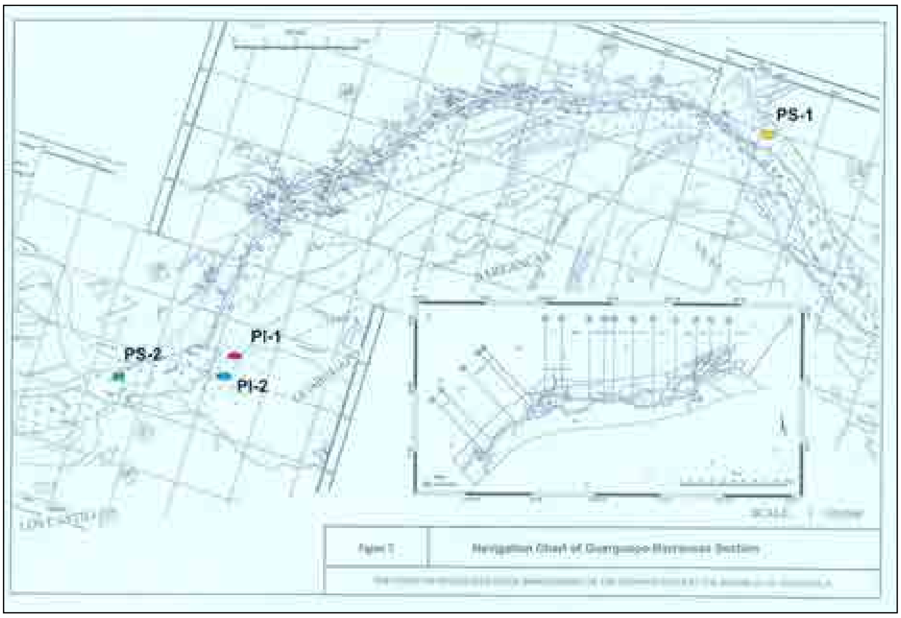


FIG. 77. Map of the sector Guargapo – Barrancas - Ya Ya, Orinoco River, Venezuela.

Note: PS-1 and PS-2 (suspended sediment injection points); PI-1 and PI-2 (bottom sediment injection points).

In relation to the suspended sediment study, two sub-superficial injections of mud labelled with ^{99m}Tc were performed in the points PS-1 and PS-2 (Fig.77).The initial activities used during the injections were respectively, 2.1 and 1.6 Ci (78 and 59 GBq). The detection was performed by a boat with two scintillation detectors placed at 1.5 m (Detector 1) and 0.5 m (Detector 2) below the water surface.

Table 16 summarize the main results obtained about the suspended sediment transport.

TABLE 16. SOME RESULTS OF SUSPENDED SEDIMENT STUDIES

Injection	Detector	Sediment.rate (S_R) (g/ton/s)	Disper. Coeff. D_L (m^2/s)	Disper. Coeff. D_T (m^2/s)	Dilution D	Advection velocity A_V (m/s)	$T_{1/2}$ (s)	$L_{1/2}$ (m)
1	1 (1.5 m)	152	3.38	0.99		0.72	4560	3283
1	2 (0.5 m)	226	1.94	0.72	515	0.72	3060	2203

Where:
D = Dilution for the distance $L_{1/2}$ referred to the first pick detected just after the injection and considering both detectors;
D_L & D_T = Longitudinal & transversal dispersion coefficients for the time $T_{1/2}$;
$T_{1/2}$ = $\ln 2/S_R$ is the necessary time for half of the suspended sediment dumped settles below the diameter of the sphere of influence of the scintillation detector, and
$L_{1/2} = A_V * T_{1/2}$ is the distance, since the dumping site, for this occurrence.

The results obtained for the behavior of the natural sediment in suspension, in the end of the low water season of the Orinoco River (April), could be used for preliminary designs of outfalls for industrial effluents which discharge particulate material with the density of fine sediment or for pollutant material that could be adsorbed by the fine sediment.

6. CASE STUDIES: NATURAL RADIOACTIVITY OF COASTAL SEDIMENTS AS “TRACER” IN DYNAMIC SEDIMENTOLOGY

6.1. BACKGROUND

Before a tracer study, sedimentologists wish to have simple means to draw up lithological map of sea or river bottom quickly, in order to locate silt or sand zones. Since 1964 this method was exploited, successfully, by A. Bastin. The follow-up of sedimentation in the sea or dams is important for geologists. If measurements are relatively easy, their interpretation is very delicate. These difficulties are due to the very variable distribution of the natural radioactive elements according to the size of the particles. Generally, the sediment particles lower than 100 µm are more radioactive than sands (250 - 315 µm). The localization and displacements of the mud banks are also largely facilitated by this method.

Radiometric measurement of gamma natural radiation is another simple and fast technique for lithological mapping of the sea bottom that could provide useful information about the origin and transport of sediments. Natural radioactivity of sea bottom sediments can provide:

- lithological map
- sediment transport trends

Careful interpretation of gamma natural radioactivity distribution could give:

- granulometric selection of sediments,
- depth limit of wave effect on sea bottom sediments,
- direction and distance of distribution of fluvial sediments,
- accretion and erosion zones along the coast line.

Natural radioisotopes distributed in sediments are uranium-238 (and its family), thorium-232 (and its family) and K-40. The radioactive decays of these three radioisotopes show that:

- 1 g U-238, (in equilibrium), emits 33 300 gammas/s and 84 000 betas/s, with energy from some tens KeV till several MeV;
- 1 g Th-232, (in equilibrium), emits 17 400 gammas/s and 15 000 betas/s, with energy from some tens KeV till several MeV;
- 10 g potassium (natural potassium contents 0.0118% K-40) emit 33 gammas/s with energy 1,46 MeV and 275 betas/s with maximal energy of 1,35 MeV.

The concentrations of uranium-238, thorium-232 and potassium-40 in sediments vary with sediment nature and origin. In the coastal sediments of Albania, there were found these values:

Silts:

- uranium-238 – 3-5 ppm;
- torium-232 – 10- 12 ppm;
- potassium – 1- 2°/o;

Sands:

- uranium-238 – 1-2 ppm;
- torium-232 - 5-6 ppm;
- potassium – 0.5- 1%.

Based on these concentrations and decays, it can be calculated that the major contributor of gamma natural radioactivity of sediments is Th-232 (over 55%), thus thorium-232 is the “natural tracer” of sediment dynamics. Moreover, Th-232 is always in equilibrium and is very resistant against chemical and mechanical agents.

50 keV was the detection system threshold for online gamma total measurement, while the spectrometric gamma natural radioactivity of samples taken from the sea bottom and beaches was measured in the following windows:

- 1.36-1,60 MeV for the K-40 (photopick 1,46 MeV),
- 1,65 –1,95 MeV for U-238 (photopick 1,76 MeV)
- 2,40 – 2,80 MeV for Th-232 (photopick 2,62 MeV)

The scope of the study was to validate the natural radioactivity method for tracing sediment transport. Natural radioactivity investigation was undertaken in two important areas of the Adriatic Sea littoral of Albanian cost, in the gulfs of Durres and Vlora, where complex studies (radiotracers included) were carried out in the frame of the maintenance of existing Durres harbor, and the design of the new harbor in Vlora. Figure 78 shows the beaches of Durres (left) and Vlora (right) where the natural radioactivity was measured online on sea bottom sediment from depth 2-3 m till 20-25 m.

FIG. 78. Gulf of Durres (left) and of Vlora (right).

6.2. RADIOMETRIC MEASUREMENTS

6.2.1. Online radiometric mapping of the sea bottom

The gamma measurements were performed in dynamic that means from moving boat with average speed of 1.5 m/s, according to the profiles perpendicular with coastal line. The detection probe (NaI (Tl) scintillator 2”x2”) was mounted in a special support, which kept constant distance probe-sea bottom of 5 cm. Online natural radiometric mapping was carried out in the same way and with the same equipment as radiotracer cloud tracking. Each profile had a length of several km and profiles were distanced 250 m from each other. It was proved that for rather homogeneous zones the count rate obtained in dynamic is the same with that in static.

Taking into account the boat speed of 1.5 m/s and the measuring interval of 30 seconds, it results that each measured value was representing around 50 m length, that is acceptable in radiometric mapping of relatively large natural zones where are not expected sharp changes in sediment size and nature. Radiometric profiles (250 m from each other) were performed in the map scale of 1: 25000, with a position error of 1 mm, equivalent of 25 m in the sea that is acceptable.

6.2.2. Treatment of radiometric field data

The plot of radiometric data was treated according to following methods.

a).Treatment with Gauss chart.

For each lithology the distribution of count rates is normal one, which means its graph in Gauss chart is linear, with a mean value characteristic for that kind of sediment.

Two count rate populations are considered significantly different when $I_1^* + s_1 < I_2^* - s_2$, where I_1^*, I_2^*, - are the mean values of two successive populations ($I_2^* > I_1^*$) and s_1, s_2 – are their standard deviations. Each radioactive population corresponds to particular sediment (lithology). To correspond a lithology to radioactivity several sediment samples were taken from the sea bottom and analyzed in laboratory (granulometric analysis).

b) Treatment with regressive analysis (trend surface analysis)
Trend surface analysis is in most respects similar to normal regression analysis. "Trend" means the least squares trend. Given a set of data, and the desire to produce some kind of "model" of that data (model, in this case, meaning a function fitted through the data) there are a variety of functions that can be chosen for the fit. The trend surface analysis methods can be used to e.g., derive a continuous smooth surface from irregular data or isolating regional trends from local variations. Trend surface for natural radiation values are approached with a polynomial:

$$X (ui, vj) == P (ui, vj) + aij,$$

where: X (ui, vj) – count rate I measured at bottom point (ui, vj); P (ui, vj) – most probable value; aij – error.

6.3. RESULTS OF MEASUREMENT OF NATURAL RADIOACTIVITY OF SEDIMENTS – GULFS OF VLORA AND DURES - ALBANIA

6.3.1. Radiometric maps of bottom sediments in gulfs of Vlora and Durres

Figure 79 shows three radioactivity classes for sediments of Vlora and Durres.

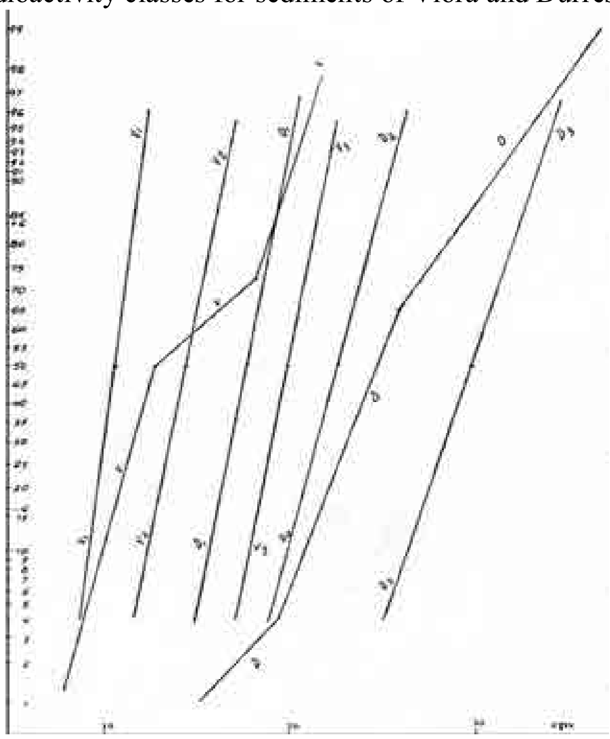


FIG. 79. Statistical distribution of sediment radioactivity's in Vlora and Durres.

Taking samples from these zones, the following relation radioactivity- lithology (granulometric classes of sediments) was found:

Vlora:

- $I_1^* = 11 \pm 1$ cps (sand grain size 100-200 μm)
- $I_2^* = 14.5 \pm 1.5$ cps (sand grain size 63-100 μm)
- $I_3^* = 19.5 \pm 1.5$ cps (silt <63 μm)

There is a zone with mixed grain sizes, called alevrit (mixture of silt with very fine size of sand). The following correlation was found between count rates I(cps) and silt (argil) content in the alevrit Cs(%):

$$I\,(\text{cps}) = 14.5 + 0.05 \times Cs(\%)$$

Durres:

- $I_1^* = 17.5 \pm 1.5$ cps (sand grain size 63-100 μm)
- $I_2^* = 21.5 \pm 2$ cps (alevrit = 50% fine sand + 50% silt)
- $I_3^* = 28 \pm 3$ cps (silt < 63 μm)

The relation count rates – silt content for Durres was found as follows:
$I(\text{ips}) = 17.5 + 0.105 \times Cs(\%)$

Figure 80 presents radiometric mapping (left) of sea bottom sediments in golf of Vlora and isocount trend surfaces (right).

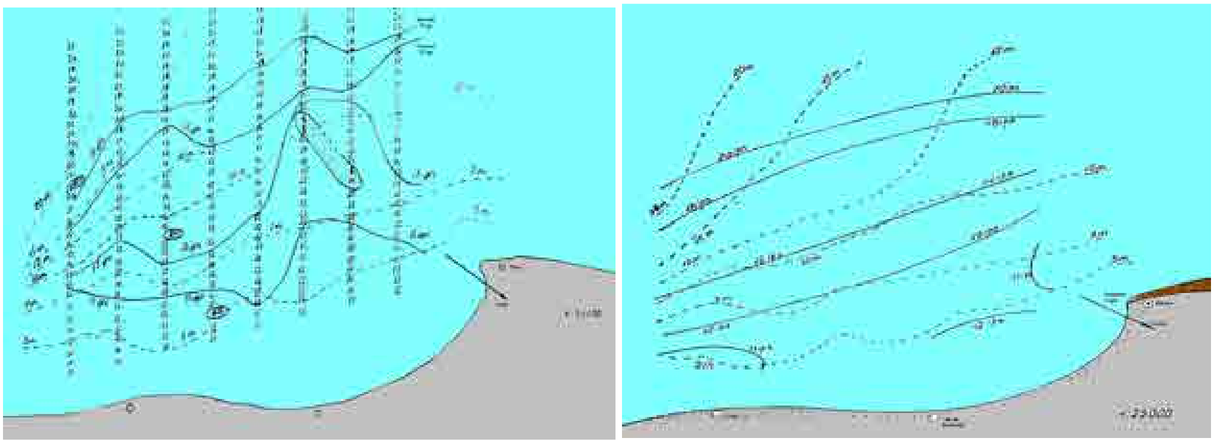


FIG. 80. Radiometric mapping of sea bottom sediments in golf of Vlora and isocount trend surfaces.

The isocount trend surfaces are parallel with bathymetry lines, passing gradually from sand to alevrits till silt (>20 cps after 15 m depth). This picture is result of wave action coming mostly from south-west direction perpendicular to the coast line, which seems to be the predominant factor of sediment transport normal with beach line. There is no evidence of the sediment transport along the shore, at least after 2-3 m. depth. Figure 81 shows the results of radiometric mapping of sediments in the gulf of Durres.

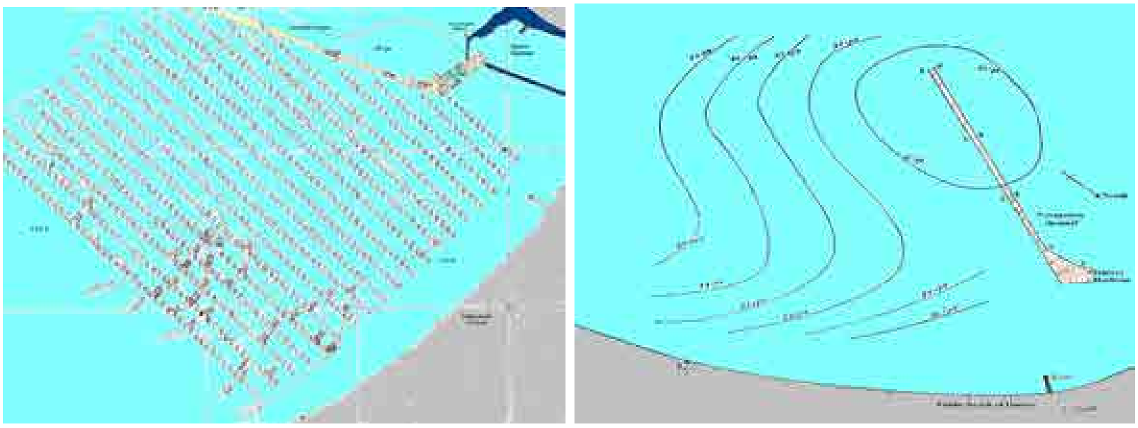


FIG. 81. Isoactive lines in gulf of Durres.

Isocount map in Durres gulf shows curved lines perpendicular to the shore line and bathymetry, that is characteristic for alongshore transport of alevrit sediments near the sea bottom.

Main conclusions obtained from the mapping of gamma natural radioactivity in Vlora and Durres gulfs are:
- sediments in Vlora have a lower radioactivity for the same granulometry than in Durres, that reflects their origins from different land stratifications,
- gulfs of Vlora and Durres have different lithological distributions; the sea bottom of Vlora consists mostly of sand, while sea bottom of Durres contains mostly alevrits.
- in Vlora gulf there is a sediment selection in profiles normal to the coast line, resulting under influence of the waves perpendicular to the shore line.
- in Durres gulf there is not any sediment selection in profiles normal to the coast line; it could be explained as an alongshore transport of alevrit sediments near the sea bottom towards the harbor and its channel.

6.3.2. Radiometric profiles in the navigation channel

Radiometric measurements along the navigation channel (on its axes and both sides) to the port of Durres (4 km long) were performed as well to investigate the silting map (Fig. 82). In fact, the channel was almost inexistent because it was filled up with sediments (estimated around 1 million m^3 sediments).

FIG. 82. Golf of Durres, the harbour, the navigation channel and the main direction of sediment transport under the action of waves coming from the south-east.

The results of four profiles measured at different periods were:
- On 10.10. 75 the average: I_{ch}= 22.6 ± 0.5 cps (correlation coefficient r = 0.22)
- On 26.3. 79 the average: I_{ch} = 22.4 ± 0.4 cps (r= 0.22)
- On 19.4. 79 the average: I_{ch}= 22.1 ± 0.3 cps (r = 0.25)
- On 8.6.79 the average: I_{ch} = 22.2 ± 0.3 cps (r = 0.20)

For the whole channel the average value was calculated I_{ch} = 22.3 ± 0.5 cps. This value of radioactivity is characteristic for alevrits (mixture of very fine sand with silt in different proportions).

There was a very good reproducibility of the measurements, which make them very reliable for interpreting even relatively small differences. There was a significant difference between the average activities of the first and second part of channel: I_{ch1} = 24.1± 0.5 cps (nearly 70% silt) and the second part: I_{ch2} = 20.5 ± 0.5 cps (nearly 30% silt). This indicates that the first part of the channel (half of it) is silted more than the second part. The average activity of the parallel profiles, both sides of the channel, was found 21.0 ± 0.5 cps that means similar with the activity of sediment within the second part of the channel.

Comparison of radioactivity distributions within the channel and both sides of it indicates that first half part of the channel is prone to higher silt deposition. The silt deposited mostly in the first part of the channel is coming very probably from the gulf centre (because they have the same radioactivity).

The waves coming from the south-east move silt towards the harbor, where it settles down trapped by harbor structures.

6.3.3. General conclusions

Natural radiometric survey of the sediments of sea bottom provided some qualitative sediment transport features, characteristics and parameters similar with those obtained with radiotracers, in particular the resultant direction and mechanism of sediment transport were made evident. This simple and low cost technique can be used for sediment transport studies as complementary to other techniques.

The radiometric survey of the sediments of sea bottom and beaches in the gulfs of Vlora and Durres has provided the following major conclusions:

Vlora
1. Waves coming from the west move sends normal to the beach line. The influence of waves of this sector is up to depth 15 m, where is the boundary between sand and silt.

Durres
1. There was not any visible granulometric selection of sea bottom sediments in the gulf of Durres.
2. There was an indication of sediment transport trend from south to the north of the gulf under the influence of waves coming from the south sector.
3. There was evidence of silting process, in particular in the first part of the navigation channel near the harbor.

7. CASE STUDIES: FLUORESCENT TRACER APPLICATIONS FOR SEDIMENT TRANSPORT INVESTIGATIONS

7.1. SEDIMENT TRANSPORT ALONG THE COAST OF ISRAEL: EXAMINATION OF FLUORESCENT SAND TRACERS

7.1.1. Abstract

The method of labeled natural sand particles was used to study sediment transport along the central Mediterranean coast of Israel. Six portions of 300 kg each were tagged with various fluorescent colors, and distributed at six different locations in the vicinity of the Herzliya Marina. The tagged sand was scattered at the end of autumn, and sampled three times during the winter. Sampling was interrupted in mid-January because of unexpected dredging at the marina canal entrance. The samples were analyzed at the Yigal Allon Kinneret Limnological Laboratory. The wave climate during that time was analyzed using wave data from Ashdod (40 km south). Seven wave storms with significant wave heights of over 2.5 m were observed. Two of them clearly indicate a dominant direction from the southwest and two others from the northwest. However, the time durations and the relative angles between the wave directions and the orthogonal to the coast of the storms propagating from the southwest are essentially larger than those arriving from the northwest. The following results were noted: (i) The drift of tagged sand particles correlated to longshore sediment transport at all depths was in a northern direction throughout the field experiment. The longest distance of transport was 5 km over a period of 86 days. (ii) "Onshore" sediment transport was present; sand from 15 m depth was found at 8 m depth. (iii) The cross-shore sediment transport carried sand to a depth of 8 m, but no colored sand from shallow water (2-4 m) was found deeper than 8 m. (iv) Although sedimentation at the marina entrance during the experiment was high, only small amounts of tagged sand were found at the entrance. (v) Findings of tagged sand showed the main area of sedimentation to be along the marina's main breakwater.

7.1.2. Background

The primary source of sediment to the southeastern Mediterranean coast is the Nile River (Fig. 83).

FIG. 83. Study area.

The Nile flow regime and the Nile's sediment transport has undergone a dramatic change in the last century because of the small (1902) and the big (1964) dams at Aswan. The Nile's quartz sand has been transported from the Nile outlets to the Israeli coast by consistent west-to-east and southwest-to-northeast longshore currents, generated by westerly approaching waves. Inman et al. (1976) estimated the wave-induced longshore sediment transport (LST) rate at the Damietta eastern promontory of the Nile Delta to be eastward at about 860,000 m^3/y. This amount decreases toward the east to about 500000 m^3/y along the outer Bardawil lagoon sandbar in northern Sinai (Egypt). No direct previous LST measurements exist of the actual sand transport along the Sinai and the Israeli coast. According to an updated estimate presented by Perlin and Kit (1999), the average net LST along the southern part of the Israeli coast decreases from 450,000 m^3/y of sand in Ashkelon to 200,000 m^3/y of sand in Ashdod.

This dramatic reduction within only 40 km is due to a significant change in coastal orientation, from azimuth = 34^o in Ashkelon to azimuth = 25^o in Ashdod. Further north (40 km) along the Tel-Aviv coast (azimuth = 21^o), the rate of the average net LST decreases to 100,000 m^3/y. It diminishes to 60,000-70,000 m^3/y at the Carmel coast (azimuth = 4^o) just before reaching Haifa Bay, the northern end of the Nile littoral cell. The question is whether the decrease in the Nile sediment contribution to the south-eastern Mediterranean coasts has already affected the coasts of Israel or whether the erosion of the Nile Delta sand storage replaces the Nile sediment. Any attempt to answer that question has to rely on field observation along the Israeli coast.

The average net LST at the Herzliya coast (azimuth = 17^o) was calculated by PERLIN and KIT (1999) and it is slightly less than 100,000 m^3/y to the north. Estimates from other research, shown in the table below, vary dramatically, mainly because they do not incorporate necessary wave directional corrections, and therefore cannot be considered reliable.

Different estimates of average net longshore sediments transport of the Herzliya coast.

Researchers	Model	Net transport $m^3/y \times 10^3$
Baird & Associates Ltd. and Research Planning Inc. 1996	COSMOS Ashdod wave data 1958–94	600 to the north
Baird & Associates Ltd. and Research Planning Inc. 1996	COSMOS Ashdod wave data 4/1993–3/1995	400 to the south
Toms and van Holland 1999	Delft3/D/2DH	30 to the north
Perlin and Kit 1999	DHI/LITPACK	100 to the north

The morphological impact of the Herzliya Marina (built in 1990-1992) on the coastal morphology of the adjacent area was studied by Klein and Zviely (2001). Since 1995, dredging of around 20000-30000 m^3/y has been done because of sedimentation at the marina entrance. Since sedimentation occurs mainly during January-April, dredging is done at the end of April, and the dredged sand is deposited some 2.5 km north of the marina, 500-1000 m from the coastline at a water depth of 6-7 m.

The fluorescent tracers have been used for many years to determine sediment movement. In the Nile littoral cell the fluorescent tracer method was used by Badr and Lotfy (1999) in their work along the delta coast. The aim of this study was to determine in a descriptive manner using colored particles the movement of sand around the marina area and the nearby coast, and enable assessment of the process of sand transport and sand accumulation at the marina entrance. The study tests the validity of the fluorescent tracer’s method to describe the coast environment and over a long, for example several-month, period of time. The results of this experiment may provide a field indication of the sediment transport process along the Israeli coast.

7.1.3. Methodology

An amount of 1.8 tons of sand were dredged north of the marina. The sand was analyzed and found to have an average grain size of 190 µm, which coincided with the findings by Baird & Associates Ltd. and Research Planning Inc. (1996) and Rosen (1998) of 160-230 µm, with an average of 190 µm. The labeling of sand was done by Shteinman and his team at the Yigal Allon Kinneret Limnological Laboratory, Israel. Six different colors were used, in quantities of 300 kg each. The colored glue was intended to last for 8 months. We planned to disperse the tagged sand in November, before the winter storms, and to draw the last sediment samples after the dredging, which was planned for the spring.

In the present work, directional wave data for this study period were measured at Ashdod, 40 km south of Herzliya Marina (Fig. 83). The measurements were made by the Coastal and Marine Engineering Research Institute (CAMERI) on behalf of the Israeli Port and Railway Authority. A Datawell Waverider buoy is deployed at a depth of 24 m to acquire 30-minute directional records of surface elevation and directional spectral information. Generally, these records were acquired once every 3 hours, but during severe storm events, attempts were made to collect data each hour. The wave data were converted from Ashdod to the Herzliya coast by using the height and wave angle corrections for generation of wave climate at particular locations along the Israeli coast (Perlin And Kit, 1999).

The colored sand was deposited on November 11, 2001. The bags with colored sand were loaded on the sea bottom by divers to eliminate dispersion of sand during sinking. The locations of the six distributing points were measured with a global positioning system device on the boat. Five of the distributing points were along a perpendicular line to the coast at different depths: 2 m (blue), 4 m (yellow), 6 m (green), 8 m (red), and 15 m (orange). The last point (pink) was at the location where the dredged sand is being deposited some 2.5 km north of the marina, 500-1000 m from the coastline at a water depth of 6-7 m (Fig. 84).

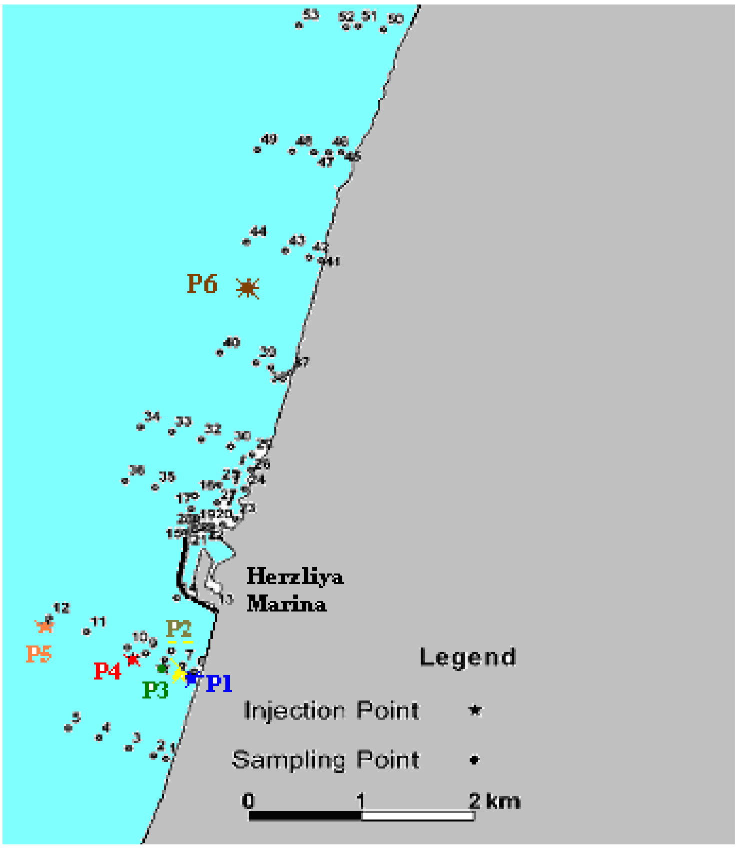


FIG. 84. Location of sand particle sampling and injection points.

In planning the outset of the experiment, it was determined that sampling would take place once per month, or after a wave storm. Sampling was done by divers, who collected the sand from the upper 10 cm in plastic bags holding about 1.5 kg each. On the boat, 500 g from each sample were put into plastic containers. The samples in the plastic containers were dried at the Kinneret Limnological Laboratory; 200 g of dry sand were used for spectral analysis.

On November 20, 2001, 9 days after depositing the sand, the first sampling took place; 24 samples were collected. The second sampling took place on December 17, 2001, 36 days after the deposit; 49 samples were collected. The third sampling was on January 13, 2002, 62 days after the deposit; 53 samples were collected. Because of unexpected dredging at the marina canal entrance, this was the last sampling.

7.1.4. Results

7.1.4.1. Wave Climate

The wave climate for the time of the experiment is given in Fig. 85. In the course of the experiment, seven wave storms occurred in which the significant wave height (Hs) was over 2.5 m, and three storms occurred with Hs over 3.5 m. During the first 9 days, a storm from the north with waves from azimuth 300^0-310^0 occurred. Since the normal to shore wave front at Herzliya measures 287^0, this storm produced a southward longshore current.

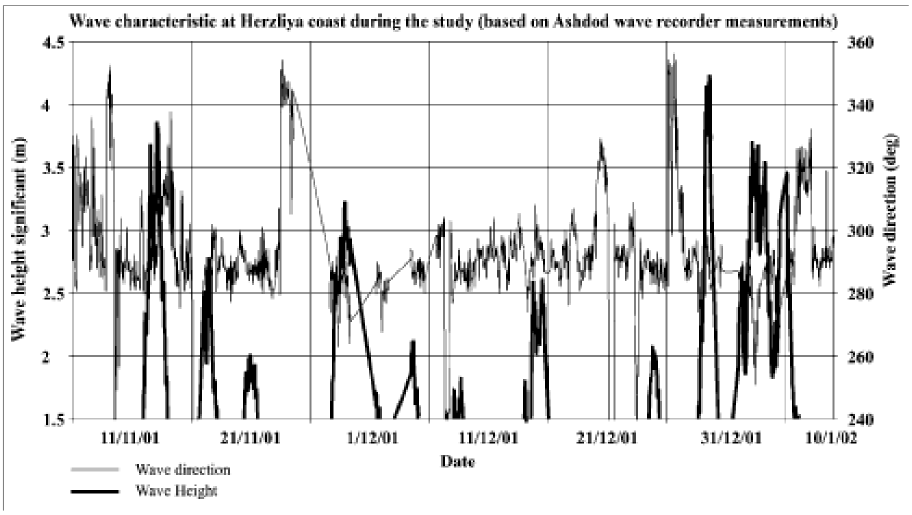


FIG. 85. Wave characteristics at Herzliya coast during the study.

7.1.4.2. Current Measurements

Nile littoral cell longshore currents along the Israeli coast can be classified according to the primary forces that generate them, waves and local winds (Kit and Sladkewch, 2001). Wave-induced currents occur primarily in shallow depths, between the coastline and 5 m (up to 10 m during heavy storms). Wind-induced currents occur at depths beyond the breaker zone, generally from 5 to 30 m. Flow data were measured by current meter, at a depth of 24 m (in the wind-induced current zone), about 1 km south of Ashdod harbor. The measurements were carried out by Israel Oceanographic and Limnological Research for the Israel Ports Authority. Therefore, the data from Ashdod can be applied to the study of the 8-and 15-m colored sand deposits made in Herzliya in water depths beyond the breaker zone.

During the first stage, from November 11, 2001 to November 20, 2001, a slow northward current of up to 10 cm/s was recorded. On November 17, 2001 a northward current of 25 cm/s was recorded.

On November 19, 2001 a southward current of 25 cm/s was recorded, the only event of flow to the south during the entire period. During the second stage from November 21, 2001 to December 17, 2001 a very slow flow northward was recorded. Flow in the third stage, from December 18, 2001 to January 13, 2002, was also northward, with maximum up to 60 cm/s. During the third stage at January 7, 2002 a fast flow of 100 cm/s to the north was recorded.

7.1.4.3. Colored Sand

The number of sand particles found in a sample is counted visually and is given as the number for 200 g of sampled sand (1 g = 10,000 particles).

Sampling points are marked on Fig.84; only points where colored sand was found are marked on Figs. 80-85, with the number of particles found. The results for each color were mapped. A disk-shaped symbol describes the number of tagged sand particles of each color found; the relative size of the pie diameter is proportional to the number of tagged sand particles found in each color.

Blue Sand Experiment (Loaded at 2-m Depth, Fig. 86)

In the sample of November 20, 2001, blue sand particles were found in 7 of 24 sampling points. Fourteen sand particles were found about 1 km south of the depositing point in a water depth of 2 m. The northernmost point where blue sand particles were found was about 850 m north of the marina or almost 2 km north of the depositing point. No blue particles were found at depths of more than 4 m. In the second sample, taken on December 17, 2001, blue sand particles were found in 12 of 49 sampling points. No blue sand particles were found south of the depositing point. The northernmost point where blue sand particles were found was about 430 m north of the marina. No blue particles were found in depths of more than 6 m.

High numbers of blue particles were found in all of the sampling points along the marina's main breakwater. In the third sample taken on January 13, 2002, blue particles were found in 12 of 53 sampling points. These results were almost identical to the results of the second sample.

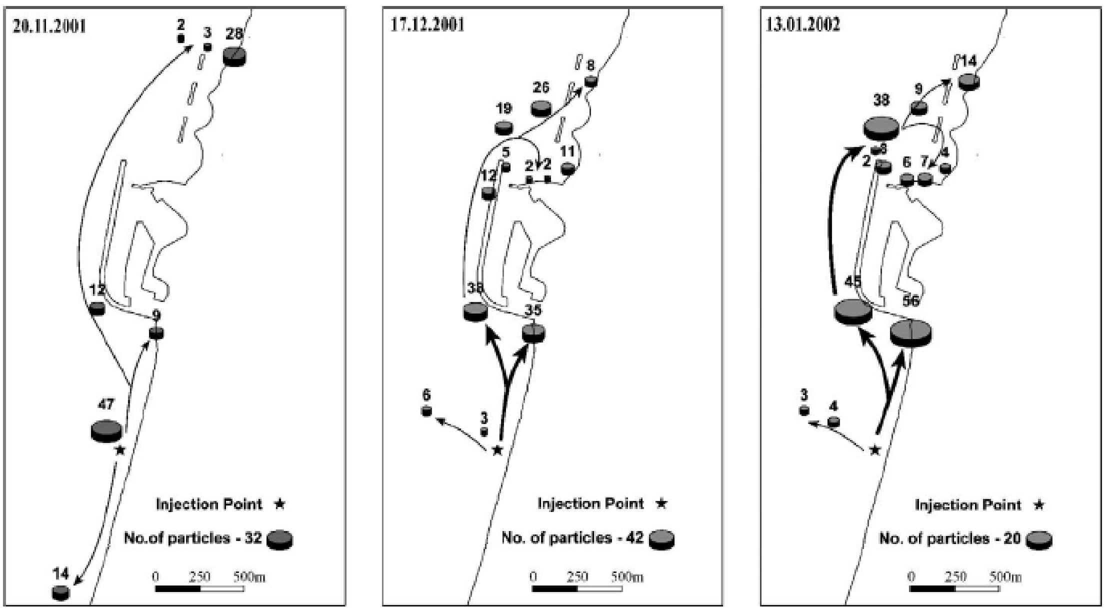


FIG. 86. Location and number of blue sand particles.

Yellow Sand Experiment (Loaded at 4 m Depth, Fig. 87)

In the sample of November 20, 2001, yellow particles were found in 8 of 24 samples. The pattern was identical to that found in the blue experiment. In the second sample of December 17, 2001, yellow particles were found in 12 of 49 sampling points. The results are similar to that of the blue color, but the yellow color was found 850 m north of the marina. Along the depositing line, yellow particles were found at a depth of 8 m. In the third sample, yellow particles were found in 14 of 53 samples. The results were almost identical to the results of the second sample, but the northernmost point was 430 m north of the marina. No yellow particles were found at depths of more then 6 m.

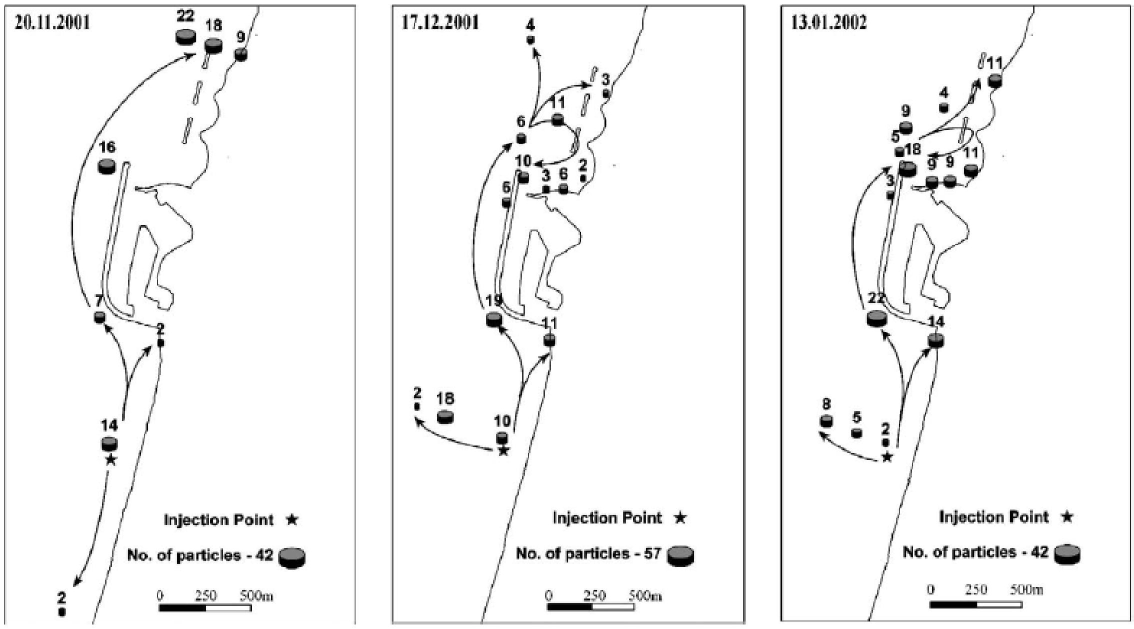


FIG.

Fig. 87. Location and number of yellow sand particles.

Green Sand Experiment (Loaded at 6 m Depth, Fig. 88)

In the sample of November 20, 2001, green particles were found in 6 of 24 samples The pattern was similar to that found in the blue and yellow experiments, but green particles were not found along the main breakwater. In the second sample, green particles were found in 10 of 49 samples. Green particles were found 430 m north of the marina. No green particles were found in depths of more than 6 m, and very few were found in shallow water (less then 2 m). In the third sample, green particles were found in 10 of 53 samples. The results were almost identical to those of the second sample.

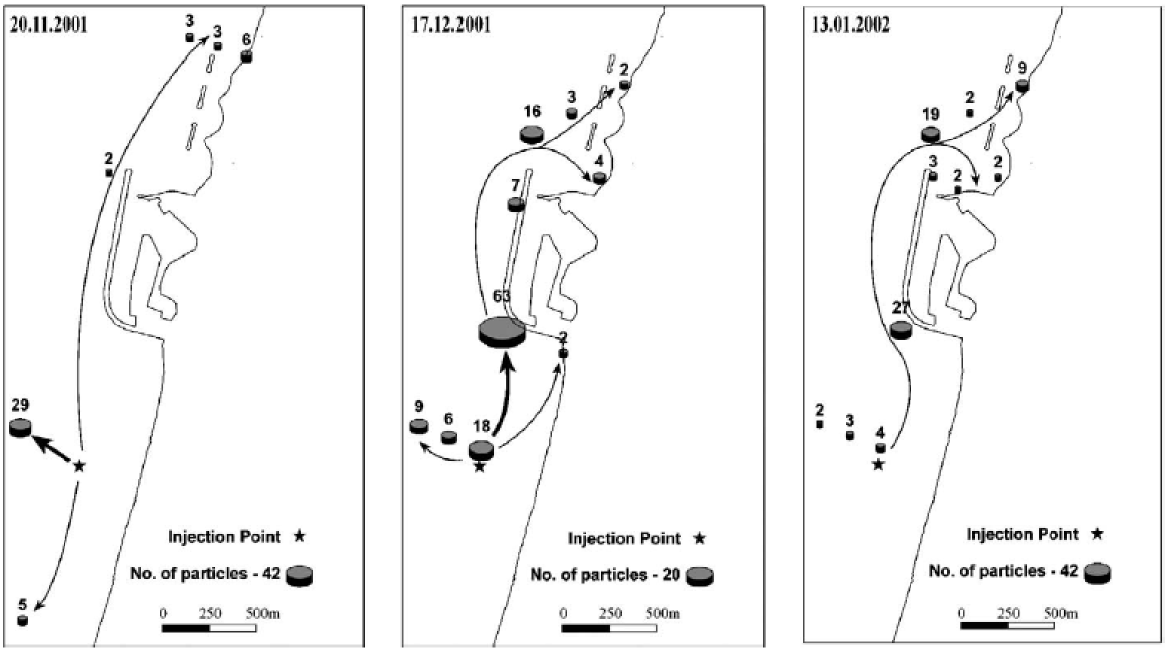


FIG. 88. Location and number of green sand particles.

Red Sand Experiment (Loaded at 8 m Depth, Fig. 89)

In the sample of November 20, 2001, red particles were found in 6 of 24 samples. No red particles were found south of the depositing point. The northernmost point where red sand particles were found was about 850 m north of the marina. Few red particles were found along the main breakwater. In the second sample, red particles were found in 19 of 49 samples. Red particles were found 4 km north of the marina. A high number of red particles was found along the main breakwater. In the third sample, red particles were found in 14 of 53 samples.

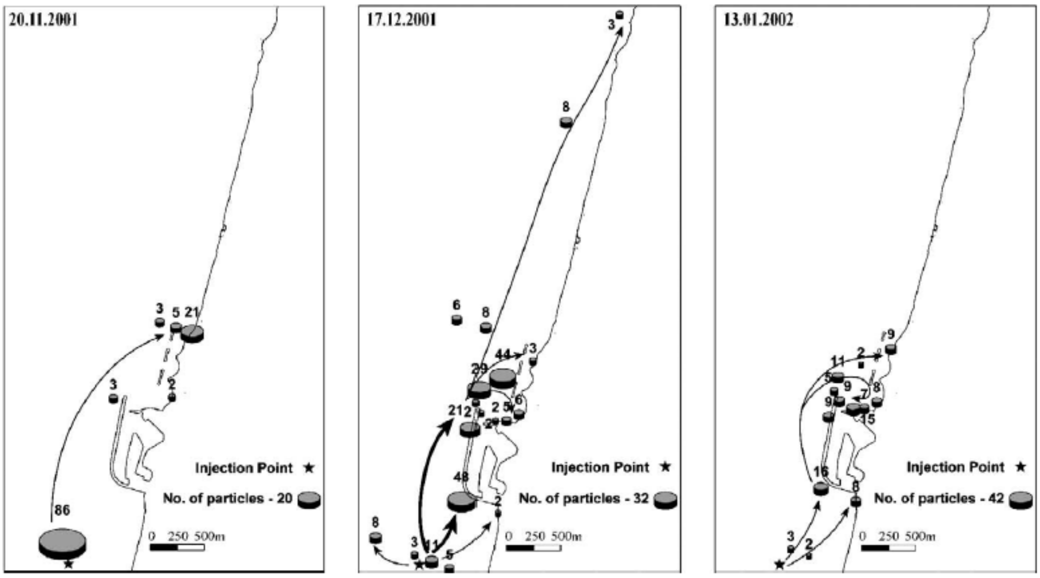


FIG. 89. Location and number of red sand particles.

Orange Sand Experiment (Loaded at 15 m Depth, Fig. 90)

In the sample of November 20, 2001, orange particles were found in 2 of 24 samples, the first at the depositing point and the second along the depositing line at a depth of 7.7 m, indicating sand transport toward the coast in water depths of 8-15 m. In the second sample, orange particles were found in 1 of 49 samples along the depositing line at a depth of 10 m. In the third sample, orange particles were found in 3 of 53 samples. The northernmost point where orange sand particles were found was about 850 m north to the marina, in a depth of 4 m.

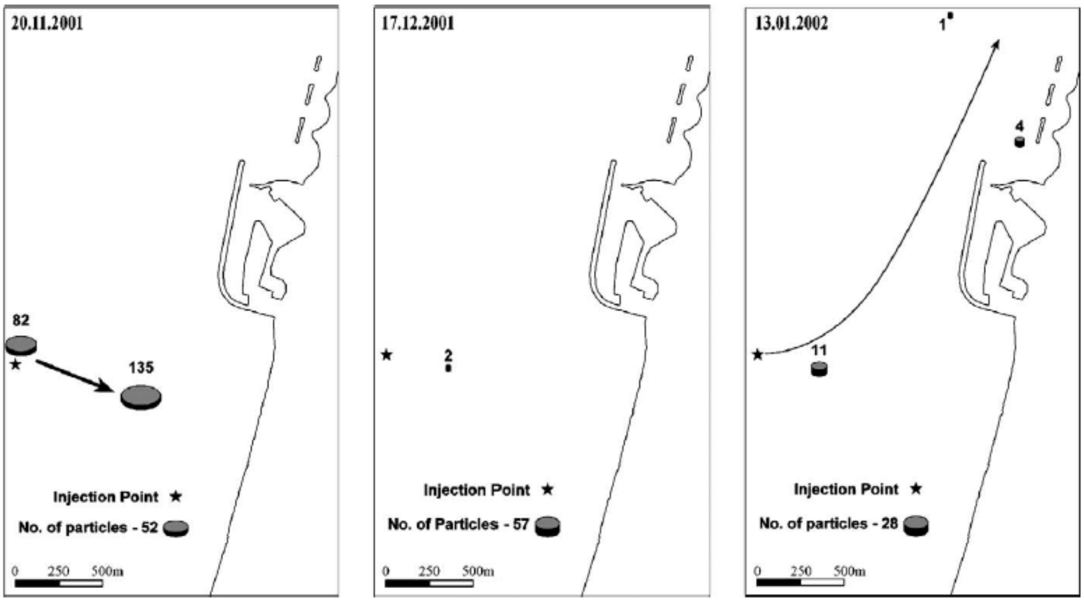


FIG. 90. Location and number of orange sand particles.

Pink Sand Experiment (Loaded at 6 m Depth, 2.5 km North of the Marina, Fig. 91)

In the sample of November 11, 2001, pink particles were found in 7 of 24 samples. Pink grains were found 500 m north and 1500 m south of the depositing point. In the second sample, pink particles were found in 4 of 49 samples, 600 m south of the depositing point and 1.6 km to the north. All four points were in water depths of 1.5-2.5 m. In the third sample, pink particles were found in 5 of 53 samples. The results were similar to the results of the second sample.

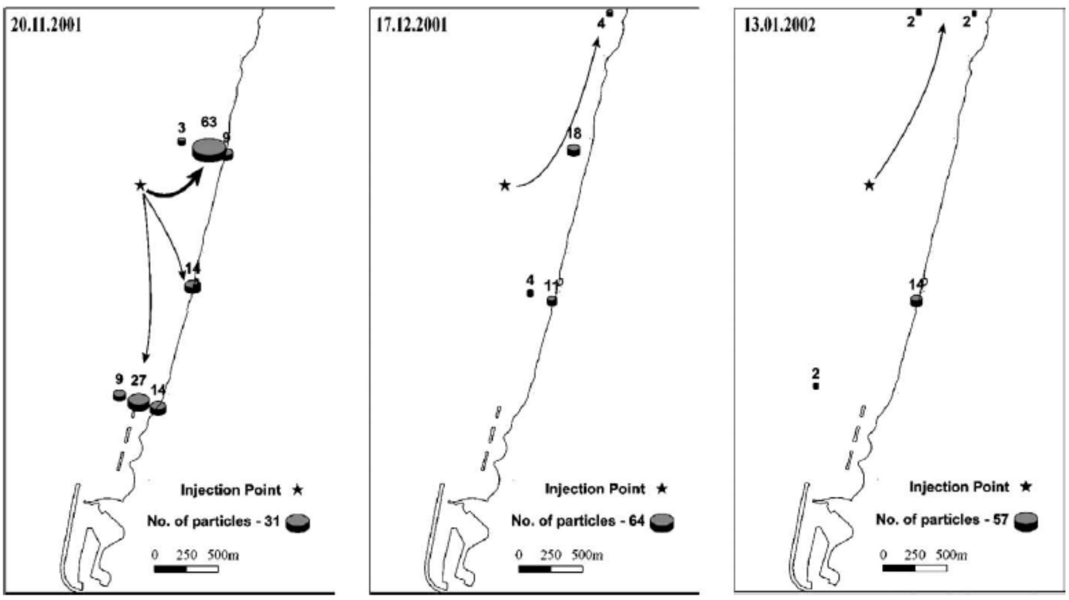


FIG. 91. Location and number of pink sand particles.

Discussion

The application of the colored fluorescent tracers in the study of coastal sediment transport by longshore current is exemplified in this study. Each one of the different colors is an experiment of its own, but we ran the six experiments at the same time using the same field and lab plan. The method of using different colors of sediment is easy to run and gives detailed results. The ability to determine the lifetime of the fluorescent particles is a significant advantage of the method.

The results of the three series of sequential sampling, and the six colors, permitted us to compare field observations to evaluation of numerical models. The sediment transport at the marina area has been evaluated using a particle tracking numerical model (Baird Associates Coastal Engineers Ltd., 1998). The particle tracking model was described by Dimou and Adams (1993) and was used to define the sediment pathways. The model provides a description of the sediment movement along the coast in the vicinity of the marina. Data from the wave-induced model was used as input to the particle tracking model, to assess the sediment transport pathways. Colored sand was injected into the flow at two points, north and south of the marina (two icons in Fig. 92).

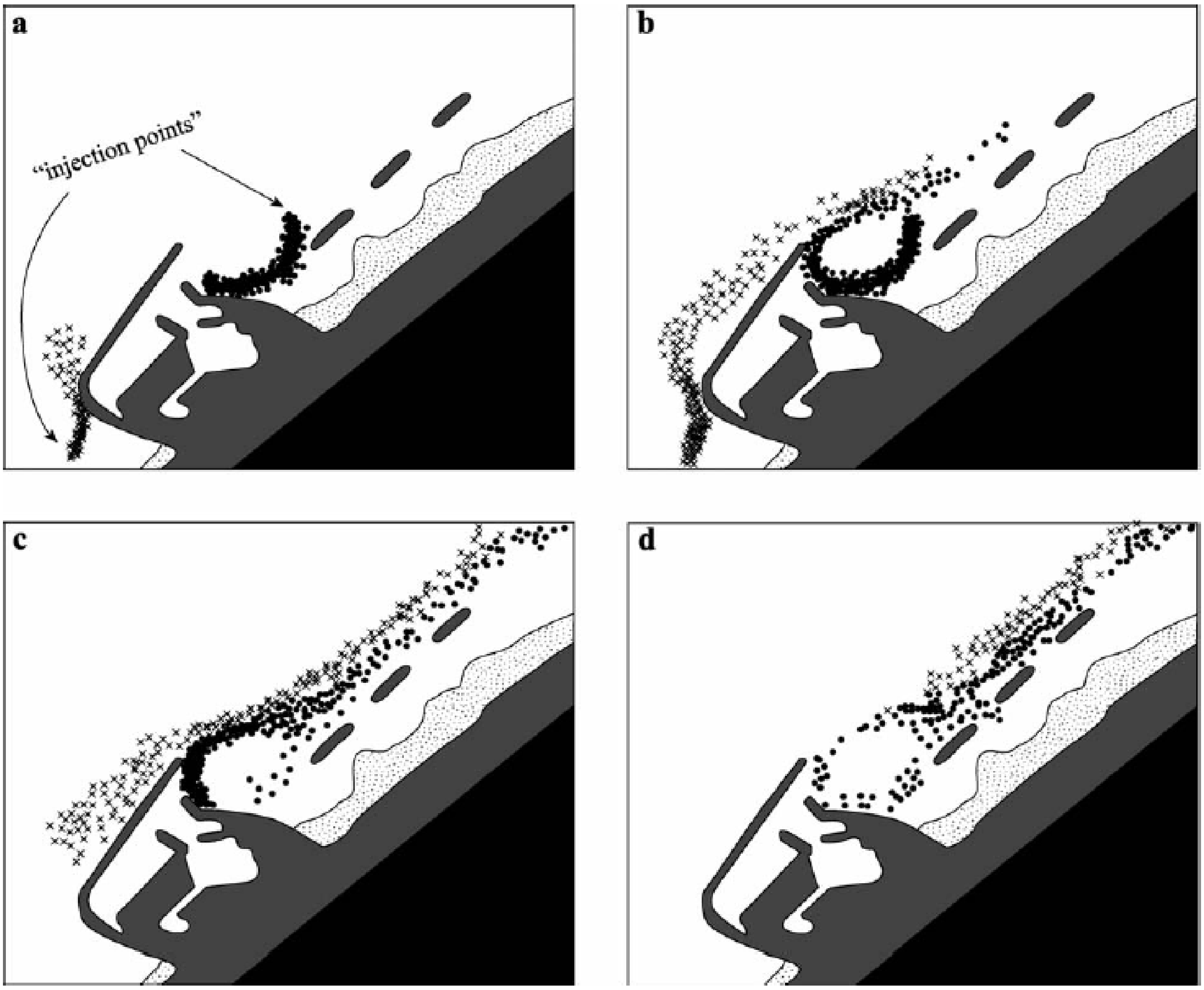


FIG. 92. Sediment pathway during southwest storm in the particle tracking model.

The movement of the particles was solved through advection-dispersion techniques, meaning the particles were transported by the current and dispersed according to a random walk component. The particles were tracked continuously through time.

Figure 92 shows the sediment pathway during a southwest storm. Sediment is transported from south of the marina in a northerly direction. The sediment bypasses the marina, but part of the sediment circulates in a clockwise eddy at the marina entrance. The limitation of the particle tracking model used is that the particles are neutrally buoyant and therefore no settling of particles is allowed for and hence prediction of accumulation area is impossible.

The findings of the blue sand, yellow sand, and green sand experiments, in which the injection points are close to the injection point of the model, resembles the result of the particle tracking model. The predicted bypass and the clockwise eddy at the marina entrance were observed. The predicted circulation pattern was verified by the scatter of the colored particles and by field observation of movement of sand from the east along the exterior side of the lee breakwater, accumulating in the marina entrance. In addition, offshore and onshore transport was demonstrated. The main areas of accumulation in the blue sand, yellow sand, and green sand experiments are along the marina's main breakwater and up to a distance of 850 m north of the marina. Part of the labeled particles was found at depth of 0 m, on the coastline, a location that was not predicted by the particle tracking model.

7.1.5. CONCLUSIONS

1. Northward sediment transport of sand in all water depths was demonstrated throughout the experiment.

2. Onshore sediment transport from the deeper sea was demonstrated; sand that was deposited at a depth of 15 m was found at 8 m after 8 days.

3. Offshore sediment transport was demonstrated by colored sand dispersed at a depth of 2 m and found at 6 m, and by colored sand dispersed at a depth of 4 and 6 m and found at 8 m. No colored sand from the breaker zone was observed in deeper sea.

4. Tagged sand was transported up to 5 km to the north within 36 days. The (red) sand that was loaded in water depths of 8 m (and therefore not affected by the marina) was transported the longest distance.

5. In spite of the rapid sedimentation at the marina entrance during the experiment, the number of colored particles found was low.

6. The main area of sand accumulation was along the marina's main breakwater.

7. In retrospect, the selection of five distributing points along a perpendicular line only 400 m south of the marina's main breakwater did not anticipate the possibility of the eddy formation to the south of the tip of the main breakwater caused by separation of southern current generated by northwest storms. The backward current in the northern direction produced by this vortex (that disturbs the southern longshore current) can explain the very low quantity of colored sand particles found 1450m south of the marina, in spite of relatively strong storms occurring from the northwest direction.

7.2. FLUORESCENT TRACERS – COATED & ARTIFICIAL: EXPERIENCE OF ENVIRONMENTAL TRACING SYSTEMS

7.2.1. Background

Fluorescent tracers could be natural sand covered by fluorescent paint or artificial particles including a fluorescent pigment. After sampling, the analysis is performed by counting the number of fluorescent particles under UV lamps or laser particle counting technique.

Fluorescent painted, coated or dyed/stained sediment, generally involves collecting the native sediment from the actual study site or a representative site, followed by drying and then painting, coating or dyeing/staining the sediment grains with a dye and occasionally a fixative. This method is generally associated with sand grains although has been used for silt grains also; however painting or coating of silt grains often results in a very hard compound that requires re-grinding back into its original constituent size fraction before use.

Research institutes and laboratories have used painted and dyed/stained sand grains since the 1950's but with varying success. One of the prime reasons for poor results has been the loss of the fluorescent label in medium or high energy environments or for studies of medium to long term duration. The paint or dye/ stain can be subject to abrasion and the fluorescent signature lost. Depending on the study site, detection of painted particles can be of the order of days to weeks, however for stained particles, detection is generally limited to days only. More recently with the development of the polymer industry, coated sand grains can be purchased with the polymer enveloping a generic sand grain taken from an unknown source. These coatings tend to be more robust and allow studies to take place over a longer duration or in higher energy environments however, the polymer coating lowers the individual sand grain density by 10-15% minimum so is not necessarily representative of the natural sand.

Figure 93 shows images of different types of coated and dyed/stained sand grains taken using a fluorescent microscope. One week after release the Dyed sand shows a significant loss of fluorescence signal for the yellow dye, being almost indistinguishable from background sand (Fig. 94).

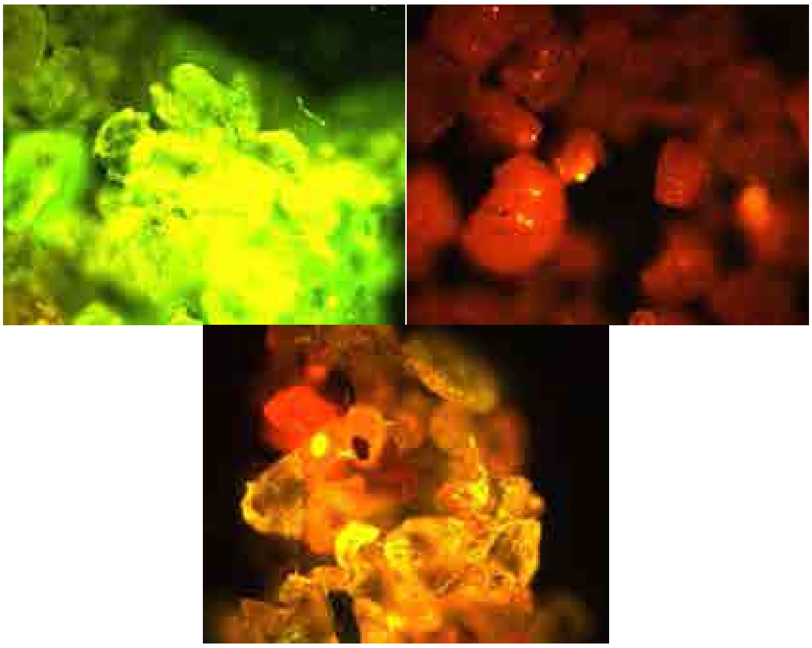


FIG. 93. Polymer coated sand.

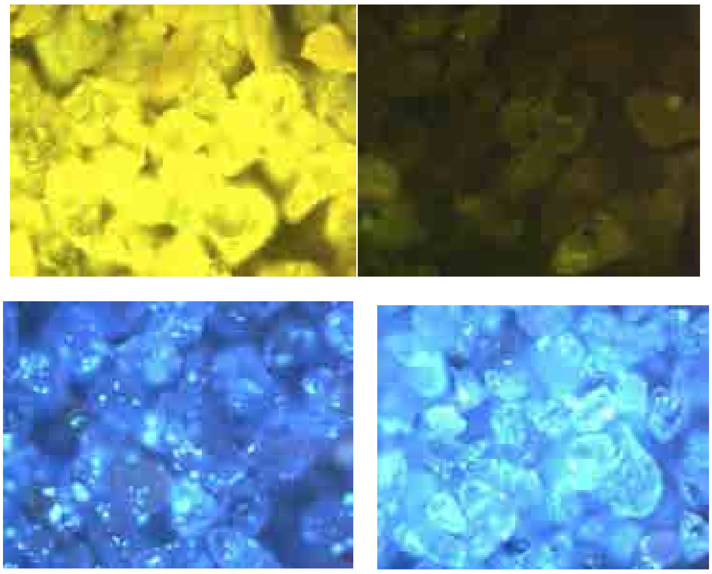
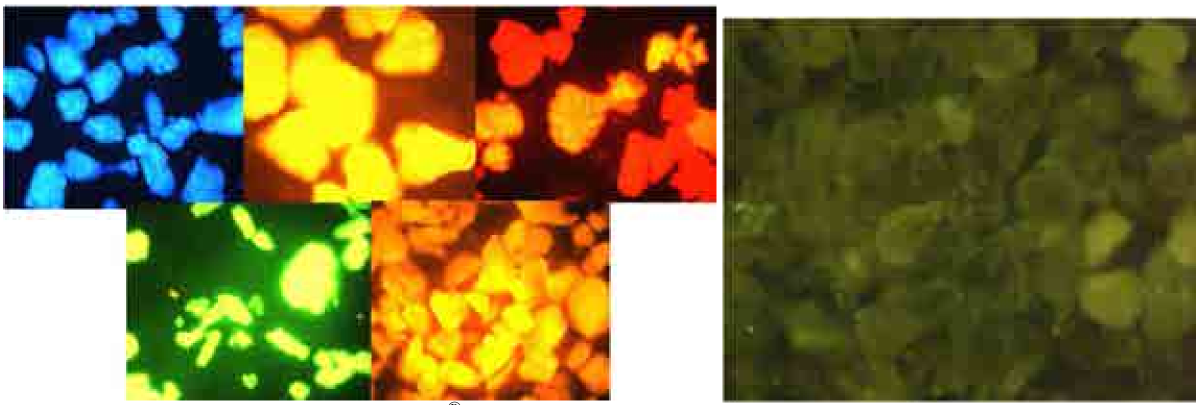


FIG. 94. Images taken of polymer coated and stained/dye sand grains. Dyed sand: Prior to release & 1 week later.

Fluorescent polymer tracer particles, such as EcoTrace particles offered by Environmental Tracing Systems Ltd. (ETS), represent environmentally benign fluorescent polymer particles manufactured to mimic natural silt and sand grains, particulate contaminants, sludge etc. Densities can be manipulated during the manufacturing process to range from floc densities of 1.1-1.8 g cm^{-3} up to individual grain densities of 2.65 g cm^{-3} such as silica or higher for volcanic source sediment. These materials can be produced to match the target particle size distribution for silts, sands or gravels with the shape and distribution modified to produce well sorted or poorly sorted sediments for a wide range of applications related to sediment transport.

Multiple colors are available to label and track different sources of sediment in the environment, different size fractions simultaneously during the same meteorological and oceanographical/flow conditions (Fig. 95). Since they are a polymer particle with the fluorescent signature throughout the particle they are particularly useful for high energy and long-term studies since they remain largely unaffected by abrasion in the same way as coated, dyed or painted sand grains.



EcoTrace® Natural sand

FIG. 95. ETS EcoTrace particles (taken with a fluorescent microscope), which are very bright and easy to detect compared with natural sand shown using the same equipment.

Detection limits are very high due to their very bright nature and there is no limit as to the number of particles that can be released. Settling velocity and fall velocity tests for silt cohesive sediment and non-cohesive sand grains respectively, confirm a very similar behaviour to natural sediments. In the case of fluorescent silt-sized particles they form and incorporate within natural flocs.

For all studies, measurement is made by first collecting bed sediment grab or core samples, sediment trap samples and water samples. Detection is made by analyzing these samples using a combination of laser excitation, optics, CCD photography and image analysis equipment centered around analytical flow cytometry and fluorescent microscopy and magnification.

ETS have also used a paramagnetic label in the tracer particles on occasions, to allow collection or capture using magnets in the ocean; ETS have experimented with this technology since 2001/02. ETS have not used paramagnetic particles widely or developed the technology further to date due to concerns over particle charge due to the presence of paramagnetic material and the interaction with natural sediment particles (particularly cohesive sediments) and the signal levels for very small (fine/medium silt sizes) and particles in the upper fine sand and medium sand fractions.

7.2.2. Tracer experimental design using artificial fluorescent particles

The information listed on tracer experimental design relates to artificial fluorescent tracer particles such as ETS' EcoTrace particles only, rather than sediment mineralogical analysis. For the case of the painted, coated and stained/dye particles some of the information listed below is applicable however the change in density and reduced detection limits will reduce the ability to carry out such studies and measure the particles successfully.

7.2.2.1. Bedload transport studies

Selection of tracer

For all studies, background information needs to be collected from the study site. Background information takes two forms; firstly sediment characteristics and morphology of the site are required and secondly the presence/absence and spectra of any background fluorescence that may interfere with the detection of the fluorescent tracer particles. In terms of the sediment characteristics and morphology of the site, this information may already be available from the client or environmental agency from previous studies. If insufficient data are available or the data are too historic, it may be necessary to obtain additional information by collecting and analyzing sediment grab or core samples for sediment particle size distribution.

Additional information relating to the selection of the tracer that can also be useful or required include grain density, sediment in-situ bulk density, current velocity, wave data, tidal range, sediment bed morphology (presence, period & amplitude of sand waves), bathymetry and geophysical data.

In terms of background fluorescence, invariably this information is not known, requiring the collection of grab or core bed sediment samples. These samples need to be analyzed back at a laboratory to determine presence and wavelength of background fluorescence.

Once these data are compiled, and the study objectives are known and agreed, it is possible to select the tracer particles. Generally the tracer particles will be manufactured to match the natural sediment across the entire size distribution, however if required the tracer particles can be manufactured to match a narrower and more specific size fraction, perhaps the fine or medium sand on the beach, rather than the complete distribution if the material is poorly sorted. Alternatively if the sediment transport study is being used to validate a model, a specific or tighter size range may be of more interest. In terms of the fluorescent color to be used, this is matched to the background fluorescence if there is any present. Once a decision is made as to the fluorescent tracer particles properties, manufacturing generally takes approximately 3-4 weeks.

Labelling

Once the EcoTrace fluorescent tracer particles are manufactured there are no further requirements to label or activate the material prior to release, however it is advisable to store this material in cool, dark and dry conditions until used.

Injection

Bed load transport studies generally require placement of the material on the bed itself in order to investigate bed sediment transport without spillage into the water column. On occasions, particularly if the sediment is coarse then it can be released in the lower water column rather than directly on the bed. ETS have conducted bedload sediment transport studies by first releasing the material from a dredge hopper; bedload transport was monitored of the fraction remaining on the seabed immediately after disposal.

Prior to release it is necessary and advisable to mix the fluorescent tracer particles with the native sediment from the site at ratios of between 1:1 to 1:2, for native sediment and fluorescent particles respectively (Fig. 96). This is carried out to ensure that fluorescent tracer particles adsorb any available surface charge from organics present, including from humic or fulvic acids or mucoid layers. This is particularly important for cohesive sediments since the processes of sediment transport including erosion, resuspension, transport, settling and deposition are affected by the electro-chemical charge of the particles, as a result of adsorption of organics rather than the individual grain density. Mixing with the native sediment also ensures homogeneous mixing and placement rather than a continuous and solid layer of fluorescent tracer particles.

FIG. 96. Mixing sand tracer and natural sand in a mixer, Mouth of Columbia River, Oregon, USA.

Once mixed, the tracer particles and native sediment are stored in numerous sealed drums or tubs until release. ETS have adopted different release methods often depending on the specific requirements of the study as follows:

In drying areas such as inter-tidal areas (mudflats, beaches) the natural sediment/fluorescent tracer particle mix can be released by placing it onto or mixing it into the sediment surface. This can be done either manually or mechanically using machinery such as a backhoe or digger (Fig.97).

FIG. 97. Placement of EcoTrace particles on a sandflat in the Tees Estuary, UK.

For bedload sediment transport studies, it is more difficult to release EcoTrace particles under the water surface without spreading them in the water column prematurely. ETS have achieved this by either freezing the material and then sheathing the frozen material in water ice to prevent premature release as a result of melting (Fig. 98).

FIG. 98. Frozen blocks of tracer and contaminated sediment to assess sediment transport in 90m water depth in the North Sea, UK.

More recently ETS have used starch based soluble bags. Material placed in such bags can be dropped or lowered to the seabed; the bags dissolve in 1-2 minutes and release the sediment tracers on the bed without spillage (Fig. 99).

FIG. 99. Decanting the sediment: tracer mixture from sealed tubs into starch-based dissolving bags prior to release at the water surface, Mouth of Columbia River, Oregon, USA.

Sampling

In order to collect data to determine the behavior, transport and fate of the fluorescent tracer particles, bed sediment samples must be collected spatially and temporally, using a sediment core sampler or grab sampler (Figs. 100 and 103). The frequency and coverage of bed sediment sampling will depend on the study site and study objectives. It is ideal and often necessary to collect several sets of samples over time in order to build up a map of transport and distribution increasing confidence in the findings. The number of samples collected per sampling survey will also be a function of the study objectives.

One consideration is that in order to build up a centroid mass or to determine the main areas of tracer particle distribution, sampling needs to be spatially relatively intense, perhaps at a frequency of 50-100 m intensity. However if the study design is focused on whether sediment transport occurs between the release point, Point A, and a sensitive environmental site some distance away, Point B, then sampling intensity between these points can be reduced.

Typically for sediment transport studies, ETS will collect a set of near-field samples immediately after the tracer release in order to define the footprint of the release area, termed a Containment Survey. Ideally this would then be followed by sampling on 3 or 4 additional occasions in order to build up an impression of the spread and re-distribution over time and area.

For each seabed sample collected, a DGPS position is noted along with time and water depth if applicable in order to plot the results in a GIS software package. On occasions, samples are also collected using sediment traps, particularly if for certain energy conditions particles are likely to be resuspended and transported. Sediment traps can be positioned at different depths in the water column depending on the anticipated energy and likely level of particles present in the water column.

FIG. 100. Operating a sediment grab sampler: Shipek grab.

FIG. 101. Pushcore sediment sample showing visible presence of magenta EcoTrace particles present, White River, Arkansas, USA.

FIG. 102. *Collecting a pushcore sediment sample, White River, Rkansas, USA.*

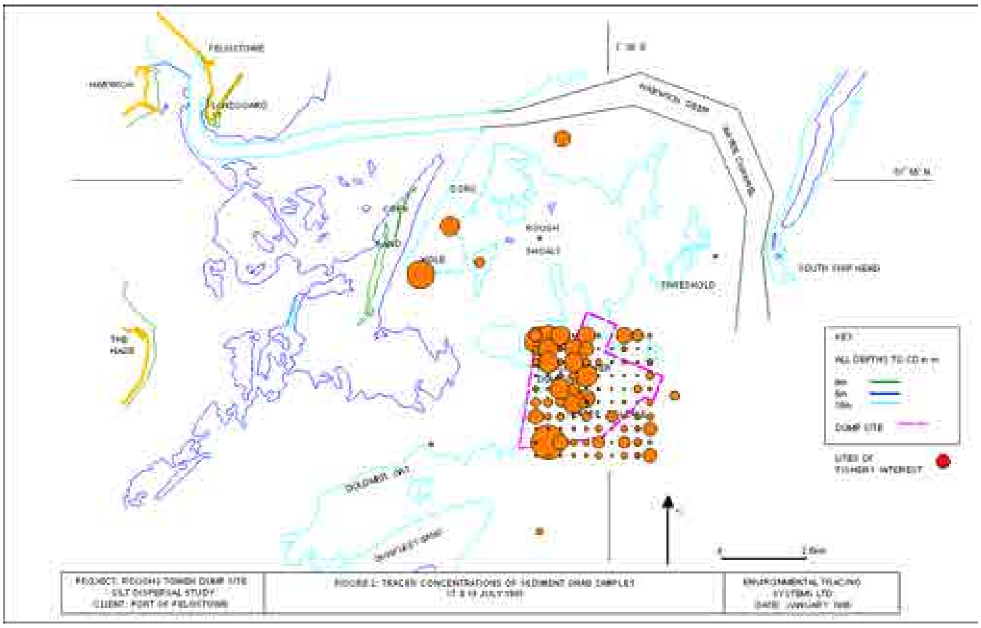


FIG. 103. An example of intensive sampling to characterise a dredge disposal site for the Port of Felixstowe, UK's largest port.

Sediment transport modeling by HR Wallingford proposed that the site was highly retentive, but bathymetry data showed no long-term accumulation of sediment and siltation was observed in the surrounding areas to the disposal site. ETS used a silt tracer to label a dredge hopper load, which was then dumped and intensive grab sampling took place over 1-2 days to measure how much of the original load remained at the site. The orange circles represent the concentration of silt tracer per grab sample indicating a northwest dominant distribution from the centre release position. By averaging the concentration over the disposal site area ETS determined that approximately 1% of total quantity of tracer particles originally released remained within the disposal site within 1-2 days. Dispersal was also seen at the surrounding siltation sites. Over the next 3 months of monitoring ETS observed the tracer concentrations to decrease to less than 0.1% at the disposal site with widespread distribution in the deeper siltation areas including the ports navigational channels and berth pockets inside the port estuary itself.

ETS released approximately 1.2 tons of fine sand-sized fluorescent tracer particles on the seabed within the disposal site operated by the Portland District of the US Army Corps, located to the north of the Columbia River navigation channel (Fig. 104). The release took place in September 2006, before winter storms with prolonged wave activity up to 10 m significant wave height. Sampling was conducted after 2 days, 2 months and 6 months; the results for distribution of tracer particles after 6 months are shown above. The sand tracer concentrations, denoted by the red concentration circles which are fluorescent tracer particle counts per 100g of dry sediment, was transported as bedload and by saltation over an area of 70 km^2 with the dominant transport pathways being to the north and west, remaining in the littoral zone of the ebb shoal area including depositing on the Washington State Beaches such as Benson Beach.

The sand tracer was monitored for more than 1 year, confirmed that sand does nourish to a degree the Washington Beaches and that sand disposed in this area enters the natural surrounding sand budget, rather than becoming distributed into deeper water offshore, or back in the navigation channel. Given the very high energy of the site and shallow water conditions relative to the Pacific Ocean swell, sediment tracers offered the only reliable way to provide data on sediment transport and ultimately dredged sediment management.

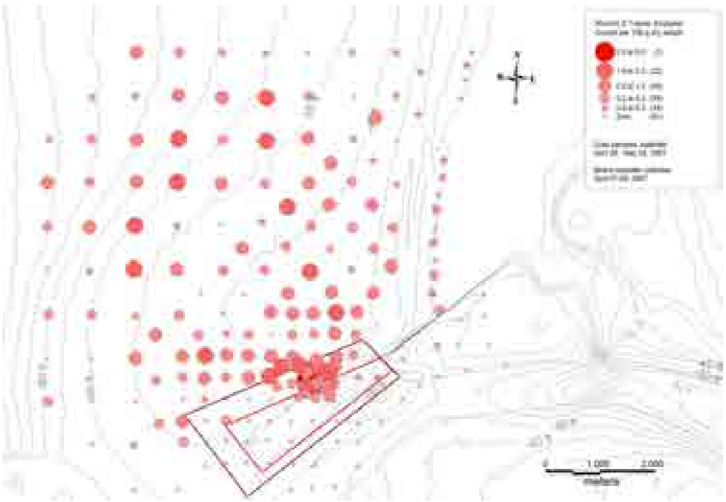


FIG. 104. Tracer concentrations measured for a sand bedload transport study at the Mouth of the Columbia River, Oregon, USA.

Analysis

In order to determine the distribution of silt or sand tracer ETS rely on collecting seabed grab samples and/or core samples. These samples are analyzed in ETS' ISO accredited laboratory using a range of techniques depending on the nature of sample, tracer particle size range, sediment size range, number of fluorescent colors used, volume of sample and the criteria of the study. Analysis can include analytical flow cytometry, fluorescent microscopy, CCD photography and image analysis techniques and fluorescence magnification.

In general terms, all collected grab and core samples are given a unique code in the laboratory prior to preparation, are then weighed as a wet sediment, dried to constant weight and then weighed to give a dry weight mass. This allows all samples to be compared relative to each other in terms of tracer counts per dry weight.

Tracer particle counting is carried out in wet form if done using flow cytometry with the sample being analyzed as wet sediment tracer particle slurry, with conversion of counts in the wet slurry back to counts per dry weight. Tracer particle counting is also carried out in dry form with the particles being counted by automated microscopy and image analysis.

In the case of sand tracer studies, sample volumes analyzed range between 50-1000g of dry sediment typically. For silt tracer studies, sample volumes analyzed range between 0.5-5g of dry sediment typically. However larger volumes can be analyzed if required.

7.2.2.2. Suspended sediment transport

Selection of tracer

Similar to Bedload Sediment Transport studies, background information is required for all study sites but in particular information on the background fluorescence and sediment characteristics of the suspended sediment at the site for a comprehensive list of information that is useful or required. Once the background sedimentology and fluorescent characteristics of the sediment are known then the scope and objectives of the study should be re-evaluated. Given that the fluorescent tracer particles will be added to a suspended sediment plume it is particularly important to ensure that the proposed scope is manageable and practical, given a 3D very dynamic study requirement.

For example if the velocities are high the plume can be advected very quickly making it very difficult to track without multiple boats and multiple sampling and measurement equipment. If there are depositional environments then sediment and tracer can settle out during slack tidal currents or slower areas of flow and also be advected requiring 2 different aspects of monitoring that are not necessarily similar. For this purpose ETS used other rapid data acquisition tools such as an ADCP to assist in predicting the likely fate of the plume, based on instantaneous water column velocities and turbidity sensors deployed vertically in the water column.

Once the scope of work has been re-evaluated and there is confidence that the project requirements are clear and achievable the tracer particles can be selected. Manufacture generally takes approximately 3-4 weeks. Generally suspended sediment plumes comprise of silt particles with density 2.65 g cm^{-3} and size ranges of silt and very fine sand.

Labelling

Once the EcoTrace fluorescent tracer particles are manufactured there are no further requirements to label or activate the material prior to release, however it is recommended that they are stored in cool, dark and dry conditions until used.

Injection

Suspended sediment transport studies generally involve the release of sediment and particles into the water column via a discharge pipe (for example from a dredge discharge pipe) or by releasing the tracer particles into a dredge hopper followed by disposal at the approved dredged sediment disposal ground.

A further alternative might be investigation of overflow or spillway discharges from dredgers into the environment; dredgers overflow in order to maximize the solids content and load to avoid shipping water, so allow water and very fine sediment to be spilled whilst the hopper fills up. This plume is often of a concern in terms of burial and swamping of fisheries areas, causing increased water column turbidity and general environmental impact. Monitoring the direction of overflow plume, concentration, rate of dispersal and fate may all be required to be known; ETS have used tracers to label and track these overflow plumes.

In all three cases the releases are controlled by the plant machinery or the engineering aspect of the study with the movement and dispersal being in part a function of the release mechanism. Therefore the behavior, fate and excursion of the suspended sediment plume is driven and controlled by the release mechanism.

Ultimately, the sediment in a suspended sediment plume can settle out and deposit. One component of understanding often requires the need to collect bed sediment samples. The spatial and temporal intensity of sampling is dictated by the dispersal range of the suspended sediment plume and the objectives of the study in terms of identifying the fate of the sediment and fluorescent tracer particle material.

In the case of the release of the fluorescent tracer particles into a dredge hopper it is strongly recommended to add the marker once the dredge hopper is at the disposal site rather than filling up or travelling to the site, since many hoppers leak potentially leaving a trail of tracer particles from the dredging site itself. It is also important that thorough mixing takes place of the tracer within the hopper, generally achievable by using a dredger's re-circulation pumps. In the case of a pump discharge, such as a dredge discharge, it is ideal to make sure the fluorescent tracer particles are thoroughly mixed in the discharge and that the particles are released over a sufficient long period to average discharge conditions or environmental conditions, perhaps releasing at steady-state for a prolonged period to simulate the dredge discharge which often can be continuous for days.

Orange silt tracer being released by ETS into a dredge hopper at Milford Haven Port, South Wales, UK in large swell conditions, to characterize a new disposal site and assess whether dredge material dispersed and impacted a marine Special Area of Conservation (mSAC) and one of only 2 Marine Parks in the entire UK (Fig. 105). ETS found that sediment was reaching the environmentally sensitive sites and a more distant disposal site had to be found and characterized with sediment tracers

FIG. 105. Orange silt tracer being released by ETS into a dredge hopper at Milford Haven Port, South Wales, UK.

Magenta silt tracer being released by ETS into a dredge discharge pipe in Atchafalaya Bay, Gulf of Mexico, US (Fig. 106), to determine whether the dredged sediment was been advected back into the navigable channel or was advected away from the channel. ETS found that the dredged sediment returned back to the navigation channel within 24 hours of release.

FIG. 106. Magenta silt tracer being released by ETS into a dredge discharge pipe in Atchafalaya Bay, Gulf of Mexico, US.

Magenta silt tracer being released by ETS via an aggregate dredge overflow in the South North Sea, UK (Fig. 107). This was then followed by tracking of the plume to assess dispersal and ultimately deposition on the bed to show whether burial and clogging of sensitive marine organisms occurred.

FIG. 107. Magenta silt tracer being released by ETS via an aggregate dredge overflow in the South North Sea, UK.

Sampling

The description below concentrates on the mapping of suspended sediment plume. It is recognized that over time or with distance from the release deposition will take place and sampling will revert back to those more typical for bedload transport studies, i.e. seabed grab and core sampling.

Monitoring of the suspended ideally requires the use of ADCP to provide rapid data acquisition of current velocities throughout the water column to predict the likely pathway prior to release, and then the actual plume movement after release (Fig. 108). ADCP's also log backscatter data which if calibrated carefully with collected water samples and/or calibrated turbidity sensors can be used to map the turbidity of the plume as well as the currents. Software is available to utilize these data more effectively but still require a great deal of calibration to use it correctly.

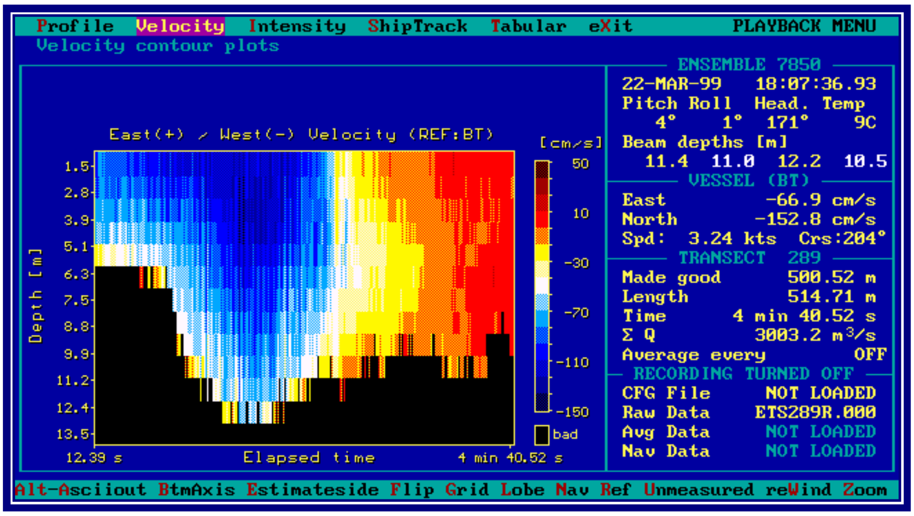


FIG. 108. ADCP data showing velocity vectors across an entire transect in a navigation dredge channel with faster currents shown in blue up to 1.5ms-1 and weaker currents in red.

ADCP data showing velocity vectors across an entire transect in a navigation dredge channel with faster currents shown in blue up to 1.5 ms^{-1} and weaker currents in red (Fig. 109). Velocity direction data is also collected simultaneously. Based on such data if the dredge plume is released in the main faster flow channel, ETS can assess how fast and in which direction the plume is likely to move. Figs. 109a and 109b below for ADCP current velocity and current direction highlight stratification in the water column for a study conducted for the Port of Rotterdam which can make a large difference in the fate of the dredge plume released.

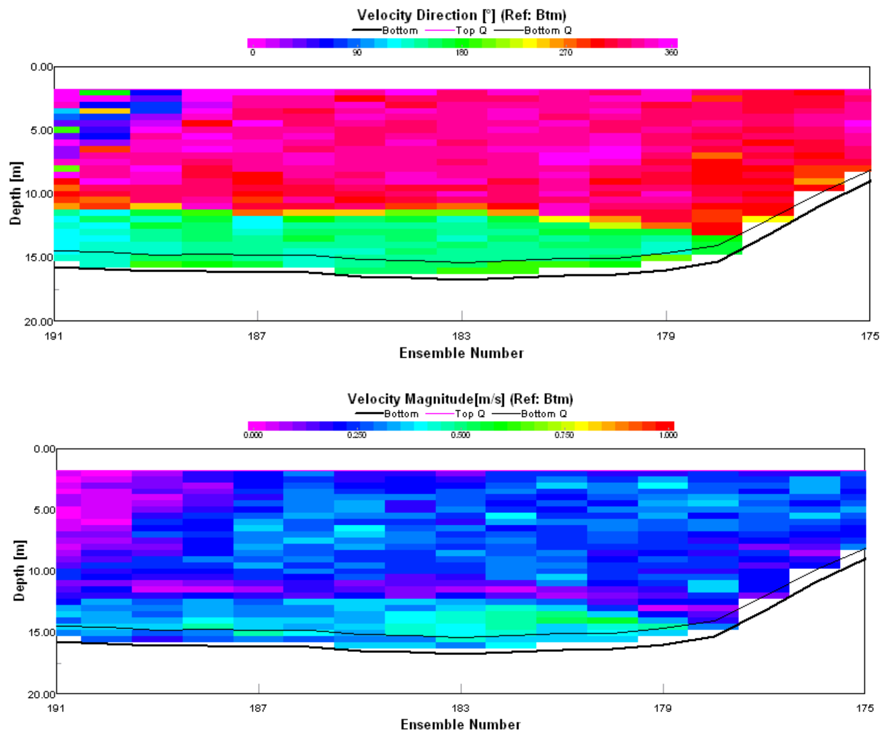


FIG. 109. ADCP data in a study for Port of Rotterdam showing very fast surface velocities leaving a dock area on the ebb tide but much weaker opposing velocities going back into the port in the lower water column.

ETS used the tracer to label the dredge plume and track its fate in terms of turbidity and the sediment silt tracer for the Port of Rotterdam, with the main highest tracer concentration close to the bed where dredged sediment was being transported back into the port (Fig. 110).

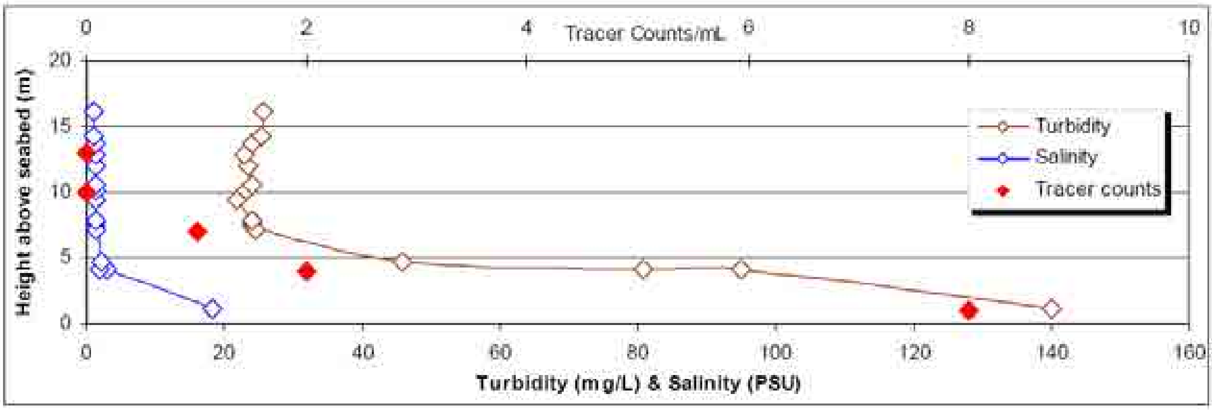


FIG. 110. ETS used the tracer to label the dredge plume and track its fate in terms of turbidity and the sediment silt tracer for the Port of Rotterdam.

For suspended sediment plume monitoring, ETS require to collect ADCP data, for both current velocity data and backscatter data, deploy a string of turbidity sensors and collect either manual water samples at different depths or pump water from different depths through on-board fluorimeters or field portable flow cytometers (Fig. 111) to measure the dredge plume characteristics in real-time. DGPS positions of the monitoring vessel and any sample collection is also logged. The instrument takes images of the positive particles to confirm shape and size and fluorescence which can be analyzed later by image analysis.

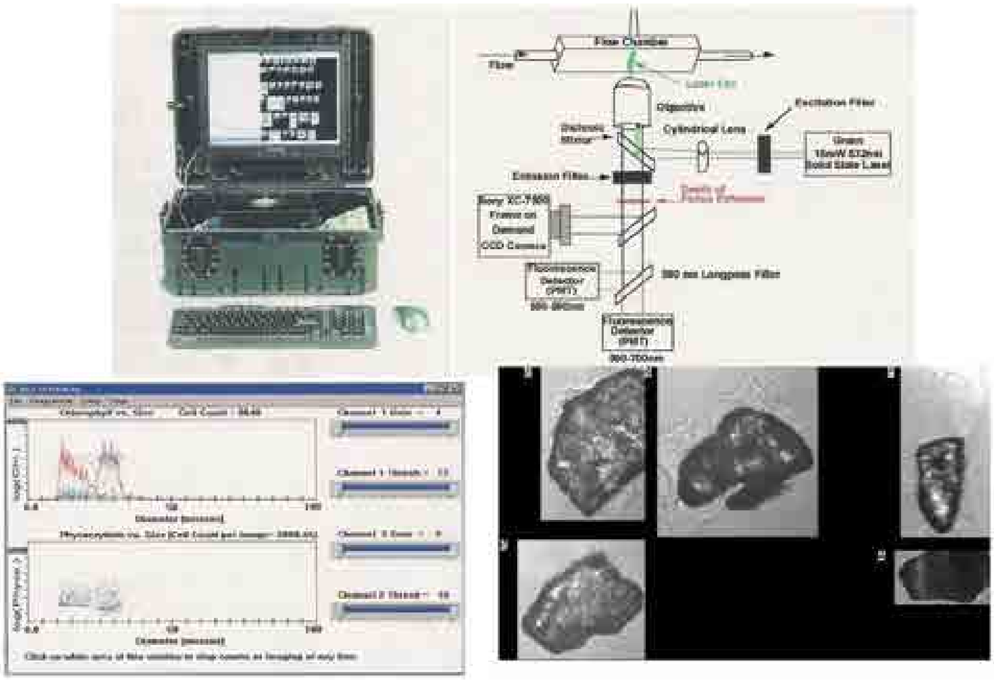


FIG. 111. ETS' Field portable TracerCam used to measure tracer particles in-situ or at the project site, by pumping water real-time or collected samples through the system.

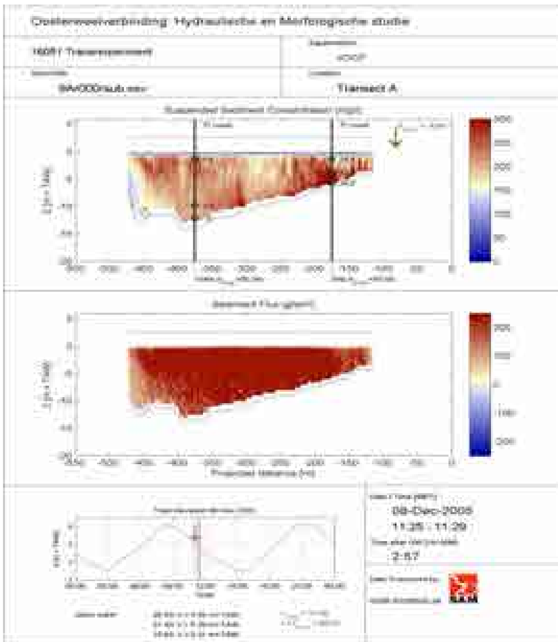


FIG. 112. ADCP backscatter data calibrated with rapid profiling Siltprofiler data.

Figure 112 shows a suspended sediment dredge dispersal study carried out by ETS in the Scheldt Estuary, Belgium, to investigate the fate of the suspended dredge plume immediately after a dredge release within a designated disposal site. Real-time ADCP data were used to assess the likely fate of the plume and then on release the actual fate by collecting backscatter data. Rapid drop Silt profiling data were collected along with sampling for silt tracer, which was released in the dredge hopper prior to dumping. ADCP backscatter data calibrated with rapid profiling Siltprofiler data demonstrating the main dredge plume, in terms of highest turbidity was to the right side of the channel (top image) with tracer concentrations measured marked on the plume. The highest tracer concentration coincided with the highest turbidity indicating this was the dredge plume.

Figure 113 shows the dispersal of the dredge plume in terms of ADCP velocity and backscatter data collected across the channel, with tracer concentrations measured at different depths. The highest tracer particle concentration coincided with the maximum turbidity close to the bed on the righthand side of the channel. Subsequently at the ebb tide slack water and the next flood tide slack water garb sampling was also carried out on the bed in order to determine spread of deposition and the distribution pattern including assessment of any increased deposition within berth pockets and dock basin entrances.

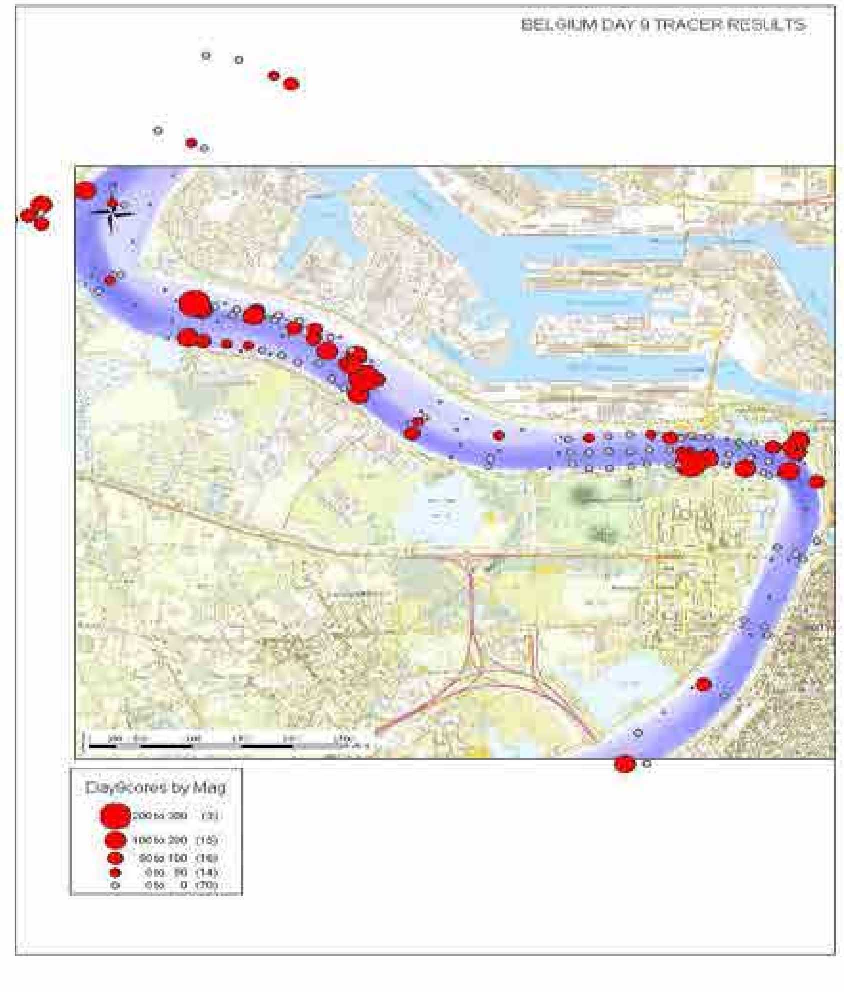


FIG. 113. Tracer concentration data collected in grab samples immediately after dredge disposal on the ebb tide and then subsequent flood tide indicating deposition on the bed as the dredge plume advected down and then back up the estuary on the return tide, showing widespread dispersal.

8. RADIOISOTOPE SEALED SOURCE TECHNIQUES FOR MEASURING SUSPENDED SEDIMENT

8.1. PRINCIPLE OF SEALED SOURCE TECHNIQUES FOR MONITORING DENSITY AND CONCENTRATION OF SEDIMENTS

The knowledge of the concentration C of suspended sediment (mass of dry sediment in a given volume of water) is an important data for the evaluation of the consequences of the human intervention in hydrographic basins: erosion problems arising from either afforestation or deforestation schemes and also from agricultural and mining activities in lake catchment basins.

Radioisotope sealed source techniques can provide continuously:

- density of the sediments deposited in a dam or a channel of navigation;
- concentration or turbidity of sediments circulating in suspension.

The absorption (photoelectric effect) or scattering (Compton effect) of electromagnetic radiations (X or γ) emitted by a radioactive sealed source are function of the concentration or the bulk density of the mixture sediment-water. In this way it is possible to construct nuclear gauges based on these principles, provided that the system is calibrated for known concentrations.

The gauges of density or turbidity function either by transmission, or by diffusion. The principles are summarized by the following diagram (Fig. 114).

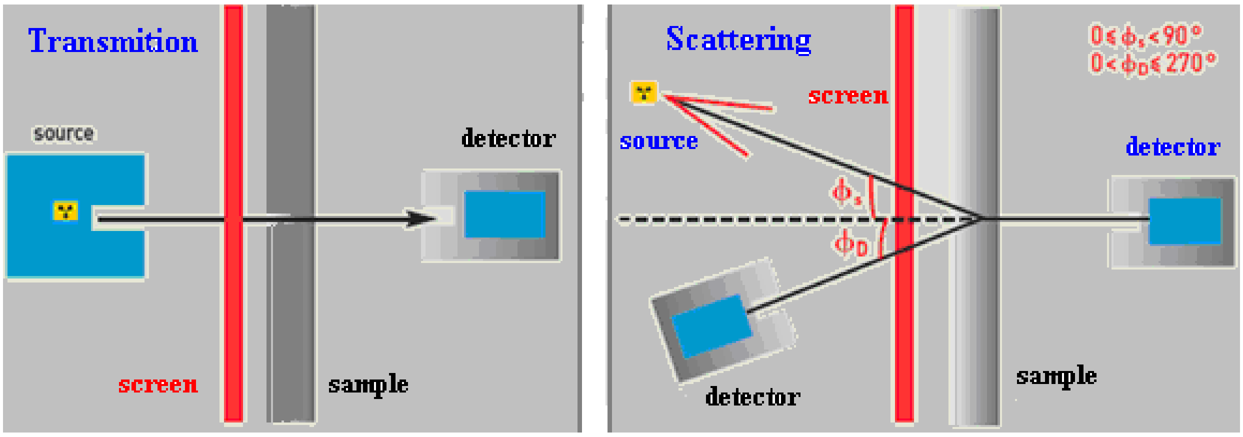


FIG. 114. Principle of measurement of sediment density or turbidity by radiation transmition (left) and scattering (right).

The "in situ" measurement of high concentrations (greater than 500 to 1000 mg/L, up 1kg/L) of suspended sediment (sand, silt and clay) in the feeding rivers and of the bulk density of fine sediments (silt and clay) deposited in reservoirs, are applications of nucleonic gauges for obtaining data for the sedimentological balance of the system or to control dam slush.

In estuarine and coastal environments the nuclear gauges can be employed for measuring the bulk density of fine sediments deposited in enclosed bays, access channels, turning basins and berthing areas of harbors, and in the well of dredgers. These measurements are related to the optimization of dredging works. There is also a potential application for nuclear gauges in measuring the high suspended sand sediment concentration in the energetic wave breaker zone.

The volume of influence of nuclear gauges is proportional to the energy of the gamma radiation of the radioactive sources: 8-10 cm diameter for ^{109}Cd sources, 20-40 cm for ^{241}Am sources and greater diameters for sources of higher radiation energy as ^{137}Cs and ^{60}Co.

8.1.1. Transmission gauges

Nucleonic gauges based on the principle of the absorption of X or γ radiations are known as transmission gauges (Fig. 115). With this type of gauge it is possible to measure the intensity $I_{s,w}$ of a radiation beam after being transmitted through water containing sediment. The intensity of the initial beam, in absence of sediment is $I_w > I_{s,w}$.

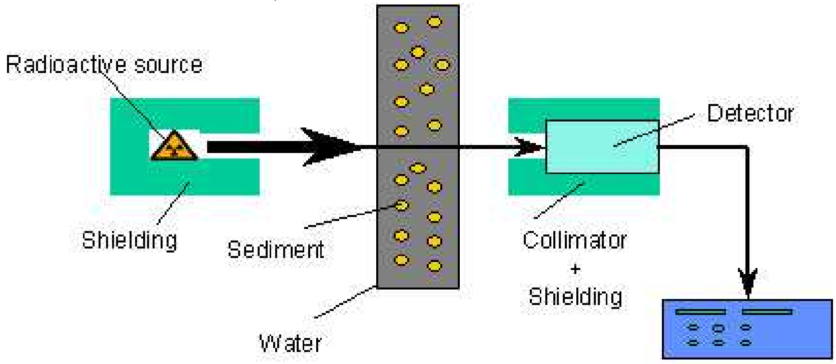


FIG. 115. Scheme of the radiation transmission measurement principle.

Designating by $R_{s,w}$ and R_0 the count rates corresponding to $I_{s,w}$ and I_0, the measured count rate after a monoenergetic electromagnetic beam is transmitted through x cm of *pure water* is given by:

$$R_w = R_0 \cdot \exp(-\mu_w \cdot \rho_w \cdot x)$$

where μ_w and ρ_w are, respectively, the mass attenuation coefficient (cm^2/g) and the density (g/cm^3) of pure water.

If the water contains sediment in suspension at a concentration C, the measured count rate will be:

$$R_{s,w} = R_0 \cdot \exp\{-\rho_m \cdot x\,[\mu_s \cdot C + \mu_w(1 - C)]\}$$

where μ_s is the mass attenuation coefficient of the sediment and ρ_m is the density of the mixture water-sediment:

$$\rho_m = \frac{\rho_s \cdot \rho_w}{\rho_s - C(\rho_s - \rho_w)}$$

where ρ_s is the density of the sediment.

The mass attenuation coefficient for the sediment increases with the decreasing in the energy of γ radiation. The sensitivity (i.e. contrast), which is the ration $R_{s,w}/R_0$, and thus accuracy of the measurements increase when the radiation energy decreases. The measurement depends on the chemical composition of the measured sediment. A compromise has to be defined between the sensitivity of the concentration measurement and the sensitivity of the instrument to the variations of the sediment composition.

Figure 116 shows the relation between the contrast and the gamma ray energy.

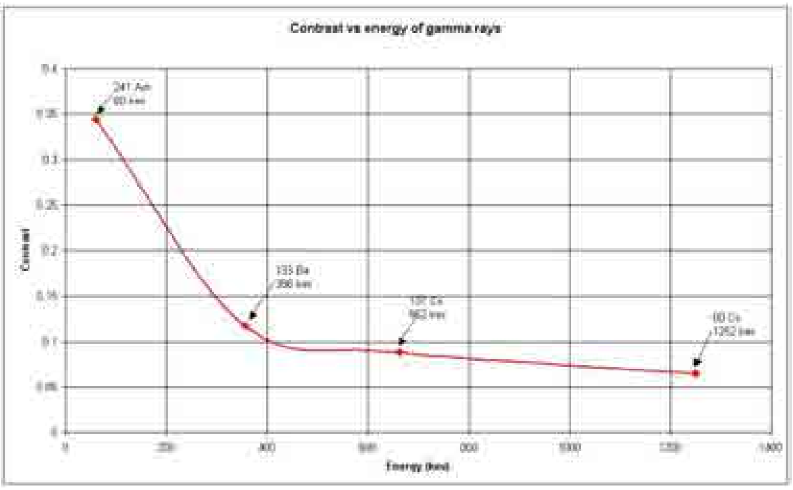


FIG. 116. Influence of the gamma ray energy on the contrast for a transmission gauge designed with a classical geometry (distance source-detector 20 cm, low collimation).

Emitters having electromagnetic radiation with low energy, such as: ^{241}Am (γ ray – 60 keV) and ^{109}Cd (X ray – 22 keV) are used in nuclear gauges, in order to increase the contrast.

The relative sensitivity of measurement is the ratio of the relative change in counting rate to the relative change in sediment concentration. The sensitivity is greater at lower energies because of the increased difference between ρ_s and ρ_w. Very low energy problems arise from the increased influence of variations in chemical composition of sediments

Practically speaking, the instruments are more efficient if they are designed or adapted to each particular situation and have to be calibrated with the sediments, which will have to be measured on the site. From these considerations it is possible to give some typical values of the measurement precision for some classical gauges (Table 18).

TABLE 18. TYPICAL VALUES OF THE MEASUREMENT PRECISION FOR SOME CLASSICAL GAUGES

Energy (keV)	Thickness of the measurement cell (cm)	Counting rate ($c.s^{-1}$)	Counting time (sec)	Measurement uncertainty at 65% confidence
30	5	40000	300	0.09 g/L
60	17	11000	300	0.28 g/L
662	30	30000	300	0.5 g/L

Example of a radiation transmission gauge using pump sampling designed for dam flushing management is shown in Fig. 117. The mixture is continuously sampled from the river with pumps and is released at the top of the system. In the example of Fig. 108 the flow has a very high speed (25 $m.s^{1}$) and so the mixture is composed of three phases (water, sediment and air).

The air is first removed in the vertical steel pipe, then the sediment + water mixture is arriving in the measurement cell between the source (^{241}Am) and the detector. After measurement, the mixture is released to the river. This gauge is robust and can be employed in strong conditions (high concentration up to 300 $g.L^{-1}$, etc…). Smaller systems also exist for normal streams.

FIG. 117. A mobile gauge (SERES) using pump sampling designed for dam flushing management.

It is important to note that, in the case of transmission gauges, the radiation source can also be an X-ray generator (Fig. 118).

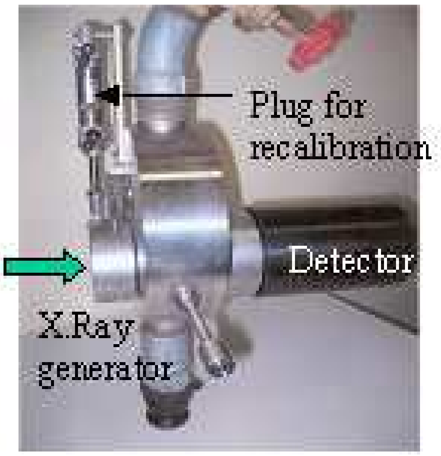


FIG. 118. Gauge based on an X-ray generator 30 KeV and a CsI detector.

This type of device has great advantages in terms of photon flux and energy of the emitted photons but has also some disadvantages. An X-ray generator needs a power supply and is less stable than a radioactive source. This relative instability induces the necessity to recalibrate periodically and automatically the system with a standard material. These generators are useful for relatively large interval of concentration measurement (0.5 to 500 $g.L^{-1}$). An important advantage using X-ray generators is the regulation aspect. There is no particular regulation if the maximum emitted energy is lower than 30 kV and if the dose rate at 10 cm from any accessible point of the system is lower than 1 $\mu Sv.h^{-1}$. Its dimensions are about 30 cm in diameter and 5cm thick.

The typical transmission nucleonic gauges have the following characteristics:

- The measurement volume depends on the collimation of the source and of the detector: distance source detector: typically between 5 to 50 cm; diameter of the beam: typically from 1 to 5 cm
- An operational range encompasses sediment concentration between 0.5 and 1000 $g.L^{-1}$.

The transmission gauges are, due to their measurement range, used both for bed density measurements (harbor basins, dam reservoir, lagoon, muddy areas...) and suspended sediment concentration in rivers. They can be operated from a boat, a bridge or the bank of the river for the mobile devices.

For bed density measurement, a small boat (rubber boat for ex.) is generally required. The probe is lowered on a suspension cable to sink into the soft bed under its own weight. In this case probe depth is given by a pressure sensor. Vertical profiles of concentration (i.e. density) are recorded along a grid in order to map the measurement area. For suspended sediment concentration measurement, the probe is towed by a cable at a defined depth in the stream or can be moved in the cross section (vertically and horizontally) to obtain the concentration field. In these two cases, the weight can be an advantage for the penetration of the probe in mud deposits and for having a good stability in the stream.

For static measurement the device has to be installed in a concrete channel. The main problem for the static systems is, as for the optical systems, to be sure of its representativity and also to be sure of the stability of the river bed.

Two operational cases are used:

- Utilization at fixed point to measure suspended sediment concentration in a stream: the installation of the device can be realized by one or two workers with some training regarding the use of the system and regulation and safety procedures.
- Utilization from a boat to measure vertical profiles of concentration in mud deposits: at least two persons are necessary, one for the gauge, and one for the boat.

8.1.2. Scattering gauges

Nucleonic gauges based on principle of the scattering radiation are known as scattering gauges (Fig. 119).The radiations measured are only those scattered by the suspended sediments into the volume of influence related to the gauge. In this way, the signal is a function of the density or concentration of the mixture water-sediment. The sources normally used for scattering gauges are ^{137}Cs (mainly) and ^{241}Am. The scattering gauges are cylindrical and, in this way, they are suitable for measuring density of fine sediments deposited in reservoirs and to measure vertical gradient of sediment densities in the well of dredgers or barges, either by fall down or being introduced in tubes previously placed at the measuring sites.

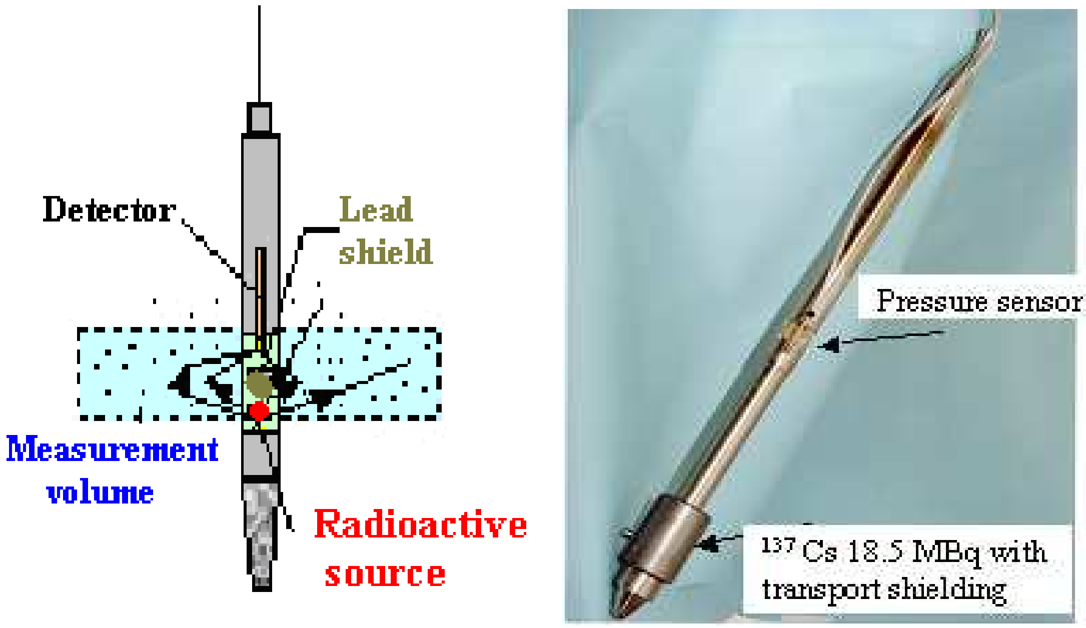


FIG. 119. Scattering principle (left) and the scattering gauge JTD3.

Figure 119 presents a typical needle-form gauge based on scattering principle. It is 1.4 m long, 6 cm diameter and 20 kg weight and is designed for in-situ measurement of vertical density profiles of mud deposits. ^{137}Cs is the radioisotope sealed source currently used for this type of gauge.

The gauge shown in Fig. 119 has the following characteristics:

- The temporal resolution depends on the requested accuracy, the concentration and the activity of the source (i.e. the flux of photons emitted by the source). For example, the measurement time will be 10 seconds for a ^{137}Cs source (18.5 MBq), a concentration of 300 $g.L^{-1}$ and an accuracy of ± 10 $g.L^{-1}$ (68% confidence level). Practically the measurement time can vary between 1 sec and 1000 sec (or more).
- Spatial resolution: The measurement volume is usually big: it is 10 cm thickness and 70 cm diameter.
- Operational ranges: This type of instrument has a measurement range which encompasses sediment concentration between 20 and 1000 $g.L^{-1}$ (is mainly used for high concentration measurement).

The count rate $R_{s,w}$ measured by the detector is a function of sediment concentration and is related to the number R_w of photons measured in pure water by the equation:

$$\frac{R_{s,w}}{R_w} = (a \cdot \rho)^n \cdot \exp(-a \cdot \rho)$$

where ρ is the density or concentration of the turbid water, while a and n are constants characterizing the gauges.

The functional relationship is obtained experimentally by calibration in laboratory conditions.

8.1.3. Data treatment

The first step in data treatment is to convert raw data into a user defined unit ($g.L^{-1}$ or density). A simple algorithm can be applied using the equation (1) including the coefficients determined by the calibration. It can be included in the data acquisition software or written by the operator under Microsoft Excel or any type of programming language. It is also possible at this stage to clean the data by smoothing, aggregation, erasing the wrong data if any, etc. The second step concerns the exploitation of the physical parameter itself. This step depends on the problem and on the site.

Suspended sediment concentration is interesting by itself but the interest will be more important if it is possible to measure at the same time the water flow rate. The integration of the information will give the mass transported by the flow and the relationship between flow rate and concentration. The exploitation of vertical profiles of mud deposited in harbor basins, dam reservoirs, etc… will take a greater value if they are shown as a map. This treatment can easily be done using Geographic Information System. Obviously this type of mapping will require on site a Global Positioning System.

A calibration curve is obtained by relating the counting rate N to the varying suspended sediment concentration values.

8.2. FRENCH NUCLEONIC GAUGES PROTOTYPES FOR TURBIDITY MONITORING

Dam silting-up problems creates difficulty in constant electric power supply, and shortfalls in electricity generation are experienced during peak demand periods. The increasing demand for electricity calls for expanded exploitation of hydroelectric dams, which requires heavy dam maintenance. Dams and reservoirs are vital in terms of water supply, irrigation, flood protection, and electricity generation. Large investments are needed for maintaining the efficiency of dam and reservoir operations. Sustainable exploitation of dams requires an in-depth understanding of the silting-up process and monitoring of sedimentation rates using both nuclear and conventional techniques.

Nucleonic gauges for measuring the sediment concentration in water streams have been designed and manufactured in France and provided to many Member States under the IAEA TC programme. They give important information on suspended sediment concentrations in rivers and sediment load to reservoirs as the basic parameters for improvement of dam maintenance.

The nucleonic density gauge can measure continuously the suspended sediment concentrations providing data for optimal operation and better management of dams and reservoirs.

Nucleonic gauge for turbidimetry, allows measuring the navigable depth in the channels of access to the ports. They are daily employed either in point fixes or at the drag by hydrographs formed with this technique. These apparatuses supplement the indications given by the sounders to traditional ultrasounds in mud zones.

Fine sediments can oscillate between the zones upstream and maritime of an estuary, alternatively in suspension or in the form of deposits, while being only slightly expelled in the sea: the estuary is clogged and the channel of navigation must be dredged. In a certain number of estuaries subjected to the effect of the tides, the sedimentation of the silts causes a reduction of navigable depths guaranteed to the ships. It is necessary to dredge then to reject (dredging work of about 2 Euro/ m^3) large volumes (5 to 10 10^6 m^3/y) for a channel of navigation.

Mud compaction according to the time of deposits, their initial concentration, height of the deposit and the salinity of the medium was investigated by a nucleonic gauge using gamma transmition. A source of ^{241}Am (3,7 GBq) is placed opposite a detector with scintillation finely collimated in order to examine only one horizontal sedimentary section of 1 cm thickness. The system source-detector moves vertically at 1 cm/s. The attenuation of the number of photons measured compared to the number of photons emitted by the source is transformed, after calibration of the device, with a precision of about 1 %, in term of concentration of the mixture at one moment and on a given level.

Studies in laboratory using this gauge allowed hydraulicians to conclude that the layer of deposited silt of which the density was lower than 1, 2 g/cm^3 remained navigable and did not impose a dredging problem.

How to measure the density of the sedimentary layers in situ? There are two operational methods:

- measuring the sediment density versus time in a fix position,
- measuring vertical profile of sediment concentration in a fix position and nearly fix time.

8.2.1. Gamma scattering and gamma transmition gauges for turbidity monitoring of mud layer

8.2.1.1. Gamma scattering gauge for turbidity monitoring JTD3

JJD3 is a gamma scattering gauge for field measurement of high concentration of sediments deposited in harbors, navigation channels, dam reservoirs and rivers. It was constructed in 1995. The radioactive source is ^{137}Cs with activity of 18.5 MBq (0.5 mCi) and the detector NaI(Tl) scintillator 12x24 mm. It weights 20 kg (Fig. 120). The range of measurement is 30-800 g/L.

FIG. 120. JJD3 turbidity gauge; the gauge (left) and measuring sea water turbidity (right).

8.2.1.2. Gamma transmission gauge for turbidity monitoring of mud layer JTT4

JTT4 is a gamma transmission gauge for continuous measurement of the density and depth of mud layer in harbor navigation channels. The gauge sits on a sledge (Fig. 121), which is dragged by a boat. It is an indispensable supplement to ultrasonic device (which gives only the position of the "top" of the layer and that of hard bottom). It helps optimizing dredging work.

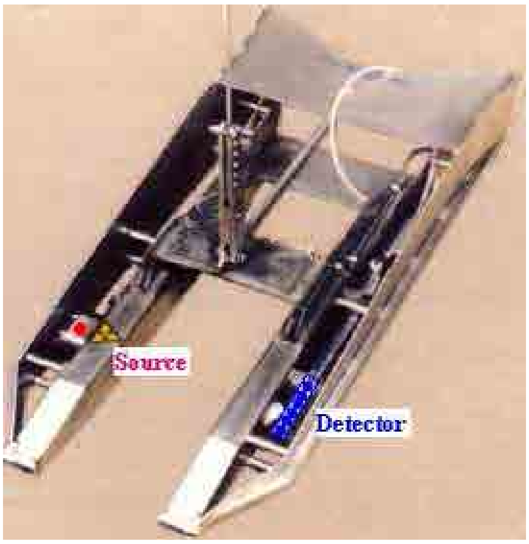


FIG. 121. JTT4 turbidity transmission gauge.

JTT4 prototype was constructed in 1998. It has a Cs-137 source with activity of 222 MBq (6 mCi) and a detector of NaI (Tl) scintillator of 24 x 36 mm. The source detector clearance (where the layer of muddy water circulates) is 20 cm. It weights 114 kg because is designed to move on the bottom of sea, river or dam (is currently used in streams with a velocity greater than 3 $m.s^{-1}$). The range of concentration measurement is 1 to 300 g/L.

8.2.1.3. Seditracker G60 gamma transmission gauge

Gauge description

The Seditracker G60 gamma transmission gauge is designed to respond the needs to measure the sediment concentration in natural environments. There are two operational methods:

- measuring the sediment density versus time in a fix position,
- measuring the vertical profile of the sediment concentration in a fix position and nearly fix time.

The first operational method (Eulerien) gives the sediment concentration versus time. The quantity of transported sediments in a period of time can be calculated knowing the liquid flow rate. The deposed sediment in a dam reservoir can be estimated from monitoring the solid sediments entering and leaving the dam. Monitoring of suspended sediment concentration is necessary for better dam management, in particular in semi-arid zones or zones with high soil erosion. In such an operational mode the Seditracker G60 has similar function like JTD3 gauge.

Monitoring the vertical profile of the sediment concentration is necessary for dam reservoir flushing and navigation channel maintenance. The gamma transmission gauge provides supplementary data to conventional echo-ultrasound technique. The ultrasound frequency of 210 kHz indicates the top of the mud layer while the frequency of 33 kHz gives the position of the consolidated bottom. The difference between them can be up to several meters. The navigation depth includes the mud layer up to the density of 1.2 g/cm^3, which corresponds to nearly 300 g/L of dry mud.

Seditracker G60 gauge (Fig. 122) allows identification of the critical mud density of 1.2 g/cm^3 thus provides the navigable depth optimizing the dredging work. In such an operational mode the Seditracker G60 has similar function like JTT4 gauge.

FIG. 122. Seditracker G60 views: in storage support (left), and reedy for use (right).

The advantages of the Seditracker G60 gauge to JTT4 (gamma transmission) and JTD3 (gamma scattering) are:

- JTD3 has a moderate weight of 20 kg and moderate sensibility; it works only for vertical profiling of turbidity (only one function),
- JTT4 has a heavy weight of 114 kg and high sensibility; it provides mud concentration profile that means the nonconsolidated mud layer above the compact bottom.
- Seditracker G60 has a moderate weight and an improved sensibility; it combines all operational functions of JTD3 and JTT4.
- Seditracker G60 is an intelligent gauge; it has in addition a very small Am-241 source (1 μCi) for internal calibration.

The Seditracker G60 system consists of three parts (Fig. 123):

FIG. 123. View of Seditracker G60 system: gamma transmission gauge, winch and data acquisition system.

- Seditracker G60 gauge,
- Winch for moving the gauge in vertical direction,
- The data acquisition system with data processing software (LATIN 2000)

Evaluation of gauge performance

The evaluation of gauge performance consisted in: radiation measurement stability, construction of calibration curve and general performance.

a. Radiation measurement stability

The radiation measurement stability test was conducted placing the gauge in the water inside the calibration tank (plastic tank with volume of 200 L water). The results of counting's during more than 10 hours (Fig. 124) gave a stability of nearly 1% [I = 26650 cps ± 250 cps (2 σ)].

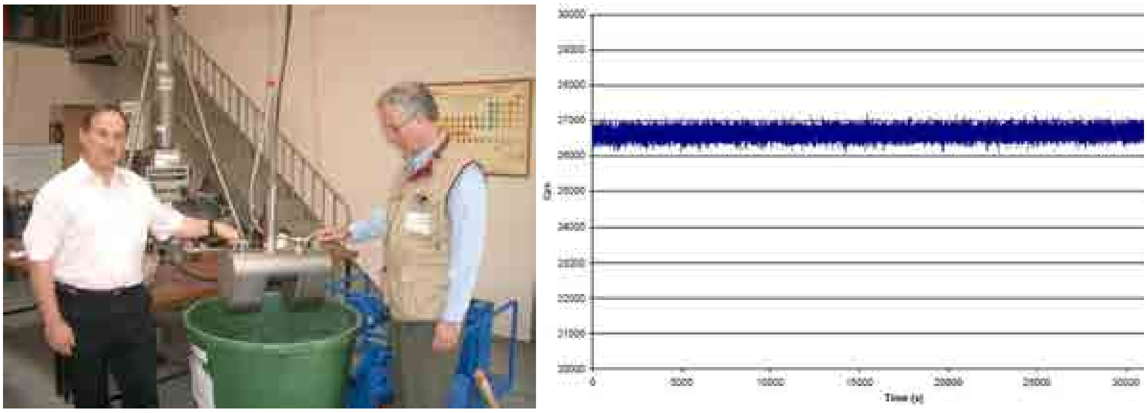


FIG. 124. View of Seditracker.

There are several Seditracker G60 gauges in operation in some countries. Figure 125 shows a Seditracker G60 nucleonic gauge arriving at Kinguele dam (Gabon).

FIG. 125. Seditracker G60 nucleonic gauge for monitoring the sediment density versus time in Kinguele dam, Gabon.

b. Calibration curve

The calibration of Seditracker G60 gauge is a simple but delicate procedure because of the possible influence of sediment properties and of the difficulty of homogenization. The sediment turbidity gauges are applied for fine sediments (silt or mud, with granulometry less than 50-60 µm), which are staying in suspension and moving easy with flowing streams. These very fine sediments are cohesive and flocculate becoming compact mud in stagnant water.

The gamma absorption properties in principle depend on the mineralogical composition of silts. In France was found that practically the gamma absorption characteristics of different silts are very similar. The silt of Loire was used for calibration of turbidity gauges. This silt was used for the calibration of the Seditracker G60 gauge as well.

The procedure of calibration is simple. The most important aspect of calibration is the homogenization of the muddy water in the calibration tank, which requests a heavy stirring in particular for higher concentrations. Figure 126 shows the main aspects of calibration, including silt introduction in the calibration tank with water, stirring with portable stirrer, and taking samples of 10 mL of muddy water with a siring.

FIG. 126. Different aspects of gauge calibration in laboratory.

Figure 127 presents the experimental calibration curve. The experimental points fit well with the linear regress approach (correlation coefficient $R^2 = 0.9919$).

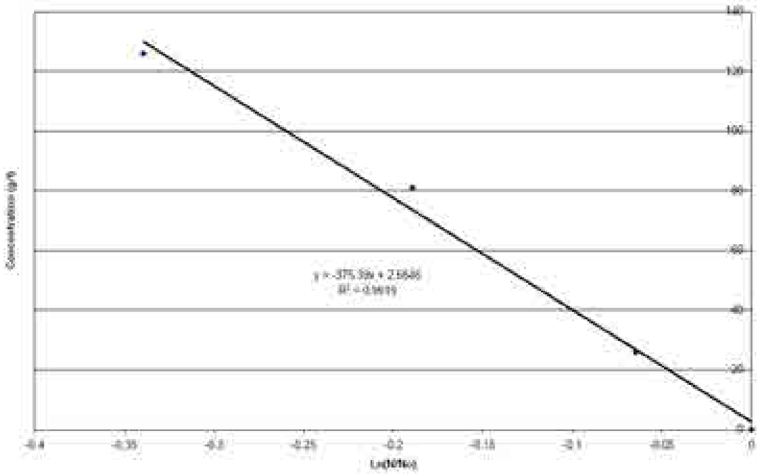


FIG. 127. Calibration curve.

Conclusion

The Seditracker G60 gauge for measuring the sediment turbidity in water streams performs well according to the designed parameter. It is a home-made gauge with new technology that complies well with field harsh conditions. The gauge is compact, watertight till 100 m, easy to operate in field condition with a moderate weight and all necessary accessories for moving and maneuvering in river, dam and sea conditions. The nucleonic gauge has a good stability and high sensibility.

8.3. CASE STUDIES USING NUCLEONIC GAUGES FOR MONITORING DENSITY AND CONCENTRATION OF SEDIMENTS

As pointed out in the beginning of this chapter, there are two main fields of application for nuclear gauges using artificial radioisotopes.

The "in-situ" measurement of high concentrations above 0.5-1.0 g/L up to 100 g/L of suspended sediment (sand, silt and clay), which occurs most of the time in torrential rivers or in flood seasons in some rivers, may be performed by means of manned gauges, allowing the vertical profiling of concentrations or using fixed gauges, for continuous unattended recording of concentration or alternatively for measuring sediment concentration only during flash floods.

In the latter case, the gauge is activated by a switch when a pre-selected water level is reached and is turned off when the level falls.

8.3.1. The draining of dam volume

Dams have to be cleaned up every n years in order to reduce the silting up of them. Gauges of turbidity, equipped with sources of ^{241}Am, measure in real time the quantities of materials evacuated during the discharge (flushing) in order to control the evacuation of mud by using the minimum of the water reserves.

Every three years is performed the evacuation of the alluvial deposits accumulated in a dam close to the town of Geneva (Figs. 128 - 129). If this preventive operation was not made, the reduction in the dam storage capacity could involve flooding of the low districts of the city in the event of storms.

The turbulent masses with strong concentrations can create problem during discharge in the downstream river. Keeping the mud discharge concentration of 5g/L the sedimentation on the river bed is prevented. The success of the operation thus rests on knowledge in real time of turbidities in various points of the site. This information, obtained thanks to gauges with transmission provided with a source of ^{241}Am.

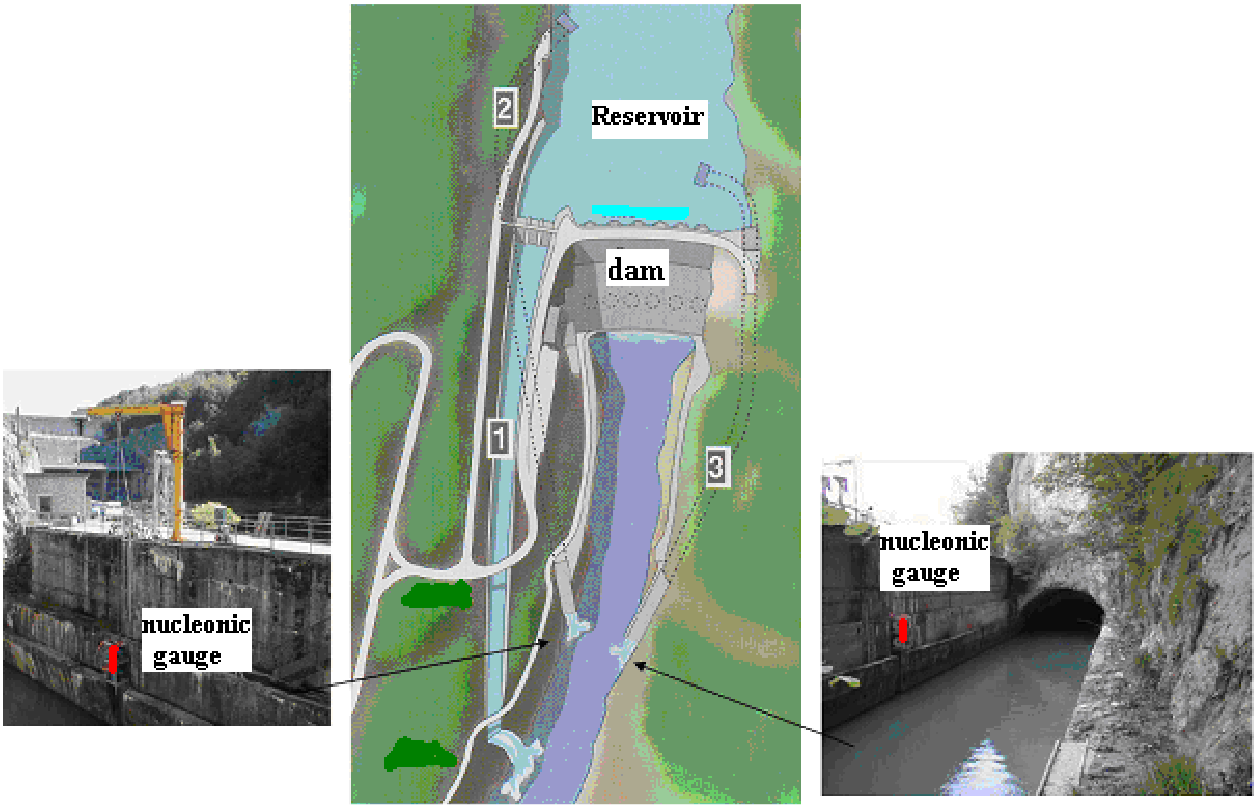


FIG. 128. Scheme of the dam with 2 exit gates.

FIG. 129. The dam seen from downstream and SERES gauge in position at one gate to monitor the draining of dam sediments.

Figure 130 presents an example of results obtained during dam flushing: concentration versus time for ten days and their comparison between CEA (nucleonic gauge – blue) and conventional techniques

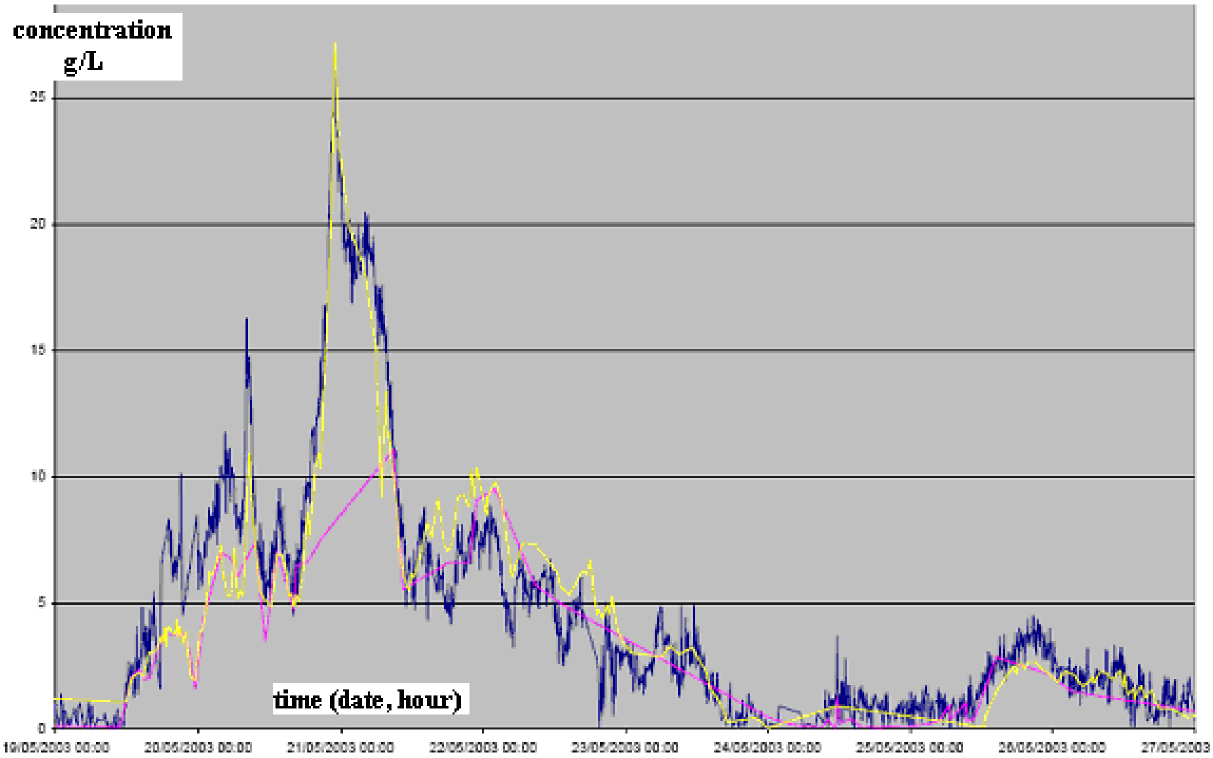


FIG. 130. Example of results obtained during dam flushing: concentration versus time for ten days and their comparison between CEA (nucleonic gauge – blue) and conventional techniques.

8.3.2. Measurement of bulk density of fine sediments deposited in reservoirs and in coastal environments

One important parameter for the sedimentological balance of the system: lake catchment basin-reservoir is the measurement of the quantity (mass) of sediments deposited into the reservoir, during a certain time interval. By means of echo sounding surveys, performed at the beginning and end of the considered time interval, it is possible to calculate the variation in volume of the reservoir, referred to a certain reference level.

In the region where the river enters the reservoir, where the deposition of the coarser (sandy) sediments occurs, a vertical density gradient does not exist. The mass of deposited sediments can be calculated, considering the variation in volume given by echo-sounder surveys and the uniform density of the coarse sediment deposited. By the way, in the region of preferential deposition of the fine sediment (silt and clay), nearer the reservoir dam, it exists a vertical density gradient, not well determined by echo sounding surveys, even by using simultaneously equipment of low (33 kHz) or high (210 kHz) frequencies having, respectively, high and low penetration capacity.

To overcome this limitation, twin-prong transmission and single-prong scattering nuclear gauges are used. These gauges are normally equipped with depth sensors and inclinometers for the underwater unit. They are used as point measuring systems and are lowered on a suspension cable to sink into the soft bed by falling down under its own weight. In this way, density profiles between 1.0 and 1.5 g/cm^3 may be determined.

As the scattering gauges are cylindrical, they are also suitable for being introduced in tubes previously placed at the measuring sites, allowing an extended range of values for the density profiles. ^{137}Cs is the source currently used for this type of gauge.

In harbors submitted to heavy fine sediment siltation, such as Rotterdam and Zeebrugge, in Europe, and in some harbors in South America and Indonesia, it exists in certain parts, a lower density layer above the more consolidated bed sediment, named fluid mud, which can attain several meters. The top interface between the fluid mud layer and the water above is generally detected by the echo sounder of 210 kHz frequency, normally employed for surveying nautical depths. It was demonstrated by ship maneuvering and laboratory studies that the fluid mud is not an obstacle to navigation, provided its bulk density is equal to 1.2 g/cm^3 or less. In this way, since the late seventies, radioactive gauges have been operated at spot locations in harbors, in conjunction with echo sounding surveys. As the product of this survey, nautical charts showing the 1.2 g/cm^3 density depth contours are prepared and used for navigation and dredging work purposes.

In harbors where large areas of fluid mud should be surveyed, it seemed interesting to perform a continuous measurement of density instead of measurements at spot locations. In this way, a towed density probe was developed. The overall system consists of a tow fish containing a ^{137}Cs transmission gauge and a depth sensor, an "intelligent" winch controlling the vertical movement of the fish in order to follow the 1.2 g/cm^3 pre-selected bulk density and a main computer which controls and runs, via the necessary interfaces, the simultaneous echo sounding and density surveys.

Another important use of nuclear gauges related to the improving of dredging works is the measuring of density profiles of dredged spoil in the well of dredgers, allowing evaluating the load efficiency of a particular dredging practice.

Problems

The construction of new wet docks and, more often, the maintenance depths in the channels of access and the harbor-basins impose important annual dredgings: 40 x 106 m^3/y in France, 230 x 106 m^3/y in the United States, 30 x 106 m^3/y for a large port like Zeebrugge (Belgium), 7 x 106 m^3/y for a European estuary subjected to the action of the tides. The expenditure is high; the average cost amounts 2 to 3 US$ for one m^3. This expenditure increases quickly if it is necessary to further reject in order to avoiding their polluting return and their effects on the littoral.

The major question posed is:
Can one limit dredged volumes by a good estimate navigable depth?

Measure navigable depths in the silted up channels

Hydrographic techniques in combination with density nucleonic gauge are used since more than 15 years. They allow monitoring the navigable depth in the channels of access to the ports while limiting to the minimum necessary the dredging work. A large French port, thanks to this method, which it strongly financed, brought back its dredge volumes from 7x10^6 m^3/y to 4x10^6 m^3/y.

The nucleonic gauge that measures the density of mud layers at the sea bottom contains a weak sealed source of Cesium. These gauges are daily employed in several harbors, either in fix points or in movement. The thickness of mud cohesive deposits in navigation channels is badly known by the traditional surveys with the ultrasounds, even with the apparatuses at double frequency. The limit of the mud upper layer (little concentrated) is diffuse while the deeper layers are confused with the sandy bed.

The hydraulics has found that the deposited mud layers with a density lower than 1,2 g/cm^3 remain navigable and do not impose a dredging. The essential problem is: How to measure the density of the sedimentary layers in situ?

Two techniques using nuclear instruments equipped with radioactive sources and sensors of depth are employed (Fig. 131):

1) A gauge of turbidity to measure in a grid the vertical gradient of the densities. A sealed source of ^{137}Cs (activity 37 MBq) is placed in a stainless steel needle of 1,2 m and 0,055 m diameter. The detector with scintillation, located at 10 cm above the source, is protected from the direct radiations of the source by a tungsten part, thus only reach him only the rays diffused in the solid mass of mud. The gradient of the densities is established as the apparatus, connected to an electric winch, progresses vertically, by gravity, in the sedimentary layers. This technique is usable only if the currents are weak as in the harbor basins and wet docks.

2) A gauge of turbidity moves on sea bottom surface by a motorboat in order to measure the density of mud layer and locate non-compact mud with density of 1,2 g/cm^3. A sealed source of ^{137}Cs with activity of five times more than above is placed vis a vis the scintillation detector. The attenuation of the radiation is related to the density of the mud which circulates between source and detector during the towing. A sensitive and precise pressure sensor indicates, permanently, the depth of immersion of the gauge. A processor gives the order to the electric winch to move up or down the gauge in order to stay constantly on the level of the layer of density 1,2 g/cm^3.

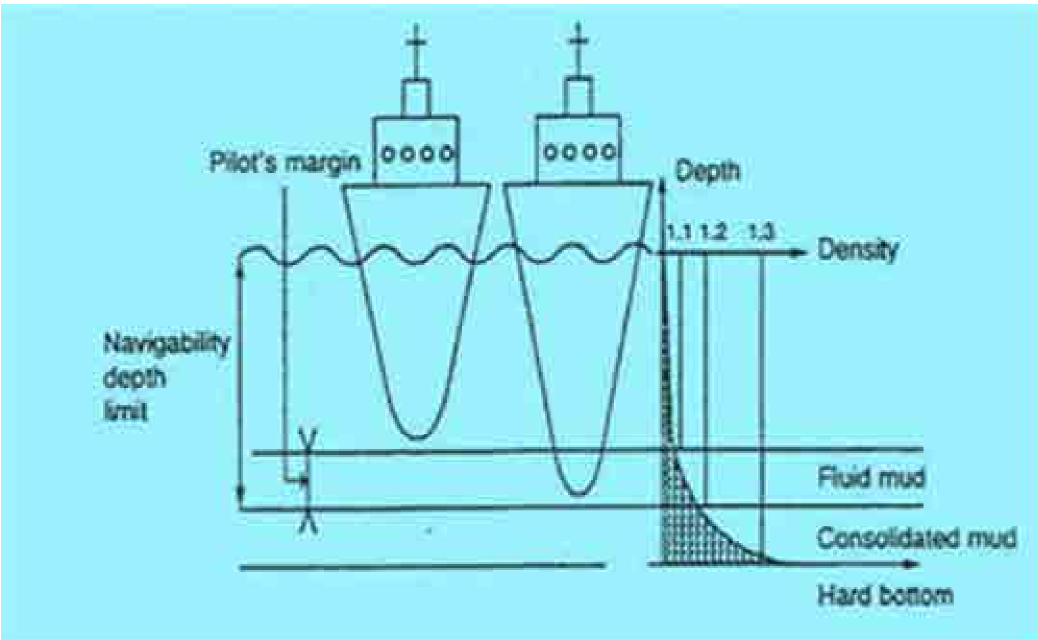


FIG. 131. Definition of the navigability depth limit in a muddy channel.

Point of view of users
Density nucleonic gauges have made a revolution in the monitoring of navigable depths. The profit in nautical depth can be evaluated to 50 cm, which represents in a harbor section a volume of 900.000 m^3 materials, which is saved each year.

Conclusion
Tables 19 and 20 summarize the techniques employed for suspend and bedload sediment transports.

TABLE 19. GUIDANCE FOR THE SELECTION OF TECHNIQUE FOR SUSPENDED SEDIMENT MEASUREMENTS

Technique	Measured Quantity	Concentr. (g/L)	Particle Size (µm)	Comments	Field Equipment (kUS$)
Nuclear backscatter	Backscatter radiation	5-1000	N/A	Good for high concentrations, not affected by particle characteristics, regulations may apply, isokinetic, generally portable	10-20
Nuclear transmission	Transmitted radiation	0.1-500	N/A	Good for high concentrations, not affected by particle characteristics, regulations may apply, isokinetic, generally portable	10-20
Radioactive tracers	Sediment transport parameters	N/A	mud, sand	Give a more regional information - Major interest for dam flushing and dredging operation - Radioactive regulations necessary. No data on suspended sediment concentrations.	5-20

TABLE 20. GUIDANCE FOR THE SELECTION OF TECHNIQUE FOR BEDLOAD MEASUREMENT

Technique	Measured Quantity	Concentration (g/L)	Particle Size	Comments	Field equipment (kUS$)
Tracer techniques	Sediment flow rate, thickness of the moving layer, average velocity of the motion	N/A	Fines to pebbles	Do not affect flow, fast response, direct measurement, integrating method, may be inappropriate with high mobile fine grained sediment	5-20
Nuclear scattering and transmission gauge	Variation of sediment layer thickness, sediment flow rate	N/A	Sand 0.1-2 mm	Do not affect flow, requires sedimentary moving forms	10-20

9. ECONOMIC BENEFITS

9.1. RADIOTRACERS

The economic benefits to be gained from the use of tracers vary greatly from application to application. The cost of a tracer investigation is evaluated considering the following factors:

- cost of tracer
- cost of transportation of tracer and equipment to the site
- per day expenditure on hiring the boat (in case of sediment and effluent dispersion studies)
- cost of measuring instruments and health physics equipment
- cost of injection system and other mechanical accessories
- cost of man power and travel

Similarly, the following main factors are considered when estimating the benefits or savings obtained from a tracer investigation:

- direct cost comparison with alternative conventional techniques
- savings due to increased production efficiency
- savings due to improved product quality
- savings due to reduction in down time of the plant or shipping channel (in case of sediment transport investigations)

On the basis of the above considerations the following relation is usually used to estimate the economical benefits grown out of the applications of radiotracer techniques in various industries. The formula is given as (IAEA, 1965):

$$\Pr ofitability = \frac{\text{Cost}}{\text{Benefits}}$$

The above formula is called 'Agency's Formula'. The cost of the tracer investigation is clearly defined whereas it is difficult to estimate the actual direct or indirect benefits.

The cost to benefit ratios of industrial applications of radiotracer carried out all over the world ranges from 1:3 to 1:5000. In one of the sediment transport investigation carried out in India, a cost to benefit ratio of 1:150 has been estimated (Eapen, 1990).

In the frame of the IAEA Technical Cooperation Project COL/8/018 on "Radioactive tracers in industry", the radiotracer techniques were applied to study the optimization of the dredging works in the lower reach of the Magdalena River (harbour of Barranquilla). The radiotracer study demonstrated that it was possible to dump the material in the Magdalena River, about 5km downstream of the dredged area, and not at a distance of 15km, in the open sea, as before.

To illustrate the economic benefit brought by radiotracer study, the Fig. 132 shows a schematic dredging cycle for a trailing suction hopper dredger. Loading curves of the dredger, according to the percentage of sand dredged (related to the total amount of sand, silt and clay), are drawn.

For a fixed travel and dumping time (same dredged region and same dumping site), and for each loading curve, there is an optimum time for dredging with overflow (t_3 - t_2), in order to get the optimum dredging cycle time (tangent to the specific loading curve). This measurement together with radiotracer studies to optimize dredging dumping sites, shortening the travel distance, could further improve the dredging works. In the radiotracer study of the harbour of Barranquilla, there was a saving of 68 min/ dredging cycle (or 35.7 %) due to the shortening of 20 km in dredging travel distance for the dumping site.

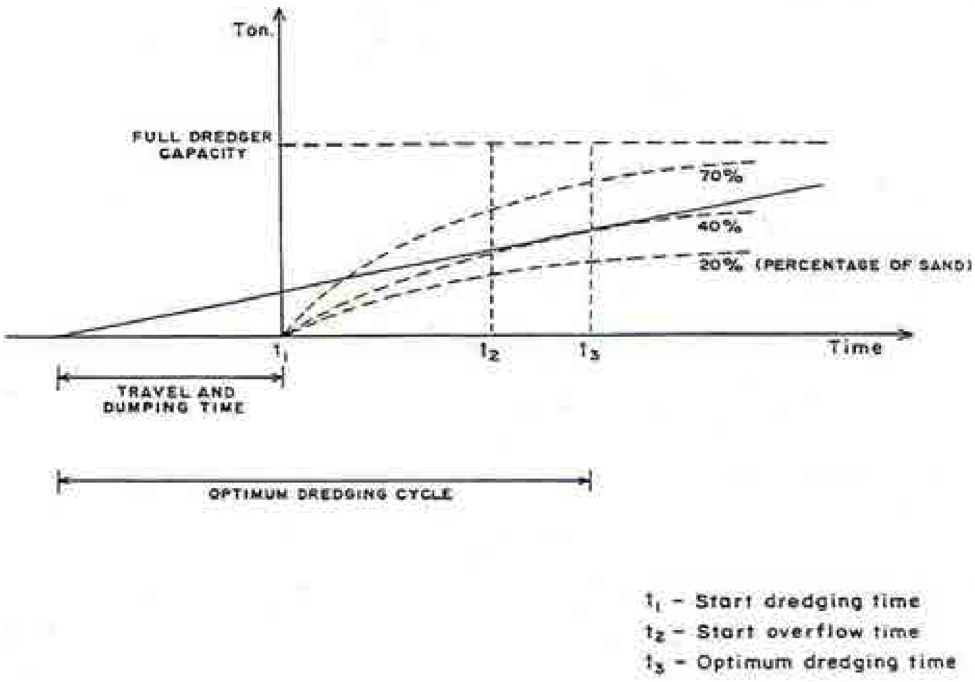


FIG. 132. Dredging cycle.

Shortening the travel and dumping time (t1 – 0) means a smaller (t3 – t2) time of dredging with overflow, taking into account the optimum dredging cycle time (tangent to the specific loading curve); converted to the monetary value of dradging savings this brings a saving of tens of Millions of US$ a year.

9.2. RADIOACTIVE SEALED SOURCES

The economic benefits of applying nucleonic gauges for monitoring sediment density are related with application to dredging works management.

As an example, in France, an industrial harbor is dredging 4 Mm^3 mud per year. A nucleonic gauge is used to measure the navigability depth limit (density 1.2 g/cm^3). The basins are now dredged only if the sediment density above the requested operational depth is greater than 1.2 g/cm^3. This new management, due to the use of the nucleonic gauge, allows 10% saving in dredged quantities. The cost of 1 m^3 of dredged material is between 2 and 3 US$. The cost of the nucleonic gauge is covered in less than 1 year savings.

Another important use of nuclear gauges related to the improving of dredging works is the measuring of density profiles of dredged spoil in the well of dredgers, allowing to evaluate the load efficiency of a particular dredging practice.

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11. GLOSSARY OF TERMS

Backscatter: Reflection of waves at an angle of 180 degrees relative to the incident direction.
Bathymetry is the study of underwater depth of lake or ocean floors.
Bedload: The part of the total stream load that is moved on or immediately above the stream bed, such as the layer or heavier particles (pebbles, gravels, coarse sand) transported by traction or saltation along the bottom.
Berms are areas that result from sand deposited on the recreational beach in fair weather during periods of relatively low wave energy.
Fine material: Particles periodically carried in suspension and deposited on the sea or river bed in regions of low flow velocity; normally silt and clay particles (particles finer than 0.062 mm).
Groins are:

- A fingerlike structure that extends from the shore. Usually with more groins, intended to trap littoral drift (alongshore transport) and/or slow down erosion.
- Perpendicular to the shore. Can be built using shore-based equipment (less expensive than breakwater), from various materials. Does not change wave height.
- Does not prevent offshore erosion. Rip currents can develop around groins and thus even increase offshore losses. May prevent accretion downdrift.

Jetties are:

- A structure that projects into a body of water to influence the current or to protect a harbor.
- Difference between jetty and groin: jetties are found at the entrances of harbors and small bays. Not as a series of structures to protect the shoreline.
- Similarities: accretion on updrift side and possible erosion on downdrift side.

Instantaneous suspended sediment flux: The rate of sediment discharge (usually presented in $kg.\_s^{-1}$)
Particle size (or grain size): A linear dimension, usually designated as "diameter," used to characterize the size of a particle. The dimension may be determined by any of several different techniques, including sedimentation sieving, micrometric measurement, or direct measurement.
Saltation: Mode of sediment transport in which the particles are moved progressively forward in a series of short intermittent leaps, jumps, hops, or bounces from a bottom surface.
Sedimentation: A broad term that embodies the processes of deposition, and the compaction of sediment.
Sediment discharge/ transport: The mass or volume of sediment (usually mass) passing a stream cross-section in a unit of time. The term may be qualified, for example as suspended-sediment discharge, bed load discharge, or total-sediment discharge.
Sediment load-flux: The mass of suspended sediment passing the measurement location per unit time.
Suspension: Mode of transport in which the upward currents in eddies of turbulent flow are capable of supporting the weight of sediment particles and keeping them indefinitely held in the water.
Suspended sediment: Sediment that is carried in suspension by the turbulent components of the fluid or by Brownian movement. Usually consisting mostly of particles <63 µm.
Turbidity: The state, condition, or quality of opaqueness, cloudiness or reduced clarity of a fluid, due to the presence of suspended matter. Only a general definition is possible because of the wide variety of methods in use.

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