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Assessment of sediment profiles applying nuclear techniques: use of a nucleonic gauge in Panama Canal watershed

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Abstract

An industrial nuclear technique based on the use of an X-ray profiler was implemented to estimate the densities or concentrations of sediments present in an Atlantic maritime zone in the areas subjected to dredging under the governance of the Panama Canal Authority (ACP).

The sediment profiles show in most areas there is a concentration of between 1.00-1.15 g/cm³ except for one area in particular, the density starts at 1.20 g/cm³ and even reaches values greater than 1.50 g/cm³; therefore, an already consolidated sediment is present, which, depending on the depth found. Values of 1.265 g/cm³, 1.297 g/cm³, 1.185 g/cm³ obtained by ACP previous studies are within the range of 1.20-1.30 g/cm³ measured with the nucleonic gauge. However, it should be noted that during the tests with the X ray profiler, sediment densities values greater than the aforementioned limit were also obtained that varying according at depths close to 12 m and 18 m with values reached up to 1.513 g/cm³ and 1.60 g/cm³, respectively. This demonstrates that sediment accumulation depends on depth. This nucleonic gauge is feasible technique for the study of the sedimentation phenomenon in channel basins and even in other projects nationwide.

Keywords. Water resource; sedimentation; nucleonic gauge; nuclear technique

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1. Introduction

The management of sediments is a crucial attention for countries around the world, whether developed or developing, whether to protect coasts and populated areas from sea level, storm surges from coastal erosion or frequency and increasing precipitation resulting in widespread flooding, landslides or loss of floodplains and land. Understanding the behavior, fate and impact of sediment movement is essential for port and port development, dredging, engineering projects, pollution transport, protection against floods and coasts, protection of the population, water quality, management of coastal zones and environmental protection. Nuclear techniques have been used to study sediment transport, there is a history of the use of radiotracers since the mid-1960s in countries such as Australia, Brazil, France, India, South Korea, and the United Kingdom, proving to be a competitive and very useful technique compared to other methods used for the analysis of these phenomena [1].

The main applications of these techniques used in Panama were towards water treatment fields, largely due to the start-up of the Panama Bay sanitation project for the study of water quality and its sedimentation [2].

The Panama isthmus has since its rise with the privilege of being surrounded by two oceans the Atlantic and the Pacific, in addition to being a connection point from pre -Hispanic stages of the northern and south of the American continent sponsoring the cultural exchange of the different civilizations from that time, an action that remained even during the Spanish conquest, which planted the idea of the development of what is now known in our country as the Panama Canal that, as in those years as a bridge of connection to the world and the main economic engine and economic engine of the Republic of Panama. Emphasize the important about the water resource of our basins, in their care, preservation and optimal use especially the hydrographic basin of the Panama Canal, which today presents a considerable degree of pollution that goes from the basin already mentioned above to the Bay of Panama and coastal ecosystems in general [3]. One of the factors that is considered detrimental to the deterioration of the quality of the hydrographic basins is the accumulation of sediments, these can be defined as any solid particle that due to natural effects of erosion accumulates in this case at the bottom of the causes of the causes from the rivers.

This prolonged and frequent accumulation of sediments can affect the morphology of the basin itself producing that, for example, the transit through the watershed is difficult to the extent not allowing the passage of large -draft vessels and in turn decreases the quality of the water that runs to the point of hindering its treatment for purification of it. These inconveniences mentioned above are those presented today for example in Lake Alhajuela which has already been observed a non -usual accumulation of sediments that can directly affect the two forms mentioned above since this lake feeds during the dry season Gatun Lake reservoir that guarantees the transit of ships in the Panama pathway and from there the water treatment facility called Federico Guardia Conte (locate in Chilibre, Panama) takes advantage of it to supply drinking water to almost the entire Panama City and San Miguelito (another large Panama City district).

Erosion is a phenomenon that occurs naturally which entails the loss of soil and that affects all lands that are exposed to the action of wind or rain. Thus, this phenomenon directly influences different sectors of the Panama Canal Basin, which reduces the capacity of the reservoirs to store water, could compromise the useful life of the reservoirs, in the same way, the sediments can cause the obstruction from water shots and background discharges, in turn this phenomenon increases water turbidity, compromising its quality and affecting the production of drinking water as well as production costs; The accumulation of sediments can at a given time affect the transit of ships through the Panama Canal.

In 2010, La Purisima storm, which occurred from December 7 to 9, had serious consequences in the values of sediment concentrations that are normally recorded in the rivers that flow into the Alhajuela reservoir. The constant rains led to the development of various landslides, in the upper part of the Chagres. It should be noted that there had never been a storm of this magnitude in the Hydrographic Basin of the Panama Canal. The effects of La Purisima storm were reflected in the quality of water and there and surrounding areas [4].

For all the above, it is of the utmost importance of knowing how the accumulation of sediments behaves in real time and more clearly possible to, with this information, carry out the action plans and the measures to be taken to counteract this event. The opportunity to take advantage of all technological resources and tools that are avantgarde and available to solve problems provide better use of resources. Particularly using nuclear techniques such as that used in the present study of a nucleonic gauge for the measurement of sediment transport, innovative methodology in Panama, but already tested in different parts of the world, which offers the opportunity to compare with other methods already applied, the most precise estimate of sediment profiles, such as that of their densities obtaining a rigorous and efficient methodology of generating information that can be used for a measurement program or monitoring plan for sediment transport and behavior of pollutants in the waters of Panama, especially in the Canal Basin, which would allow proper management of resources, the proper functioning of the Panama Canal, as well as the conservation of water resource in the country.

As a sediment transport study carried out using a nucleonic gauge there is the Grand Port Maritime de Nantes Saint Nazaire, in France. Resulting an optimization of dredged work of 10%, saving even 3 million euros per year and improving the management of environmental protection in sediment accumulation areas in ports that are contaminated with heavy metal [5]. In addition, in Larache, Morocco, as an initiative for teaching the use of these techniques and the correct management of the information collected, for the elaboration of profiles in the seabed [6].

The present study seeks to implement an industrial nuclear technique based on the use of an X-ray profiler to estimate the densities or concentrations of sediments present in an Atlantic maritime zone in the areas subjected to dredging under the governance of the Panama Canal Authority (ACP). The foregoing developed will allow the technical evaluation of how efficient the proposed methodology is compared to the technological approaches handled by the dredging division to measure the presence of sediments.

2. Materials and methods

2.1. Study site

The hydrographic basin of the Panama Canal has an area of 3,313 km² and covers 41 villages located in 7 districts of the provinces of Panama and Colón. The Basin is not a geographical area delimited in political-administrative terms, but rather is defined by the sub-basins that drain their waters towards the Alhajuela, Gatún and Miraflores.

The Isthmus of Panama is bathed by the two great oceanic masses of the Atlantic and Pacific, which are the main sources of the high humidity content in the environment and as a consequence of the narrowness of the strip that separates these oceans, the climate reflects a great maritime influence. The semi-permanent anticyclone of the North Atlantic greatly affects the climatic conditions of Panama, since from this system originate the trade winds from the northeast that reach our country in the lower layers of the atmosphere. Similarly, there is a confluence zone of the trade winds of the northern and southern hemispheres, the Intertropical Convergence Zone (ITCZ), this zone affects the climate of the places that fall under its influence, it moves following the movement apparent sun throughout the year. This north-south migration of the Intertropical Convergence Zone produces the two characteristic seasons of most of the territory, the dry season, and the rainy season.

These natural phenomena are the cause of the geological erosion of the soil, while the torrential rains and strong winds transport loose material such as sand, silt, and clay, depositing them on the earth's surface or in bodies of water, resulting in sedimentation. Other natural phenomena corresponding to climatic variations and that also affect Panama are the El Niño and La Niña phenomena, which cause heavy rainfall and droughts.

On the other hand, there is the accelerated anthropological erosion due to the constant threat to which both soil biodiversity and the general health of these organisms are subjected due to deforestation, change in land use, fires, pollution, monoculture, excessive use of chemical products, soil clogging and urban sprawl, among others.

The site where the measurements with the nucleonic gauge were carried out is located in the area of Anchorage A in Limón Bay, very close to the port of Cristóbal in the province of Colón (Fig.1). This place is chosen in order to have a sampling of the material that is being removed by the Quibián cutter-suction dredger, a site where it is important to be able to control the sedimentation accumulated at the bottom of the seabed for the passage without interruptions of the maritime route of the ships. These results obtained allow them to be compared with other results obtained by other sediment sampling methods to verify the efficiency of the equipment and its profitability for future applications for the study of sedimentation in other points of the Canal that may be necessary.

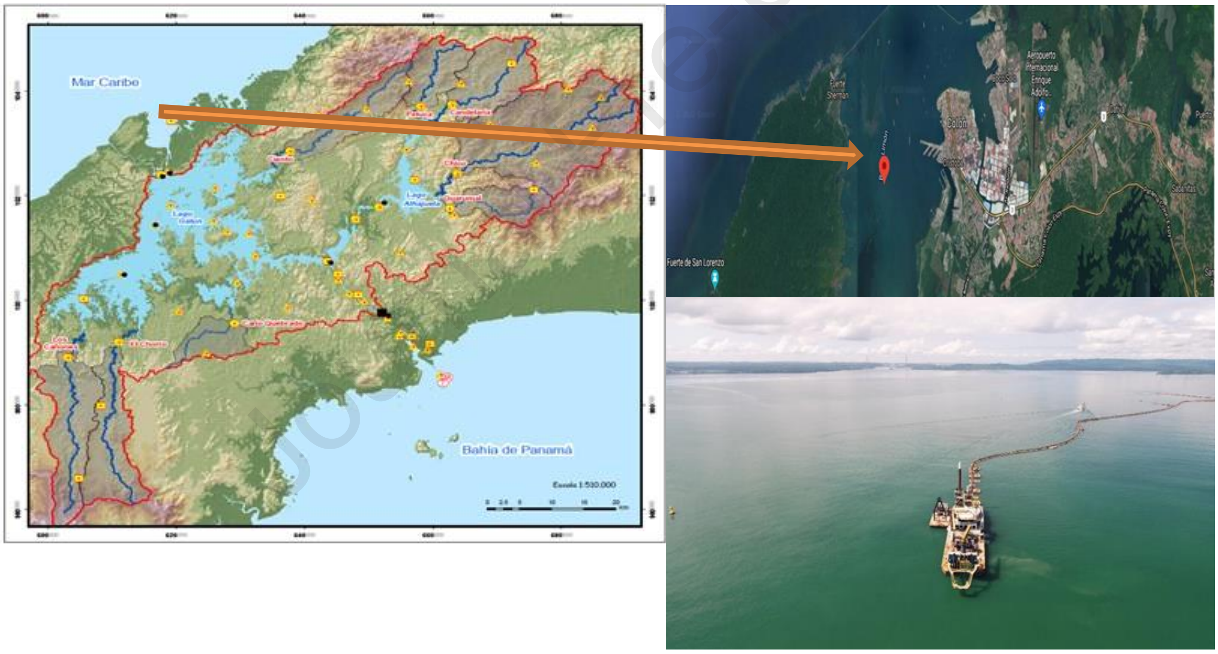

Fig. 1. Map showing location of the sediment measurements in Anchorage A at Limón Bay, Colón and the Quibián dredger vessel. Images courtesy from ACP, La Purísima 2010 Report [4] and Google Maps.

2.2. Equipment description

The measurement system is composed of: The XDP30 itself, a winch, a control-command unit and a control-command of the winch, a control and safety system for the generator of internal x-rays, one with acquisition and control software (Fig.2). The up/down movement of the gauge is controlled by the computer, or by the manual winch control box. XDP30 provides, in a vertical profile, information´s on mud density and related depth every 100msec approx. The gauge is supplied with a calibration bench for safe maintenance operations and to check if the gauge is in working order. The XDP30 gauge (Table 1) was designed for profiling the density of mixtures in natural environments and to supplement depth measurements by echo sounder. The limit depth of navigability is defined as the depth of a layer of the water-sediment mixture corresponding to a critical stiffness threshold. This threshold is itself dependent on the density of for a given sediment. Usually, it corresponds to a mud layer of 1.2. XDP30 allows the direct localization of this layer and the determination of the navigable depth. This determination allows significant savings and environmental protection thanks to the optimization of dredging work.

The ASTER-JTTX software is part of the computer package that has the XDP30 probe, this is responsible for capturing the data obtained by the probe by measuring the density difference of the surrounding particles of the medium (sediments) in the place where it is determined to carry out the study. The data obtained by the probe are transmitted by the connection cable with the winch that in turn is connected to the laptop that the software contains, said software collects the data and the analysis provided, which provides information on the depth, and density and associated with the GPS system, it allows to locate the coordinates of the points more clearly on the study site. These data obtained and processed from the software also give the ease of being able to work these data with tools such as Excel.

Fig. 2 The XDP30 and a winch (left), a control-command of the winch, and safety system for the generator of internal x-rays unit (center), and one computer with acquisition and control software (right).

2.3. Physical principle of measurement.

The principle is the transmission of X-rays emitted from a micro-tube in the medium between source and detector. The photons emitted by the source interact with the matter along their path. The higher the density, the higher the number of electrons. Only the photons interacting in the crystal NaI(Tl) detector are taken into account by the gauge. The signal received by the detector is a decreasing function with the density of the mixture. The relationship between the average density *d* and the signal delivered by the detector is:

$$d = Kdo + Kd1.\left(\frac{Nc}{No} - 1\right) + Kd2\,.Ln\,\left(\frac{Nc}{No}\right) \qquad (1)$$

where:
d is the medium density
No is the signal delivered by the detector in clear water
Kdo, Kd1 and *Kd2* are the calibration coefficients of the gauge
This equation is presented here in a general form with 3 terms.
The first term *Kdo*, is mainly related to salinity,
The second term *Kd1* (Nc/No - 1) is used for a backscattering gauge
The third term *Kd2* Ln (Nc/No) is used for a transmission gauge

A pressure sensor gives the depth of the density measurement. Its accuracy depends upon the type of sensor 2 contacts ensure a security function allowing the functioning of the gauge, i.e., the emission of X rays, only when the gauge is under water or inside the calibration system. A blinking lamp notifies the gauge is working, i.e., the emission of X-rays. An

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electrotowing cable bears the gauge and the winch, also ensuring the transfer of data to the control-command unit and the computer.

Table 1
XDP30 general characteristics [7]

Gauge	Stainless steel 316L
Weight	Approx 50 kg
Dimensions	700 x 300 x 100 mm
Gap	90 mm
Max depth	50 m
Emission X ray tube magnum 40	< 30 kV
Detector NaI(Tl)	ϕ 38 x 25 mm
Measurement range	Density 1 a 1.4 Concentration since 0.5 to 500 g/l
Precision of concentration measurement	± 2% in 1 second
Measurement time	Approx 0.1 s - 100 000 s
Stability	< 0.1% between 5 and 40 °C
Pressure sensor	Precision ± 10 cm full range (50 m)

2.4. Collection and processing of sediment samples

To carry out the calibration of the nucleonic gauge sedimentary material of the seabed of the place in question is collected a few days before the measurements and in a place very close to the test site in the Anchorage A close to the Quibián dredge vessel, for this, it was mobilized by boat and required to use a small manual dredge (Van Veen dredge) supplied by ACP personnel. This dredge was tied with a rope taking into consideration the average depth of the place for the length of this, with which the seabed was thrown next to the ship, it was expected to play background, this dredge had an insurance that when hitting with the bed it made it released and closed in order to be able to take the sample. This was repeated until a reasonable amount of sample for the calibration of the probe is obtained, it is taken to the dock to store it in the hangar where the calibration was performed, in addition to the sample of seawater that when homogeneous in the whole site is collected close to the dock (Fig. 3).

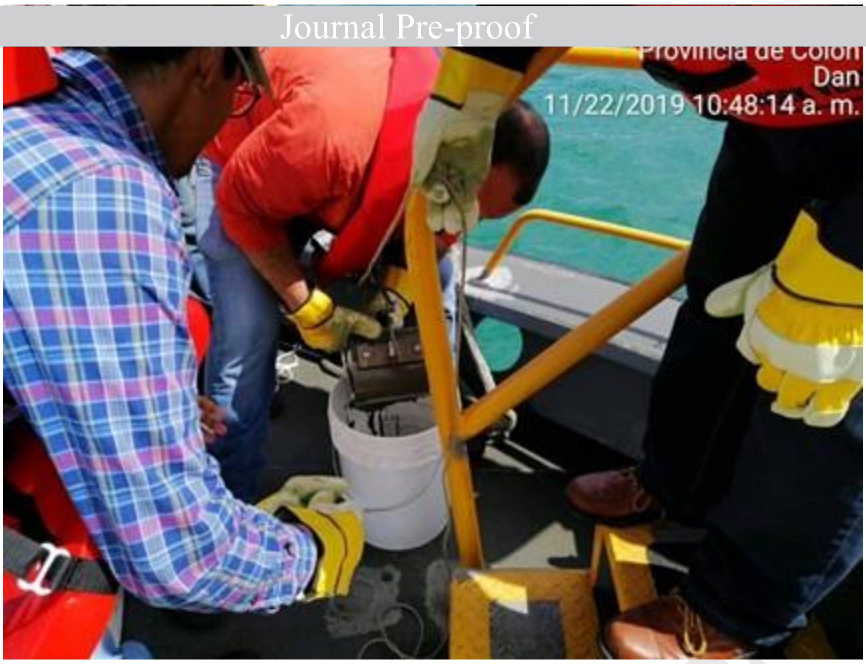

Fig. 3 Collection of samples of the seabed for measurements in the Anchorage A

2.5. Nucleonic Gauge calibration

The samples of mud already collected from the place of study and the seawater sample were taken so much (in this case because the water is quite homogeneous and does not present considerable differences, this sample was taken very close to the dock). The next thing is to take the measures of the mass in grams of each of the empty containers R's (Fig. 4) that are going to be used for measurements and the mass of the clear water with the same volume, in this case the containers are equal, so a measure is taken using a balance resulting in 89.5 g for the empty container, drawing the difference with the container full of water and the empty container resulting in 401.0 g for the mass of the water.

To get the counting rate N0 corresponding to 0g/L concentration i.e., density 1, the first container (R0) is filled by clear sea water. A good stirring of the mixture (mud + water) was necessary. After the preheating time of the X-ray tube (around 5 minutes), the first sample was placed between the tube and the detector, record the counting rate N0 related to clear sea water and measure its weight Mo. The second specimen containing the mixture was placed in the same spot, recorded the counting rate N1 and measured its weight M1. This operation was repeated for all the remaining 5 containers (Fig. 5). Finally, the calibration curve is obtained by relating the counting rate N measured to the varying suspended sediment concentration values.

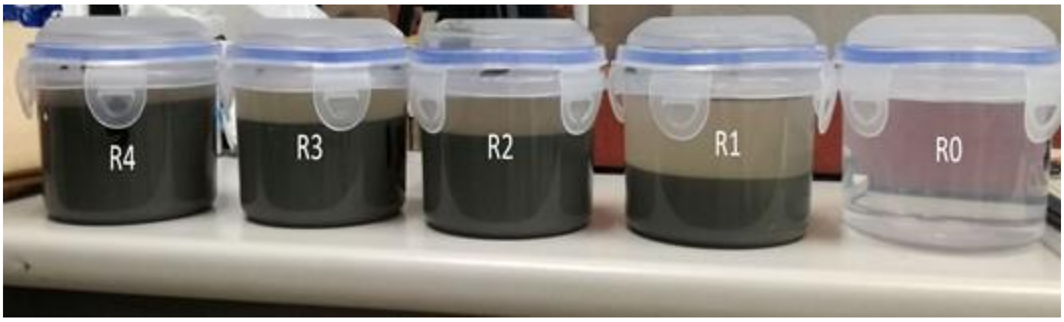

Fig. 4 Containers with samples of the seabed for calibration process

Fig. 5 Nucleonic gauge calibration carried out in ACP Facility, Colón

The data that were recorded were first the masses of each of the containers with their samples, the number of counts per second (cps) provided by the Aster software on the computer, which indicates with what ease the X ray beam passes from the transmitter to the receiver through the container, being the most dense sample, this value will be lower, these values were worked in Excel and are summarized in Table 2.

Table 2
Sample data taken for nucleonic gauge calibration

Containers	Mass (g) [empty]	Mass (g) [H_2O]	Mass (g) [Sediment + H_20] total	Rate count (cps) Ni	Density (Mass (mix)/ Mass(water))	No=170000 ln (Ni/No)
R0	89.5	401.0	490.5	170000	1.00	0.00
R1	89.5	401.0	560.0	4500	1.17	-3.63
R2	89.5	401.0	630.0	1500	1.35	-4.73
R3	89.5	401.0	665.0	450	1.44	-5.93

With the values of the last two columns, the calibration curve is plotted and fitted, as can be seen in Fig. 6. This equation is introduced to the Aster software to calibrate the nucleonic gauge and thus carry out the measurements on site.

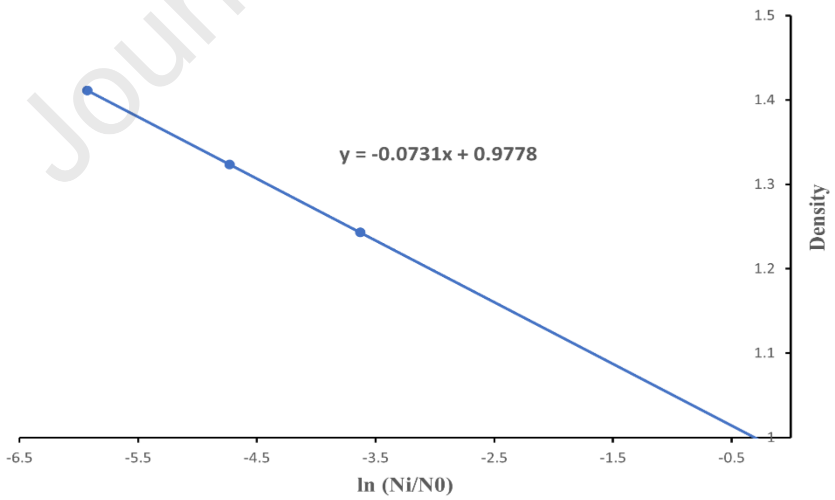

Fig 6 Calibration curve for the nucleonic gauge

2.6. Depth calibration

The pressure sensor gives the depth of the density measurement with a working range going from 0 up to 50 m (precision of ± 10cm). The equation of calibration is a function of the signal delivered by the pressure sensor and gives as a result the real depth of the gauge:

$$Real\ depth = a \times (Measured\ signal) + b \qquad (2)$$

Where a and b are constants. The real depth is a linear function of the measured signal; therefore, we need 2 different vertical points to calculate a and b.

By using a metric tape attached with the towing cable of the gauge, we will measure the depth of the first point named D_1, simultaneously the sensor will deliver a signal S1corresponding to same point (Fig. 7).

Similarly, to the first point, we get D_2 and S_2 from the second point. We calculate then the constant a by this relation: $a = \frac{D_2 - D_1}{S_2 - S_1}$

and the constant b by a simple substitution in the first equation, $b = D_1 - a \times S_1$

The insertion of these two constants in the interface of depth calibration in "aster" program is the final step of the calibration of the depth.

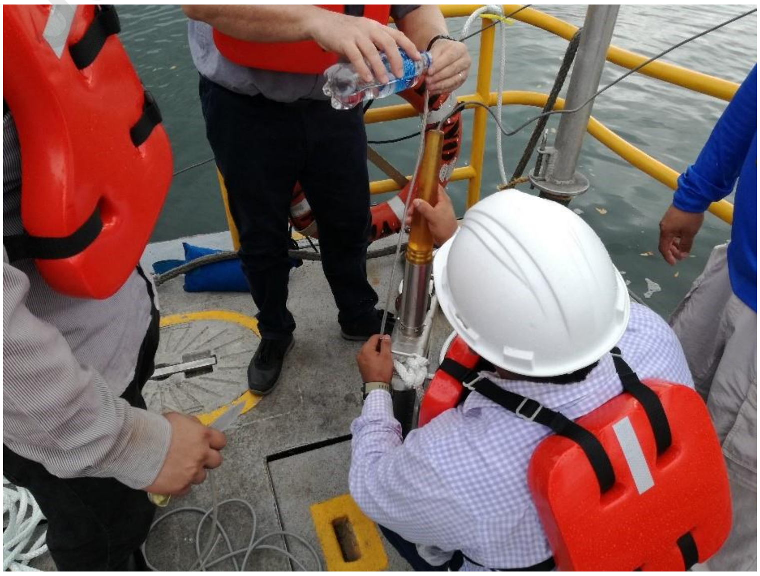

Fig. 7 Calibration of pressure sensor

3. Results and Discussion

3.1. Sediment profiles

The measurements were made between the days on November 26 and 27, 2019. On the first day it was measured in the area farthest to the Quibián dredge at a maximum depth close to 15 meters this test was characterized by not so favorable weather conditions due to the strong waves, causing to stop the measurements earlier than expected. For the next day on November 27, measurements were made near the dredge and at a maximum depth close to 13 meters in this case the weather conditions were suitable, which allowed to cover the sites that were scheduled to measure and collect the entire data necessary for the study. The collected data was reviewed and to clean the information, in addition to generating the preliminary sediment profiles. Fig. 8.

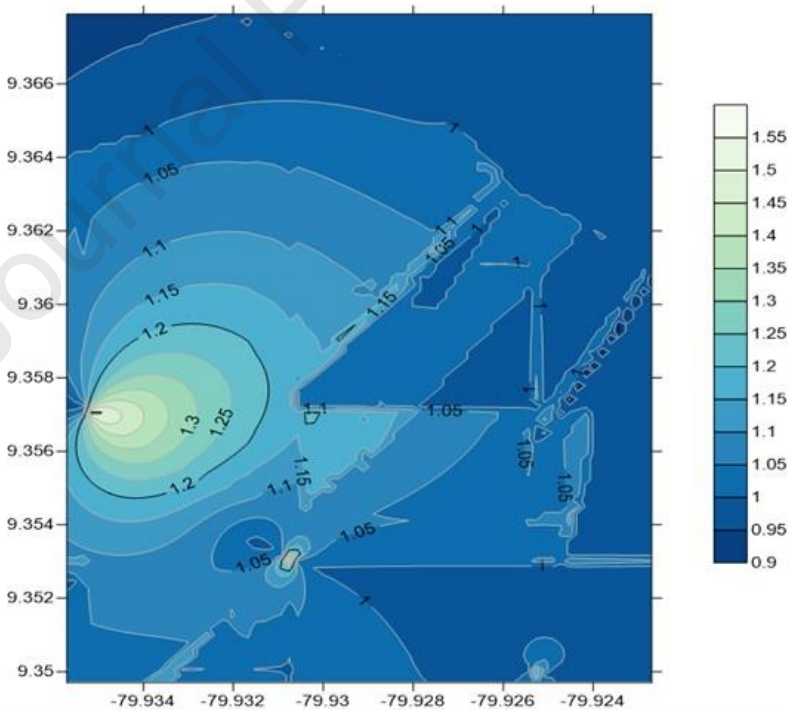

Fig. 8 Sediment profile for study area

These values indicate the distribution of sediments in g/cm^3 where the clearest areas that are distinguished in Fig. 8, where this ratio is greater than 1.20 indicates that in those areas there is a considerable accumulation of sediment. This is much more observable using a 3D model such as Fig. 9, where the peaks are very notable where the density is greater, which demonstrates the critical areas that would be considerable to dredge in case this part of the Anchorage A is required to enable, with these profiles as mentioned, the behavior of the sediment accumulation phenomenon in the areas of this study can be intuited in a more visual way.

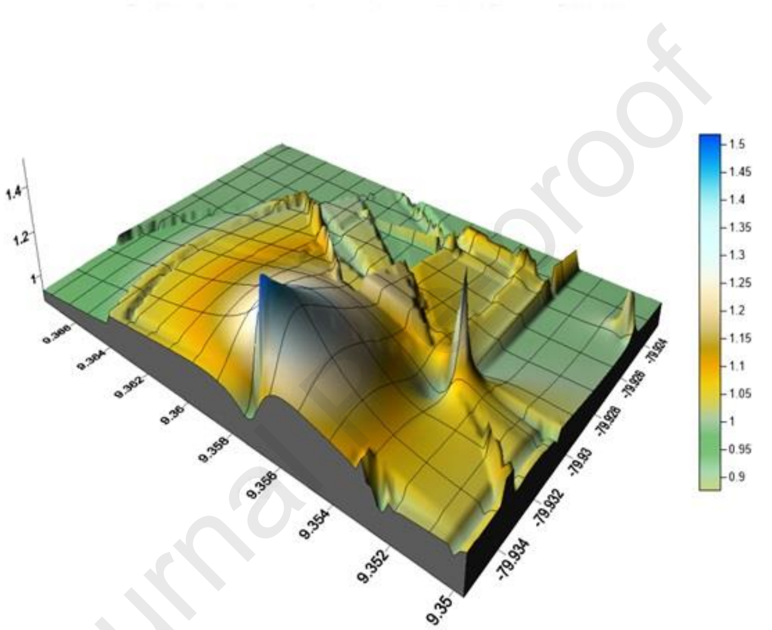

Fig. 9 Sediment 3D profile for study area

3.2. Sediment profiles analysis

The main objective is to determine the density of the sediment that is accumulating in the study site, with values less than 1.20 being desirable since it indicates that the sediment is still fluid and allows navigability and is not necessary at the moment. carry out a dredging action, in case these values are higher, we would already be talking about a consolidated sediment that would require dredging, this is best exemplified in Fig. 10, which summarizes what is proposed in this study.

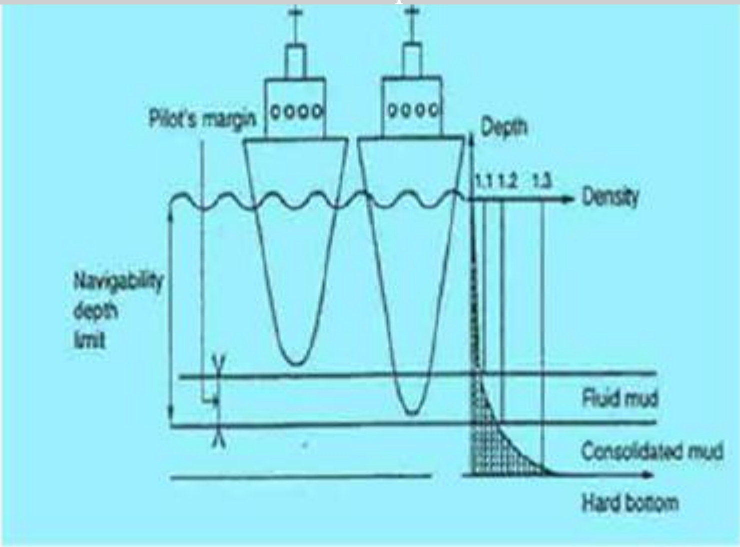

Fig. 10 Definition of the navigability depth limit in a sedimented channel. Image from [1]

What can be observed from the sediment profile (Fig. 11) of the study site with all the data collected at that time, in most areas there is a concentration of between 1.00-1.15 g/cm³ except for one area in particular, the density starts at 1.20 g/cm³ and even reaches values greater than 1.50 g/cm³; therefore, an already consolidated sediment is already present, which, depending on the depth found, should be considered by dredging this zone.

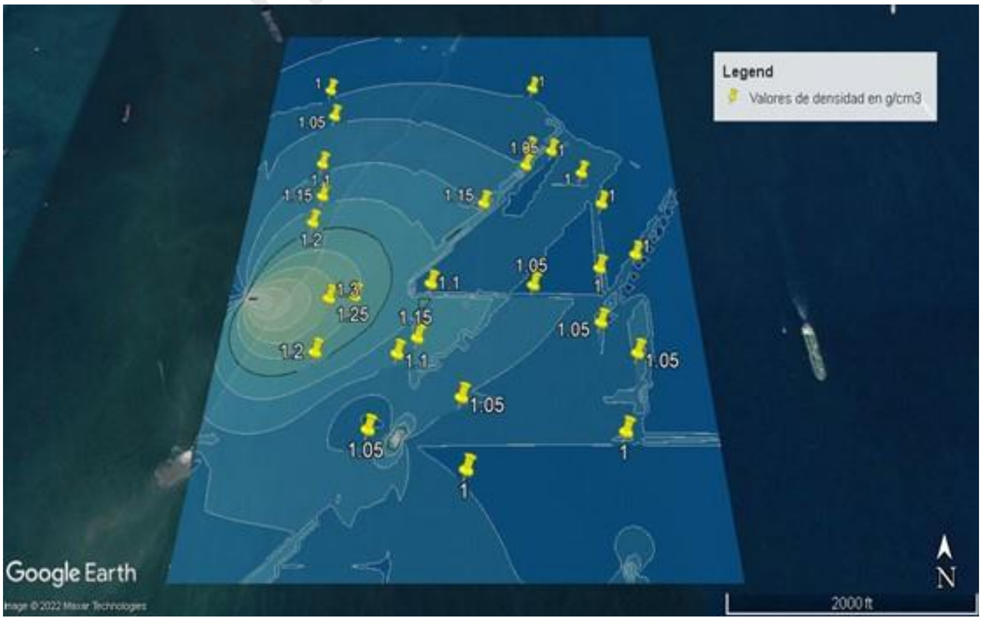

Fig. 11 Sediment profile for study area

observed on site during the measurements, which is a site where several dredging works are carried out, typical of an anchorage and also considering that due to the movement of sea currents it can favor the accumulation of sediments brought from other nearby sites (Fig. 12).

Fig. 12 Deposit of the dredged material of Anchorage A, Limón Bay, Colón

3.3. Comparison with ACP monitoring sampling results

In this section, a comparison is made of the results that were provided by the ACP soil laboratory of three samples obtained near the dredging areas. Table 3.

Table 3. ACP measurement density values [8]

Sample	Total Density (Wet) soil sample (g/cc)	Dry soil Density (g/cc)
M1196-1	1.770	1.265
M1196-2	1.793	1.297
M1196-3	1.713	1.185

The three values of 1.265 g/cm³, 1.297 g/cm³, 1.185 g/cm³ are within the range of 1.20-1.30 g/cm³ measured with the nucleonic gauge. This indicates that these latter values are consuming with the tests performed by the ACP. However, it should be noted that during the tests with the X profiler, values greater than the aforementioned limit were also obtained, as seen in Fig. 13. In this coordinate site Length -79.9357 and latitude 9.3574 presented a sediment already consolidated at depths close to 12 m with values that exceed 1.20 g/cm³ and reached up to 1.513 g/cm³, results that contrasts with the measurements taken in another close place of coordinate length -79.9274 and latitude 9.3653, which as shown in Fig. 14 that the consolidated sediment is presented in depths close to 18 m and with values that reach 1.60 g/cm³.

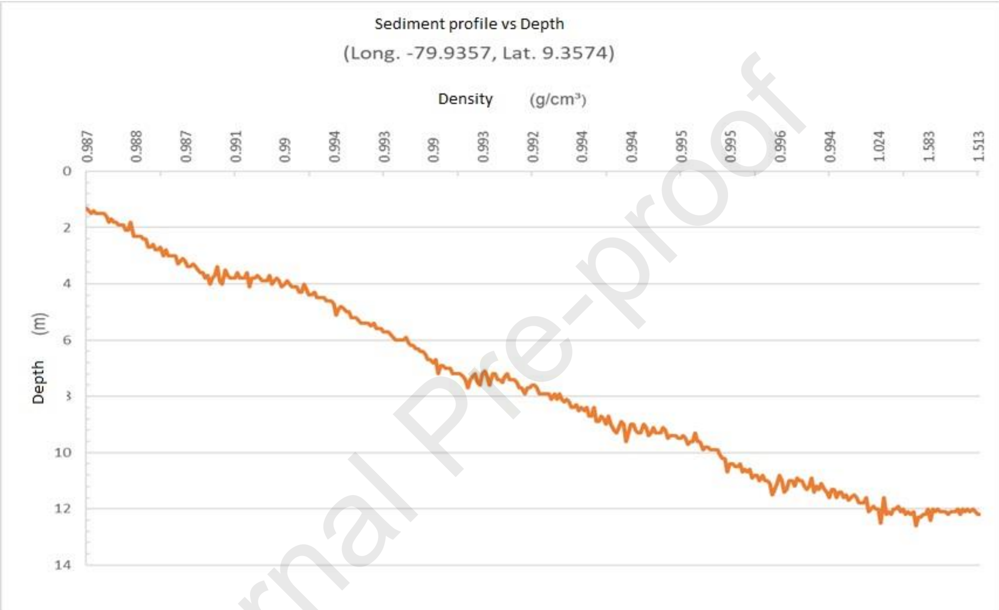

Fig. 13 Sediment density values at a depth of 12 m

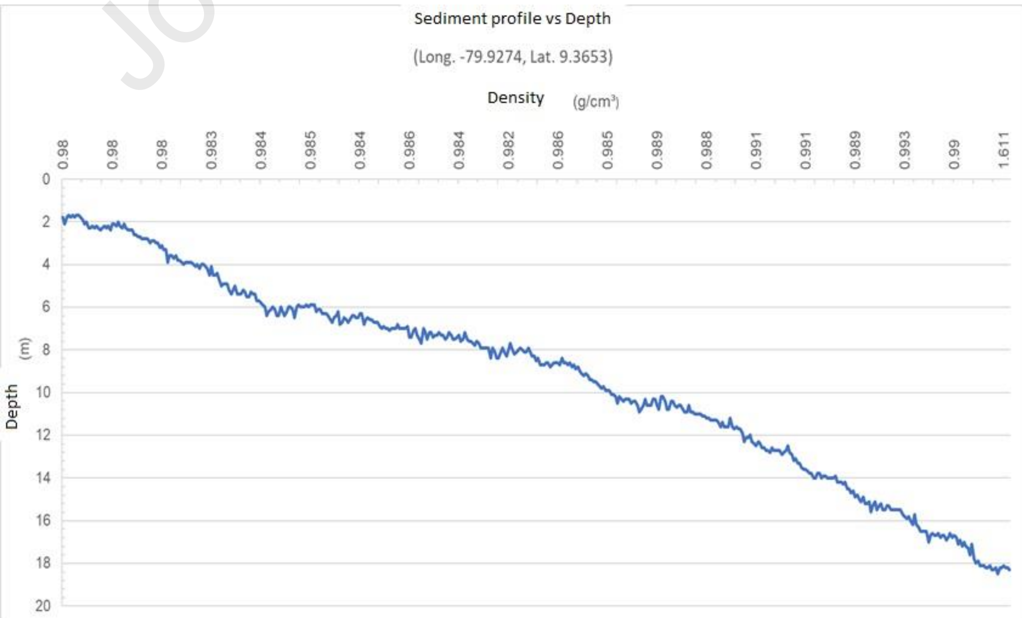

Fig. 14 Sediment density values at a depth of 18 m

consolidated sediment is presented at a lower depth are the places that would have to be monitored so that this does not affect the ship's drafts. Therefore, the nucleonic gauge capacity to measure that variability of the sediment density versus the depth that is not constant on the surface of the seabed in addition to the results consistent with those provided by the ACP and the large area coverage capacity that it can be carried out in relative short time give valid arguments to consider this feasible technique for the study of the sedimentation phenomenon in the channel basin and even in other projects nationwide.

4. Conclusions

The study of sediment transport that occurs in coasts and rivers is very important for the development of civil works such as docks, dams, navigation channels, irrigation projects, etc., even more importance for Panama by having the Interoceanic route of the Panama Canal. The use of these nuclear techniques (nucleonic gauge) showed that it is a correct and more efficient methodology to measure the density and depth of the sediment helping dredging work. The collection of the data by the nucleonic gauge compared to the method that uses the ACP for this test (sampling), is much faster to see the preliminary results in situs during the measurements. In comparison with the results of the ACP, the nucleonic gauge allowed to cover much greater extension of marine background resulting in a representation closer to reality. With the information collected during the measurements in the anchorage A of Limón Bay in Colón, estimates of the sediment profiles could be made, and the behavior of sedimentation at those points could be seen more visually. With the experience acquired using these techniques, it gives us a basis for its future application in other research or studies projects as well as on the channel or in other places in the country. Finally, it opens a development opportunity in this field for both students and people interested in learning these techniques which could become a new industry in the country.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.