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SOILS POLLUTED BY HYDROCARBONS IN COCHABAMBA, BOLIVIA

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ABSTRACT

This paper presents the geotechnical evaluation accomplished on the contamination caused by pouring of oil in a sector of the petroleum field Carrasco, located in the northeast of the department of Cochabamba, Bolivia. The continuous emission of contaminants affected an approximate area of 2500 m^2, which can be estimated from the observed superficial pollutants storage, identified as Total Petroleum Hydrocarbons. The most affected zone is found 500 meters away from a waste pipe that pours the residues of the refinery to the environment, becoming the source of contamination. The work was directed to estimate the underground path of the pollutant through a mathematical model generated in the programs SEEP/W and CTRAN/W of Geoslope International. In this way, the study has determined the location of possible affected zones at the moment of the fieldwork and predicted the advance of contamination in a long-term period. The analysis consisted of a characterization of the subsoil using borings and sampling of the soil from different depths, geophysical work with an electrical resistivity equipment to obtain deep profiles, assessment of the coefficient of hydraulic conductivity from field tests and finally, the determination of the type of pollutant (Total Petroleum Hydrocarbons) and the concentration based on analysis from superficial and underground waters. According to the results, it is estimated that at present, the infiltration of the pollutant reaches a depth of 15 meters, depth that can be easily tripled in the next 5 years. It has also been demonstrated, in comparative form, the principal differences between the movement of the pollutants in saturated conditions and the movement of the same compounds in unsaturated conditions for different periods of evaluation. Finally, the equipotential lines of concentration were established, in order to estimate the possible affected zones and the volume of soil contaminated within the next 5 years.

Key Words: **Soils, Permeability, Hydrocarbons, Contamination, Geotechnical Modeling, Cochabamba, Bolivia.**

INTRODUCTION

Since 1995, the area between the south parallels 17º50´-17º30´ and west meridians 64º45´-64º15´, corresponding to the tropical zone of Cochabamba (Figure 1), has become the principal producer of petroleum and natural gas of Bolivia. Currently, the zone consists of 5 petroleum fields connected internationally through a net of pipelines.

In general, the region presents a dense vegetal coverage, typical of a tropical climate. However, in the petroleum field Carrasco, in several points located throughout a natural channel originating at the refinery, some biological changes have been taking place, due to the spill of oil. Part of the affected zone is used for agricultural proposes, that is why peasants, the actual owners, have given the alert.

Figure 1. Geographical Location

ANALYSIS

Contamination System

The Contamination system, in the area of investigation, consists of a waste pipe that pours the residues originating at the refinery and deposits them in a natural channel that transports and assimilates the toxic compounds which are finally deposited in Izozog River, a natural water course. Figure 2 presents a general plan of the path that carries the pollutant and the relevant features.

The natural channel has a length of 1100 m between the source of emission and Izozog River. Throughout the entire channel, a moderate environmental deterioration can be observed; however, in 2 specific regions, named reservoirs 1 and 2 (Figure 2), exhibit greater environmental degradation. It is presumed that at these points the concentration of the pollutant is much higher; therefore resulting in greater infiltration of compounds in the subsoil.

Water Analysis

Previous to the present investigation, there were 10 tests carried out on shallow waters, 7 accomplished by the Laboratory of Water Treatment at San Simón University (UMSS), and 3 by the Consulting Company Dames & Moore. In order to complement this information, the Laboratory of Geotechnics of San Simón University, obtained 3 underground water samples, which were evaluated by the Laboratory of Water Treatment. Figure 2 represents the location of the different points of sampling, and Table 1 shows the results for the most important results. The points of sampling have been located in strategic areas: in the refinery, pipe that pours the contaminant into the environment, underground water around the natural channel and water from the stream of Izozog river.

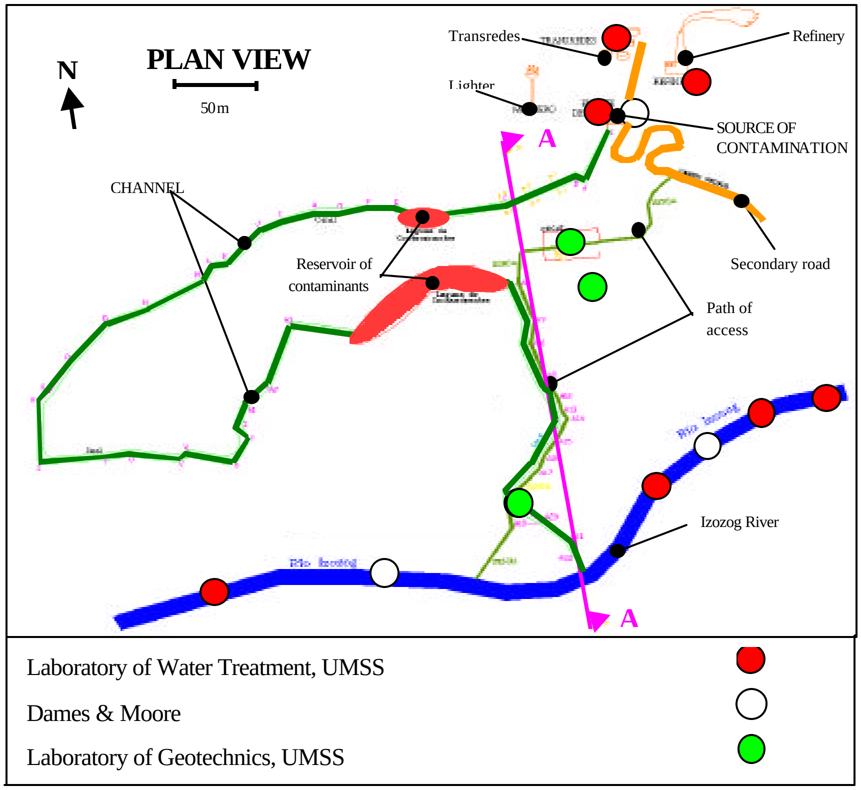

Figure 2. General location of the zone and the superficial and underground water samples

The chemical tests determined that the pollutant, identified as Total Petroleum Hydrocarbons (TPH), presents concentrations that surpass the tolerable in Bolivia. Following the results presented in Table 1, it is evident that the concentration of the pollutant poured in the source of emission (292 mg/l) decreases in the current of the Izozog River, below 3% of the initial concentration. Therefore the soil is identified as an extenuating element of this pollutant process.

Table 1. Contaminant concentrations

Location of the samples	Concentration of TPH (mg/l)	Source*
Refinery (Separator API)	349740	Laboratory of Water Treatment, UMSS
Source of emission (Pipe)	292	Dames & Moore
Underground water next to the Izozog River	14.5	Laboratory of Geotechnics, UMSS
Superficial waters of Izozog River	2.3	Laboratory of Water Treatment and Dames & Moore
Tolerable maximum concentration	20	According to Bolivian standards of superficial waters in industrial waste

* Average values of all tests, except the underground samples

Geotechnical Characterization

The geotechnical characterization was carried out in order to establish the general profile of the region, detecting also the groundwater level and the depth that encompasses the contamination in the subsoil. This work was accomplished through 7 manual perforations with an average depth of 2.30 meters below the surface.

In addition, the coefficient of hydraulic conductivity was determined using 6 tests in the field, which gave a real approximation of the infiltration conditions in the soil of the area, sand and clay.

Finally, 3 electrical soundings (SEV) made possible the attainment of the soil profile up to 32 meters. For the dense vegetation in the zone, the probes covered a maximum superficial length of 80 meters. Figure 3 presents the location of the different tests performed at the site.

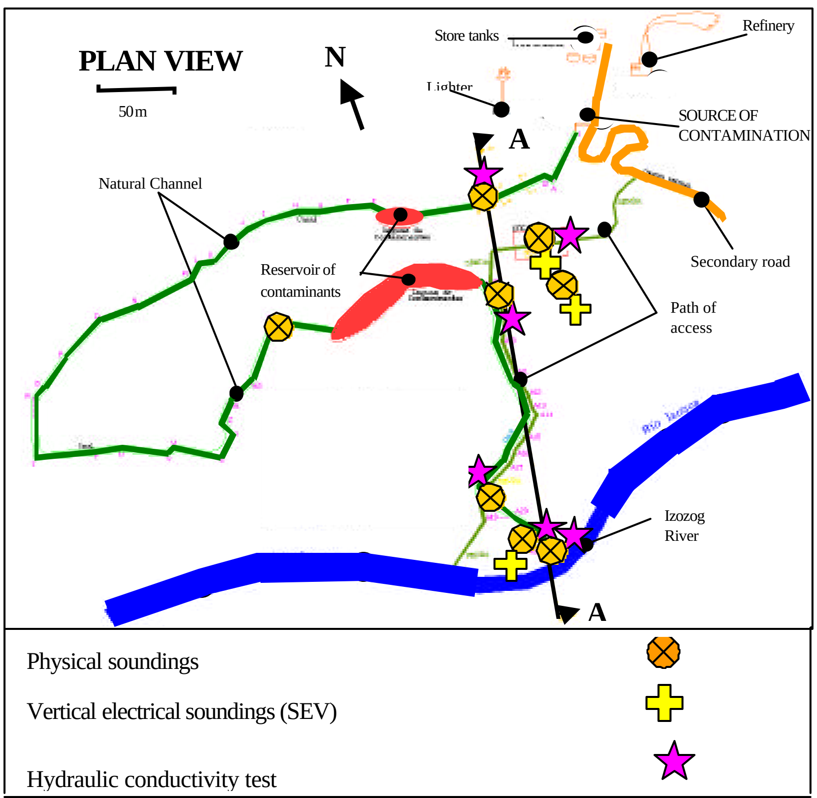

Figure 3. Location of the geotechnical tests

Geotechnical Properties of Soils

From the field and laboratory tests, it could be determined that the area is composed of a stratum of lean clay (CL), with an average depth of 3 meters. Additionally, the presence of a clayey sand stratum (SC) has been established. The thickness could not be defined visually, but, by means of the geophysical tests of electrical resistivity, it reached an approximate thickness of 15 meters. Figure 4 presents the profile of the cross section A-A, which can be observed in Figures 2 and 3.

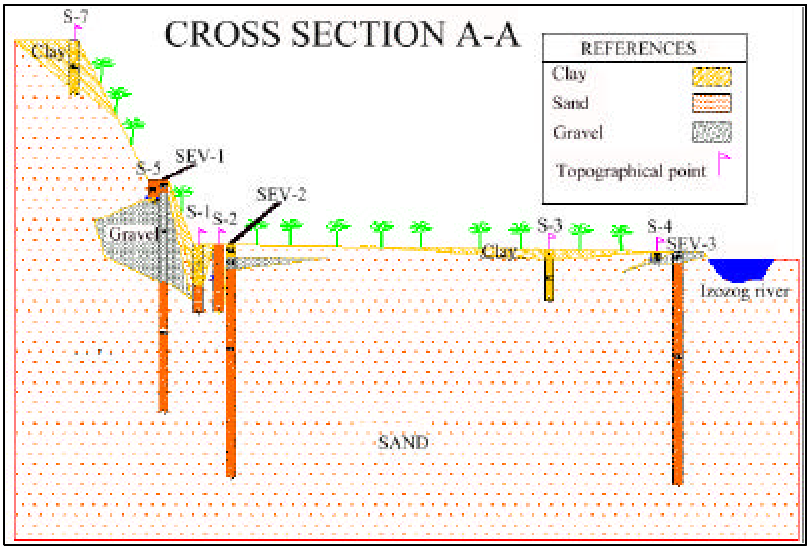

Figure 4. Cross section A-A

Table 2 presents the magnitude of conductivity found in the different tests and the principal geotechnical characteristics of soils.

Table 2. Characteristics of soils

Description of the Material	**Coefficient of Conductivity k (m/s)**	**Observations**
Clayey sand, SC	$7.14x10^{-5}$ (*)	Material in all the physical soundings, 3 m depth
Lean Clay, CL	$6.50x10^{-7}$ (*)	Material below the clay strata
Poorly graded sand, SP	3.94x10-5	Material founded next to the Izozog River
Poorly graded gravel with sand GP	$1.71x10^{-4}$	Lenses of gravel next to the Izozog River
Clayey Gravel GC	$1.82x10^{-5}$	Lenses of gravel next to the Izozog River

* Average Value of all tests

Geotechnical Modeling of the Problem

For the modeling of the problem, specialized computer programs (SEEP/W and CTRAN/W of Geoslope International[7]) have been used, establishing a total of 764 nodal points that group 563 differential elements. Additionally, the geometric and geotechnical properties have been established from a topographic survey and the geotechnical study. All the geometric and geotechnical characteristics of the soil, besides the physical and-chemical conditions of the pollutant are presented in Table 3. Considering that the emission of the waste is continuous during all year around and, it generates a superficial flow on the channel, the analysis of Advection-Dispersion has been adopted as the prevailing condition of the superficial and underground flow.

The mathematical evaluation of the problem has been split into 2 parts. In the first stage the movement of the pollutant is analyzed in saturated conditions (constant permeability). Then, the same analysis is carried out supposing unsaturated conditions, adopting the functions of water content and hydraulic conductivity in agreement with the coefficient of permeability found in the field and specialized bibliography (Ho[7] 1997). Simultaneously to the concentration analysis, the computer programs made the follow-up of 24 tracers possible in different conditions of saturation of the soil.

Table 3. Geometric, Geotechnical and Pollutant Properties

Geometric Properties	Values	Justification
Thickness of clay stratum (average)	3 m	Perforation tests
Thickness of sand stratum (channel input)	107 m	Electrical resistivity soundings, SEV
Thickness of sand stratum (channel outlet)	15 m	Electrical resistivity soundings, SEV
Length of the polluted channel	1113 m	Topographic survey
Geotechnical Properties	**Values**	**Justification**
Hydraulic Conductivity of sand (k)	5.27×10^{-5} m/s	Constant-head tests in field
Volumetric content of water in the sand (Θ)	0.372	Data assumed according to Ho[7] (1997)
Hydraulic conductivity of clay (k)	4.80×10^{-7} m/s	Variable-head tests in field
Volumetric content of water in the clay (Θ)	0.393	Data assumed according to Ho[7] (1997)
Properties of the contaminant	**Values**	**Justification**
Type of contaminant	Hydrocarbons	Chemical analysis in polluted waters
Input quantity	10 l/s	Pipe (source)
Kinematics viscosity	0.745 m^2/s	According to Kessler-Lenz[8] (1994)
Relative Density	0.879	According to Kessler-Lenz[8] (1994)
Concentration of contaminant	192 mg/l	Chemical analysis in polluted waters
Longitudinal dispersion coefficient (α_L)	12.2 m	Geometry of the adopted model
Transversal dispersion coefficient (α_T)	1.22 m	Geometry of the adopted model

RESULTS

Flow Analysis

The behavior of flow tracers in a saturated media is characterized by the great displacement of the particles in periods of time that can be considered short compared with the low saturation conditions. Figure 5 presents the displacement that accomplishes the flow tracers (122 meters) in high saturation conditions for an evaluation time of 3 months. On the other hand, the displacement of the particles presented in the Figure 6, shows clearly the movement of the tracers in unsaturated conditions (15 meters) for a time of 36 months (3 years).

The analysis shows the fact that the particles in unsaturated conditions present a very slow displacement; however once they reach a saturated regime acquire a greater infiltration speed.

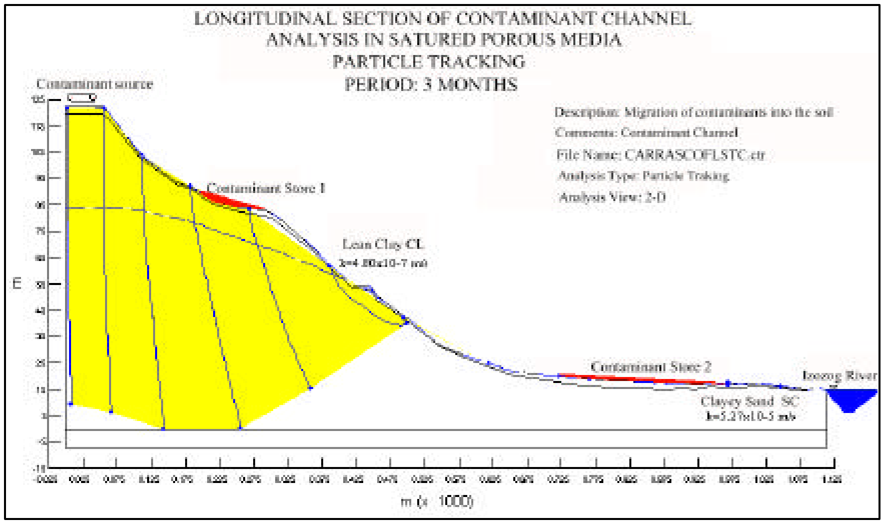

Figure 5. Motion of flow particles in saturated media. Period of evaluation: 3 Months

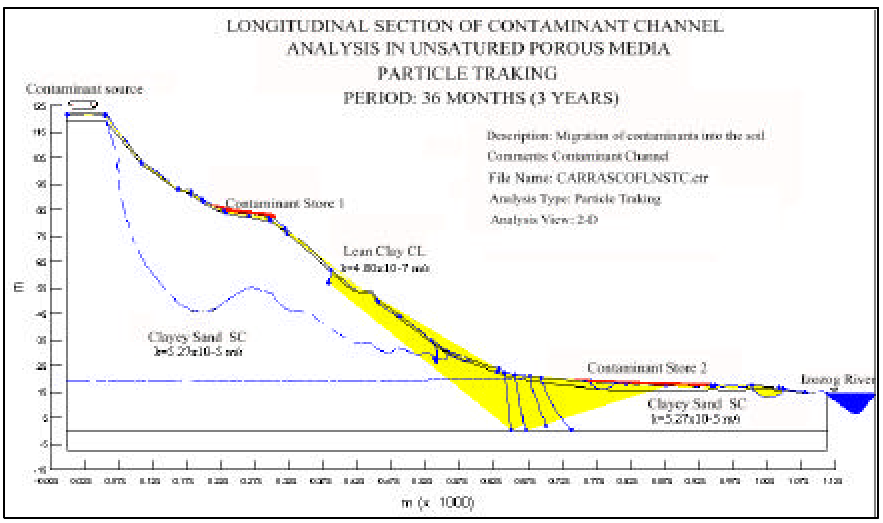

Figure 6. Motion of flow particles in unsaturated porous media. Period of evaluation: 36 Months (3 years)

Concentration Analysis

The results obtained in the advection-dispersion analysis were developed from concentration equipotential lines whose minimal value was governed by the maximum quantity of pollutant present in the soil (20 mg/l).

Figures 7 and 8 present the pollutant processes in the subsoil for the saturated and unsaturated conditions respectively. In either case, a contamination time of 6 months is considered. The movement of the pollutant in saturated conditions progresses approximately 8 times more rapidly than its movement in unsaturated conditions. Also, the tolerable concentration in soil (20mg/l) in low saturation conditions is achieved 120 meters from the surface where the concentration is 192 mg/l. In the graphics, each line represents an increment equal to the tolerable concentration in the soil. Each line defines the number of times that soil surpasses the tolerable maximum concentration. According to the Figure

7, in approximately 6 months the zone would be contaminated up to 122 meters from the surface.

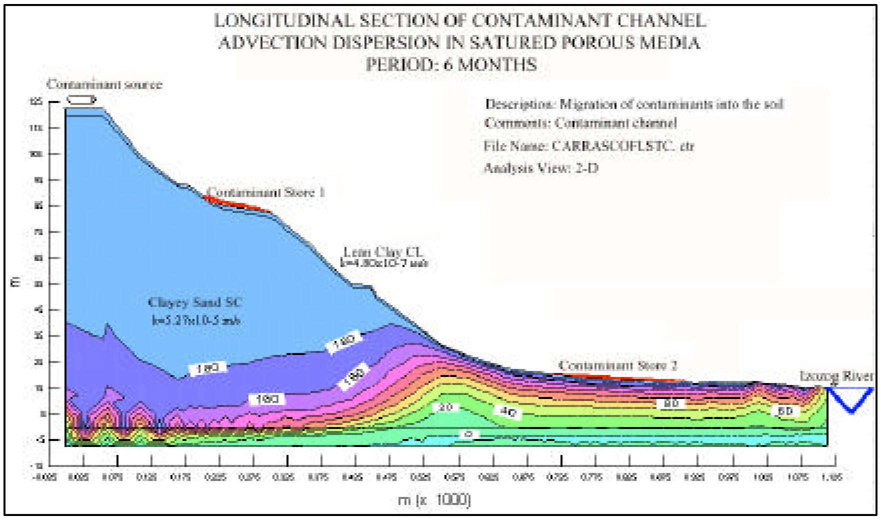

Figure 7. Advection-Dispersion analysis in satured porous media. Period of evaluation: 6 Months

Comparing the results of the analysis with the soundings accomplished on field, it can be concluded that the behavior of the pollutant in totally saturated conditions is considerably far from reality.

In the unsaturated model (Figure 8) the displacement of the pollutant is slower, the material is infiltrated to depths that according to the field conditions, where greater level of contamination is near the reservoir 2.

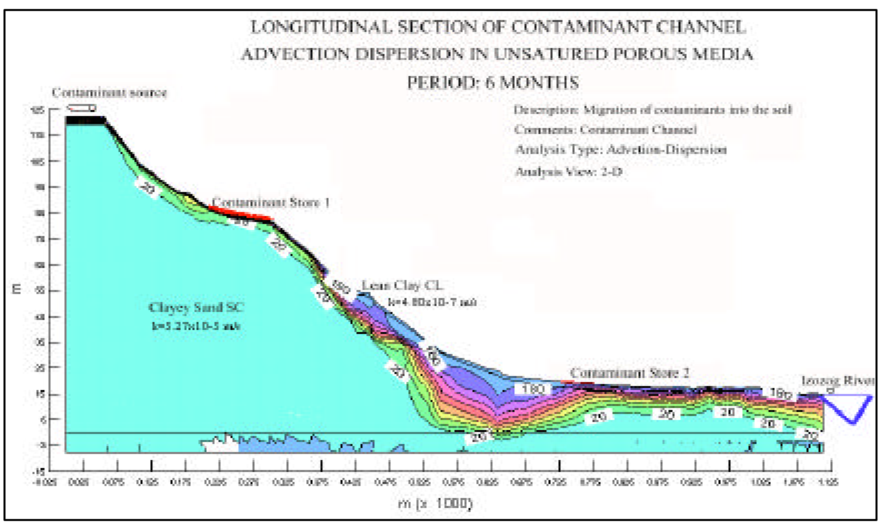

Figure 8. Advection-Dispersion analysis in unsatured porous media. Period of evaluation: 6 Months

The contamination analysis in unsaturated conditions is approximated to the conditions found in the field, an evaluation of the possible movement of the compounds for different time intervals was carried out. Possible affected-soil volumes for periods of 1, 5 and 10 years are presented in Table 4. In order to calculate these volumes, it has been considered that the width of contamination is the same as the natural channel and the plume moves in the same path.

Table 4. Quantities of Soil Affected by TPH (Until 20 mg/l)

Period of contamination	Length of the contaminate zone (m)	Deep of contaminations (m)	Broad defined by the transverse channel section (m)	Volume of contaminated soil (m^3)
1 year	350	15	7	36750
5 years	350	30	8	84000
10 years	450	40	9	162000

Figure 9 shows the analysis of Advection-Dispersion accomplished for a period of 10 years, 5 years since the fieldwork. The most damaged zone is near reservoir 2, with a depth of penetration of 40 m and a length of 450 m.

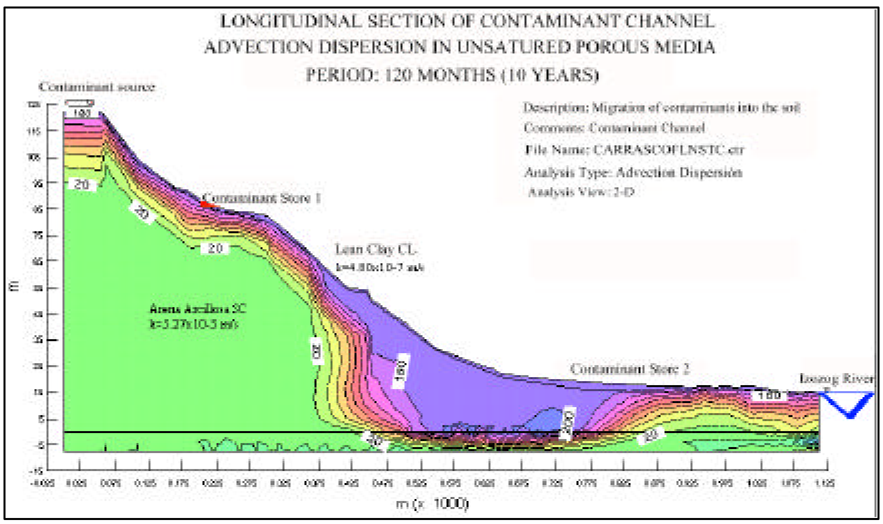

Figure 9. Possible affected area for a 10 years of contamination

CONCLUSIONS

A geotechnical study has been carried out in a sector of the petroleum field Carrasco, Cochabamba, Bolivia, in order to determine the pollutant effect due to oil spills. The pollutants have been identified as Total Petroleum Hydrocarbons (TPH). The concentration of the solution, obtained from chemical analysis, poured by a pipe, as the source of contamination, exceeds the tolerable by Bolivian laws.

It has been established, in comparative form, that the soil is the element that assimilates all the contamination as a natural filter, it reduces the concentration of the pollutant in a length of 1100 meters from the source of emission.

The zone of investigation is constituted by a lean clay (CL) with a thickness of 3 m, and a coefficient of permeability of 4.8 x 10^{-7} m/s. The clay stratum underlies a clayey sand (SC) whose thickness is greater than 15 m, with a coefficient of permeability of 5.27 x 10^{-5} m/s. According to what was observed in the mathematical tracers analysis of flow in an unsaturated and saturated media (Figures 5 and 6), the movement in low conditions of saturation is approximately 50 times slower than a saturated flow movement. This movement condition of the underground flow is applicable to any compound that is found dissolved in the water or this present in liquid form into the subsoil.

The analysis has taken the unsaturated conditions as representative of the observed in the field and the prediction of movement of contaminant is presented in Figure 9. The estimation of the functions of hydraulic conductivity and content of water volume (unsaturated flow) in the modeling process can reduce the reliability of the results. However, this consideration, made it possible to simulate the flow according to field observations.

It is important to accomplish a more detailed work in the zone then verify the results found through the model. It is suggested that specific characterization projects be performed constituted by perforations and chemistry tests in soils and underground waters. Additionally, it is necessary to accomplish a more detailed topographic survey, detailing with greater precision the characteristics of the channel and cross sections.

ACKNOWLEDGEMENTS

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