* DO NOT USE THE INVERTED COMMAS IF EL TREBOL IS THE ACTUAL NAME, AS IT IS USED HERE. ALSO CORRECT WITHIN THE TEXT

Causes and consequences of the Sinkhole at "El Trebol" of Quito, Ecuador - Implications to economic damage and risk assessment

Theofilos Toulkeridis[1]*, Fabián Rodríguez[1], Nelson Arias Jiménez[2], Débora Simón Baile[1], Rodolfo Salazar Martínez[1], Aaron Addison[3], Dora Carreón Freyre [4], Fernando Mato[1] and Carmen Díaz Perez[5]

ttoulkeridis@espe.edu.ec, ffrodriguez3@espe.edu.ec, nelsonarias1959@gmail.com, ddsimon@espe.edu.ec, rjsalazar@espe.edu.ec, aaddison@wustl.edu, freyre@geociencias.unam.mx, fjmato@espe.edu.ec, carmen.diaz@espoch.edu.ec

[1]Centro Geoespacial, Universidad de las Fuerzas Armadas ESPE, Sangolquí, Ecuador

[2]Empresa Metropolitana de Alcantarrillado y Agua Potable de Quito, Quito, Ecuador

[3]Washington University St. Louis, Missouri, USA

[4]Universidad Nacional Autonoma de México, Campus Queretaro, México

[5]Escuela Superior Politécnica de Chimborazo, Riobamba, Ecuador

*Corresponding author

Part of this study has been presented at the
NINTH INTERNATIONAL SYMPOSIUM ON LAND SUBSIDENCE, NISOLS 2015,
15 - 19, November, 2015, Nagoya Congress Center, Nagoya, Japan

Abstract

The so-called "El Trébol" is a critical road interchange in Quito connecting the north and south regions of the city. In addition, it connects Quito with the highly populated "Los Chillos" valley, one of the most traveled zones in the Ecuadorian capital. El Trébol was constructed in the late sixties in order to resolve the traffic jams of the capital city and for that purpose the Machángara river was rerouted through a concrete box tunnel. In March 2008, the tunnel contained a high amount of trash furniture that had been impacting the top portion of the tunnel, compromising the structural integrity. On the 31st of March 2008 after a heavy rainfall a sinkhole of great proportions was formed in the Trébol traffic hub. In the first few minutes, with an initial diameter of 30 meters. The collapse continued to grow in the following days until the final dimensions of 120 meters in diameter and some 40 meters of depth, revealing the Machángara river at the base of the sinkhole.

A state of emergency was declared, the cause of the sinkhole was a result of the lack of monitoring of the older subterranean infrastructure where trash had accumulated and damaged the concrete tunnel that channelized the Machángara river until it was worn away for a length of some 20 meters, leaving behind the sinkhole and the fear of recurrence in populated areas.

In an intend to understand the causes and consequences of this sinkhole event, rainfall data are shown together with hydrogeological characteristics and a view back to the recent history of sinkhole lineation or arrangement of the city of Quito. The economic impact is also emphasized, where the direct costs of the damage and the reconstruction are presented and compared to indirect costs associated with this socio-natural disaster. These analyses suggest that the costs of indirect financial damage, like time loss or delay, and subsequent higher expenses for different types of vehicles,

are equivalent to many times the costs of the reconstruction of El Trébol.

Keywords: Subsidence, sinkholes, economic damage, Quito

IN THE FIRST TWO PARAGRAPHS REFERENCES TO FIGURES (1-4) IS COMPLETELY MISSING

1. Introduction

The so-called "El Trébol" is a critical road interchange in Quito connecting the north and south regions of the city. In addition, it connects Quito with the highly populated valley "De los Chillos", one of the most traveled zones in the Ecuadorian capital. El Trébol was constructed in the late sixties in order to resolve the traffic jams of the capital city and for that purpose the Machángara river was rerouted through a concrete box tunnel. In March 2008, the tunnel contained a high amount of trash such as refrigerators, furniture, old parts of vehicles and even some motorbikes. These materials were impacting the top portion of the tunnel, compromising the structural integrity.

Considering this context, on the 31st of March 2008, during a regular working day, a heavy rainfall took place within an already extremely wet season, and around 2 p.m., a sinkhole of great proportions was observed in the Trébol traffic hub. In the first few minutes, the sinkhole started to be generated in the form of a crater with a diameter of 30 meters. The collapse continued to grow in the following days until the final dimensions of this almost round sinkhole reached approximately 120 meters in diameter and some 40 meters of depth, revealing base of the sinkhole, and the Machángara river.

Although fortunately no person was harmed in any way, the generation of this sinkhole paralyzed the traffic of the south-central part of the city for the following weeks and therefore the state of emergency was declared. Soon the cause of the sinkhole was a result of the lack of monitoring of the older subterranean infrastructure where trash had accumulated and compromized the concrete tunnel that channelized the Machángara river until it was worn away for a length of some 20 meters leaving behind the sinkhole and the fear of recurrence in populated areas.

In order to understand the causes and consequences of this sinkhole event, rainfall data are shown together with hydrogeological characteristics and a view back to the recent history of sinkhole lineation or arrangement of the city of Quito. The economic impact is also emphasized, where the direct costs of the damage and the reconstruction are presented and compared to indirect costs associated with this socio-natural disaster. These analyses suggest that the indirect financial damage, like time loss or delay, and subsequent higher expenses for different types of vehicles, has been many times the costs of the reconstruction of El Trébol.

Sinkholes can be of artificial, natural or combined origin as studied and observed in a variety of cities and regions (Beck, 1991; Aisong and Jianhua, 1994; Salvati and Sasowsky, 2002; Williams, 2003; Beck, 2004; Waltham et al., 2005). Sinkhole collapses in urban areas however, may be a man-made result of a forgotten and covered as well as outdated sewer system, of which its real magnitude appears to be a potential risk of unknown proportions. Such sinkholes may be absolutely devastating in the area where they appear and the appearance itself may be with signs or without any warning. Prominent examples of sinkholes appeared in recent years in the United States like the Macungie Sinkhole in 1986 (Dougherty and Perlow Jr.,1988), Daisetta Sinkhole in 2008 (Paine et al., 2009), and in Guatemala City (Guatemala) 2007 and 2010 (Hermosilla, 2012) and even in desert areas like in Kuwait (Shaqour, 1994). Man-induced sinkholes are associated with the increasing industrialization and urbanization of cities and the intense human economic activity in the investment of the corresponding hydrological systems (Reese et al., 1997; Gutiérrez et al., 2007; Brinkmann et al., 2008; Gutiérrez et al., 2009).

Based on considerably high economic damages caused by sinkholes in urban areas, the monitoring and detection with geophysical tools and geographic as well as historic data of sinkholes has recently been a major focus in city planning and hazard prevention (Orndorff and Lagueux, 2000; Lei et al., 2004; Gutiérrez-Santolalla et al., 2005; Gutierrez et al., 2008; Brinkmann et al., 2008; Bruno et al., 2008; Kaufmann and Romanov, 2009; Krawczyk et al., 2012; Margiotta et al., 2012).

In Quito (Ecuador), a variety of sinkholes occurred during the 20th century. However, it has not been until 2008, when the great sinkhole within the area called "El Trebol" appeared and reminded the city population and city planners to re-evaluate the spatial distribution of past sinkholes and further areas, which might be vulnerable of such a hazard. It is of fundamental interest to society and authorities, to identify their potential distribution and to prevent the occurrence of further sinkholes, and assess the potential economic damage and loss of lives. Therefore, the aim of this study is of twofold as it focuses firstly on the causes of the sinkhole in 2008 and its direct and indirect economic damage while secondly a historic reconstruction of past sinkholes and the older sewer system may be able to help to indicate where future hazards may be triggered in order to monitor and prevent them involving adequate and corrective mitigation measures in time.

2. Geological setting and geo-mechanical behavior of involved deposits

In Ecuador two prominent cordilleras limit to the west and to the east the so-called the Interandean Depression, which was created at the end of Lower Pliocene and where many thousands of meters of pyroclastics and sediments were deposited, mostly due to the erosion and high volcanic activity up to the present day (Winter and Lavenù, 1989; Tibaldi and Ferrari, 1992; Coltori and Ollier, 2000). The “El Trebol” (traffic hub) sinkhole is situated within the thick sequence of sediments of the Interandean Depression, right next to the western flanks of the Pichincha Volcanic Complex (Monzier et al., 2002; Robin et al., 2008). These Quaternary deposits are composed of the (a) Cangahua formation, (b) Conglomerates, (c) alluvial sediments and (d) refilling of sediments and materials (Clapperton and Vera, 1986).

The Cangahua Formation is a 25–30-m-thick sequence has usually a yellowish-brownish color and is composed of paleo-soils, fine-grained volcanic tuff, pumices, eolian-reworked volcanic ash and glacial loess as well as occasionally having mud-flows and alluvial channels (Hall and Mothes 1997). Generally the grain size distribution of the Cangahua Formation is silty to sandy, well consolidated, with low permeability and extremely stable when dry. In contact with water, the strength of these materials is highly reduced producing instability of slopes, which in turn collapse in forms of big blocks (O'Rourke and Crespo, 1988).

The conglomerates, that outcrop in the vicinity of the sinkhole, are composed sub-rounded to rounded blocks and gravels, with a silty to sandy compacted matrix. Nonetheless, these deposits are absent in the stratigraphy of the sinkhole. In the lower part of the sequence are sub-rounded, up to meter-sized fluvial transported blocks, surrounded by smaller material of previous terraces. This deposit is very compact, presenting a high resistance to loosening.

In order to construct the transport exchanger designed for that site, the deviation of the Machángara river has been performed on a stretch of approximately 300 m. Above this structure a silty-sand compacted filling was placed, corresponding to materials involved in the subsidence. At the northeastern side of the compacted filling, a non damaged area was observed, having a middle-high strength, these materials presented N values between 17 and 28 obtained by a Standard Penetration Test (SPT)drilling. No water phreatic level has been observed in this area. Nonetheless, at the southern and southwestern side of the slopes of the sinkhole water flows have been observed at a depth of 20 m, which will be discussed in this paper.

3. Hydrological conditions

The distribution of rainfall along the year considering data from 1962 shows the prevalence of two periods with abundant rainfall being these, February-May and October-November respectively, while the drier seasons correspond to June-September and December-January (EMAAP-Q, 2006; Fig. 5). On the other hand, as for the multiannual distribution of rainfall it is important to highlight that the wet season between January and March of 2008 was considered the strongest of the last 20 years with accumulated rainfall during the first three months of 2008 being much higher that the recorded during another heavy rainy seasons of 1989, 1993 and 2000 (Salazar et al., 2009). In particular, a peak of 21.2 l/m^2 was registered on the 31st of March 2008 during a heavy rainfall that lasted 4 hours from 1p.m. to 5 p.m (INAMHI, 2008; El Comercio, 2008; Salazar et al., 2009). Additionally, within the whole 2008 and coinciding in the three meteorological stations closest to El Trebol, March recorded continuous raining since it was the month with the highest number of days of rain, with 27 and 29 out of 31 days in Iñaquito and Izobamba respectively (Fig 5a, 5b, 5c).

The hydrographic network of the South Valley of Quito is classified as dendritic, having the Machángara as its main river course. The Machángara rises in the steep foothills of Atacazo volcano and crosses the valley from south-west to north-east running parallel to the basin until it reaches the Trebol area (Panecillo) where it takes a turn to the East, gets deeper and flows to the valleys of Cumbayá and Tumbaco. Another important drainage is the so-called "Quebrada Grande" that has its source in the northwest foothills of Atacazo volcano and for a stretch it aligns parallel to the Machángara river until it becomes its tributary. When it exits to the valley, the Machángara river flow varies between 3 m^3/sec during dry season and 170 m^3/sec during the wet season. Furthermore, the Machángara river is the main sewage receiver of Quito.

5. **Hydrogeology of the study area**

After the subsidence and collapse took place, groundwater emerged in the south and southwestern slopes at a depth of 20 meters from the upper rim of the slope (Fig. 6), These water springs contributed with a total flow of around 6 l/s, which decreased 50% due to drilling of pumping wells strategically located. These springs revealed the presence of a free aquifer located in the south side of the sinkhole. Indeed, the existence of the aquifer was determined after field observations followed by three drillings; the water table is located between 12 and 15 meters deep. The aquifer is composed by granular materials within a silty-sandy matrix, with a thickness of around 18 m with a gradient from southwest to northeast, the direction to the Machángara River (Fig. 7). The aquifer recharge probably takes place in the Luluncoto gorge situated 2 km to the southwestern.

A flow of around 10 l/s was obtained from the aquifer considering two sources: (1) the continuous pumping from the wells and (2) the water springs from the south slope of the sinkhole. Despite this 10 l/s flow that was permanently extracted, the aquifer kept on flowing, suggesting that its recharge must have been higher than 10 l/s. Therefore, this flow should be taken into account when performing any reconstruction work in the area (Table 1).

5. Historical hydraulic facilities of the area

The site where El Trébol was constructed is about 300 - 600 m downstream of the confluence of Jerusalem and El Tejar streams with the Machángara River. Today, the channeled stream of Jerusalem is the Boulevard 24 de Mayo Avenue and its extension to the old bus station, current Qumandá Park. The channeled stream of El Tejar, after passing below the historic center, merges and flows with the stream of Manosalvas down in the low neighborhood of San Juan, in the area that is the center's transit transfer, now known as La Marin, before reaching Machángara River.

As a result of uncontrolled growth of the city, this natural drainage system was conducted on sewer channels below the construction of roads for vehicular traffic. Historical records include 12 sinking holes (Table 2; Fig. 8) of different magnitudes, defined as ". declines or collapses of roadway in the filler material streams, caused by faulty sewers", as well as the filling, initially performed with debris and garbage, the age, type of construction and degree of deterioration of the physical work of the channels, sewers and collectors (Pewter, 1986).

The former sinkholes were located on the old bed of the filled streams, so we can assume that it will continue to occur, especially in periods of daily rainfall above the historical average. In the area of El Trébol, the first serious collapse was registered the 31st of March 2008, 10 years after channels were made for the construction of the infrastructure to solve the problems of the traffic jams. Furthermore, there was a second sinkhole of lower rate on 10 January 2014 (Fig. 9).

6. Analysis of the causes of the sinkhole

The sinkhole generated in "El Trébol" site, involved 25.000 m^3 of earthy material disappeared. This area is the most important southern inter-connector of the city to the "Los Chillos" Valley in the eastern end of Quito, but serves as well to connect the southern to the northern side of the city, where an extremely high amount of vehicles transit daily. This site was constructed four decades before its collapse. The sinkhole started in form of a crater with a diameter of approximately 30 m, amplifying its size constantly due to the instability of the slopes, when contact water from the high precipitations prior to the event. Further presence of groundwater has been noticed in the southern slope of the sinkhole, when the diameter reached some 120 m in diameter and a depth of 40 m, determined from the top part down to the previously covered river. That river was detected after the visible collapse of the squeezed river concrete channel of the river Machángara for a distance of some 20 m. The result of this subsidence led to a traffic collapse and the declaration of the state of emergency of the Municipality of Quito. This analysis intend to identify the causes of this subsidence and afterwards to search for further areas with similar problems and vulnerabilities in order to avoid future disasters where potentially people could be involved.

Three hypothesis were taken into consideration as the most potential cause for this disaster: (a) extreme water discharge, (b) erosive process and chemical alteration through time and finally (c) influence of the groundwater.

6.1. Extreme water discharge

One of the most likely triggers may be the high amount of flowing and floating material that was carried by the river. A strong rainfall with 21 liters per m^2, appears to have damaged the weakest area of the vault, located 145 meters from the gate of the Machángara river. Materials found two meters above the highest tunnel entrance

HOW WAS THIS INDICATED?

point, indicate that the channel was working under a high pressure. The detachment of the concrete cover of the vault of the channeled part of the tunnel produced a drag filler, which formed in a few hours a conduct of about 30 ~~meters~~ in diameter at the surface, which later got even extended.

WHAT DO YOU MEAN BY "DRAG FILLER"?

6.2 Erosive processes and chemical alteration with time

As previously described, the Machángara river has a variable behavior in time. Typical significant decreases in dry seasons reached a minimum of 3 m^3 / s, while sharp increases in wet season, generated floods up to 170 m^3 / s. These variations have been the main cause for the deterioration of the structural elements of the channel (iron and concrete) and will be described below.

6.2.1. Potential damage of structures by the river in dry season

Considering that the Machángara River is the largest recipient of discharges of sewage and industrial effluents from the city of Quito and water consumption in the city is about 7 m^3 / s and 40% of this flow (2.8 m^3 / s), is ~~for use~~ A PRODUCT of the southern part of Quito, then we imply* that in dry seasons the flow through the river Machángara corresponds to sewage and industrial effluents that are produced in the south of the city (Arias Jiménez, 2008). Furthermore, at drier times the potential of chemically altered waters may ~~be~~ additionally influence structures by corrosion, ~~also~~ AND may cause systematic deterioration of the elements and the weakening of the structures as a whole. Nonetheless, as the waters flowing though the Machángara river are sometimes altered, being slightly basic, this aspect may be disregarded.

YOU STATE THAT THE RIVER HAS A CORROSIVE POTENTIAL AND THEN YOU NEGATE IT. THIS IS VERY CONFUSING. PLEASE EXPLAIN

6.2.2 Potential damage of structures by crescents of the river

* I DO NOT UNDERSTAND THE REASON BEHIND THIS ASSUMPTION. INSTEAD I IMPLY THAT THIS PERCENTAGE IS KEPT ALSO IN DRY SEASON. PLEASE EXPLAIN THIS ASSUMPTION AND WHY IT IS NECESSARY

= m³/s?

In winter times the river has high flow rates, reaching up to 170 l / s, there is sufficient capacity to both receive sewage and cause a dilution of the elements, changing hereby dramatically the water chemistry (reduction of the conductivity, pH, etc.), becoming a less aggressive water (Arias Jiménez, 2008).

The water with the chemical conditions described above, does not cause a significant effect on the elements of the collector at all. The potential alteration is rather directly related to the high speeds of the water and sediment carried by the river (LARGE boulders ~~large~~, scrap wood, etc), which COLLIDE ~~colliding~~ with the structures PRODUCING ~~produce~~ weakening, fracturing and erosion, mainly at the floor (see figure 10a) (Arias Jiménez, 2008).

Based on the analysis of the behavior of the river in dry and wet seasons, we may be assume that the collapse of the channel was caused by a systematic alteration of structural elements by the erosion produced by big sediments and to a very less extend by the chemical action of the waters.

This hypothesis is based on the fact that in the collapsed collector on the left margin of the channel there are no vestiges of the floor. It would have a higher weight considering that the channel on that site makes a small break and the force of the water colliding directly in the union of the right gable with the floor, causing weakening and faulting. The water caused floor erosion, leaving the right transept without support and initiated a process of dragging of sediments filling and covering the channel, causing the phenomenon known as piping, a process that accelerated due to the presence of underground streams water (Arias Jiménez, 2008), as illustrated in Figures 10a-c.

THIS WHOLE SENTENCE IS NOT CLEAR (WHAT WEIGHT?) AND THE ENGLISH MUST BE REVISED

As a result of piping a cavern was formed, * the soil lost sustainability and collapse of the filling occurred leading to the formation of the sinkhole in form of a crater. As stated above at first the sinkhole had a diameter of 30 to 40m, while a little later, due

* WHERE DO YOU THINK THAT ALL THE COLLAPSED MATERIAL GO? TRANSPORTED BY THE RIVER TO THE SEA? DO YOU HAVE ANY NOTION ABOUT THIS?

to the constant landslides caused by the action of rain and the presence of groundwater it reached finally a diameter of 120 to 40 m.

Nonetheless, we do not rule out the hypothesis that the modification of the river with the channel and squeezed river has been a factor in the collapse, because the river sought its natural course.

6.3 Influence by the groundwater.

A last hypothesis to be considered is the potential influence of groundwater, directly related to the construction process. For the construction of the channel and subsequent filling thereof, the designs did not consider a drainage system for groundwater that surfaces in the south slope, to avoid saturation of the filling material and control the pore pressure, which may reach very high values. There are many examples where pore pressure is associated with the fracture of walls in hydraulic works such as dams, tunnels, reservoirs, viaducts, etc. (Arias Jiménez, 2008).

7. Direct and indirect financial damage

The Sinkhole in the traffic exchanger known as "El Trebol" was the consequence of previous downpour rain. According to Salazar et al. (2009) January, February and March of 2008 was a record making, just the day before of the sinkhole creation, rain fell with an intensity of 21,2 lts/m^2. All these heavy rain triggered an enormous pressure on old drainage system, which induced Machangara's River drainage vault to collapse.

The day after sinkhole, the Ecuadorean Government create a line of credit of 60 million USD to help the city and start the reconstruction (La Hora, 2008). At the same day, the Quito's Major and the City's Council created an emergency fund of 200 thousand dollars. This emergency fund was increased to about 1 million. The day after drainage vault collapsed, rebuilding process started with a team of five hydraulic excavators, five power shovels, ten roll-off trucks, four system equipment of mobile industrial lighting. In the rebuilding process 210 workers teams were at the site 24/7 (El Universo, 2010). The reconstruction of the cloverleaf interchange took 8 months to full traffic recovery, yet the entire reconstruction of the site took 22 months (El Universo, 2010). El Trebol total reconstruction cost reached over 13 million US dollars (Table 3).

However, this overall cost do not reflect the real cost because it does not take in account the externalities implicit with the sinkhole. An externality is defined as uncompensated effects that affect user utility o wellbeing the social cost (Cowen, 1992), meaning how users were affected by the sinkhole and cloverleaf interchange reconstruction. For instance, local authorities closed schools during the first week after the event, cost of students losing classes are not included neither teachers income lost who were in per hour contracts.

We analyzed those costs of users who were affected by and were not compensate for. Because of lack of official information, we concentrated our efforts to estimate the cost of losing time during the reconstruction of reconstruction of the cloverleaf interchange and drainage vault, as well as the additional cost in gasoline of users of this crucial cloverleaf interchange.

In case of additional cost in gasoline, there were eighty thousand of vehicles circulate and use El Trebol every day, in addition of 400 inter-parish public transportation buses (La Hora, 2008). In order to estimate the value lost by user, we concentrated in private transportation under the assumption that a car-owner who uses his car to go to his job and back home fill his car gas tank once a week. This assumption seems reasonable for most of car owners. Yet, we did not include public transportation because we don't know how many times a transportation unit fills bus gas tank in a week. Based on public estimations, we used a value of 0.07 US dollars as additional cost that an owner has to pay to fill his gas tank. It is reasonable also to assume that a car owner spend 20 dollars/week filling his car tank. These 0.07 dollars seems a low bound, but still reasonable. Then, we multiply the value of one gallon of gasoline adding these 0.07 dollars.

Based on AIHE statistics (AIHE, 2015), we know that 21% of car owners used a "super premium" gasoline which has a price of 2,00 dollars/gallon and 78% uses "extra" gasoline with a price of 1,48 dollars/gallon. Based on the number of vehicles which circulated at that time "El Trebol" every day, 80.000 cars/day, we can say that approximately 17 thousand cars used "super premium" gasoline and over 62 thousand used "extra" gasoline type. We estimated that additional cost in gasoline for private car owners was 85 million of dollars for those 8 months of traffic problems at "El Trebol".

We did not include capital depreciation, even now, it is well known that keep a car running while waiting depreciate its value faster than normal conditions. We didn't include both public transportation and car owners who own a diesel engine car.

Concerning the cost of time lost (an opportunity cost), we estimate its value from per hour salary multiply for the additional time that users had to spend during the reconstruction process. We considered that a time between 25 up to 35 minutes are reasonable to believe users lost during their travel to workplaces or going back their homes. User lost between 2,23 up to 3,12 dollar/hour. This value is multiply for the total time lost during site reconstruction. Since user came from different directions, we estimate the lost value separately. According to media reports, at that time 80.000

private own vehicles circulated throughout “El Trebol” per day, 48.000 came “Los Chillos” Valley (CPVTOTAL), 22.000 came from southern part of Quito (CPSTOTAL), 10.000 were coming toward the valley or southern part of the city (CPAvVITOTAL) and 400 units of public transportation (CPTTOTAL). Regarding public transportation, we assume that each unit was carrying 40 passengers each trip, which it is a low bound because rush hour, these units can be a full capacity (around 72 passengers).

Finally we estimate users’ opportunity cost multiplying per hour lost times the time of “El Trebol” reconstruction, which was total of 8 months. The users’ opportunity cost for each category is presented table 5.

Users lost a considerable amount of time when reconstruction took place, adding all users (the aggregate value) it turned out that the real cost of the sinkhole increases significantly. As the table shows, under the assumption that users lost only 25 min, the opportunity cost reaches over 68 million dollars during the 8 months of reconstruction, and under the assumption that user lost up to 35 minutes, the opportunity cost reaches over 95 million. As a result the real cost (under 25 min assumption) reached 133.316.960,61 dollars, a below 35 min assumption reached 160.665.120,61 as real cost.

The ratio between reconstruction cost and the other cost presents that reconstruction cost is only a low percent of real cost, as table 6 shows, the ratio between reconstruction cost and additional gasoline cost is only 0,26 meaning that reconstruction cost is only about 26% of real cost, only 19,8% of opportunity cost for 25 min, and 14,2% for 35 min.

8. Conclusions

As main conclusion of this event, after the analysis of cost damages we consider as a priority to carry out corresponding actions to prevent future collapses. Taking in consideration the alignment of the actual and past sinkholes, the zones in which the alignments appear, need to be reinforced in order to avoid future disasters in these areas. Besides the potential risk of lives losses, as demonstrated in our study, the real costs of damages are much higher in the indirect damage of such sinkhole events rather in the reconstruction of the disaster site itself. Unfortunately, the enforcement of the potential subsidence areas did not take place yet, as demonstrated by a new sinkhole in 2014 in a zone where the vulnerability has been previously emphasized. To prevent future collapses, from a risk-management approach we mainly suggest: (1) the need for a detailed study about hydrological and hydrogeological characteristics of urban and industrial areas; (2) an action plan to act on areas identified as potentially vulnerable with monitoring and mitigation measures; and (3) the need to develop in the future sustainable and sustainable urban and industrial projects considering a hydrogeological approach.

Acknowledgements

We thank the Universidad de las Fuerzas Armadas ESPE for logistic and financial support. We also acknowledge the inspiration of the Facebook group called "All scary sinkholes in one place" to publish this article. Fernando Mato acknowledges support from the Prometeo Project of the National Secretariat of Higher Education, Science, Technology and Innovation (SENESCYT), Ecuador.

References

AIHE, 2015: Estadísticas, Asociación de la Industria Hidrocarburífera del Ecuador, Quito. (http://www.aihe.org.ec/index.php?option=com_content&view=article&id=122:estadisticas&catid=67&Itemid=142)

Aisong, D. and Jianhua, J., 1994: Land subsidence, sinkhole collapse and earth fissure occurrence and control in China. Hydrological Sciences journal, 39(3): 245-256.

Arias Jiménez, N.E., 2008. Hundimiento El Trebol" Respuesta a la emergencia". Unpublished Thesis, Instituto de Altos Estudios Nacionales, Quito, Ecuador: 52pp

Beck BF. 1991. On calculating the risk of sinkhole collapse. In Appalachian Karst. Proceedings of the Appalachian Karst Symposium,

Beck, B.F., 2004: Soil piping and sinkhole failures. In Enyclopedia of caves. White WB (ed). Elsevier: New York; 523–528.

Brinkmann, R., Parise, M. and Dye, D., 2008: Sinkhole distribution in a rapidly developing urban environment: Hillsborough County, Tampa Bay area, Florida. Engineering Geology, 99(3): 169-184.

Brinkmann, R., Parise, M. and Dye, D., 2008: Sinkhole distribution in a rapidly developing urban environment: Hillsborough County, Tampa Bay area, Florida. Engineering Geology, 99(3), 169-184.

Bruno, E., Calcaterra, D. and Parise, M., 2008: Development and morphometry of sinkholes in coastal plains of Apulia, southern Italy. Preliminary sinkhole susceptibility assessment. Engineering Geology, 99(3): 198-209.

Clapperton, C. M., and Vera, R., 1986: The Quaternary glacial sequence in Ecuador: a reinterpretation of the work of Walter Sauer. Journal of Quaternary Science, 1(1), 45-56.

Coltorti, M. and Ollier, C.D., 2000: Geomorphic and tectonic evolution of the Ecuadorian Andes. Geomorphology, 32: 1–19

Cowen, Tyler, ed., 1992: Public Goods and Market Failures. New Brunswick, N.J.: Transaction Publishers.

El Comercio, 2010: Después de 2 años, el túnel de El Trébol, listo. http://www.elcomercio.com/actualidad/quito/despues-anos-tunel-trebol-listo.html

Dougherty, P. H. and Perlow Jr, M., 1988: The Macungie Sinkhole, Lehigh valley Pennsylvania: Cause and repair. Environmental Geology and Water Sciences, 12 (2): 89-98.

2010 IN THE TEXT

El Universo, 01/04/2008: Se buscan vías alternas por hundimiento en sector El Trébol de Quito. http://www.eluniverso.com/2008/04/01/0001/12/555F7445DA114F59A5A7C7D8C0564C44.html

EMAAP-Q, 2006: Estudio Hidrogeológico del acuífero del Valle de los Chillos", Quito, Ecuador: 112pp

Gutiérrez-Santolalla, F., Gutiérrez-Elorza, M., Marín, C., Desir, G., & Maldonado, C., 2005: Spatial distribution, morphometry and activity of La Puebla de Alfindén sinkhole field in the Ebro river valley (NE Spain): applied aspects for hazard zonation. Environmental Geology, 48(3): 360-369.

Gutiérrez, F., Cooper, A. H. and Johnson, K. S., 2008: Identification, prediction, and mitigation of sinkhole hazards in evaporite karst areas. Environmental Geology, 53(5): 1007-1022.

Gutiérrez, F., Galve J.P., Guerrero, J., Lucha, P., Cendrero, A., Remondo, J., Bonachea, J., Gutiérrez ,M. and Sánchez J.A., 2007: The origin, typology, spatial distribution and detrimental effects of the sinkholes developed in the alluvial evaporite karst of the Ebro River valley downstream of Zaragoza city (NE Spain). Earth Surface Processes and Landforms, 32 (6): 912-28.

Gutiérrez, F., Galve, J. P., Lucha, P., Bonachea, J., Jordá, L., and Jordá, R., 2009: Investigation of a large collapse sinkhole affecting a multi-storey building by means of geophysics and the trenching technique (Zaragoza city, NE Spain). Environmental Geology, 58(5): 1107-1122.

Hall, M. and Mothes, P., 1997: El origen y edad de la Cangahua superior, valle de Tumbaco, Ecuador. In: Zebrowski C, Quantin P, Trujillo G (eds) Suelos volcánicos endurecidos. Mem III Symp Intern ORSTOM, Quito: 19–28

Hermosilla, R. G. (2012). The Guatemala City sinkhole collapses. Carbonates and evaporites, 27(2), 103-107.

Kaufmann, G. and Romanov, D., 2009: Geophysical investigation of a sinkhole in the northern Harz foreland (North Germany). Environmental geology, 58(2), 401-405.

Krawczyk, C.M., Polom, U., Trabs, S. and Dahm, T., 2012: Sinkholes in the city of Hamburg—New urban shear-wave reflection seismic system enables high-resolution imaging of subrosion structures. Journal of Applied Geophysics 78: 133–143.

La Hora, 06/04/2008: El Trebol se cayó en Quito.

(http://www.lahora.com.ec/index.php/noticias/show/703827/-1/El_Tr%C3%A9bol_se_cay%C3%B3_en_Quito.html#.VT4-MtJ_NHw)

Lei, M. T., Li, Y., Jiang, X. Z., Gan, F. P., & Meug, Y., 2004: Preliminary study on the technology and method of sinkhole collapse monitoring and prediction: As an example of sinkhole collapse monitoring station in Zhemu Village, Guilin City. The Chinese Journal of Geological Hazard and Control, 15(7): 142-147.

Margiotta, S., Negri, S., Parise, M. and Valloni, R., 2012: Mapping the susceptibility to sinkholes in coastal areas, based on stratigraphy, geomorphology and geophysics. Natural hazards, 62(2), 657-676.

Monzier, M., Samaniego, P., Robin, C., Beate, B., Cotton, J., Hall, M.L., Mothes, P., Andrade, D., Bourdon, E., Eissen, J.P., Le Pennec, J.L., Ruiz, A.G,, Toulkeridis, T., 2002: Evolution of the Pichincha volcanic complex (Ecuador). Proceedings of fifth international symposium on Andean geodynamics, Toulouse: 429–432

Municipio del Distrito Metropolitano de Quito (MDMQ): Balance de los Estudios Urbanos (1985–2005) de la Coperación IRDMunicpio de Quito, in: Movilidad, elementos esenciales y riesgos en el Distrito Metropolitano de Quito, edited by: Demoraes, F., Co-edición MDMQ-IFEA-IRD, Quito: 218pp, 2005

National Institute of Meteorology and Hydrology (INAHMI): Meteorological yearbook, Nr. 50, Quito, Ecuador: 139pp, 2010

National Institute of Meteorology and Hydrology (INAHMI): Meteorological yearbook, Nr. 48, Quito, Ecuador: 123pp, 2008

O'Rourke, T. D. and Crespo, E., 1988: Geotechnical properties of cemented volcanic soil. Journal of Geotechnical Engineering, 114(10): 1126-1147.

Orndorff, R. C. and Lagueux, K. M., 2000: Using geographic information systems (GIS) to determine geologic controls on the distribution of sinkholes in the Ozarks of south-central Missouri. In Abstracts with Programs-Geological Society of America (Vol. 32, No. 3, p. 38).

Paine, J. G., Collins, E. W., Wilson, C. R., Buckley, S. and John, A., 2009: Preliminary investigations of subsidence, collapse, and potential for continued growth of the Daisetta Sinkhole, Liberty County, Texas. 17 pp.

Peltre, P., 1989: Quebradas y riesgos naturales en Quito, in: Riesgos Naturales en Quito, edited by: Peltre, P., Corporación Editora Nacional, Quito, Ecuador: 45–89.

Reese, A. J., Cantrell, A. and Scarborough, J., 1997: Sinkhole and drainage planning in Johnson City, Tennessee. The Engineering Geology and Hydrogeology of Karst Terranes, 265-271.

Robin, C., Samaniego, P., Le Pennec, J.L., Mothes, P. and van der Plitch J., 2008: Radiocarbon dating of Late Holocene phases of dome growth and Plinian activity at Guagua Pichincha volcano (Ecuador). J Volcanol Geotherm Res 176: 7–15

Salazar, D., Demoraes, F., Bermúdez, N. and Zavgorodniaya, S., 2010: De Trébol a girasol: consecuencias de un hundimiento ocurrido el 31 de marzo de 2008 en un eje esencial de la red vial de la ciudad de Quito. Bulletin de l'Institut français d'études andines, 38, 3: 561-572.

Salvati, R. and Sasowsky, I.R., 2002: Development of collapse sinkholes in areas of groundwater discharge. Journal of Hydrology, 264: 1–11.

Shaqour, F., 1994: Hydrogeologic role in sinkhole development in the desert of Kuwait. Environmental Geology, 23(3): 201-208.

Tibaldi, A. and Ferrari, L., 1992: Latest Pleistocene–Holocene tectonics of the Ecuadorian Andes. Tectonophysics 205: 109–125.

Waltham, T., Bell, F. and Culshaw, M., 2005: Sinkholes and Subsidence. Springer: Chichester.

Williams, P., 2003: Dolines. In Encyclopedia of Caves and Karst Science, Gunn J (ed). Fitzroy Dearborn: New York; 304 –310.

Winter, Th. and Lavenù, A., 1989: Morphological and microtectonic evidence for a major active right-lateral strike–slip fault across central Ecuador South America. Ann. Tecton. 3, 2: 123–139.

Table captions

Table 1: Characteristics of wells and slopes

Description	Depth (m)	Diameter (inches)	Depth of phreatic level (m)	Depth of static level (m)	Depth of pumping (m)	Volume l/s.
Well 1	32	8	12	20	25	1.2
Well 2	37	8	15	22	24	2.0
Well 3	38	8	15	23	27	4.0
Slopes	20		-	-	-	3.0
					TOTAL:	**10.2**

Table 2: Historical register of sinkholes and collapses

Former event	Streets (on top of former streams) where sinkholes occurred	Associated former stream
29/05/1907	Morales (La Ronda), Benalcázar y García Moreno	Jerusalem
09/05/1909	Benalcázar, Espejo	Manosalvas/La Marín
02/03/1910	Benalcázar, Sucre	El Tejar
10/04/1911	Avenida 24 de Mayo	Jerusalem
07/01/1919	Pereira al norte de Santo Domingo	Manosalvas/La Marín
06/03/1920	Flores (Manosalvas), Sucre	Manosalvas/La Marín
24/02/1921	Del Correo (Venezuela), Espejo	Manosalvas/La Marín
06/10/1922	Guayaquil, Manosalvas	Manosalvas/La Marín
06/10/1922	Mideros	Manosalvas/La Marín
14/12/1922	Morales (La Ronda), García Moreno	Jerusalem
10/01/1928	Venezuela	Manosalvas/La Marín
21/03/1928	Guayaquil, Sucre, Bolívar	Manosalvas/La Marín
25/04/1950	Rocafuerte, Guayaquil	Manosalvas/La Marín
24/01/1983	Paredes, Morales (La Ronda)	Jerusalem
29/01/1983	García Moreno, Venezuela, Guayaquil	Manosalvas La Cava

Table 3: List of the costs of the reconstruction in US$. Data from MDMQ (2015)

NEW TUNNEL	7.575.872,21
RENTAL OF EQUIPMENT	352.622,93
LAND MOVEMENT	151.526,15
LABOR	801.546,35
CONSTRUCTION MATERIALS	435.495,03
SERVICES	219.061,16
OTHER COSTS	31.236,78
EMOP	2.000.000,00
VIDA PARA QUITO	2.000.000,00
TOTAL	13.567.360,61

Table 4: Vehicle type and different gasoline prices in US$

VEHICLE TYPE	GASOLINE PRICE DOLLAR/ GALLON	TOTAL COST[1]
17456	2,00	11.210.941,44
62544	1,48	40.168.258,56
TOTAL GASOLINE		51.379.200,00

1 adding 0,07 dollars

Table 5: Cost category expressed in delay of 25 and 35 minutes

COST CATEGORY	25 min	35 min
CPVTOTAL	34.185.200,00	47.859.280,00
CPSTOTAL	15.668.216,67	21935503,33
CPAvVITOTAL	7.121.916,67	9970683,333
CPúTOTAL	11.395.066,67	15953093,33
TOTAL COST	68.370.400,00	95.718.560,00

Table 6: Cost category

COST CATEGORY	AMOUNT $	RATIO
RECONSTRUCTION COST	13.567.360,61	
ADDITIONAL GASOLINE COST	51.379.200,00	0,264
OPPORTUNITY COST 25 min	68.370.400,00	0,198
OPPORTUNITY COST 35 min	95.718.560,00	0,142

→ BETEEW WHAT?

Figure captions

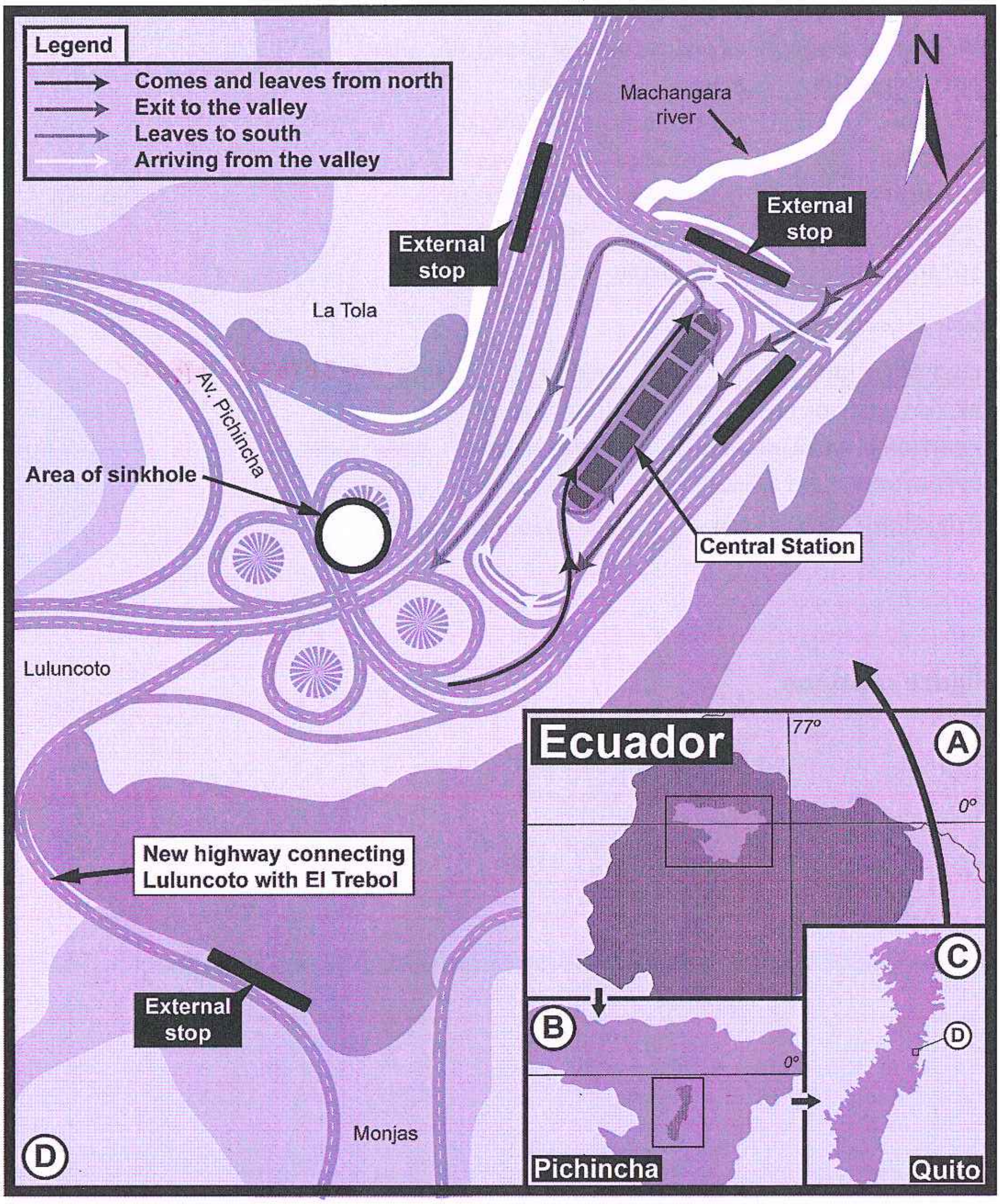

Figure 1: Overview of the setting of a) Ecuador, b) Province of Pichincha, c) city of Quito, d) El Trebol and surrounding infrastructure

THE DIFFERENCE BETWEEN THE TWO GREY ARROWS IS ALMOST INVISIBLE; EITHER PROVIDE A COLORED FIGURE OR USE A DIFFERENT SYMBOLOGY (E.G. A DASHED ARROW).

CAN YOU TRACE THE ROUTE OF THE RIVER UNDERGROUND AS WELL?

Figure 2: Initial stage of sinkhole at "El Trebol".

Figure 3: Panoramic view of the final stage of the sinkhole at "El Trebol". On the background the Panecillo volcanic dome.

Figure 4: View into the sinkhole with the appearance of the Machángara river at its base.

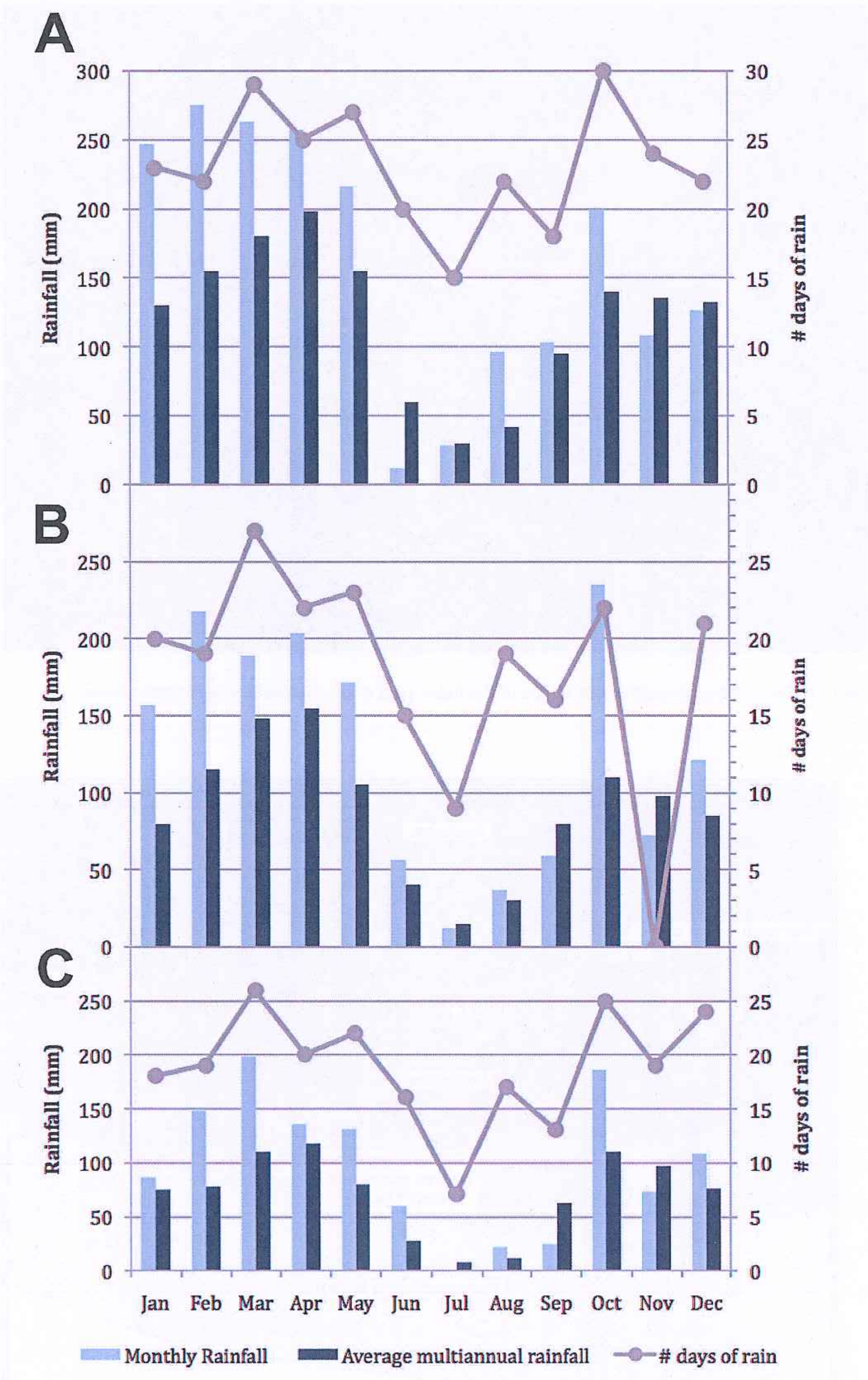

Figure 5 a, b, c: Total monthly rainfall, average multiannual rainfall number of days with rain per month (higher than 0.1 mm) of the three meteorological stations closest to El Trebol (, Iñaquito and La Tola). A) Izobamba: Lat.: -0.366089, Long.: -78.555061; Alt.: 3085.00 m.a.s.l.; B) Iñaquito: Lat.: -0.175000; Long.: -78.485278; Alt.: 2789.12; C) La Tola Lat.: -0.175000; Long.: -78.485278; Alt.: 2789.12 m.a.s.l. From INAHMI (2010).

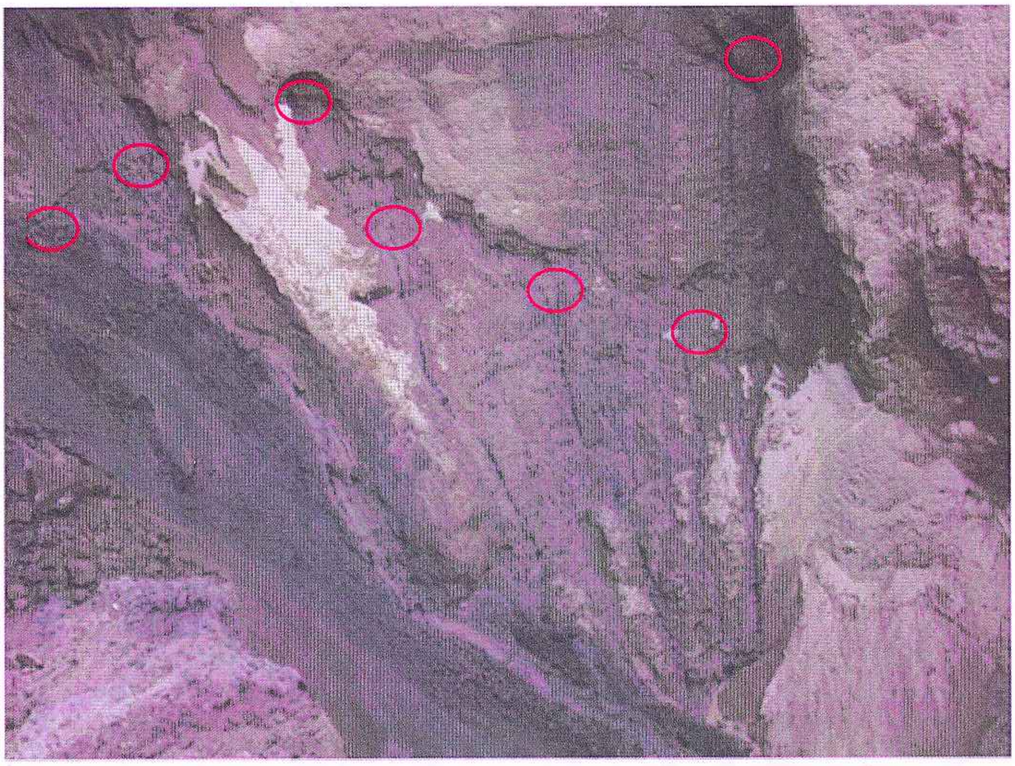

Figure 6: Southern and southwestern side of the inner part of the sinkhole, where water flows.

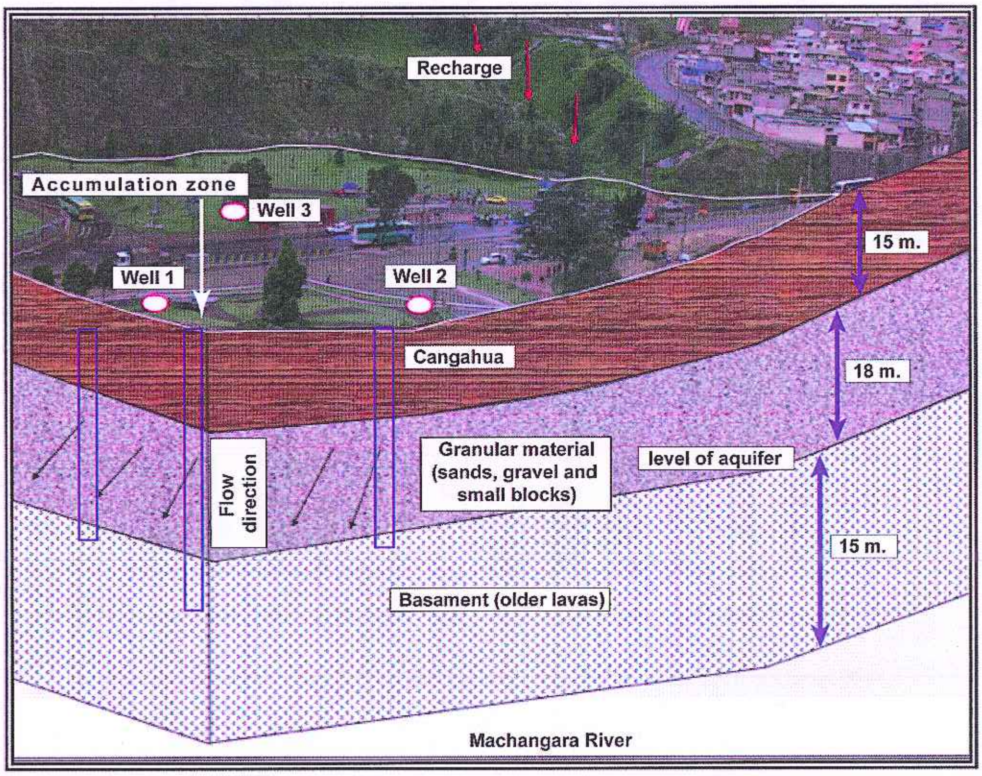

Figure 7: Conceptual model of the aquifer with the site of the wells and the flowing direction.

* WHAT DO YOU MEAN BY SUBSIDENCES? SINKOLES? IN THE TEXT (LINE 216) YOU SAY THAT ONLY 12 SINKHOLES HAVE BEEN RECORDED

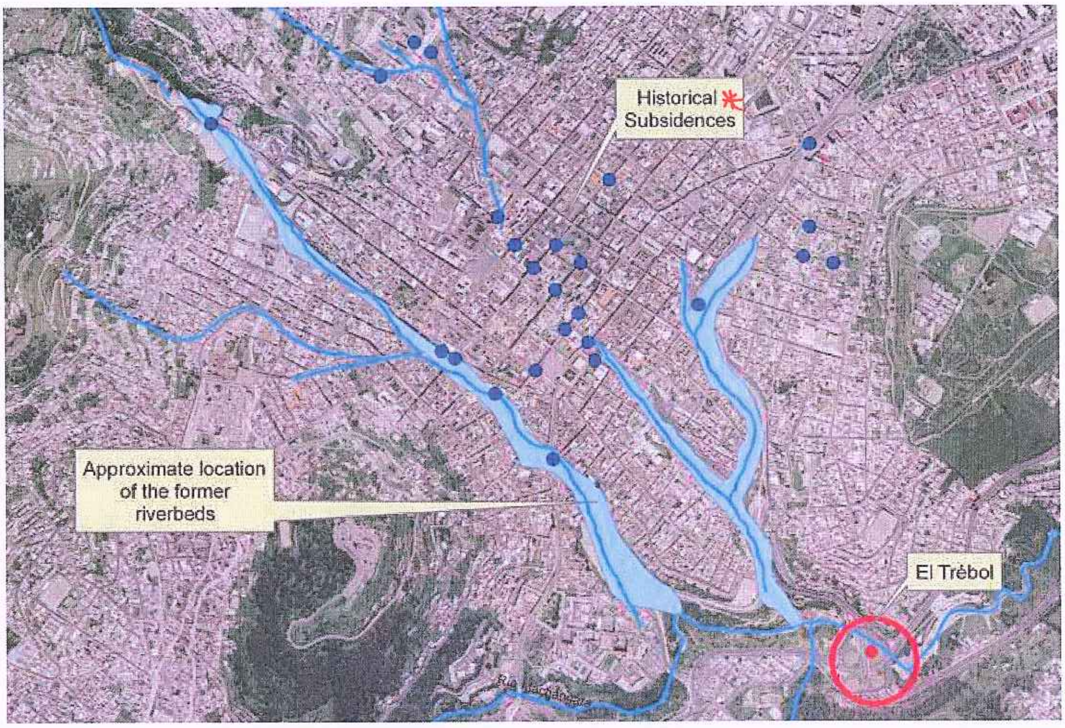

Figure 8: Historical subsidences at Machángara river, including the El Trébol sector (marked with the red circle).

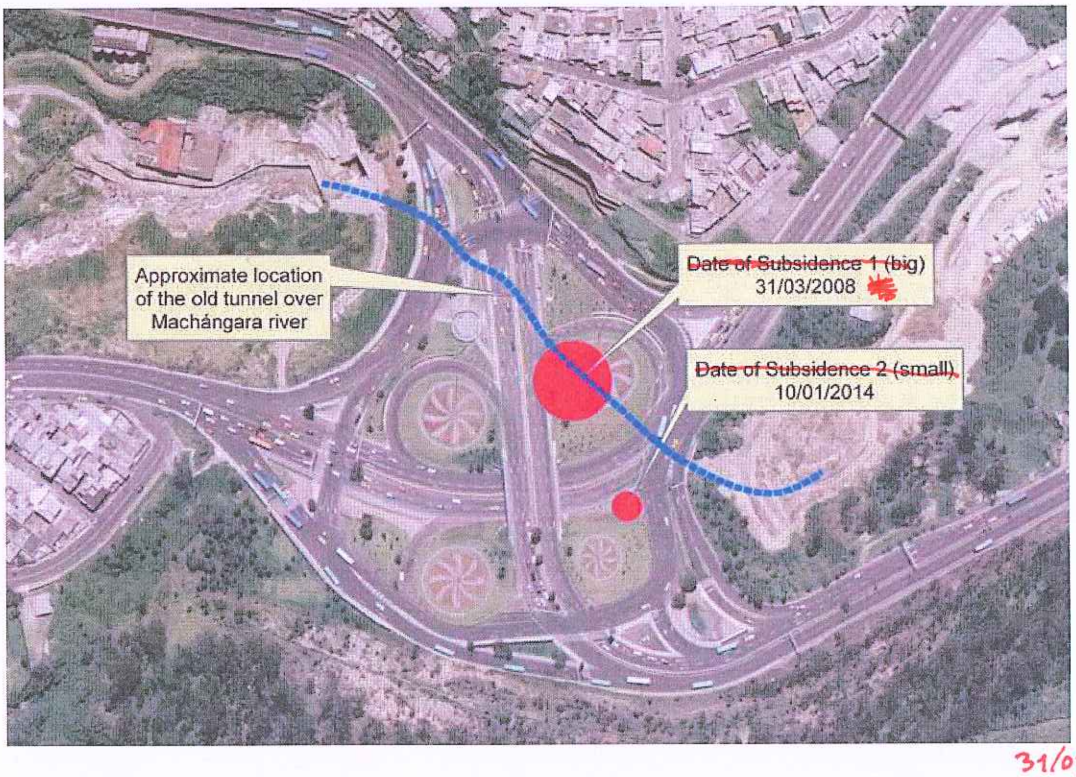

Fig. 9: El Trébol sector with the flowing direction of the Machángara river including the sinkholes of ~~2008~~ 31/03/2008 (big red circle) and the ~~recent in 2014~~ SMALLER ONE OF 10/01/2014 (small red circle).

THIS LINE INDICATES A PERSPECTIVE BUT THIS IS NOT CLEAR IN A CROSS-SECTION LIKE THIS ONE. IT SEEMS SOME SORT OF DIVISION. PLEASE REMOVE IT

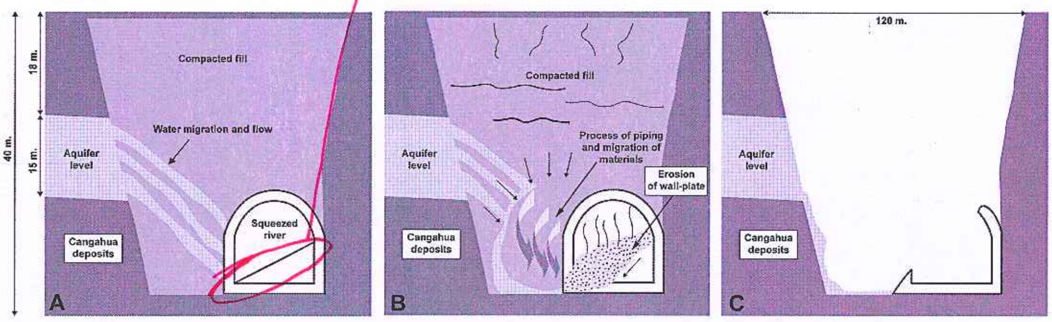

Figure 10: a) Schematic view of the channelized river, the characteristics of the terrain and of the compacted fill; b) Alteration of the compacted fill, process of piping and migration of materials, initial stage of the collapse; c) Formation of sinkhole, material drags surroundings due to river activity.