Contaminated land in Colombia: A critical review of current status and future approach for the management of contaminated sites

Victor Andres Arias Espana[a*] Alfonso R. Rodriguez Pinilla[b,c], Paul Bardos[d,e], Ravi Naidu[a,f],

[a] *Global Centre for Environmental Remediation (GCER), Faculty of Science, ATC Building, The University of Newcastle, NSW 2308, Australia.*
[b] *Universidad de La Sabana, Chía, Cundinamarca, Colombia*
[c] *r3 Environmental Technology SAS, Colombia office: Carrera 13 # 71 - 46, Bogotá, Colombia*
[d] *r3 Environmental Technology Ltd, H9, TOB1, University of Reading, Earley Gate, Reading, RG6 6AT,UK*
[e] *School of Environment and Technology, University of Brighton, Lewes Road, Brighton BN2 4GJ, UK*
[f] *Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (CRC CARE), Newcastle, NSW 2308, Australia.*
**Corresponding author: alfonso.rodriguez@r3environmental.com.co*

Abstract

Environmental contaminants can have negative effects on human health and land, air and water resources. Consequently, there have been significant advances in regulation for protecting the environment in developed countries including the development of remediation frameworks and guidelines. On the other hand, fewer studies have been reported on the risks and health effects of contaminants in developing regions and there is scarce information regarding contaminated land assessment and environmental remediation. Colombia is an important emerging economy and has started to take the first steps towards the development of a framework for the management of contaminated sites and there are opportunities for the country to learn from countries with well-established frameworks such as the United States (US) and the United Kingdom (UK) and for international collaboration with organisations such as CRC for Contamination Assessment and Remediation of the Environment (CARE). We review main pollution issues, current status of contaminated land management in Colombia to identify the gaps in policy and regulation. We also review the UK and US contaminated land policies and regulations to identify the elements of those experiences that could support progress in the country. Finally, we propose recommendations (e.g. risk based approach, soil screening criteria, clean-up funding, liability) for Colombia that could support further development and implementation of a more effective contaminated land management framework.

Keywords: Remediation, management of contaminated sites, risk, Colombia

1. Introduction

Colombia is situated in the Nothwest of the South American continent, with an area of 1’141,748 km^2, a marine zone that covers 928,660 km^2 and a population of 46’581,823 (DANE- Departamento Administrativo Nacional de Estadística, 2011), which to put it into perspective, represents the fourth most populated country in the American continent. The vast majority of the population is set in the central (Andean) and north (Caribbean) regions. The country is divided into 32 geographic regions and a capital district, Bogotá, which holds 7’879,000 habitants.

Colombian economy is considered as an emerging economy and belongs to the intercontinental economic group in which members are considered emerging economies with a high development potential, known as CIVETS (Colombia, Indonesia, Vietnam, Egypt, Turkey and South Africa) and also member of the continental Community of Latin American and Caribbean States (CELAC). To put into perspective the Colombian economy occupies the fourth place in Latin America, just below Brasil, México and Argentina; sixth place in the American continent and 33rd place in the world (Montoya, 2010). The Colombian economy is mainly based in production of primary materials for export and consumer products for the internal market. The main export activities in Colombia are oil production (fourth place in Latin America and six place in the continent) and mining especially carbon, gold, emeralds, sapphires and diamonds (Ministerio de Desarrollo Sostenible, 2016). The most relevant industrial sectors in the Colombian economy are the textiles, automotive, chemical and petrochemical industries.

As in many other developing countries, industrial growth in Colombia has resulted in contamination of land. In a recent study conducted by the Ministry of Environment and Sustainable Development (MESD) (Ministerio de Ambiente y Desarrollo Sostenible, 2016), 1843 sites were considered to be potentially contaminated across a range of economic sectors. However, Colombia lacks of a formal structure for the assessment and management of contaminated sites. Clean-up efforts in Colombia are mainly voluntary actions of social responsibility, whose efforts are constrained by financial resources.

There are a number of countries with more developed policies and frameworks for managing pollution and contaminated land. For instance, the United States (US) and the United Kingdom (UK) have well established frameworks for pollution prevention, and the assessment and management/remediation of contaminated sites following a risk-based approach. Several lessons from these can be learnt at a global level, especially in the development of cost effective innovative approaches.

Colombia could benefit from the experiences learnt by these two countries and adapt these to develop a robust local framework and best practices for the management of contaminated land, in particular incorporating risk assessment to determine levels of harm, prioritise issues, and inform policy for contaminated land management.

To this end, this review will first look at the status of the art of contaminated land management in the South American country of Colombia, identify existing gaps, identify well established approaches from overseas (i.e. US and UK) that can be adapted and applied to the country and provide a road map for the management/remediation of contaminated sites in this country.

2. Principal causes of contamination problems in Colombia

There are a range of causes that resulted in pressures on the land that are leading to land contamination in Colombia.

2.1 Gold mining

Colombia is the second largest producer of gold in Latin America, with an annual production of 47,838 kgs (López A. Suarez OJ. Hoyos M. & Montes C., 2012). However, most is produced in an artisanal manner with 200,000 miners officially producing 30 tonnes of gold per annum (Cordy, 2011). Some 50% of gold mining activities is thought to be informal mining (PNUMA & Ambiente), 2012). Despite some attempts to implement better gold extraction techniques that do not use or minimise the use of mercury during extraction, the use of mercury for gold extraction continues to be the main component of the gold extraction process. About 98% of mercury imported into Colombia is used in gold mining, and the approach is still considered economically attractive and efficient (Malm, 1998; Prieto G. & Gonzalez M., 1998). The National Mercury Inventory indicates that total mercury emissions to be around 77 tonnes each year in Colombia (47 tonnes of mercury being released to the atmosphere, 15 tonnes to water and 15 tonnes to soil) due to gold mining and related activities (OECD/ECLAC, 2014).

The use of mercury by gold mining has resulted in extensive mercury emissions and has become one of the most critical environmental issues in the country. According to United Nations Industrial Development Organization (UNIDO) (UNIDO, 2012), Colombia was ranked as the world's third most contaminated country in terms of quantity of mercury released to the environment despite only ranked 14th in terms of amount of gold produced. More concerningly, the highest concentration of mercury in urban air (1000 $\mu g/m^3$) ever measured in the world was found in mining towns in Antioquia with an average level in residential areas of 10 $\mu g/m^3$(Cordy, 2011). To address this critical issue, UNIDO combined efforts with the Government of Antioquia, National University of Colombia and University of British Columbia to implement "The Colombia Mercury Project". This project aimed to minimise mercury use and losses and included activities such as assessment of mercury losses, health monitoring and awareness campaigns. The results were very positive achieving a significant reduction in mercury losses (63%) and consequently around 46 to 70 tonnes/annum of mercury were prevented to entering the Colombian environment when compared to 2010 data (García et al., 2015).

2.2 Other forms of mining

MESD (Ministerio de Ambiente y Desarrollo Sostenible, 2016) indicated that the mining sector is the largest contributor of brownfields with 42%, followed by the oil and gas sector with 24% and finally the waste management sector with 14%.

2.3 Petrochemical industry

Colombia occupies the fourth place in Latin America for oil production and despite the economic incentives, their related activities can cause several environmental problems (Cusaria A. and Guerra JA . 2004).

These environmental impacts have been significantly magnified by internal conflicts caused by direct attacks to oil piping and infrastructure resulting in the spills of millions of litres of crude oil (Londoño, 2005). For instance, between 1986 and 1998 about 2 millions of barrels of crude oil were spiled as a result of terrorist attacks (de Mesa, 2006) in the Colombian territory. To put into perspective, the amount spilled is equivalent to 7.6 times of the infamous Exxon Valdés oil tanker disaster that occurred in 1989 between Alaska and Canada. There were 920 terrorists' attacks in Colombia against oil infrastructure (up to November 1998) and 575 of those occurred in the Caño Limón-Coveñas oil pipeline. The affected environment included 6000 hectares of land for potential agricultural use, 2600 Kms of rivers and valleys and 1600 hectares of cienagas and wetlands (de Mesa, 2006). From the year 2000 to 2003 these terrorist attacks have been reduced significantly. For instance, 263, 74 and 60 attacks were reported for the years 2001, 2002 and 2003; respectively and these attacks are expected to cease since a peace and end of conflict agreement has been recently signed (Sept 2016) after over 50 years of internal war.

2.4 Hazardous Waste Management

Colombia produced 147,718 tons of hazardous waste in the year 2011 (IDEAM, 2011). The sector that generated the largest amount of hazardous waste was the extraction of hydrocarbons i.e. crude oil and natural gas extraction (IDEAM, 2011). Other sectors contributing significantly to the generation of hazardous waste were the iron and steel manufacturing industries and hospitals

Inappropriate disposal of hazardous wastes is also leading to land contamination problems. There have been several reports of inappropriate management of hazardous solid waste (Vivas, 2005; Gaviria 2012). For instance, the Landfill known as "Doña Juana", which is the largest landfill in the country and mainly receives solid waste from the Capital District (Bogotá) and nearby localities. It also receives different types of hazardous waste originating from industrial activities and health care facilities mixed with ordinary waste household (municipal solid). This practice is suspected to also be occurring in other landfills around the country (Gaviria, 2012). Based in a study carried out by (Vivas, 2005), 88% of the health providers in the capital district did not have an appropriate management of their produced hazardous waste including waste containing mercury and these hazardous waste ended up in "Doña Juana" landfill. Similarly, in the region of Santander, contaminants including lead, chromium and mercury within the common solid waste fraction was reported (Cogan AM. & Saavedra IC, 2000).

2.5 Biocides use

During the 70's Colombia intensified its use of pesticides especially for cultivation of cotton, corn, rice and potato, which consumed 90% of the produced pesticides. The main facilities considered potential sources of land contamination include aerial fumigation of land (64 aerial fumigation facilities have been identified across the country), farming storage facilities and farming research facilities.

The department for sustainable development (Dirección desarrollo sectorial sostenible, 2007), updated the inventory for pesticides containing persistent organic pollutants (POP) including Aldrin, Dieldrin, Endrin, Clordano, HeptacloroHexaclorobenceno, Mirex, Toxafeno and DDT and identified the pesticides POP contaminated sites in the country. The inventory data are presented in supplementary section.

2.6 Industrial activities contributing to heavy metal pollution

There are a number of industrial activities related to environmental pollution by heavy metals including cadmium (Cd), chromium (Cr) and arsenic (As).

The industrial use of Cd include: carbon combustion, mining, fertilizers production, pigments production, fabrication of electrical conductors, preparation of alloys for batteries, iron production and metal refining (Ministerio de Ambiente y Desarrollo Sostenible, 2012). Moreover, Colombia is the fourth importer of products containing cadmium in Latin America (PNUMA & Ambiente), 2010).

The use of Cr is associated with industrial activities such as chromium refining, graphic arts, cement production and tanning of leather products. The latter activity encompasses in their process manipulation of animals skin and their modification for industrial purposes. There are approximately 800 factories in the country dedicated to fabrication of leather products, from which majority are carried out in artisanal manner with very limited personal protective equipment and inappropriate management of waste (Téllez, 2004). In addition, it is estimated that the discharge to the Bogotá River from 327 industries dedicated to this activity is about 4000 m^3/day and produce 50 tons of solid waste per day (Téllez, 2004).

There are two main sources of environmental As: natural processes (e.g. volcanic emissions, weathering and biological activity) and human activities (e.g. mining, industrial processes, smelting of metals, production of pesticides and wood preservatives, and use of fossil fuels).

2.7 Conflict impacts

From 1950, Colombia experienced different social and political circumstances that resulted in an internal conflict in extended areas and resulted in a dramatic large number of internal migration from rural areas to main cities in a phenomenon known as "slums formation" (BIRF, 1996). This overpopulation phenomenon resulted in cities being unable to cope with the demand for sanitation systems designed for much smaller population and consequently causing an impact in the environment including water, air and soil pollution and deterioration of quality of living and landscaping. It is important to note that this internal conflict have ceased as peace agreement has been signed recently (Sept. 2016).

3. Principal risk drivers

As stated by (R. Naidu, Arias Espana, Victor A., Yanju, L. and Jit J., 2016) it is now well recognised that irrespective of a country's economic status, contaminants may present a potential risk to human health and the environment. For these reasons, the focus of the discussion will be potential risks to human health, water, ecology, food chains by mercury and other heavy metals, pesticides and petroleum hydrocarbons.

3.1 Mercury

Mercury (Hg) has been detected in various regions of Colombia in different environmental media. For instance, high levels of Hg in the sediments of the Cartagena bay (94-10,293 mg/kg), Santa Marta bay (20-109 mg/kg, respectively) in the North-east cost of Colombia (D. Alonso, Pineda, Olivero, González, & Campos, 2000) and Cienaga de Ayapel (160-301mg/kg) in the Cauca State (Marrugo J. Lans E. & Benítez L., 2007) have been reported. Moreover, the organic matter content in the sediments is a crucial factor in determining Hg levels and a correlation of 0.65 was established and verified for the Cienega of Ayapel during different seasons (Marrugo J. Lans E. & Benítez L., 2007).

A number of studies have reported the detection of Hg in soil. For instance, a maximum level of 0.27 mg/kg in the industrial area of Bucaramanga (state capital of North Santander) have been reported (Muñoz, 2006).

Hg has also been detected in surface waters (e.g. rivers and dams) such as the Bogotá River (0.1 ng/mL), Muña dam (0.61ng/mL) and Cauca river (1.69-23.33ng/mL) (Sarmiento MI. Idrovo AJ. & Restrepo M., 1999; Soto C. Gutiérrez S. Rey A. & González E., 2010; Vasquez A., 2001).

Moreover, several studies have also reported the detection of Hg in fish in different regions of the country, indicating potential risks to local ecosystems. A summary of the reported data is presented in the supplementary information.

More recently and more concerningly, during routine food testing by Secretary of Health in the Department of Atlántico, a batch of canned tuna was considered contaminated (it contained 3.9 mg/kg of Hg and was above the maximum level for fish products (1 mg/kg) (T. P. a. M. Correa, María Mónica 2016)) and was removed from supermarket's shelfs.

These data and reports indicate that Hg have been detected in sediments, soil and rivers, potentially posing a risk to the environment and may have entered the human food-chain.

Hg causes a range of neurological problems including uncontrollable shaking, lose balance (positive Romberg) and neurotoxicity (Pradilla 1992, Tirado 2000). In addition, harmful obstetrical effects attributed to Hg exposure from gold mining include congenic malformations and perinatal mortality (Alzate 1996).

In Colombia it is compulsory for health services providers and the National epidemiology watchdog system to report acute mercury intoxication cases. Interestingly, despite the high levels detected in the country only two cases of intoxication by heavy metals were reported in 2010 and of those, one was attributed to Hg (SIVIGILA, 2015). Moreover, vast majority of cases are chronic and may be unreported by the system since notification is not immediate. For this reason, these results need to be taken cautiously.

3.2. Lead

High levels of lead (Pb) have been detected in the sediments of the Tunjuelo and Chicu Rivers near the capital district (2mg/kg and 102mg/kg, respectively) as well as in their surface waters (0.04 and 0.07 mg/L, respectively) (Rodríguez L. & Sierra D., 2011; Romero S. & Guevara L., 2011). Other places in which high levels of Pb were detected included the Cauca River (3.76-47.7µg/L)(W. Correa, 2009) and the Bogotá River (0.028 mg/L)(A. G. Rodríguez, JF. & Martínez RS.,, 2009). Siachoque (2001) identified the areas with high mobility of (heavy) metals and high metals concentrations in basins and rivers of Colombia andthe data are presented in the supplementary section.. Other impacted ecosystems include shellfish (with a maximum reported value of 1.23 mg/kg) and fish (Eremophilus mutisii) (Marín, 1996; A. G. Rodríguez, JF. & Martínez RS.,, 2009).

In regards to risks to the population, it is considered that the group to be at higher risk of Pd exposure are workers in the battery manufacturing and recycling industries, and therefore studies have focused on this group. These studies (Cárdenas-Bustamante, Varona-Uribe, Núñez-Trujillo, Ortiz-Varón, & Peña-Parra, 2001; Martínez O. & López M., 1997) found high levels of Pb in blood samples with values between 30 µg/dL and 108.5 µg/dL for this population. Furthermore, vulnerable populations (children and pregnant women) are also at risk and several studies reported lead blood levels above reference levels. For instance, one study in children under 12 years whom were indirectly exposed due informal recycling of Pd from car batteries found that all children in the study (n=32) presented high blood levels of Pb (values ranged between 54 and 90 µg/dl) and one third resulted intoxicated (Hurtado C. Gutiérrez M. Echeverry J. , 2008). Similarly, other studies reported values of up to 21µg/dL in children (n=189) in the city of Cartagena (Olivero-Verbel et al., 2007).

The health effects caused by Pd are well known and include: alterations of the haematological system, disturbance of neurological system (e.g. long term memory loss, vision and hearing loss, etc), alterations of cardiovascular and renal system (González D. & Rojas W., 2008; Patiño, 1999).

3.3 Cadmium

Similarly, high levels of cadmium (Cd) in sediments in the Tunjuelo and Chicu Rivers (Average: 0.5 and 13 mg/kg, respectively) and in their surface water (0.04 and 0.03 mg/L, respectively) were reported (Rodríguez L. & Sierra D., 2011; Romero S. & Guevara L., 2011). Siachoque (2001) identified the areas with high mobility of (heavy) metals and high metals concentrations in basins and rivers of Colombia and Fig. 3 shows the results obtained for Cd.

On the other hand, very limited studies have investigated exposed Colombian populations to Cd. Only one study reported cadmium blood levels below reference (between 3 and 54.9 nmol/L) for a population (n=355) near the Bogotá River (Combariza, 2009). In regards to health effects produced by cadmium one study indicated a positive association between cadmium levels in urine and alterations of renal system functions (Aroca, 1996).

3.4 Chromium

There is no information available on the distribution of chromium (Cr) in the Colombian territory. However, the presence of Cr(VI) in workers in the tanning industry have been reported. For example, a study carried out in workers (n=800) of the tanning industry in Bogotá, indicated that average levels of Cr(VI) in the urine were around 5µg/L with a maximum value of 399µg/L (Cuberos, 2009). The same authors reported that the two most frequent clinic alterations were hypertrophy of nasal passage and irritation of mucous membranes and dermis.

It is well known that the hexavalent form of chromium is toxic and can cause reversible and irreversible, acute and chronic effects in different systems of the human body. Moreover, it has been classified as a carcinogenic compound by the International Agency of Cancer Research (IACR).

3.5 Arsenic

In a comprehensive study (Siachoque, 2001) identified the presence of arsenic (As) in different media (soils, sediments and water) across the country. The areas where arsenic presence have been reported is shown in the supplementary information. A risk model based on a geographic information system (GIS) database developed by the Environmental Systems Research Institute (ESRI) predicts that the population that is at risk from arsenic pollution in alluvial groundwater is approximately 1,664,092 which represents approximately 5% of the Colombian population (Ravenscroft, 2007).

On the other hand, there has been very limited research to assess As exposure and associated health effects in Colombia. Sarmiento MI. Idrovo AJ. & Restrepo M. (1999) reported that As content in hair (biomarker) samples ranged from 10.5 to 2078 mg/kg (n = 50) for a population near the Muña reservoir. These results are comparable to those of Bolivia (37-2110 mg/kg) and significantly lower than Argentina (400-20,000 mg/kg). Moreover, high levels of As in water used for human consumption and irrigation purposes have been reported, with values up to 52 mg/L as well as high levels in fruits (0.36 mg/kg), vegetables (5.4 mg/Kg), milk (76µg/L) and meat (1.58mg/kg) (D. L. Alonso, Latorre, Castillo, & Brandão, 2014). These findings indicate a high risk for As to reach the food chain and consequently a potential risk to human health.

The health effects of As ingestion and/or inhalation at high concentrations are well known and include carcinogenic effects (can induce skin, lung, and bladder cancer), diabetes, skin lesions and gastrointestinal disorders (IARC, 2004). Furthermore, non-carcinogenic health effects includes cognitive deficits in children and adults (Tyler, 2014), neuritis (Tsai, 2003), skin disorders (Ahsan, 2000), increases the formation of thrombocytes i.e. induces thrombosis (Lee, 2002) and disturbs the development of the foetus during pregnancy (Chattopadhyay, 2002).

3.6 Biocides

There is a lack of information on the distribution of pesticides in the Colombian territory. However, a number of studies have identified a number of pesticides and herbicides in the Colombian population and their health effects. Results are shown in the supplementary section and indicated low levels of Aldrin and DDT in blood samples of six different exposed groups.

Another herbicide of concern in Colombia is glyphosate, which is used for the eradication of illicit farming mainly cocaine and poppy crops. There is some debate over whether or not this herbicide is carcinogenic. The European Chemical Agency (ECHA) does not classify glyphosate as a carcinogen, as toxic for reproduction or as a mutagen substance but it can cause severe eye damage and can be toxic to aquatic life with long-term effects (ECHA, 2017). In contrast, to acute toxicity to aquatic animals, the spray mixture used in Colombia did not present a risk to human health due to the low exposure values (Solomon, 2007). However, acute and chronic cytotoxicity was observed at higher doses (4.75-5.75mM) including DNA damage (Monroy, 2005), suggesting potential health risk at higher exposure levels. More research in this area is required including more specific epidemiology studies.

In a comprehensive study (n=8867), the occurrence of adverse effects in reproductive outcomes in a population occupationally exposed to pesticides in the floriculture industry in the Bogotá area was evaluated. The results indicated a moderate increase in the frequency of spontaneous abortion, prematurity, and congenital malformations in pregnancies that occur after the start of work in floriculture industry (Restrepo, Mu, xf, oz, Day, Parra, xe, de Romero, et al., 1990). Moreover, 76% of 535 children born to these workers were medically examined and it was found an increased risk for birthmarks, and specifically for hemangiomas (Restrepo, Mu, xf, oz, Day, Parra, xe, Hernandez, et al., 1990). On the other hand, no cytogenetic effects were observed (n=30) for occupational health exposure to pesticides (Hoyos et al., 1996) at low levels.

3.7 Petroleum Hydrocarbons

A number of studies have indicated the presence of petroleum hydrocarbons (PHs) in different matrices across the country. For instance, (Parga, 2002) reported high PHs concentrations in sediments in the north of Cartagena Bay with concentrations above 100 µg/g with a maximum of 1415 µg/g. Moreover, PHs values were also detected in nearby ecosystems at relatively low values (8-30 µg/g for bivalves, and 10-40 µg/g for fish). Similarly, petroleum aromatic hydrocarbons (PAHs) were detected in the sediments of Bahia de Buenaventura, -sector Isla Cascajal, with an average concentration of 23.27µg/g and at lower levels in marine waters (4.67µg/L) (Ríos, 2006).

On the other hand, there is a lack of studies in Colombia looking at health effects associated with the exposure to petroleum hydrocarbons. However, there are some data available related to exposure due to oil spills in the international literature. Symptom surveys performed short after an oil spill event identified the following symptoms: prevalence of headache, throat irritation, and sore or itchy eyes in exposed individuals and others reported a slight rate increase of diarrhoea, nausea, vomiting, chest and abdominal pain (Rodríguez-Trigo, 2007). Other effects include acute genetic toxicity manifested by enlarged DNA damage and mental health effects including anxiety, depression, posttraumatic stress disorder, and psychological stress (Sabucedo, 2010). In addition, aromatics of low molecular weight such as benzene, toluene, ethylbenzene and xylene (BTEX) are volatile compounds that are well known to cause respiratory irritation and affect the central nervous system (CNS). Moreover, Benzene is known to cause leukaemia in humans, and toluene is a known teratogen (Agency for Toxic Substances and Disease Registry (ATSDR), 1999). Similarly, higher molecular weight hydrocarbons such as naphthalene have been listed by the US National Toxicology Program as potential to cause cancer in humans (National Toxicology Program, 2005) and polycyclic aromatic hydrocarbons (PAHs) contain mutagens and probable carcinogens.

4. Contaminated land management in Colombia today

Current environmental management practices of Colombia were assessed based on a desktop review of existing policies, relevant legislation, specific measures related to contaminated land management, current practice and projects and identification of data gaps.

4.1 Broad policy context and relevant legislation

The Colombian constitution of 1991, established the consideration, management and preservation of natural resources and the environment through the following fundamental principles:

- The right to a clean environment;
- The natural environment is a common asset;
- Sustainable development;

There are thematic regulations including norms for solid waste (e.g. Law 09 from1979, which regulates management of solid waste; Resolution 2309 from 1986, which defines special wastes and criteria for identification, treatment and register), soil as a resource (e.g. statuary order 2811 from1974 part VII, which regulates agriculture and non-agriculture uses of soil); mining activities (e.g. statuary order 2655 from 1988) and policies for land management (e.g. Law 388 from 1997, Article 33).

Another important legislative development is the Law 99 of 1993, which created the Ministry of the Environment and later named MESD. This law reorganized the Public Sector in charge of the management and conservation of the environment and renewable natural resources and created the National Environmental System (SINA). It is perhaps the most important law in environmental matters that has been issued in Colombia. It has aspects that are important both from an organisational and functional point of view (e.g. creation of the MESD) as well as substantial aspects of environmental rights.

In 1998, Colombia implemented a comprehensive hazardous waste policy (Law 430), later regulated by the Ministry of Environment (Law 430, Decree 4741). On the other hand The Stockholm Convention on Persistent Organic Pollutants was signed by the National Government on 22 May 2001 and was ratified by Law 1196 on 5 July 2008 (MADS, 2017).

Similarly, important aspects for environmental management in the mining sector were established in Law 685 of 2001, which issued the Mining Code. The main objective of this law is to promote technical exploration and exploitation of the mining resources of state and private property. The Mining Code was updated in 2010 by strengthening the mine closure and abandonment stages.

In regards to regulation of food contaminants residues in Colombia, it is based on the Resolution 4506 from 2013, while the food pesticides residues law is based on the Resolution 2906 from 2007. These regulations establish all the limits permitted in food products. However, there are some discrepancies and these maximum levels are considered to be part of lax legislation, contradictory and inexact. For instance, ICONTEC indicates that commercial fish products should not exceed a value of 0.5 mg/kg of mercury, while INVIMA allows for twice this value. Both values are well below USA and European agencies (1mg/kg) and do not consider daily intakes based on person's weight (e.g. FAO/OMS indicates that weekly intake 0.1 µg mercury/kg of body should not be exceeded) (T. P. a. M. Correa, María Mónica 2016).

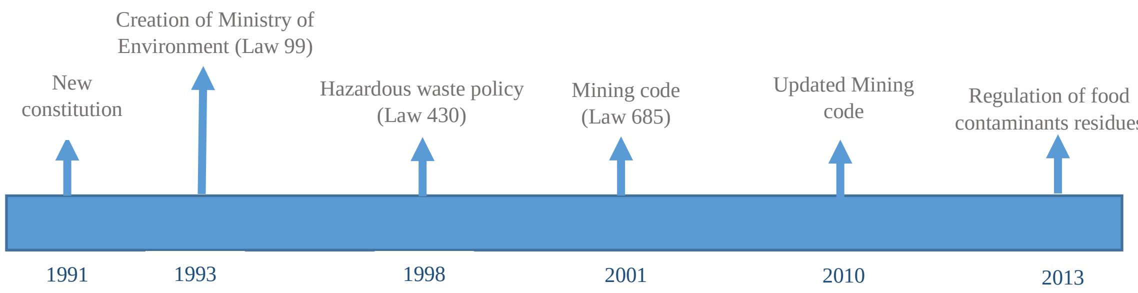

Figure 1. Timeline indicating the development of contaminated land management policy in Colombia

Furthermore, Colombia has signed several international agreements such as responsibility for damage caused by contamination of seawater by hydrocarbons (1969) and protocol CLC 69/76 (1976); United Nations agreement for the right to sea - Jamaica, 1982; biologic diversity - Rio de Janeiro, 1992, Kyoto Protocol (2008), Minamata convention (2010) among others.

4.2 Specific Measures for Contaminated Land Management

A national strategy was identified for the management of contaminated sites at a national level (The Bureau of National Affairs 2008). As a result, Colombia has implemented a National Development Plan (2010-14 national development plan (PND)) that includes concrete targets and measures to promote environmental sustainability and risk prevention, and to improve the environmental quality of life (OECD/ECLAC, 2014). In fact the Colombia's PND includes the development of a new regulation for contaminated sites in several economic sectors such as oil and gas, mining, pesticides production and electric. Likewise, under Colombian Law, the use of any natural resources or the development of any activity or project that has the potential to affect the environment is subject to the control of the local environmental authorities, which have made significant progress in creating control tools and requesting specific remediation processes to the specific sectors mentioned above.

Moreover, mechanisms for environmental authorities to impose penalties on people or organisations causing contamination of the environment have been developed. For example, Law 1333 of 2009, establishes the environmental sanctioning procedure, in which the presumption of guilt of the possible offender is highlighted. This law provides for the imposition of penalties and / or preventive measures. At the moment it is the most important means for the environmental authorities to follow up the different cases of contamination, however, it is difficult to implement effectively due to lack of specific regulation (eg, contaminated soils regulation).

Another example is Law 23, Art. 15 of 1973, which establishes that any person who uses components and chemicals capable of producing contamination must inform the national government and consumers of the potential hazards involved and Art. 16 of the same law specifies that they are responsible for any resulting damages to human health or the natural environment (The Bureau of National Affairs 2008). Similarly, hazardous waste management laws (Decree 4741 2005) enforces long term responsibilities on producers and importers of hazardous products. These responsibilities include the monitoring, characterization and remediation of contaminated land, surface waters, and groundwater. Likewise, disposal of hazardous wastes in unlicensed sites is proscribed and subject to penalties (Decree 4741, Art. 3) and the responsibilities for the person causing contamination include characterisation and remediation of the site (Decree 4741, Art. 19).

4.3 Current practice and projects

The Colombian government has commenced a formal process for the categorization and regulation of environmental liabilities in the country. The lead organisation, MESD, is working on a new regulation and the design of technical instruments for the management of environmental liabilities in Colombia, some of these instruments include specific methodologies in how to develop different remediation processes in contaminant sites (MADS 2015). This process also involves strategic planning to conceptualization and management of environmental liabilities in Colombia including funding mechanisms and involves cooperative work from several government institutions including Planning Unit Mining Energy - UPME and the National Mining Agency. Moreover, it is expected that this process will contribute to the development of environmental remediation in Colombia in the next few years.

Another example of cooperative projects aimed at improving existing practices for contaminated land assessment or management is the development of the Technical Manual for the Execution of Risk Analysis for Distribution Sites of Hydrocarbons (E. MADS, MME, Asociacion Colombiana del Petróleo, ERM y otros., 2008), based on the methodology of risk analysis developed jointly by consultants, private companies and government bodies.

Recently a project in Colombia has investigated the use of low input “gentle” remediation for mercury contaminated land, with a view to restoring it for soft end uses such as renewable energy. This project, supported by Colombian Ministries and the UK prosperity fund found a number of potential gentle remediation approaches might be deployed including phytoremediation and immobilisation *in situ* on biochars, and a good potential for renewable energy production (P. Bardos, Cundy, Andy., Maco, Barbara., Kovalick, Walter., Rodríguez, Alfonso., Hutchings, Tony., Hall, Euan., Rodríguez., Angela., 2017a; P. Bardos, Rodríguez, Alfonso.,Cundy, Andy., Hall, Euan., Hutchings, Tony., Kovalick, Walter., de Leij, Frans., de Leij, Rebecca., Maco, Barbara., Rodríguez, Angela., 2017b; A. Rodríguez, Bardos, Paul., Cundy, Andy., Hall, Euan., Hutchings, Tony., Kovalick, Walter., de Leij, Frans., de Leij, Rebecca., Maco, Barbara., Rodríguez, Angela., 2017a; A. Rodríguez, Bardos, Paul., Cundy, Andy., Kovalick, Walter., Maco, Barbara.., Rodríguez, Angela., 2017b).

4.4 Gaps

Despite several advances, the country has not yet:

- developed regulations for historic contaminated sites or mechanisms for identification,
- does not have a framework for the clean-up of contaminated sites or guidelines in the management or assessment of contaminated sites,
- a funding mechanism to support land remediation,
- a strategy to identify and assign liability,
- public information related to remediation Carried out recent studies to acquire contamination data of different environmental matrices.

The country also lacks:

- a comprehensive and overarching system to support risk-based decision making,
- processes for verification of remediation outcomes,
- record keeping methods,

- identification and incorporation of contamination issues into land use planning,
- procedures for inclusion of health and safety considerations during execution of remediation projects,
- incorporation of costs-benefit analysis and
- overall sustainability.

Moreover, Colombia has a number of operational limitations that have an impact on the development of effective management of contaminated land. These limitations are:

- lack of adequately trained and experienced personnel who understand the technical aspects of contaminated land risk assessment and management,
- weak and ambiguous definition for contaminated land,
- include scarce funding to support the assessment and management of contamination, in addition to application of existing regulations.

5. Establishing sustainable risk based land management in Colombia

Fig.2 summarises the steps for the development of risk- based land management framework in Colombia. Risk based land management (Vegter, 2002) has the fundamental principle of ensuring that land and water is fit for purpose (i.e. appropriate for future use) and does not pose an unacceptable risk to human health or the environment. Moreover, it establishes that there has to be exposure before harm from the exposure can occur. This maxim clearly distinguishes between harm and risk and that means that without receptors being exposed to site contamination, the chance of exposure is zero and harm cannot occur and consequently the risk cannot be realised. It has become a powerful tool for decision makers as it gives them flexibility for management by considering the association between the source, exposure pathway and the receptor, establishing any links between these components and identifying appropriate strategies to reduce exposure e.g. remedial options may include risk management instead of total clean-up of the site (R. Naidu, Pollard, S.J.T., Bolan, N.S., Owens G. and Pruszinski A.W. , 2008).

Added benefits of the risk based approach is that can be incorporated into “environmental regulation” to avoid remediation strategies that are prescriptive and avoids unnecessary assessments and the associated costs and more importantly allow solutions that are suitable for future land use i.e. fit for purpose. Also, it provides evidence to justify decisions and increases transparency (Reinikainen & Sorvari, 2016).

This approach have been successfully implemented in countries like the UK and the US, which have established a comprehensive framework based on the prevention of existing activities to cause contamination and a sustainable risk-based approach for the management of legacy contamination.

More recently, sustainability thinking has also become much more firmly embedded in contaminated land management thinking, i.e. sustainable risk based land management (Rizzo, 2016). Sustainable remediation can be defined as: “*the practice of demonstrating, in terms of environmental, economic and social indicators, that the benefit of undertaking remediation is greater than its impact, and that the optimum remediation solution is selected through the use of a balanced decision-making process”*(CL:AIRE, 2010).

Colombia could benefit from the lessons learned from these countries (see Table 1) and use them in the development of a robust contaminated land management framework. By using existing knowledge and capabilities to its advantage, Colombia could expect a decrease in both the cost and timeline for comparable policy and regulatory development.

To that end the first step is to have a clear statuary definition of contaminated land, which allows to differentiate between lands that are considered contaminated land and those that are not (Catney, 2006). A clear definition, which avoids ambiguity can set the basis to establish the extent and scale of contamination.

The next step is to adopt decisions to prioritise the remediation/clean-up of contaminated sites in Colombia and should be based on a risk-based approach. Opportunity exist to adopt risk-based best practices into the decision process of contaminated land management from countries with extensive experience such as Australia, UK or US. As mentioned earlier, in a risk-based approach a clear link between the source (pollutant) and the receptor must be established (i.e. adopt the source-pathway-receptor (SPR) model) (Reinikainen & Sorvari, 2016). If there is no link there is no risk, but if risk exists, an assessment is required to identify those sites that potentially present a risk to receptors (Nathanail, 2013). The benefits are multiple as mentioned before. The implementation, however, is not an easy task. One of the issues is the perception of perpetual management of the hazard (source) if the chemical substance is not removed. As a result, questions of ongoing liability and transfer of information remain. Also, when there is a strong emphasis on hazards in a setting of public outrage, a risk based approach may not gain the support for management of contamination. For these reasons, implementation of a risk-based approach for management of contaminated land will require education of stakeholders, allow communities to become contributors to scientific knowledge and at the same time maintain their sense of natural justice and exchange of new ideas via forums related to remediation such as CleanUp Conference Series by CRC for Contamination Assessment and Remediation of the Environment (CARE) in Australia, Sustainable Remediation Forum for Australia & NZ (SuRF ANZ), Sustainable Remediation Forum for UK (SuRF UK) and collaboration with Environmental authorities e.g. EPAs.

In addition, in order to implement regulations in an effective manner requires that the regulatory system to be coordinated across the different levels and that comprises National (Colombian government), State (State's Government) and local (local councils). A coordinated system will avoid duplication of efforts, conflicting environmental management and corruption. It is also important to consider when redefining roles and responsibilities, that environmental enforcement and environmental licencing responsibilities need to be separated to avoid opportunities for conflict of interest, which may also encourage corruption.

Similarly, it is of outmost important to develop screening values (SVs), which are pre-determined contaminant concentrations for soil or groundwater that represent a threshold concentration designed to protect human health and environmental receptors (e.g. a river, local fauna, etc.) from exposure to long-term contamination, above which further risk assessment may be required (Cheng & Nathanail, 2009). Colombia needs an overarching national guideline that sets out a clear methodology that can be applied to the Colombian context and at the same time ensuring protection of both human health and the environment. This national guideline should avoid confusions of terminology (e.g. trigger values, intervention levels, etc) and should be fit for purpose i.e. land use. As a result, practitioners and regulators will not be faced with the uncertainty occurring in other countries (Ambituuni, Amezaga, & Emeseh, 2014; UNEP, 2011).

Another important aspect of contaminated land management is the associated cost of clean-up, which can be prohibitive and consequently funding is arguably the most challenging one. The US tackles this challenge by the use of taxing mechanisms to chemical and petroleum industries (i.e. the Superfund) and transfer funds to clean-up projects. Colombia could adopt similar funding mechanisms, for example, a percentage of excess crude oil exports could be assigned to a contaminated land management fund.

In complementing funding, it is important to implement mechanisms that stablish liability. Colombian law framework can be potentially used to establish liabilities against parties responsible for contamination of the environment. However, despite the significant progress towards establishing liabilities in Colombia, there is a lack of structured approaches for assigning legal responsibilities similar to those used in Australia, UK and the US. Existing mechanisms need to be improved and incorporate the polluter pay principle with very clear steps that allows easy implementation. Moreover, Colombian structure should also incorporate clear protocols for the identification of the polluter, mechanisms to decide liability and the extent of polluter's participation and potential defence.

Considering that there is very limited number of practitioners and regulators with the skills and expertise in the area of contaminated land and the practice of the field is a constant evolving area, is important to incorporate education and training of professionals. In the absence of technical expertise, Colombia has the opportunity to develop international partnerships (for example with organisations such as CRC for Contamination Assessment and Remediation of the Environment (CARE)), to provide the most needed training. The benefits of these partnerships include a rapid up-skilling of the workforce and instant introduction of international best practice into Colombia. In the long-term and once the technical expertise level has reached satisfactory levels, the country can develop its own training platform.

Another aspect is the public awareness concerning contaminated land, which is very low in Colombia. The use of public consultation in Colombia is rare, for this reason, it is important to initiate public awareness by using local mechanisms such as communications in local papers, or local radio to inform local communities and successfully create environmental awareness, for example, impacts of contamination on soil fertility or fishing waters. Moreover, incorporation of public consultation at early stages of contaminated land and risk assessment projects will ensure confidence, transparency and support by the different stakeholders.

Table 1. Lessons based on the UK and USA experiences that might benefit contaminated land management in Colombia

	UK	USA	Current practice	Recommendations
Statuary definition	Clear definition for contaminated land that makes reference to the link between Source-Pathway-and Receptor.	Clear definition for contaminated land that makes reference and highlights the importance of the link between Source-Pathway-and Receptor.	There is no existing definition for contaminated land.	Revise existing guidance to provide a statutory definition for contaminated land that refers to the Source-Pathway-Receptor model.
Structure of regulators and capacity	The local and environmental authorities are well coordinated, have a clear role and have developed standards. Moreover, are equipped with technical personnel.	The US EPA is well coordinated with a clear understanding of its roles. Moreover, the agency is sufficiently equipped with sufficient training, technical, and human resources.	Lack of periodic training and capacity building and development platforms.	Requirement for a specific agency, similar to that of US EPA, dedicated to contaminated land assessment and management. Development of guidelines that clearly define roles and responsibilities of the agency responsible for assessment and management of contaminated land.
Funding	Government funding has been reduced. Existing policy encourages voluntary remediation by private land owners.	Superfund by taxing petro-chemical and other industries. At the same time, voluntary remediation is encouraged.	Mainly relies on voluntary actions.	Incorporation of the polluter pays principle into existing legislation, including mechanisms of enforcement (e.g. for pollution events) and prioritisation approaches to deal with 'orphan sites'. In the short term, a Trust Fund (similar to US superfund) should be established with contributions from crude oil sales to fund contaminated land clean up.
Technical approach	Land use is considered in the assessment of contaminated land. Screening values of contaminants are derived based	Land use is considered in the assessment of contaminated land. Screening values of contaminants are derived based on a scientific basis.	Use of generic screening values for contaminated land screening (mainly based in international guidelines), which might be inappropriate for the Colombian	Develop nationally consistent methods for deriving human health and ecologically appropriate screening values that take into consideration land use (i.e. fit for

	on a scientific basis.		environment. Technical personnel lacks the knowledge and expertise.	purpose). Education and training of professionals by strategic international partnerships.
Liability	A structured process identifies the person responsible (known as Appropriate Person).	A structured and strict process identifies the potential responsible party (known as PRP). It also practices joint liability.	Lack of structure for the identification or allocation of liability to a polluter.	Strictly implement the polluter pays principle. Implement means to identify a polluter and allocate liability.
Incorporation of cost-benefit analysis	Incorporate social benefits and at the same time reduction of costs and environmental damage in the management and decision making of contaminated land.	Mainly focus in the reduction of environmental footprint in the management and decision making of contaminated land.	Fail to incorporate cos-benefit analysis and consequently social benefits are not maximised.	Develop a policy that incorporate net social benefit, reduce costs (i.e. economic benefits) and reduce environmental impacts into decision making.
Engagement of public and stakeholders	Public consultations are aimed at the education of the general public and create awareness (e.g. new policies, new changes in policies) related to contaminated land management policies.	Public awareness programmes are aimed at the education of the general public and stakeholders related to changes to policy and newly identified contaminated sites.	Lack of public awareness and participation in the management of contaminated land.	Increase public awareness using different mechanisms such as: short communications letters, local media, symposia and workshops in rural and urban areas to inform the public about contaminated land policies, the risks and impacts in human health and the environment.

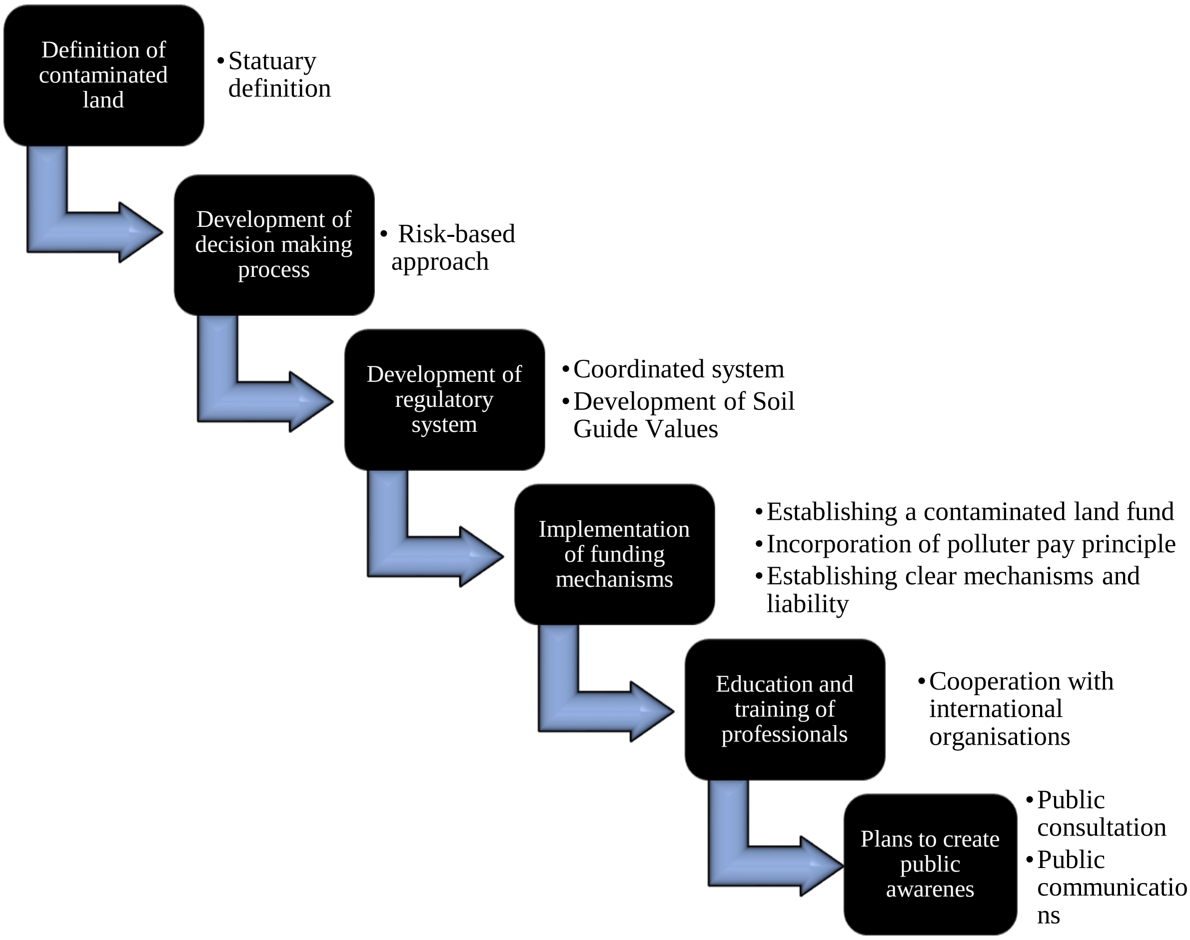

Figure 2. Recommended steps for the development of risk- based land management framework in Colombia

5.1 The expected benefits and opportunities

The main benefit of adopting and implementing a well-structured risk based remediation framework in Colombia is that it provides an integral sustainable solution for restoring the usability and economic value of land and it is characterised by:

- risk reduction,
- human health protection,
- environment protection,
- reduction of aftercare requirements and
- reduction of liabilities.

Moreover, it will facilitate land re-use, avoidance of losing green (virgin land) and removing hazards from communities and supporting their betterment.

There are a number of opportunities for Colombia to address existing challenges in contaminated land risk assessment and remediation including:

- Establishing channels between Colombia and other countries with extensive experience in the area of contaminated land management that will assist shared learning (i.e. learn lessons from these countries) and understanding of current issues to improve existing system,
- Forming a positive broad-based partnership between all relevant stakeholders (community, regulators, scientists, landowners, industries and business),
- Promoting the development of a robust framework to maximise and sustain contaminated land management,
- Creating a common framework to protect human health and the environment from chemical hazards caused by land contamination,
- Promoting business opportunities between Colombia and other countries including technical cooperation.

5.2 Initial steps taken towards better management of contaminated land

Colombia has recently joined the Red Latinoamericana de prevención y gestión de sitios contaminados (ReLASC), which is a regional (Latino American region) net initiative supported and maintained by private and public organisations aimed to foment the production, distribution and exchange of knowledge in the area of prevention, management and rehabilitation of contaminated sites. The MESD is an active member of ReLASC.

Initiatives like ReLASC in the county are great platforms to create awareness, to share information and experiences effectively, to support generation and strengthening of technical capabilities and to potentiate collective actions.

The Colombian contaminated land management system lags behind those of more experienced countries such as Australia, US and the UK including its efficiency to identify contaminated sites, conduct proper detailed risk assessments and to initiate remediation activities. However, the country has initiated creating platforms to exchange knowledge and commenced a formal process for the categorization and regulation of environmental liabilities and those are the initial and steps in the right direction towards better management of contaminated land in the country.

6. Conclusions

Colombia has made significant improvements in environmental management including consideration, management and preservation of natural resources and the environment in the Colombian constitution and especially in the management of solid waste (e.g. Law 09 from1979, Resolution 2309 from 1986, etc).

However, there is no existing framework for the management of contaminated land. A consistent framework that incorporates a risk-based approach to remediation of contaminated sites and engages all stakeholders (government, community, key industries and policy makers) is vital and urgently needed.

To this end Colombia can learn from the lessons learnt from different countries with extensive experience and well established frameworks (e.g. UK and US) and use these experiences to its advantage in the development of the Colombian contaminated land management framework.

To this end it is recommended that the Colombian government consider the following steps:

1) a clear and unambiguous definition of contaminated land,

2) development of a decision making process that follows a risk based approach,

3) development of a regulatory system that is consistent, transparent, and integrative,

4) implementation of funding mechanisms, education and training of professionals and program to create public awareness and gain public support.

Development of a contaminated land management framework will provide several benefits to the country and provide an integral sustainable solution for restoring the usability and economic value of land. This paper contributes towards the advancement of land contamination management practice in Colombia, and could be used as an example for other countries in the region.

7. **References**

Agency for Toxic Substances and Disease Registry (ATSDR). (1999). Toxicological Profile for Total Petroleum Hydrocarbons (TPH). Atlanta: US Dept of Health and Human Services, Public Health Service.

Ahsan, H., Perrin, M., Rahman, A., Parvez, F., Stute, M., Zheng, Y., et al. (2000). Associations between drinking water and urinary arsenic levels and skin lesions in Bangladesh. *J Occup Environ Med 42*(12), 1195-1201.

Alfonso, A. N. Z. (2014). Principales Normas Ambientales Colombianas. Bogotá: Universidad EAN.

Alonso, D., Pineda, P., Olivero, J., González, H., & Campos, N. (2000). Mercury levels in muscle of two fish species and sediments from the Cartagena Bay and the Ciénaga Grande de Santa Marta, Colombia. *Environmental Pollution, 109*(1), 157-163. doi: http://dx.doi.org/10.1016/S0269-7491(99)00225-0

Alonso, D. L., Latorre, S., Castillo, E., & Brandão, P. F. B. (2014). Environmental occurrence of arsenic in Colombia: A review. *Environmental Pollution, 186*, 272-281. doi: http://dx.doi.org/10.1016/j.envpol.2013.12.009

Ambituuni, A., Amezaga, J., & Emeseh, E. (2014). Analysis of safety and environmental regulations for downstream petroleum industry operations in Nigeria: Problems and prospects. *Environmental Development, 9*, 43-60. doi: http://dx.doi.org/10.1016/j.envdev.2013.12.002

Aroca, G. P., E.; Ortiz, J.; De la Hoz, F.; Cardenas, V.; Fals, E.; Iglesias, A. (1996). Daño renal asociado con exposición ambiental crónica al cadmio. *Salud UniNorte (Barranquilla, Col), 11*(1), 14-20.

Bardos, P., Cundy, Andy., Maco, Barbara., Kovalick, Walter., Rodríguez, Alfonso., Hutchings, Tony., Hall, Euan., Rodríguez., Angela. (2017a). Strategies for rehabilitating mercury-contaminated mining lands for renewable energy and other self-sustaining re-use strategies. Output 2. DOI: 10.13140/RG.2.2.29241.47205. Bogotá: r3 Environmental Technology.

Bardos, P., Rodríguez, Alfonso.,Cundy, Andy., Hall, Euan., Hutchings, Tony., Kovalick, Walter., de Leij, Frans., de Leij, Rebecca., Maco, Barbara., Rodríguez, Angela. (2017b). Policy Briefing: Strategies for rehabilitating mercury-contaminated mining lands for renewable energy and other self-sustaining re-use strategies Output 3. DOI: 10.13140/RG.2.2.22530.58560. Bogotá: r3 Enviromental Technology.

BIRF, B. I. d. R. y. F. P. d. G. U., [MINSALUD] Ministerio de Salud de Colombia; [MINAMBIENTE] Ministerio de Ambiente de Colombia; & [OPS] Organización Panamericada de la Salud. (1996). Análisis sectorial de residuos sólidos en Colombia. Washinghton: BIRF, MINSALUD, MINAMBIENTE, OPS.

Cárdenas-Bustamante, O., Varona-Uribe, M. E., Núñez-Trujillo, S. M., Ortiz-Varón, J. E., & Peña-Parra, G. E. (2001). Correlación de protoporfirina zinc y plomo en sangre en trabajadores de fábricas de baterías, de Bogotá, Colombia. *Salud Pública de México, 43*, 203-210.

Catney, P., Henneberry, J., Meadowcroft, J. and Richard Eiser, J. (2006). Dealing with contaminated land in the UK through ‘development managerialism’. *Journal of Environmental Policy and Planning, 8*(4), 331-356.

CL:AIRE. (2010). Surf-UK: A Framework for Assessing the Sustainability of Soil and Groundwater Remediation. ISBN 978-1-905046-19-5. London: Contaminated Land: Applications in Real Enviroments (CL:AIRE).

Cogan AM. & Saavedra IC. (2000). *Diagnóstico, análisis y planteamiento de alternativas ambientales para minimizar la contaminación originada por los residuos tóxicos y peligrosos en el* *vertedero municipal El Carrasco, Bucaramanga* Universidad Industrial de Santander, Bucaramanga.

Combariza, D. (2009). *Contaminación por metales pesados en el embalse del Muña y su relación con los niveles en sangre de plomo, mercurio y cadmio y alteraciones de salud en los habitantes del municipio de Sibaté (Cundinamarca)* Universidad Nacional de Colombia, Bogotá.

Cordy, P., Veiga, M.M., Salih, I., Al-Saadi, S., Console, S., Garcia, O., Mesa, L.A., Velásquez-López, P.C. and Roeser, M. (2011). Mercury contamination from artisanal gold mining in Antioquia, Colombia: The world's highest per capita mercury pollution. *Science of the Total Environment, 410*, 154-160.

Correa, T. P. a. M., María Mónica (2016). La regulación del mercurio en Colombia es muy laxa *El Espectador*. Retrieved from http://www.elespectador.com/noticias/medio-ambiente/regulacion-del-mercurio-colombia-muy-laxa-articulo-660971

Correa, W. (2009). *Especiación del Plomo, Cromo y Cadmio con resina amberlita XAD-16 y cuantificación de Mercurio en aguas del río Cauca en Santiago de Cali por espectrometría de absorción atómica.* Universidad del Valle, Santiago de Cali.

Cuberos, E., Rodríguez, A., & Prieto, E. . (2009). Niveles de Cromo y Alteraciones de Salud en una Población Expuesta a las Actividades de Curtiembres en Bogotá, Colombia. *Revista de Salud Pública, 11*, 278-289.

Cusaria A. and Guerra JA . (2004). Petróleo, ambiente y conflicto en Colombia. *Sociedady medio ambiente* 464-501.

Chattopadhyay, S., Bhaumik, S., Purkayastha, M., Basu, S., Nag Chaudhuri, A., Das Gupta, S. (2002). Apoptosis and necrosis in developing brain cells due to arsenic toxicity and protection with antioxidants. *Toxicol Lett 136*(1), 65-76.

Cheng, Y., & Nathanail, P. C. (2009). Generic Assessment Criteria for human health risk assessment of potentially contaminated land in China. *Science of The Total Environment, 408*(2), 324-339. doi: http://dx.doi.org/10.1016/j.scitotenv.2009.09.021

DANE- Departamento Administrativo Nacional de Estadística. (2011). *Estimación y proyección de población nacional, departamental y municipal total por área 1985-2020.* Bogotá: Retrieved from http://www.dane.gov.co/index.php?option=com_content&view=article&id=75&Itemid=72.

de Mesa, J. B. L., Gladis Quintero, Andrea Liliana Guevara Vizcaíno, Diana Carolina Jaimes Cáceres, Sandra Milena Gutiérrez Riaño, and Johanna Miranda García. (2006). Bioremediación de suelos contaminados con hidrocarburos derivados del petróleo. *Nova, 4*(5).

Dirección desarrollo sectorial sostenible. (2007). Consolidación del Inventario de Plaguicidas COP. Bogotá: Dirección desarrollo sectorial sostenible.

ECHA. (2017). Glyphosate not classified as a carcinogen by ECHA. ECHA/PR/17/06. Retrieved 20th of July, 2017, from https://echa.europa.eu/-/glyphosate-not-classified-as-a-carcinogen-by-echa

García, O., Veiga, M. M., Cordy, P., Suescún, O. E., Molina, J. M., & Roeser, M. (2015). Artisanal gold mining in Antioquia, Colombia: a successful case of mercury reduction. *Journal of Cleaner Production, 90*, 244-252. doi: http://dx.doi.org/10.1016/j.jclepro.2014.11.032

Gaviria, A. M., EY. . (2012). *Análisis para la Gestión de residuos peligrosos domiciliarios en el municipio de Medellín.* Copororación Universitaria Lasallista, Caldas, Antioquia.

González D. & Rojas W. (2008). *Relación entre la exposición crónica ocupacional al plomo y los efectos neurocomportamentales, revisión documental.* Pontificia Universidad Javeriana, Bogotá.

Hernández, L., Guerrero, E., Cubillos, F., & Salazar, F. (1986). Niveles sanguíneos de insecticidas organoclorados en varios grupos de población colombiana. *Revista Colombiana Ciencias Químico Farmaceuticas, 45*, 49-58.

Hoyos, L. S., Carvajal, S., Solano, L., Rodriguez, J., Orozco, L., López, Y., & Au, W. W. (1996). Cytogenetic Monitoring of Farmers exposed to pesticides in Colombia. *Environmental Health Perspectives, 104*(Suppl 3), 535-538.

Hurtado C. Gutiérrez M. Echeverry J. . (2008). Aspectos clínicos y niveles de plomo en niños expuestos de manera para ocupacional en el proceso de reciclaje de baterías de automóviles en las localidades de Soacha y Bogotá, D.C. *Biomedica, 28*, 116-125.

IARC, I. A. f. R. o. C. (2004). Some drinking-water disinfectants and contaminants, including arsenic. In IARC (Ed.), *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans* (Vol. 84).

IDEAM, I. d. H. M. y. E. A. (2011). *Informe del estado del medio ambiente y los recursos naturales renovables*.

Lee, M., Bae, ON., Chung, SM., Kang, KT., Lee, JY., Chung, JH. (2002). Enhancement of platelet aggregation and thrombus formation by arsenic in drinking water: a contributing factor to cardiovascular disease. *Toxicol Appl Pharmacol 179*(2), 83-88.

Londoño, M., Martínez, Ledy.,. (2005). *El medio ambiente, otra víctima del conflicto armado colombiano actual*. Semillero de Investigación en Derecho y Conflictos Ambientales "SIDCA". Facultad de Ciencias Jurídicas de la Universidad de Manizales. Retrieved from http://ridum.umanizales.edu.co:8080/xmlui/bitstream/handle/6789/2027/Trabajo%20de%20Grado%20Ledy%20Johana%20Martinez%20y%20Maria%20Consuelo%20Londo%C3%B1o%20Holguin.pdf?sequence=1

López A. Suarez OJ. Hoyos M. & Montes C. (2012). Perfil nacional de sustancias químicas en Colombia (2nd ed.). Bogotá D.C.: United Nations Industrial Development Organisation & Ministerio de Ambiente y Desarrollo Sostenible.

MADS. (2017). Plan Nacional de Aplicación del convenio de Estocolmo PNA. from http://www.minambiente.gov.co/index.php/component/content/article?id=252:plantilla-asuntos-ambientales-y-sectorial-y-urbana-sin-galeria-18

MADS, E., MME, Asociacion Colombiana del Petróleo, ERM y otros. (2008). *Manual Técnico para la Ejecución de Análisis de Riesgos para Sitios de Distribución de Derivados de Hidrocarburos.* . Bogotá, Colombia.

Malm, O. (1998). Gold mining as a source of mercury exposure in the Brazilian Amazon. *Enviromental Research, 77*, 73-78.

Marín, C. (1996). *Determinación de mercurio y plomo en organismos marinos y su correlación con los niveles de estos metales en la población expuesta* Universidad del Valle, Santiago de Cali.

Marrugo J. Lans E. & Benítez L. (2007). Hallazgo de mercurio en peces de la ciénaga de Ayapel, Córdoba, Colombia. *Revista MVZ Córdoba, 12*, 878-886.

Martínez O. & López M. (1997). Prevalencia de alteraciones hematológicas en intoxicación ocupacional por plomo. . *Acta Médica Colombiana, 22*, 233-239.

Ministerio de Ambiente y Desarrollo Sostenible. (2012). *Diagnostico Nacional de Salud Ambiental*. Retrieved from https://www.minsalud.gov.co/sites/rid/Lists/BibliotecaDigital/RIDE/INEC/IGUB/Diagnostico%20de%20salud%20Ambiental%20compilado.pdf.

Ministerio de Ambiente y Desarrollo Sostenible. (2016). *Diseño de una estrategia comprensiva para el manejo de pasivos ambientales en Colombia.* . Bogotá.

Monroy, C., Cortés, AC,. Sicard, DM., & De Restrepo, HG. (2005). Citotoxicidad y genotoxicidad en células humanas expuestas in vitro a glifosato. *Biomedica, 25*, 335-345.

Montoya, J. D. (2010). Actividades economicas de Colombia. *Actividades Economicas* Retrieved 06/04, 2016, from http://www.actividadeseconomicas.org/2012/03/principales-actividades-economicas-de.html

Muñoz, F. (2006). *Determinación del mercurio en suelos de Bucaramanga, utilizando un prolizador acoplado a un detector de mercurio basado en espectroscopia de absorción atómica diferencia del Zeema*. Universidad Industrial de Santander, Bucaramanga.

Naidu, R., Arias Espana, Victor A., Yanju, L. and Jit J. (2016). Emerging contaminants in the environment: Risk-based analysis for better management. *Chemosphere, 154*, 350-357.

Naidu, R., Pollard, S.J.T., Bolan, N.S., Owens G. and Pruszinski A.W. . (2008). Chap[ter 4: Bioavailability: The Underlying Basis for Risk-Based Land Management. In R. Naidu (Ed.), *Developments in Soil Science* (Vol. 32). Oxford, UK: Elsevier.

Nathanail, C. P., Bardos, R.P., Gillett, A.,McCaffrey, C., Ogden, R., Scott, D., Nathanail, J. (2013). *International Processes for Identification and Remediation of Contaminated Land*. Nottingham, UK: Land Quality Management Ltd.

National Toxicology Program. (2005). Naphthalene. Report on Carcinogens. 11th. Retrieved 22/04, 2016, from http://ntp.niehs.nih.gov/ntp/roc/eleventh/profiles/s116znph.pdf

OECD/ECLAC. (2014). OECD Environmental Performance Reviews: Colombia 2014: OECD.

Olivero-Verbel, J., Duarte, D., Echenique, M., Guette, J., Johnson-Restrepo, B., & Parsons, P. J. (2007). Blood lead levels in children aged 5–9 years living in Cartagena, Colombia. *Science of The Total Environment*, *372*(2–3), 707-716. doi: http://dx.doi.org/10.1016/j.scitotenv.2006.10.025

Parga, L. C. H., Marrugo, Gonzalez A., Fernandez-maestre, R. (2002). Hydrocarbon contamination in Cartagena Bay, Colombia. *Marine Pollution Bulletin 44*(1), 71-81.

Patiño, C. (1999). *Aspectos neuropsicologicos en memoria, atencion, rapidez y destreza manual en población ocupacionalmente expuesta e intoxicación por plomo.* Pontificia Universidad Javeriana, Bogotá.

PNUMA, & Ambiente), P. d. l. N. U. p. e. M. (2012). Sinopsis nacional de la minería aurífera artesanal y de pequeña escala Bogotá: Ministerio de Ambiente y Desarrollo Sostenible.

PNUMA, & Ambiente), P. d. N. U. p. e. M. (2010). Estudio sobre los posibles efectos en la salud humana y el medio ambiente en américa latina y el caribe del comercio de productos que contienen cadmio, plomo y mercurio. Mexico: PNUMA.

Prieto G. & Gonzalez M. (1998). Diagnosis of environmental problems related to vein goldmining in Colombia *Environmental Geochemistry in the Tropics* (pp. 185-191). Berlin Heidelberg: Springer.

Ravenscroft, P. (2007). Predicting the Global Extent of Arsenic Pollution of Groundwater and its Potential Impact on Human Health. Final Report. NewYork: UNICEF.

Reinikainen, J., & Sorvari, J. (2016). Promoting justified risk-based decisions in contaminated land management. *Science of The Total Environment, 563–564*, 783-795. doi: http://dx.doi.org/10.1016/j.scitotenv.2015.12.074

Restrepo, M., Mu, xf, oz, N., Day, N., Parra, J., . . . Giraldo, A. (1990). Birth defects among children born to a population occupationally exposed to pesticides in Colombia. *Scandinavian Journal of Work, Environment & Health, 16*(4), 239-246.

Restrepo, M., Mu, xf, oz, N., Day, N. E., Parra, J., . . . Nguyen-Dinh, X. (1990). Prevalence of adverse reproductive outcomes in a population occupationally exposed to pesticides in Colombia. *Scandinavian Journal of Work, Environment & Health, 16*(4), 232-238.

Ríos, A. S. (2006). *Evaluación de la contaminación por hidrocarburos aromáticos totales en aguas y sedimentos marinos en la Bahía de Buenaventura sector isla Cascajal* (Ingeniero Ambiental y Sanitario), Universidad de La Salle, Bogotá.

Rizzo, E., Bardos, P.; Pizzol, L., Critto, A., Giubilato, E., Marcomini, A., Albano; C., Darmendrail, D., Döberl. G., Harclerode, M., Harries, N., Nathanail, P., Pachon; C., Rodriguez; A., Slenders, H., Smith, G (2016). Comparison of international approaches to sustainable remediation. . .*Journal of Environmental Management, 184*, 4-17 doi: 10.1016/j.jenvman.2016.07.062

Rodríguez-Trigo, G., Zock, JP., Isidro Montes, I. (2007). Health effects of exposure to oil spills [in Spanish]. *Arch Bronconeumol.* , *43*(11), 628-635.

Rodríguez, A., Bardos, Paul., Cundy, Andy., Hall, Euan., Hutchings, Tony., Kovalick, Walter., de Leij, Frans., de Leij, Rebecca., Maco, Barbara., Rodríguez, Angela. (2017a). Strategies for rehabilitating mercury- contaminated mining lands for renewable energy and other self-sustaining re-use strategies. Output 1. DOI: 10.13140/RG.2.2.19175.14242. Bogotá: r3 Enviromental Technology.

Rodríguez, A., Bardos, Paul., Cundy, Andy., Kovalick, Walter., Maco, Barbara.., Rodríguez, Angela. (2017b). Strategies for rehabilitating mercury-contaminated mining lands for renewable energy and other self-sustaining re-use strategies. Output 4. DOI 10.13140/RG.2.2.14980.83841: r3 Environmental Technology.

Rodríguez, A. G., JF. & Martínez RS.,. (2009). Accumulation of Lead, Chromium, and Cadmium in Muscleof Capitan (Eremophilus mutisii), a Catfish from the Bogota River Basin. *Archives of Environmental Contamination and Toxicology, 57*, 359–365.

Rodríguez L. & Sierra D. (2011). *Evaluación preliminar del impacto ambiental por contaminación de plomo y cadmio en agua, suelo y sedimento en 4 puntos de la sub-cuenca del rio Tunjuelo* Universidad de la Salle, Bogotá.

Romero S. & Guevara L. (2011). *Evaluación de los impactos ambientales ocasionados por la contaminación de cadmio y plomo en suelo, agua y sedimento, de los municipios Tabio y Tenjo, pertenecientes a la Sub-Cuenca del río Chicú* Universidad de la Salle, Bogotá.

Sabucedo, J., Arce, C., Senra, C., Seoane, G., Vázquez, I. . (2010). Symptomatic profile and health-related quality of life of persons affected by the Prestige catastrophe. *Disasters, 34*(3), 809-820.

Sarmiento MI. Idrovo AJ. & Restrepo M. (1999). Determinación de arsénico total en cabello de individuos expuestos al embalse contaminado del Muña (Sibaté, Cundinamarca. *Revista de la Facultad de Medicina de la Universidad Nacional de Colombia, 47*, 205-209.

Siachoque, Y. (2001). *Distribución de metales en los sedimentos de diferentes cuerpos de agua de Colombia.* Universidad de La Salle, Bogotá.

SIVIGILA, S. N. d. V. e. S. P. (2015). Estadisticas. Retrieved 13/04, 2016, from http://www.ins.gov.co/lineas-de-accion/Subdireccion-Vigilancia/sivigila/Estadsticas%20SIVIGILA/Forms/public.aspx

Solomon, K. R., Anadón, A., Carrasquilla, G., Cerdeira, A.L., Marshall, E.J.P. and Sanin, L.H. (2007). Coca and poppy eradication in Colombia: Environmental and human health assessment of aerially applied glyphosate. In P. d. Voogt (Ed.), *Reviews of Environmental Contamination and Toxicology* (pp. 43-125). New York.

Soto C. Gutiérrez S. Rey A. & González E. (2010). Biotransformación de metales pesados presentes en lodos ribereños de los ríos Bogotá y Tunjuelo. *NOVA Publicación Científica*(8), 195-205.

Téllez, J., Carvajal, RM., Gaitán, AM. (2004). Aspectos Toxicológicos Relacionados con la Utilización del Cromo en el proceso Productivo de Curtiembres. *Revista Facultad de Medicina Universidad Nacional de Colombia, 52*, 50-61.

Tsai, S., Chou, HY., The, HW., Chen, CM., Chen, CJ. (2003). The effects of chronic arsenic exposure from drinking water on the neurobehavioral development in adolescence. . *Neurotoxicology 24*(4-5), 747-753.

Tyler, C. R., & Allan, A. M. (2014). The effects of arsenic exposure on neurological and cognitive dysfunction in human and rodent studies: a review. *Current Environmental Health Reports, 1*(2), 132-147.

UNEP. (2011). *Environmental Assessment of Ogoniland*. Switzerland

UNIDO. (2012). Proyecto Mercurio Colombia, United Nations Industrial Development Organization. Vienna: United Nations Industrial Development Organization.

Vasquez A. (2001). *Evaluación por espectrometría de absorción atómica de mercurio en aguas del tramo sur del río Cauc.* Universidad del Valle, Santiago de Cali.

Vegter, J., Lowe J. and Kasamas, H. Report. . (2002). Sustainable Management of Contaminated Land: An Overview. . Spittelauer Lände 5, A-1090 Wien, Austria: Austrian Federal Environment Agency, 2002 on behalf of CLARINET.

Vivas, I. (2005). *Gestión integral del mercurio generado en centros de atención de salud vinculadas al convenio de producción limpia del DAMA y centros odontológicos en Bogotá.* Universidad de la Salle, Bogotá.

Walton, W. (1997). Bad Land and Bad Law: The Role of Local Authorities in the Formulation of New Legislation and Guidance for Contaminated Land in the United Kingdom. *Environment and Planning C: Politics and Space, 15*, 229–244.

Supplementary Information

1. Hazardous Waste management Information

Fig. 1 shows the amount of hazardous waste generated by sector in Colombia.

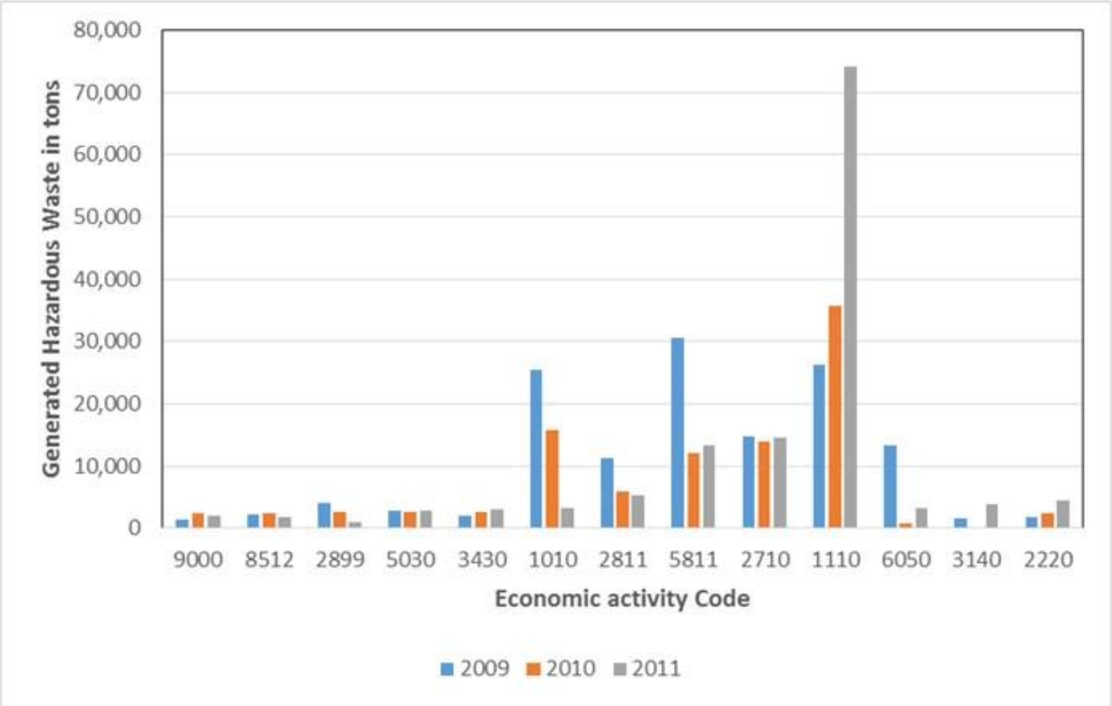

Figure 1. Main economic activities contributing to the generation of hazardous waste in Colombia

2220-Printing Activities; 3140-Manufactures of accumulators and electric batteries; 6050-Piping transport; 1110-Extraction of crude oil and natural gas; 2710-Primary industries of iron and steel; 8511-Activities related to health services including hospitalization; 2811-Manufacture of metal products for structural use; 1010-Open cut carbon extraction ; 3430- Manufacture of spare parts, and luxury accessories for automotive industry; 2899-Manufacture of metals products not classified elsewhere; 8512-Activities related with medical practice; 9000-Elimination of waste and residual waste related to wastewater treatment and similar activities.

Source: Modified IDEAM, 2011

2. Mobilisation data and distribution of heavy metals in Colombian territory

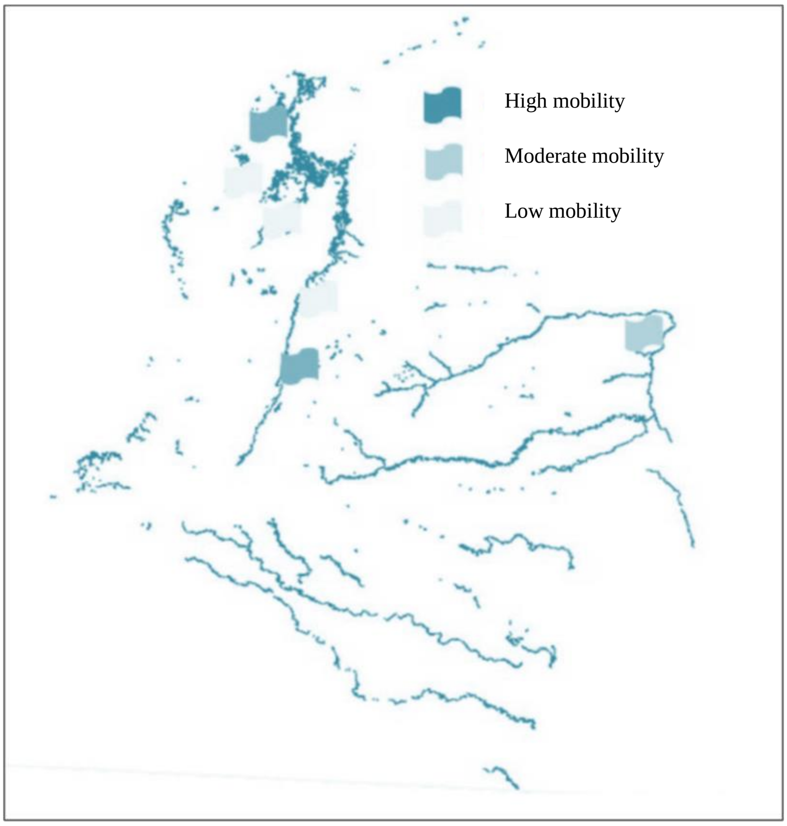

Figure 2. Mobilisation levels of lead in Colombian rivers and basins

Source: Modified (Siachoque, 2001)

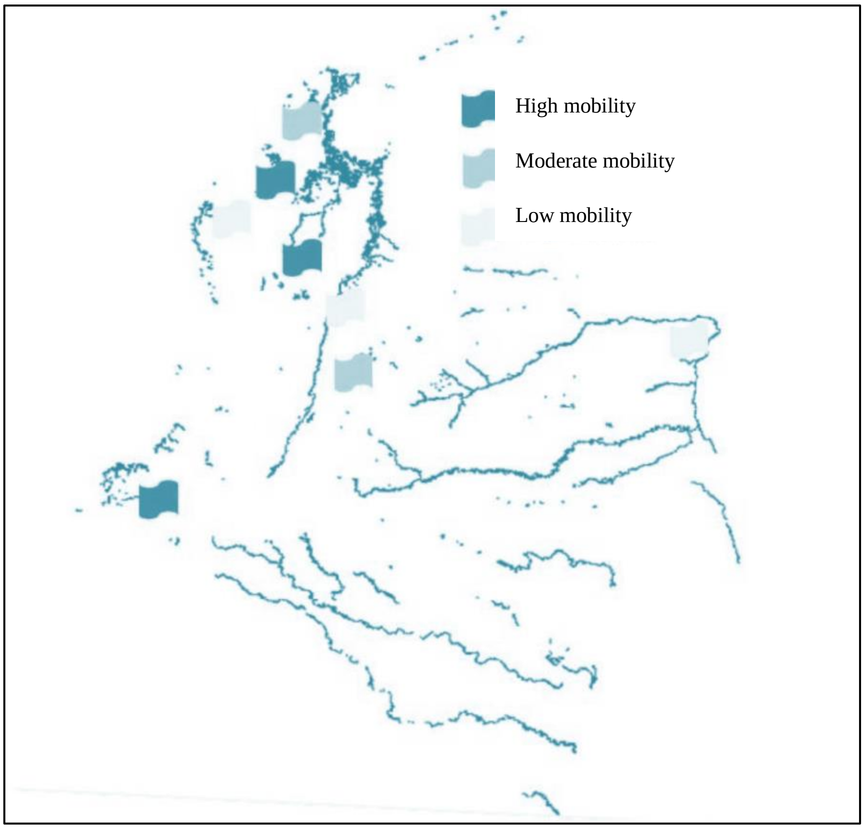

Figure 3. Mobilisation levels of cadmium in Colombian rivers and basins

Source: Modified (Siachoque, 2001)

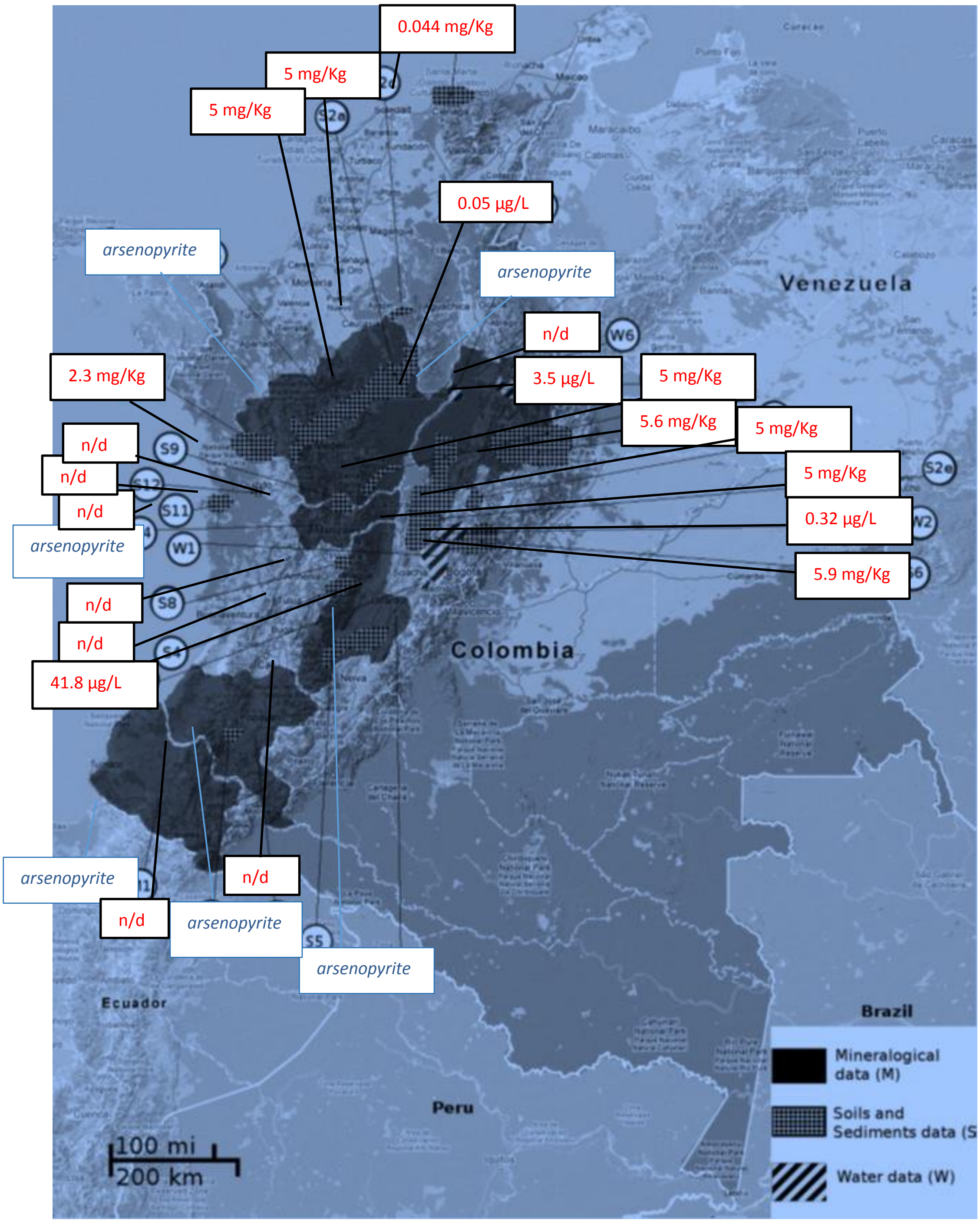

Figure 4. Colombian sites where arsenic presence have been reported

Source: Modified (Alonso et al. 2014)

3. Pesticides inventory and fish' concentrations and blood samples of different exposed groups

Table 1. Pesticides inventory

Description	Type of POP pesticide	Amount (kg)	Identified sites
Stored	DDT	159,812	4
Buried	Miscellaneous	Unknown	7
Contaminated soil	Miscellaneous	Unknown	12
Spired stored pesticides	Miscellaneous	40,440	29
Spired buried pesticides	Miscellaneous	Unknown	5

Source: Dirección desarrollo sectorial sostenible, 2007

Table 2. Mercury fish average concentrations in Colombia

Location	Type of Fish	Level detected
Ayapel, Córdoba		0.00218±1,77 mg/g
Bahía de Cartagena	carnivorous	0.100±0.006 mg/g
	omnivorous	0.076±0.014 mg/g
	detritivores	0.028±0.001 mg/g
Ciénaga de Ayapel, Córdoba	detritivores	0.000288±0.145 mg /g
	carnivorous	0.000346±0.13 mg/g
	non-carnivorous	0.000184±0.10 mg/g
Ciénaga de Ayapel, Mojana		0.298 + 0.148 mg/g
Mojana	carnivorous	0.160–0.3 mg/g
	non-carnivorous	0.155 ± 0.108 mg/g
San Benito		0.000386± 0.260 mg/g
Ayapel		0.000370±0.123 mg/g
San Marcos		0.000296±0.167 mg/g
Guaranda		0.000268±0.168 mg/g
Caimito		0.000240±0.165 mg/g
Majagual		0.000117±0.057 mg/g
Sucre		0.000091±0.059 mg/g
Bahía de Cartagena		0.852 mg/g
Ciénaga Grande de Santa Marta		0.068 mg/g
Nichi River		0.00004-0.000934 mg/g
Miel River		0.000008-0.000092 mg/g

Source: Compiled from (Ministerio de Ambiente y Desarrollo Sostenible, 2012)

Early studies carried out in the 80's indicated low levels of Aldrin and DDT in blood samples of six different exposed groups as shown in Table 3.

Table 3. Aldrin and DDT concentrations (µg/L) in blood samples of six different exposed groups

Group	Aldrin	DDT
Formulators	n/d	39
DDT applicators	0.86	159
Applicators of agricultural products	0.17	45.2
Areas for agricultural and sanitary land use	0.010	21.8
Areas for agricultural land use	0.11	32.3
Areas with no exposure	0.03	3.7

Source: Hernández et al. 1986