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Review of improving the water management for the informal gold mining in Colombia

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Revisión sobre mejora de la gestión del agua en la minería informal de oro en Colombia

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ABSTRACT: Colombia is one of the largest producers of gold in Latin America and it has recently increased its production, especially in the Departments of Antioquia, Chocó, Bolívar and Córdoba, which in 2014 produced 90% of Colombia's gold. Most of this production comes from artisanal and Small-Scale Gold Mining (ASGM). Parallel with this boost in production, there is concern about the health of rivers, since many local mines discharge untreated waters and tailings directly to waterways. This situation has awakened awareness in the communities of Colombia. Water is essential to carry out daily activities and for their society and economy. This article review displays three current challenges in Colombia that have been identified with local government, universities, environmental authorities, consultants and mining industry. These challenges are: water pollution; aquifer protection; and changes in natural sedimentation in rivers. Based on previous work done in the region, this paper suggests new research directions to create opportunities for more sustainable practices. In particular, this paper identifies the opportunity to implement a series of practices to manage water and tailings at informal mining sites. The paper also highlights the importance of engaging communities, informal and formal miners, government and researchers in order to create consciousness of the importance of water in Colombia. This is an opportunity to create discussions that help miners to manage water and tailings, adapting these practices to their specific needs and through simple technologies.

RESUMEN: Colombia es uno de los mayores productores de oro en América Latina, y recientemente ha aumentado su producción, especialmente en los departamentos de Antioquia, Chocó, Bolívar y Córdoba, los cuales en 2014 tuvieron una participación del 90% en la producción total de oro del país. La mayor parte de esta producción proviene de la Minería Aurífera Artesanal y de Pequeña Escala (ASGM, por sus siglas en ingles). Simultáneamente a este aumento en la producción, existe una preocupación por la contaminación que se genera sobre los recursos hídricos del país, debido a que la mayoría de minas artesanales e informales arrojan los relaves o desechos del proceso de recuperación de oro a los afluentes hídricos sin recibir ningún tipo de tratamiento previo. Esta situación ha despertado preocupación en las comunidades cuya economía se ha visto afectada, pues el agua que proviene de los ríos no solo es utilizada para satisfacer sus necesidades, sino también en la agricultura para el riego de los cultivos. En este trabajo se exponen tres desafíos actuales que posee el país frente a la utilización del agua en la mineria de oro tradicional, estos retos fueron identificados gracias a la colaboración del gobierno local, entes académicos, las autoridades ambientales, consultores y la industria minera. Estos desafíos son: la contaminación de los ríos producto de los desechos o relaves de la mineria artesanal de oro, la protección de los acuíferos y los cambios en la sedimentación natural de los ríos. En este artículo se propone, además, una metodología con el fin de llevar acabo prácticas de sostenibilidad con el medio ambiente. En particular, este trabajo identificó la oportunidad

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de colocar en práctica una serie de métodos para la adecuada utilización del agua y el tratamiento de residuos contaminantes generados por las minas tradicionales en el proceso de recuperación de oro. El documento también destaca la importancia de la comunidad minera artesanal y entes gubernamentales como el gobierno y las universidades, con el fin de crear conciencia sobre la importancia del agua. Esta investigación ofrece la oportunidad de crear discusiones que ayudan a los mineros artesanales a gestionar prácticas sostenibles para la utilización del agua en los procesos mineros, a través de la implementación de tecnologías no contaminantes.

1. Introduction

Colombian gold production has had a dramatic increase through the years, reaching 57 tonnes in 2014 [1]. Gold production for the period 2009-2013 grew by 16.5%, from 47.8 tonnes to 55.7 tonnes in the same period. For the five-year period analyzed, the average production was 55.9 tonnes, so that Colombia became the 5th largest gold producer in Latin America [1-3]. Colombia expects to increase its production with new deposits found in many regions, for example: The Colosa with resources of about 24 Moz, Gramalote with resources 4 Moz, Angostura with about 5 Moz and Quebradona with a potential gold and copper still not determined are emerging as the next production projects in Colombia [4, 5]. Numerous foreign and local companies are operating in different areas of the country, especially in the Departments of Antioquia, Chocó, Córdoba and Bolívar [3]. Some of these companies belong to the large-scale mining sector, for example: Anglogold Ashanti Colombia S A., Gran Colombia Gold, Continental Gold and Mineros S.A. They are the companies with most mining titles granted by the Colombian State [6, 7]. But the majority of them are part of the medium or even small-scale sector, only in the Northeast of the Deparment of Antioquia, there are 17 mining towns and between 15,000 and 30,000 artisanal gold miners [8, 9].

The recent boost of world gold price has awakened interest in Colombia for gold mining, particularly in areas that have traditionally been used for these purposes [1]. Therefore, many groups of investors have started to set up mining projects in areas that are recognized for being rich in gold [7, 10]. For example; in Antioquia Department, mining has greatly influenced the development of the region, where between 65 and 70% of the population dependent directly of the mining, generating between 20 and 25 thousand direct jobs [11, 12]. Whereas that gold production figures for the Chocó deparment increased, according to official sources, over 265% between April and December 2009. The region became the second largest gold producer in Colombia [13]. Only the departments of Antioquia, Chocó, Bolívar and Córdoba have almost 80% of Mining Production Units (MPUs) in Colombia, Antioquia with 39.9% (1,526 MPUs), Bolívar with 23.4% (967 MPUs), Chocó with 12.3% (507 MPUs) and Córdoba with 0.8% (33 MPUs) [2]. In many cases, these groups lack government authorization to extract gold (illegal mining) and/or lack environmental licences that certify that sustainable practices are carried out (informal mining). In fact, illegal and informal mining together represent 86% of mining operations in Colombia [14].

In Colombia, there are two main methods of extracting gold; one is through underground mining where the mineral is confined to veins beneath the surface, generally fault zones have a near-vertical planar or sheeted distribution. The other way to mine gold is placer mining where gold is found in alluvial deposits. In this type of mining, gold has flowed from an original source such as a vein until it reaches parts of the river where the water flow slows. The gold accumulates at the base of placer deposits because of its density. In Colombia, the majority of mining activities are carried out by placer mining (51%) and underground mining (30%) [1]. Both methods are very dangerous to the environment and the human health because they use a lot of mercury (Hg) in their processes [15]. During this operation, a large amount of Hg is accidentally or intentionally discharged to the environment and eventually reaches nearby fresh water bodies where, together with the significant amounts of mercury supplied by wet atmospheric deposition, it is subjected to methylation and subsequently bioaccumulation in aquatic fauna [16]. In order to recover the gold, the amalgam is heated in open charcoal furnaces either on site, or in small workshops (or even in the home of the miner) and the emitted Hg vapors are inhaled by the unprotected artisanal miner-smelters, but also outdoors and at home by residents of the mining communities [17, 18]. Mercury vapour impacts public health most directly, causing problems with the respiratory tract in short-term exposure to high levels of mercury vapour. Symptoms include chest pains, dyspnoea, cough, haemoptysis, impairment of pulmonary function and interstitial pneumonitis [11, 18, 19]. The mercury contamination in Colombia by artisanal gold mining has been recognized by a number of researchers and local authorities for over a decade. Colombia is likely the world's 3rd largest source of mercury emissions from ASGM after China (240 to 650 tonnes of Hg/year) and Indonesia (130 to 160 tonnes of Hg/year) and is the world's highest per capita mercury polluter [19, 20].

Therefore, informal mining activities are carried out through underground or alluvial mining. The absence of legal and formal procedures combined with the dearth of appropriate and clean technologies to mine gold have left a legacy of contamination in surface waters as well as in aquifers. Gold mining is thus a natural option for the rural inhabitants in Colombia. However, without technical assistance gold mining started in a very rudimentary fashion and has been generating huge environmental and health impacts [21]. Gold that comes from underground activities is further processed near the pithead, which in the informal sector is characterised by the absence of adequate mechanisms and technologies to manage water on the site. Meanwhile, placer mining activities are carried out in alluvial terraces beside rivers or into river benches, pumping water from the nearest stream. Both processes involve the use of mercury and the first one includes also cyanide to recover gold, and the processing machinery uses fuels and lubricants; all of which may be discharged directly to water bodies without treatment [22]. In other cases, polluted tailings with these components are left near waterways and their run-off can contaminate superficial water and groundwater. However, water contamination is not the only concern, there is another issue with alluvial mining in which the use of dredgers and backhoe loaders remove material from the river bottom and banks. This directly alters the natural hydrodynamics as well as, indirectly through erosion and deposition. Therefore, the informal mining sector has impacted water quality and landscape modification [23]. Also, these issues trigger public health problems, since in these regions communities need potable water for domestic and economic activities such as agriculture and fishery [24].

In Colombia, to produce 1 g of gold between 0.45 m^3 and 1.06 m^3 of water is needed [25, 26]. The value within this range depends on the mining and processing techniques, and water recycling capacity installed, which in informal mining is non-existent [27]. The quantity of water used by this sector is unknown, as well as the kind of practices that might be adopted to reuse water and control water discharges to meet environmental requirements. In this paper, we aim to show the current problems and challenges in some regions of Colombia and present the opportunity to develop a water and tailings management plan to bring technical support to informal gold miners in these areas. This is also an opportunity to plan and to promote research programs towards having an in-depth knowledge of the environment, hydrology and ecosystems within the regions, enhancing current water resource planning and monitoring programs. This will require increased collaboration between different governmental and non-governmental institutions, such as NGOs, local and foreign universities and environmental corporations in order to support sustainable development of informal mining.

The objectives of this work were:

- To identify water issues linked to informal gold mining in Colombia and its impact on the community and the environment.

- To propose possible actions in Colombia in order to achieve sustainability in artisanal gold mining and to improve water management in this economical activity.

- To present new research directions to create opportunities for more sustainable practices in artisanal gold mining.

2. Gold Production and River Systems in Colombia

The study is focused on four Departments of Colombia with the most importance in gold production and the importance of their river systems. The Departments of Antioquia, Chocó, Bolívar and Córdoba were the areas selected for this investigation because they have the record to be the highest gold producers. In 2014, they produced 90% of Colombia's gold. Most of this production comes from ASGM [2]. Simultaneously, these departments are the highest consumers of mercury in Colombia due to their gold production [28]. Table 1 shows the production of gold for the most important departments in the mining sector from 2000 to 2014.

Table 1 Gold Cumulative production for departments from 2000 to 2014 [29]

Department	Cumulative production (Tons)	Nacional participation (%)
Antioquia	304.66	50.76%
Chocó	126.72	22.98%
Bolívar	47.13	8.59%
Córdoba	52.12	6.90%

Two of Colombia's main basins run through to Antioquia Department; Cauca and Magdalena. They are located in the Northeast and Bajo Cauca regions of Antioquia. These basins play an essential role in the Colombian hydrological system since downstream, where the mountainous topography from the Northeast of Antioquia turns into an alluvial valley, the River Cauca flows into the River Magdalena creating several wetlands and swamps that control flooding in the North of Colombia [30]. Furthermore, the Bajo Cauca region in Antioquia has a mixture of geological, hydrogeological and geomorphological conditions that create valuable unconfined and confined aquifers [31]. Due to these conditions there is an abundant water supply for both regions, where the main economic activities are agriculture, livestock, fishing and mining operations [32].

Chocó is a Department of Colombia known for its large Afro-Colombian population. It is in the West of the country, and is the only Colombian Department to have coastlines on both the Pacific Ocean and the Atlantic Ocean. It includes the basins of the Atrato and San Juan Rivers [33]. The Atrato River to be in one of the wettest areas of the world, it is considered the watershed with highest performance in Colombia. The Atrato River watershed, captures in average of 1,298 m3 / sec [34]. While The San Juan basin measures 16,465 km^2 and consists of 12 mountain tributaries [35]. The San Juan River is 352 km long and originates in the Western Cordillera at an elevation of 3,900 m at Cerro Caramanta [36]. The San Juan River has one of the most extensive and the best developed deltas on the Pacific coast of South America, measuring 800 km2. The river drainage basin measures 16,465 km2 and is located in one of the areas with the highest precipitation in the western hemisphere. The annual rainfall varies from 7,000 to 11,000 mm, and as a result the San Juan River has the highest water discharge, sediment load and basin-wide sediment yield on the west coast of South America [36].

The Department of Bolívar is located to the North of the country, the fluvial axis of Bolívar is the Magdalena River, which runs through its eastern side and serves as limit with the Departments of Santander, Cesar and Magdalena to the Canal del Dique. The main tributaries are the Rivers Magdalena, Cauca and San Jorge [37]. The Magdalena River has the greatest length (1,612 km) and drainage area (257,400 km^2) of any river system in Colombia and its watershed occupies 24% of the Colombian territory [38]. The Magdalena River has its origin the Colombian Andes mountain ranges in the valley located between the Cordillera Central and Cordillera Oriental [39].

The hydrographic system of the Department of Córdoba consists of the Sinu Valley, covering 1,207,000 hectares, and includes the southern tributaries of the Department; the valley area of San Jorge, which covers 965,000 hectares in the southeast of the Department [40]. The Sinú, along with the Magdalena and Atrato, is one of the most important rivers on the Caribbean coast of Colombia [41]. The River Sinú is the main water system in Córdoba, since besides fertilizing its valley which is the stage of an intense agricultural and livestock activity. It represents an important supplier of fish species, thus becoming one of the main ecosystems of the Colombian Caribbean coast [42]. Figure 1 shows the location of the departments of Antioqia, Córdoba, Chocó and Bolívar.

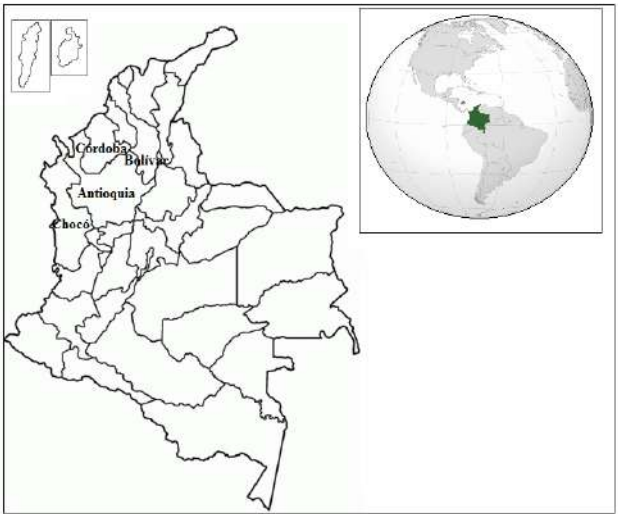

Figure 1 Map of Colombia indicating the Departments of Antioquia, Chocó, Bolívar and Córdoba [40]

There is concern about water management in these regions, particularly because once the Cauca and Magdalena Rivers reach Antioquia, they receive polluted loads caused by mining activity from tributaries from the Northeast and Bajo Cauca regions. The Census of Mines of Antioquia shows that more than 90% of gold mines located in the Northeast and Bajo Cauca regions do not have an environmental licence to operate. There are no premises to capture and dump waters and there is a scarcity of technical studies and infrastructure for environmental control [25]. Several research show that the departments of Chocó, Córdoba, Antioquia and Bolívar have high level pollution by mercury in their rivers [11, 13, 42, 43]. This has triggered several issues in these regions.

3. Challenges

Gold mining activities demand high volumes of water to obtain the metal and this leads to surface and underground water bodies being altered in several ways. Various departments in Colombia as Antioquia, Chocó, Bolívar and Córdoba are largely affected by informal gold mining and the challenges discussed below have been identified as priorities. These challenges have been identified with the support of different corporations, government and universities that are interested in assessing them, in order to create capacity building within stakeholders.

3.1. Water Pollution

The departments of this investigation suffer from water pollution since informal mining operations use different products to recover gold and to operate equipment. These elements are directly discharged to waterways without treatment generating high changes in the natural state of rivers. Whilst there are many water pollutants associated with informal mining, suspended sediment, organic matter, acid drainage, metals, grease, oils and fuels [44]. One of the biggest concerns in recent years is pollution by mercury in air and waters [45]. Artisanal and small scale gold miners use mercury to extract gold in developing nations worldwide, contributing an estimated 25% of global gold production and 30% of global mercury emissions annually. Mercury is used by miners to recover free gold through amalgamation where it is released to the air by burning or is left in tailings which pollute soils, water and air [11]. In the case of Antioquia, the total amount of mercury used in the Northeast and Bajo Cauca regions is around 93.4 tonnes/annum. This fact has ranked these regions with the shameful first position as the largest world's mercury polluter per capita from artisanal gold mining [21].

Varieties of entities have studied this problem; one of the most important was the Global Mercury Project by ONUDI and La Corporación Autónoma Regional del Centro de Antioquia (Corantioquia), where some studies have shown the levels of mercury in the air and the current mercury consumption in these regions [14, 46]. The Chain Study of Mercury in Colombia with Emphasis on Gold Mining by El Ministerio de Minas y Energía and La Unidad de Planeacion Minero Energetica (UPME) shows that Antioquia has more than 1,526 Mining Production Units [24] and there are more than 17 mining towns and between 15,000 and 30,000 artisanal gold miners directly exposed to mercury

[19]. According to Sistema de Vigilancia en Salud Pública (SIVIGILA), during the period 2007-2011, 450 cases of mercury poisoning were reported. In 2009, the highest number of mercury poisoning cases was reported, with 159 cases. Antioquia was the department that made the largest number of notifications in the five years, with 407 cases; Antioquia statistics show that reported more than 90% of the national total cases [47, 48].

Metal studies that have been conducted in the Department of Córdoba related to the detection of mercury levels in fish species in the basin of San Jorge river, show that in most cases this metal exceeds the specified threshold (200 ng/g) for populations at risk established by the World Health Organization (WHO) [42, 49]. Other studies show mercury contamination in plants, fish and sediments in some water bodies in the region of the Mojana [20, 41]. Similarly, significant concentrations of mercury in water, plants, fish and sediments swamp Ayapel was found [15]. Sources suggest that all the problems of metal contamination are associated with mining activities on the main gold zone of Colombia and the San Jorge River basin [49].

There are scarcities of studies that assess environmental problems caused to the local ecosystems from mercury, cyanide and chemical loads. There are any studies that track their mobility with tailings in waterways. The research indicated that mining activities caused great destruction to the water environment. The heavy metals are difficult to clear away from the natural environment or even from a secondary pollution [50]. The Colombian Government has recently launched a decree to reduce and control mercury use, especially in the gold mining industry. In addition, it is working on a database of sources of mercury [51]. However, government and environmental corporations argue that these studies have to move to the next step, which is the implementation of technologies that stop the use of mercury and the adoption of technologies to treat worked water in gold mining sites [12]. Currently, the Government of Antioquia, Corantioquia, Universidad Nacional de Colombia and BioRedd are developing programs to help informal miners to improve their mining circuit and are introducing technologies that avoid mercury use in their process. They presented a proposed plant design that eliminates the use of mercury by replacing gravity concentration processes taking advantage of the characteristics of the treated material.

Gravity concentration methods separate dense particles (such as gold) from lighter gangue materials based on their response to the force of gravity and the movement of a viscous fluid, which is generally water [52]. It is one of the simplest and the most economical methods of concentration [53]. Their application is recommended because it allows recovery of minerals in sizes as thick as possible, reducing costs crushing, grinding and concentration [54]. Today, coarse free gold is usually recovered in batch or semicontinuous gravity devices, such as Knelson or Falcon brand Batch Centrifugal Concentrators (BCCs).

Gravity Recoverable Gold (GRG), is a specific term which refers to free gold reporting to the concentrate stream with a small mass yield if separations are performed using BCCs. Gold particles associated with sulfides typically will not report to the concentrate stream (in an appreciable amount) of a BCC unit because the apparent particle density of the mineral is lower than that of a particle made entirely of gold and the mass pull of a BCC unit is too small to recover a significant fraction of contained sulfide mineral [54]. Figure 2 shows the performance of a Falcon brand Batch Centrifugal Concentrators (BCCs).

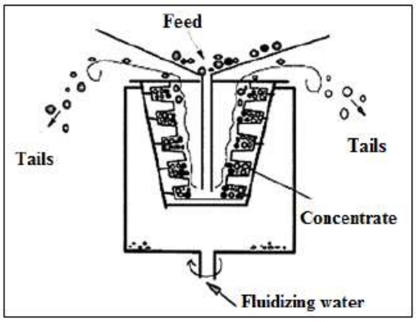

Figure 2 BBC diagram [54]

In recent years, many companies have re-evaluated gravity systems due to increasing costs of flotation reagents, the relative simplicity of gravity processes, and the fact that they produce comparatively little environmental pollution. Significant results were obtained regarding the recovery of precious metals and present a methodology that can be replicated in other mineral beneficiation plants that use gold amalgamation processes. This implies a significant reduction in mercury use and decreased risk of human contamination associated with this. They are proving to miners that with technical support and using alternatives to mercury they are able to recover more valuable material than they do at present [55].

A similar program can be implemented to support informal gold miners to develop tailing and water management plans for their mines where the main aim is to receive professional suggestions to treat and recycle worked waters and stoke tailings in dams that avoid seepage. This could be achieved with cooperation and agreements between stakeholders.

3.2. Aquifers

Although the aquifers represent the largest reserve for times of drought and regions with supply difficulties in several areas of the Colombia, they are overexploited and polluted [31, 32]. For example; in the Bajo Cauca region (Antioquia) informal gold mining activities that have been carried out for decades in this region are one of the main practices contributing with polluted loads to this aquifer, where the principal sources of pollution are faecal pathogens, heavy metals, acid drainages and toxic microorganisms [9, 12, 19]. Thus, there is a high or extreme risk of underground water pollution in Bajo Cauca's unconfined aquifer [56]. The biggest problem is that the communities use these aquifers to satisfy their needs because the current access to potable water in this region is deficient due of the absence of water supply networks [57]. It has been estimated that more than 26,000 m^3 of underground water is daily pumped in approximately 2,000 wells located in the Bajo Cauca region [56]. Bajo Cauca's unconfined aquifer is recharged by three sources; one is direct infiltration, second is through the hydraulic connection between the main rivers in the area such as Cauca River and the third is the indirect recharge from the regional metamorphic rock system. As a consequence, underground water quality in Bajo Cauca's free aquifer depends from the water input upstream in the Northeast region since they are in the same hydrological system.

Another case is Morroa aquifer, it has an area that comprises 526.9 km^2 and it is located in the central part of the Department of Sucre, Northwest of Colombia [58]. The Morroa aquifer is the most important source of water supply and human development for the communities of the municipalities that surround it, as Sampués, Sincelejo, Corozal, Morroa and Oveja and Los Palmitos in the Department of Sucre and Chinú in Córdoba and El Carmen de Bolívar, in Bolívar Department [59]. For decades, the community has been making a number of tasks of human activity in the recharge area aquifer, including the massive use of pesticides to control crop pest, consequently, the water is exposed to agrochemical contamination [59]. Another source of contamination is the domestic wastewater due to urban expansion and growth poblacional [60]. One shows off that due to the intensive and uncontrolled explotaition of the aquifer and the intensitive deforestation in the recharge area, the aquifer has presented descents in its registered levels in the exploitation wells [61].

Mining activities often require dewatering to lower groundwater levels. These activities in the majority of cases have altered underground water levels, modifying its flow and its capacity to supply water into surface waterways. The current underground water exploitation in Colombia is performed without following a water allocation plan. Therefore, the inhabitants have been indiscriminately using this resource to supply their necessities and to develop their economic activities. Connecting the aquifers with water quality issues there is again the opportunity to support informal miners in elaborating their own water management plan in order to teach them how to reuse, process and dispose water at mine sites.

Various entities in Colombia, as Antioquia government, environmental authorities and universities have assessed the risk that mining and other activities pose to Bajo Cauca's unconfined aquifer and have formulated the first step for the Environmental Plan Management of Aquifers to create a sustainable use of this resource [32, 62].This plan has been developed for the Bajo Cauca region where stakeholders and aquifer threats have been identified in order to evaluate the plan [12, 56]. As the plan has been carried out with the community support, there is the opportunity to integrate this current plan into a water management plan in the informal mining sector to help them to create an understanding of the connection between surface and underground waters. It will also help them to create consciousness to avoid pollution in surface waters and to plan the underground's water use for their mining activities.

3.3. Sediments

An important number of informal mines are located nearby or within rivers. For example; it has been estimated that in Northeast and Bajo Cauca regions in Antioquia there are approximately 1,011 backhoes that carry out alluvial mining. Each machine moves around 900 m^3 of material per year. In the department of Chocó, the use of dredges for to removal of heavy sands on the banks of the rivers in search of gold and platinum completely changes the crystal clear water of the tributaries and changes the natural landscape [63]. Worst of all is that the problems do not stop at the rivers, as these supply many populations. It is the case of Cabi River, it is the main source for the aqueduct of Quibdo, where the water come with a lot of sediments and dirty [64].

The bulk of tailings from such informal mining end up in rivers, modifying their natural hydromorphology and increasing the load of sediments in rivers downstream. This can trigger water damming, increase flooding risk, reduce capacity of water storage dams and contaminate water with suspended solids. The change in sedimentation patterns, also alter biological communities that in many cases disappear.

At the moment, there is an absence of studies that assess the state of watersheds that have been affected by high sedimentation because of mining and evaluate changes in hydromorphology over years. This process will be necessary to establish rehabilitation options and to estimate the cost that the government will face in the near future. Therefore, the informal sector in this region needs urgently to move towards more sustainable practices, in order to manage impacts on sediment pollution and hydromorphology caused by inadequate management of tailings and the absence of mining plans. Tailings management and mining plans must be connected with a water management plan since sediment alterations are directly linked with tailings and water management.

4. Opportunities

The current scenario of informal mining activities in Colombia has displayed three main challenges that reflect the existing state of water quality and river dynamics. This situation generates opportunities to enhance research programs and to support informal mining in the improvement of their mine plans, including development of water management and tailings management plans.

Different approaches to intervening in mining communities are taken by different groups, governments and organizations around the world to reduce mercury use, emissions and release. Some believe legislation is the key [45]. Government representatives, academics and NGOs have concentrated their efforts on solutions for mercury pollution based on political actions that can reduce the availability of mercury to artisanal miners [65, 66]. In 2011, the European Union introduced restricted control for countries exporting mercury through a treaty signed with United Nations Environmental Programme (UNEP). The US followed-up in 2013, with similar restrictions on mercury commercialization. The result of this measure was that international price of mercury has increased [67]. The restrictions on mercury access have yielded better results than legislation limiting its use, such as in Brazil and French Guiana [68]. Similar to Brazil and Indonesia, the government of Philippines, Guyana and Colombia established or are establishing laws to prohibit or limit mercury use [45]. Without any type of enforcement, these laws are a waste of valuable time and money that could be used to educate miners about cleaner procedures [69] .

The departments of Antioquia, Chocó, Bolívar and Córdoba need more scientific research to evaluate presence or circulation of the pollutants in watershed systems. There are metals, mine acid drainage and sediment suspension in waters which need to be measured and monitored in mining areas since these elements are changing the natural state in surface and underground waters [50, 64, 70]. Water quality is a big concern in many communities downstream of mines. Mercury levels are of particular concern, having been found in hydrological and biological systems including humans. Nevertheless, there are numerous other compounds that are discharged into rivers without treatment, which are not well understood in terms of their concentrations, distributions and effects [71]. It may be concluded that, if mining is to become sustainable in terms of pollution control, it is necessary to invest more in studying the behaviour of elements used for mining operation within the hydrological and ecological systems.

The effect of alluvial mining in those regions creates a research opportunity to evaluate the effect on river dynamics. Once material is moved from river benches or banks, the natural river morphology is modified triggering a change in hydraulic patterns [72]. These activities have consequences on flooding and erosion of banks in these regions and downstream of them. It is advocated to formulate a research project to study watersheds that have been largely affected by sedimentation because of mining activities. This process will be necessary to establish mechanics and costs to rehabilitate basins in the near future.

These studies and research programs are the first step to create a database for monitoring and tracking polluters in mining areas' basins. This information should be also used as a control measurement for environmental authorities and as a complement to the current Water Resources Plan in Colombia.

Furthermore, it is important to highlight that there is an opportunity to support informal miners for implementing their own water and tailings management plans since they are directly responsible for river systems that are affected by mining practices. The first step should be to create in them an awareness of sustainability and to teach them the importance of water in these regions. This work requires an interdisciplinary approach to articulate this plan with the inclusion of government, universities, large-scale mining, environmental authorities, NGO's and communities to provide technical and economic support. For example: The US Department of State and the University of British Columbia established a project to train miners from 2010 to 2013, on mining and processing methods. A demonstration plant in Portovelo, Ecuador was used to train 46 Peruvian, 50 Colombian and 115 Ecuadorian small miners and processors on methods to reduce and eliminate mercury increasing gold recovery by gravity concentration, flotation and cyanidation. Miners had the opportunity to learn unit operations of mining engineering and they realized that their rudimentary processes were very inefficient to extract and recover gold from complex sulphide ores. Due to this fact and through education, mercury levels in the region were reduced at least by 50% from the 2010 levels [73].

The idea to support informal miners in developing their own tailings and water management is an interdisciplinary work that requires social, environmental, technical and financial support. The first idea is to set up a group of stakeholders led by the government [45]. This group needs the interaction of several disciplines in order to generate a general comprehension of sustainability in the mining sector. This support should be carried out in phases where stakeholders can establish training sessions to identify, design and monitor water and tailings management plans.

China and the US have compliance programs for reducing consumption and emissions of mercury and other metals [2]. These countries have a lot of artisanal gold miners that pollute the rivers and aquifers due to inadequate miner practices [45, 51, 73]. The lessons learned in both countries were:

- Designing a general project to reduce the concentrations of mercury in artisanal gold mining.
- Identifying informal mining activities in the regions.
- Setting up meetings and training sessions between informal miners and stakeholders to develop sustainability concepts in mining highlighting the environmental wealth in Colombia. Furthermore, in these meetings, the groups can identify as a whole the threats that their waters are facing caused by inadequate water and tailing management practices in job sites and can create general solutions for this issue.
- Creating schemes where qualified professionals in environmental sciences and engineering can assist each mine site create their own water and tailings management plan.
- Supporting technically and financially the construction of infrastructure needed in order to reach sustainable practices in informal mining sites.
- Engaging miners in establishing monitoring for checking and reporting the characteristics and qualities of worked water that will be discharged into rivers.

- Constant feedback between miners and stakeholders to share new ideas in enhancing current plans and evaluating the whole process.

The water and tailings management plans are essential to face the challenges that these regions have, since poor mining practices have been causing water pollution and overburden of sediments in waterways. The opportunity to support water and tailings management in the informal mining sector is also the opportunity to connect government and academia in order to create clean technologies to deal with water issues and work with this sector instead of against them. For instance, informal miners that are located near each other can be grouped to share joint facilities. Technical and scientific professionals can advise on the design and construction of water treatment plants and tailings dam that could be shared by the group of miners. Worked water could be conveyed to the communal plant to be treated and this water can be reused at job sites or could be made safe to discharge. Tailings can be stored in a communal dam avoiding its disposal on soils, rivers or streams. The government could assist with resourcing this, if the solution was shown to be cheaper than the cost of environmental degradation of the river if downstream users are unable to utilise the river for their economic activities.

Moreover, the development of this program must be connected with current water management plans in the regions and with the Environmental Plan Management of Aquifers that the government and environmental corporations are working on.

5. Conclusion

This review has identified that the three priority areas for the departments of Antioquia, Chocó, Bolívar and Córdoba in Colombia are water pollution, aquifer protection and changes in natural sedimentation in rivers. Most of these problems are caused by the absence of formal governance of numerous mines where immediate economic benefits are not balanced with the benefits of sustainable practices.

Different institutions including Government of Colombia, Universidad Nacional de Colombia, Universidad de Antioquia, Corantioquia, ONUDI and BioRedd have been working on research and support programs to reduce pollution impacts left by poor mining practices that deal with the care of natural and social resources. Affected areas in these regions need to be measured through research programs that reveal the state of the environment. These studies can involve the current effect of certain contaminants on water quality, human health and ecosystems. Furthermore, they should include the analysis of watersheds strained by the increase of sediments and undermining activities that are changing natural dynamics of rivers. These studies are an important tool for planning, monitoring and designing strategies to enhance the current Regional Water Resources Plan to achieve a sustainable balance between meeting human needs and those of the environment.

The informal mining sector in Colombia needs to be supported by the government to promote sustainable mining. This presents an opportunity to build sustainable concepts in this sector through programs to teach informal miners ways to protect their water while continuing to generate profits. One of them is assisting them to develop their own mine plan that must include water and tailings management. This plan has to be elaborated according to specific environmental, social and technical necessities of each job site where the current Water Resources Plan and Environmental Plan Management of Aquifers of the regions should be incorporated. Moreover, the elaboration of these plans needs interdisciplinary teams such as; government, academia, technical experts, stakeholders and the community involved (miners).

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