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Environmental management of small-scale and artisanal mining: the Portovelo-Zaruma goldmining area, southern Ecuador

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This paper considers technical measures and policy initiatives needed to improve environmental management in the Portovelo-Zaruma mining district of southern Ecuador. In this area, gold is mined by a large number of small-scale and artisanal operators, and discharges of cyanide and metal-laden tailings have had a severe impact on the shared Ecuadorian–Peruvian Puyango river system. It is shown to be technically possible to confine mining waste and tailings at a reasonable cost. However, the complex topography of the mining district forces tailings management to be communal, where all operators are connected to one central tailings impoundment. This, in turn, implies two things: (i) that a large number of operators must agree to pool resources to bring such a facility into reality; and (ii) that miners must move away from rudimentary operations that survive on a day-to-day basis, towards bigger, mechanised and longer-term sustainable operations that are based on proven ore reserves. It is deemed unlikely that existing environmental regulations and the provision of technical solutions will be sufficient to resolve the environmental problems. Important impediments relate to the limited financial resources available to each individual miner and the problems of pooling these resources, and to the fact that the main impacts of pollution are suffered downstream of the mining district and, hence, do not affect the miners themselves. Three policy measures are therefore suggested. First, the enforcement of existing regulations must be improved, and this may be achieved by the strengthening of the central authority charged with supervision and control of mining activities. Second, local government involvement and local public participation in environmental management needs to be promoted. Third, a clear policy should be defined which promotes the reorganisation of small operations into larger units that are strong enough to sustain rational exploration and environmental obligations. The case study suggests that mining policy in lesser-developed countries should develop to enable small-scale and artisanal miners to form entities that are of a sufficiently large scale to allow adequate and cost-effective environmental protection.

Keywords: small scale mining, environmental impact, management, environmental policy.

Introduction

The environmental impacts associated with small-scale and artisanal mining have received considerable attention. Such activities are most common in Lesser Developed Countries (LDCs), and the impacts are often said to relate to wasteful and primitive techniques of extraction and processing, coupled with inefficient or non-existing pollution control. The existing literature is divided into two fairly distinctive parts: (i) those that are technical-scientific in nature and describe the chemical and biological character of the impacts caused by certain mining operations (e.g. Grösser *et al*., 1994; Malm *et al*., l995; Meech *et al*., 1998); and (ii) those that are concerned with the socio-political and economic characteristics of small scale and artisanal mining activities, and which may identify policy measures aimed at improving the miners often poor environmental performance (e.g. DSE and UN/DTCD, 1991; Warhurst, 1994; Barry, 1996).

Conversely, there is a lack of holistic studies that considers both the local specific nature of

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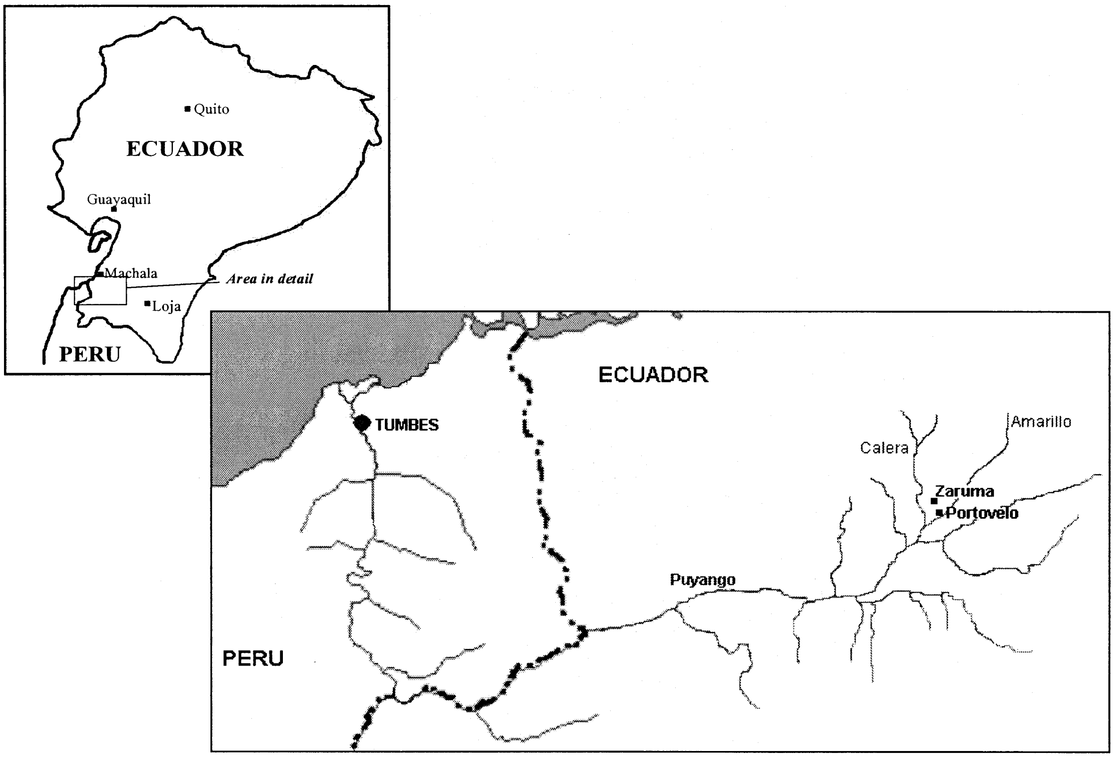

Figure 1. The Puyango river basin with the twin mining cities of Portovelo and Zaruma in the upper catchment.

environmental impacts and socio-economic conditions and how these factors may inform efforts to improve environmental management. Such work is needed in order to assess the applicability of the policy research that has been performed to date to real case scenarios. It is also important given the debate on whether small-scale developments are environmentally preferable to large-scale developments (e.g. Schumacher, 1973; Beckerman, 1995).

This paper considers technical remediative measures and policy initiatives that are needed to mitigate the environmental impacts caused by small scale mining in the Portovelo-Zaruma gold-mining area of southern Ecuador (Figure 1). These impacts have recently been studied and described in detail (e.g. Tarras-Wahlberg *et al.*, 2000a; Tarras-Wahlberg *et al.*, 2001; Tarras-Wahlberg and Lane, in review). Further, in 1999–2000, an Environmental Management Plan was developed for the Portovelo-Zaruma district, within the framework of the World Bank mining development project Prodeminca (*Proyecto Desarrollo Minero y su Control Ambiental*) (SGAB-Prodeminca, 2000; Tarras-Wahlberg *et al.*, 2000b). The research proceeds through considering: (i) the nature of the environmental impacts caused by the Portovelo-Zaruma mining activities; (ii) the characteristics and organisation of the mining activities in this district; (iii) the technical measures needed to counteract the identified environmental impacts; (iv) the financial cost of such measures in relation to pertinent economic data. In this way, constraints to the implementation of technical remediative measures are identified, and policy measures aimed at addressing such constraints are considered. Lastly, conclusions are made as to the case study's implications for the wider field of research.

The Portovelo-Zaruma area and the Puyango river basin

The mining district which is centered around the twin cities of Portovelo and Zaruma area is Ecuador's oldest and most important gold mining area, with a several hundred year old mining tradition. In the first half of the twentieth century, mining was performed by an American company (Sadco) which operated what was, by international comparison, a big mine. This was followed by a period when the Ecuadorian state ran the mine, but with ever diminishing returns. Finally, in 1984, the old Sadco mine was invaded by local miners, many of

Table 1. Social indicators for the two municipalities of Portovelo and Zaruma. Data for the whole of Ecuador are included for reference. Infant mortality is calculated from the number of babies that die within one year of birth. Incidence of poverty is estimated on the basis of household expenditure. Illiteracy refers to people over the age of 15 that cannot read or write. Data from Predesur (1994 and 1999)

Social indicator	Portovelo		Zaruma		Ecuador
	urban	rural	urban	rural	
Incidence of poverty (%)	25	64	13	58	24
Infant mortality (ppt)	39	48	34	61	53
Illiteracy (%)	4	12	3	14	21

whom had lost their jobs as the fortunes of the old mine diminished. Thereafter, mining and processing assumed its present artisanal and small-scale character. These are conducted at numerous locations, in a 16×9 km area, situated north and south of the confluence of the Calera and Amarillo rivers (Figure 1). These two rivers, in turn, form part of the Puyango river catchment which flows southwest, eventually through Peruvian territory and enters the ocean at the city of Tumbes.

The Puyango river basin is sparsely populated, remote and poorly developed. In 1990, the total population in the Ecuadorian part of the basin was estimated at 103 000 which converts to an average population density of about 30 persons per km. The population is heavily concentrated in the upper part of the catchment, with about 60% of the regional population living in the area surrounding Portovelo and Zaruma. The remaining 40% live mainly in small towns situated in the highlands away from the main Puyango river. Only a handful of villages, each comprising less than one hundred individuals, are situated on the main river downstream of the mining district. Table 1 gives social indicators for the Portovelo-Zaruma area, and these are compared to values for the whole of Ecuador.

Hoeck *et al*. (1990) report that about 126 000 people lived within the Peruvian part of the river basin in 1990, about two-thirds of these in the city of Tumbes. The most important economic activities in the Peruvian part of the basin are trade, fishing and agriculture. The fishing takes place in the sea, and to some limited extent in the river estuary, whereas the river itself is not used. Extensive agriculture relies on the river for irrigation in an area which is otherwise too dry to support such activities (SGAB-Prodeminca, 2000).

The Puyango river system was studied in detail in the 1970s and 1980s during the Ecuadorian–Peruvian irrigation scheme, led by the World Bank and known as the Puyango-Tumbes project. This proposed use of the waters of the Puyango river to irrigate large areas in dry regions that straddle the international border, and to generate hydroelectric energy on both sides of the border. However, as armed conflict between Peru and Ecuador erupted in the 1980s and 1990s, the project was neglected. With the signing of a peace agreement in 1999, the implementation of the Puyango-Tumbes project has again been put onto the political agenda in both countries.

Environmental impacts

The environmental impacts associated with the Portovelo-Zruma district were first acknowledged in a number of studies in the early 1990s (Schreckinger *et al*., 1990; Hoeck *et al*., 1990; Torres, 1991). These studies were followed by more detailed work later on in the decade (SES, 1999; SGAB-Prodeminca, 2000; Tarras-Wahlberg *et al*., 2000a; Tarras-Wahlberg *et al*. 2001; Tarras-Wahlberg and Lane, in review). The mining and processing activities are causing a variety of environmental problems, including deforestation and increased erosion, noise and dusting from heavy transport, as well as the destabilising effect on land of a myriad of poorly planned and maintained mine adits. The most serious problems are, however, related to the discharge of process tailings to the Amarillo and Calera rivers (SGAB-Prodeminca, 2000; Tarras-Wahlberg *et al*., 2001). The ecological effect of these discharges is drastic. The Calera river is, downstream of the mining area, a dead river with no fish nor any invertebrates, whereas the Amarillo river has had its fauna severely diminished. Moreover, fish and aquatic invertebrates are non-existent more than 20 km after the confluence of the two rivers. Further downstream, some life reappears, although the invertebrate fauna is still severely reduced up to 160 km downstream of the mining area, within Peruvian territory.

Metals and cyanide levels in river water regularly exceed environmental quality criteria downstream of the mining district. Due to the prevalently neutral to slightly alkaline river waters, metals are mainly associated with sediments and suspended solids (rather than being dissolved). However, elevated metal levels in fish and benthic invertebrates in affected river stretches that still support some life show that these metals, including mercury, are available for biological uptake. It is indicated that the total extinction of all life in some river stretches is caused by discharges of cyanide, whereas the less drastic reduction of faunal diversity further downstream is caused by metal contamination. Tarras-Wahlberg *et al*. (2001) conclude that the management of the waste products deriving from the mining and processing activities must be radically improved if the ecological health of the river system is to be restored. However, it is indicated that an almost complete mitigation of the environmental problems may be achieved by the construction of adequate impoundments for the confinement of mining waste and process tailings.

Small-scale and artisanal mining and the environment

Strict definitions of 'small-scale' and 'artisanal' mining do not exist, although characteristics used for classification (Spiropolous, 1989) include: (i) mine output; (ii) productive capacity; (iii) number of people employed in any one operation; and (iv) size of ore reserves. Mine output is most commonly used and small-scale mining often means an operation with an annual production of less than 100 000 tonnes of ore (e.g. Noetstaller, 1987; Davidson, 1989; DSE and UN/DTCD, 1991). Further, a recent definition of artisanal mining describes it as '. . . the most primitive type of informal, small-scale mining, characterised by individuals or groups of individuals exploiting deposits (usually illegally) with the simplest equipment . . . ' (Barry, 1996).

Small-scale and artisanal mining activities make significant contributions to world mineral production. In 1985, it was estimated that the contribution of small-scale miners amounted to 16% of the gross value of the global output of metals and industrial minerals (DSE and UN/DTCD, 1991). Artisanal mining is very labour intensive, and Noetstaller (1987) estimated that such activities employed about 6 million people worldwide, almost all of these in LDCs. Small mines are regarded as important in terms of employment, as a vehicle for the development of indigenous entrepreneurship, for infrastructure development and for generation of public revenue, all of which are important development goals in LDCs (DSE and UN/DTCD, 1991).

Small-scale and artisanal mining activities are often associated with interrelated problems of poor social, health and safety conditions, illegal mining, resource waste and unacceptable environmental impacts (DSE and UN/DTCD, 1991; Barry, 1996). The environmental impacts relate to: (i) a lack of proper environmental awareness and concern among small-scale operators; and (ii) administrative constraints associated with the difficulty experienced by the authorities in controlling a large number of operators in what may often be remote areas. Noetstaller (1987) illustrates these two problems by suggesting that miners and authorities are caught in two connected cycles of cause and effect. Thus, on the part of the miners, the use of inadequate mining and processing techniques leads to low productivity and low mineral/metal recovery, which in turn result in low revenues and an inability to accumulate funds for investments. The lack of funds, to improve methods and acquire appropriate equipment, traps miners in crude and inefficient mining and processing, so closing the circle. The authorities are trapped in a similar cycle that limits their ability to control mining activities. Thus, mining authorities are often unable to enforce regulations because of a lack of operational resources. This leads to illegal operations, poor environmental and health and safety standards and a loss of fiscal revenues. The lack of revenues limits the ability of the authorities to perform their regulatory function and perpetuates uncontrolled mining.

Efforts to counteract the environmental problems associated with small-scale and artisanal mining generally attempt to break one or both of the causal circles described above. Commonly, this is attempted through: (i) strengthening the authorities charged with environmental supervision and control of mining activities; and/or (ii) attempts to introduce more efficient and environmentally friendly mining and processing technologies (e.g. DSE and UN/DTCD, 1991; Barry, 1996). Further, with regards to artisanal miners, the formalisation and legalisation of activities, and the disseminations of information about the value of a clean environment are often regarded as crucial in order for miners to assume a more responsible attitude (DSE and UN/DTCD, 1991; Barry, 1996). However, such initiatives have encountered problems due to a variety of reasons. First, even the best funded system for environmental control would encounter difficulties in monitoring the often large number of individuals, companies and cooperatives that typically operate in small-scale mining districts. Hence, the enforcement of mining regulations may require resources that are beyond the budget of essentially all LDCs. Second, in spite of the often poor mineral/metal recovery achieved by small-scale miners, the methods used are remarkably cost effective, and they also require a minimum of start-up capital (DSE and UN/DTCD, 1991). Since the methods used are simple and require a minimum of infrastructure, miners are able to operate in remote and difficult terrains. Therefore, miners seldom find it worth their while to invest in 'better technology'. Third, attempts to formalise/legalise small-scale mining often encounter problems that are rooted in a general distrust on the part of the miners of the benefits of becoming legal. A legal operator will have to pay taxes and/or royalties. Small miners are also often unable to fund and/or conduct Environmental Impact Assessments (EIA) or other required environmental work, which makes them even less likely to opt for legal status (DSE and UN/DTCD, 1991).

Thus, the mitigation of environmental impacts caused by small-scale and artisanal mining requires considerations of a wide range of interrelated issues, therefore, the next section will provide a holistic description of the relevant issues that relate to the Portovelo-Zaruma case study.

The Portovelo-Zaruma mining activities

Legal requirements, supervision and control

Ecuadorian regulations, stipulating how mining and processing should be performed in an environmentally responsible way, exist. Mining ventures are required to prepare, and have accepted, an EIA, which details how environmental impacts will be managed, and provides adequate plans for mine closure. Further, miners must submit yearly environmental audits that show to what degree the stipulations of the EIA are followed. Miners are responsible for both the direct contamination caused by them and environmental damages that occur after mine closure, although bonds or insurances to ensure reclamation after mine closure are not required. Importantly, the contamination or degradation of natural resources, be it deliberate or by negligence, is deemed a criminal offence.

Artisanal miners are afforded special status. Such miners can be permitted to mine in an area without having to apply for a mining concession, provided that the relevant concession is not actively mined by someone else. Further, the Ecuadorian government is required to provide a program of information, education and capacity building aimed especially at artisanal miners. On the other hand, artisanal miners are required to recuperate mercury used in amalgamation and to store adequately any tailings produced during mining.

It is the central government's responsibility to ensure that both the constitution and national laws are followed. Hence, the Ministry of Mines and Energy is charged with the environmental supervision and control of mining activities, and this work is performed through the Mining Environmental Unit (MEU), a department with about a dozen employees based in Quito. Further, the recent 'Law of environmental management and decentralisation' (1997) places some of the responsibility for environmental control and management on municipalities. This law also states that any member of the public has a right to participate in decision-making with regards to developments that may have environmental impacts.

Characteristics of the mining industry

The gold is associated with sulphide-rich quartz veins, and the mining techniques used are in general primitive, with much of the extraction and transporting of ore being undertaken manually. Currently, there exist about 400 small mines in the area, and more than 80% of these are rudimentary operations that collect fill material left behind in the old Sadco mine. Most of these mines produce in the region of 0·5–2 tonnes of ore daily, whereas only a handful produce more than 5 tonnes per day. In 1999, it was estimated that these types of operations produced a total of approximately 175 000 tonnes of ore, containing 50 000 oz (1·6 tonnes) of gold. Very little is known about the gold reserves available to these small-scale miners and therefore the mines operate on a day-to-day basis, without any longer term planning.

In contrast to the mainly primitive mining activities, most processing operations have reached at least a modest level of mechanisation. The ore is gravity-concentrated following crushing and grinding, and the gold is subsequently recovered from the heavy mineral concentrates by amalgamation with mercury. Additionally, a large number of cyanidation plants of various types and sizes treat the gravity and amalgamation tailings. In 1999, there existed 65 plants for crushing, grinding and amalgamation, and about 80 cyanidation plants in the area.

The mid-90s saw a small renaissance of more technologically advanced mining with the establishment of Bira, a modern but small-scale mining and processing operation. The Bira mine produces about 125 tonnes of ore daily, and the yearly production of gold is about 28 000 oz (0·88 tonnes). Additionally, Bira has established mineral reserves for at least a few years production.

Of an estimated 288 000 tonnes of tailings produced in the area in 1999 (with some ore imported from other mining areas), 44 000 tonnes were adequately confined in the Bira tailings storage facility, 84 000 tonnes were deficiently stored, whereas 160 000 tonnes were discharged to rivers. Of the discharged material, about 33 000 tonnes were associated with dilute slurries with elevated levels of metals that derive from milling and amalgamation activities, whereas the remainding 127 000 tonnes were associated with metal and cyanide rich pulps discharged from cyanidation plants (SGAB-Prodeminca, 2000).

Data from 1994 indicate that nearly 11 000 people were directly involved in mining activities in the district (Predesur, 1994). SGAB-Prodeminca (2000) estimate that 80–90% of the economically active population of Portovelo and Zaruma belonged to the mining community in 1999. Within the two mining towns, there exist no clear divisions between miners and non-miners. Practically everyone who is not actively mining is either related to, or economically reliant upon, someone who is.

However, the mining community is heterogeneous with regards to activities, level of mechanisation, and capital investments (Table 2). Three main groups are identified by SGAB-Prodeminca (2000): (i) artisanal miners; (ii) small-scale, and semi-mechanised miners; and (iii) small-scale, industrial operations. About 70% of the people involved in mining activities belong to group (i): informal small-scale miners who mine with primitive and rudimentary tools and techniques; and the industrial group (iii), represents a mere 5% of the individuals engaged in mining. Importantly, all but a handful of all operations, are run and owned by local people. The Bira operation is owned by a family from the Ecuadorian city Guayaquil. Although this family has lived in the area for more than a decade, it is still regarded as 'not local'.

Group (ii) has of late become increasingly organised, and there now exist a small number of formalised groupings of such companies and/or individuals. These groups have made some efforts to agree upon joint measures of environmental remediation, and also strive to achieve legal status for their members (Cenda, 1996). The operators in this group have typically invested in equipment that allows them to buy and process ore produced by the more numerous artisanal miners. SGAB-Prodeminca (2000) identifies this group as being responsible for the vast majority of discharges to rivers.

Technical solutions to mining related pollution

Prodeminca's Environmental Management Plan (EMP) contains three technical measures that aim to ensure that tailings discharges to rivers are discontinued. They comprise: (i) a Tailings

Table 2. Summary characteristics of the three main groups of miners that are active in the Portovelo-Zaruma district (adapted from SGAB-Prodeminca, 2000)

	Artisanal activities	Small-scale, semi-mechanised	Small-scale, industrial
% of miners	70	25	5
Legal status	Informal	30% legal; 70% informal	Legal
Activities	Mining and mercury amalgamation	Processing, rarely mining	Mining and processing
Work condition	Artisanal, no safety measures. Informal group of 1–2, rarely more than 10 people	Semi-mechanised, few safety measures. Work performed in small entities with about 10 people	Industrial processes, acceptable working conditions
Economic situation	Miners own few tools; only about 40 percent of available gold extracted; no capital; subsistence mining; no investment	Firms may own a few mills/pools for cyanidation and 1–2 trucks. Some capital and limited investment made	Full ownership of industrial equipment. Substantial capital and investments

Management Plan (TMP); (ii) the recirculation of process chemicals and water; and (iii) the relocation of processing plants to more suitable areas, Of the three, (i) is an absolute requirement, whereas measures (ii) and (iii) may be seen as important supportive projects, although each with a more limited scope. The EMP includes cost estimates for implementation of these measures. The cost estimates were calculated to be precise to about $\pm 25\%$ at present-day values.

Tailings management

The Tailings Management Plan (TMP) was developed to eliminate all current discharges of tailings solids, tailings solutions and cyanidation wastes to rivers. The TMP was developed according to international best practice, which includes considerations of sustainability and safety during extreme conditions (e.g. tectonic activity, heavy rainfall etc.).

The Portovelo-Zaruma area is characterised by a high and complex relief. The few flat areas that exist are located in river beds and are small. Therefore, adequate tailings storage areas close to individual or even groups of operations are not available. This fact directed the TMP towards a communal storage dam concept, with sufficient capacity for all tailings produced in the area.

Thorough investigations showed that a plateau situated directly south of the Amarillo river is the only location suitable for such a tailings facility within a reasonable distance of the mining district. Further, the area is currently used for cattle grazing, making it of limited economic value. Considerations of storage and construction volumes and a required minimum ten year lifetime led to the identification of a preferred site with an estimated maximum life of 27 years. The TMP was developed to ensure that tailings are transported to this site for final confinement, and it consists of the following main components (Figure 2):

(i) a pipeline system for the collection of tailings slurries from each operation, followed by transportation of slurries via high density polyethylene pipelines (mostly through gravity but with a limited requirement for pumping for the most southerly processing plants) to a central pumping station;
(ii) pumping of tailings from the pumping station to the tailings dam, using energy generated via a hydroelectric plant powered by water captured from the Amarillo;
(iii) storage of tailings in a lined, downstream raise tailings dam, with this design necessary due to seismic activity in the area, and the ARD generating potential and cyanide content of the tailings;
(iv) treatment of tailings decant water, and a small polishing pond downstream of the tailings dam with subsequent release of treated water to the environment and of solid precipitates to the tailings dam; and
(v) closure by water cover.

The costs for the dam were estimated for all aspects of the dam's construction. In short, the financial outlays with time rise fairly linearly from an initial US\$ 3·4 million investment in year 1 to a total of US\$ 18·1 million in year 27. Assuming a yearly storage of about 290 000 tonnes of tailings during these 27 years, this equates to an average annual cost of confinement of US\$ 0·67 million and a tailings storage cost of US\$ 2·3 per tonne, which is comparable to internationally accepted costs for such facilities.

Recycling of water and process chemicals

Most processing plants use water and process chemicals indiscriminately. Consequently, opportunities exist to achieve both an improved efficiency of resource use and environmental gains (so called 'win-win solutions'). Cyanide represents a major

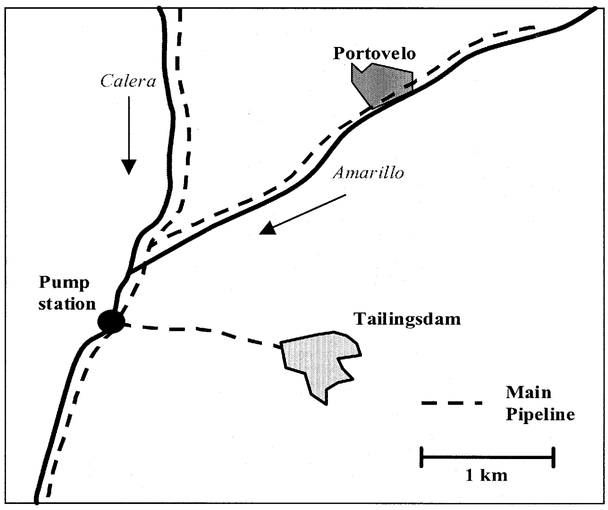

Figure 2. Illustration of the main components of the Tailings Management Plan (TMP). The dam is situated at 750 masl and the pumpstation at 590 masl. Pipelines from individuals operations are not included.

cost for plant owners, yet it is often used in excessive amounts. Studies performed within Prodeminca show that plant owners could make substantial economic savings by re-using cyanide after re-circulating it through activated carbon cells (SGAB-Prodeminca, 2000). The investment needed to enable an average sized cyanidation plant in the area to re-circulate its cyanide is estimated at about US$ 8000, and such an investment should be paid off within a year (SGAB-Prodeminca, 2000). Further investigations show that economic opportunities exist for the recovery and subsequent sale of cyanide and residual gold from tailings that are now discharged to rivers.

Water rights are not paid for. Hence, the re-circulation of water does not provide direct economic savings. However, water may at times be scarce in the dry season and its use should, for environmental reasons, be limited when possible. The milling and gravity concentrator plants use the largest amounts of water. Their water use could be drastically reduced for a modest cost by initiating re-circulation. The EMP proposes that smaller plants construct settling ponds for their waste water, with pumps that re-route the cleared water back into the process. The somewhat larger operations may also include a thickener tank to make the process more efficient. The estimated cost for these installations vary from US$ 2500 for each of the smaller plants to US$ 10 000 for the larger operations (SGAB-Prodeminca, 2000).

Relocation of processing plants

The municipalities of Portovelo and Zaruma have made some efforts to direct the establishment of processing plants to certain areas, notably the banks of the Calera river, and to avoid having such plants intermixed with human habitation. However, as yet, there exists no overall land use plan for the area. Consequently, many processing plants have been established in remote areas, often where local roads cross small rivers. Such locations are unsuitable for tailings storage as the relief is steep, making even the temporary storage of tailings impossible. The tailings are discharged directly to the streams. A further problem is the deforestation and landscape spoliation that is initiated by the establishment of new processing plant in previously undeveloped areas.

To counteract these problems, the EMP includes recommendations for how to initiate and enforce land use planning. The most pressing issues are to direct the establishment of new processing plants to areas suitable for this purpose, and to relocate operations that are now situated in isolated areas where no space whatsoever exists for the adequate storage of tailings. A further benefit entailed in focusing processing activities to certain areas would be to make the capture and transport of tailings to a central tailings dam more economical and less technically challenging.

Economic aspects of the contamination

A rapidly growing body of literature is concerned with assessing the opportunities (Pearce *et al.*, 1989; Jacobs, 1991) and problems (Kelman, 1990; O'Neill, 1993) of evaluating environmental impacts in financial terms. The rationale behind this approach is that: (i) pollution has adverse consequences for the resources available to society; and (ii) reducing pollution implies costs so that reducing pollution may itself have adverse consequences for the economic resources available to society. Thus, the severity of pollution may be assessed in the form of a financial cost-benefit analysis where the quantity of damage or physical impact of any given form of pollution is compared with the costs of preventing pollution.

Reliable data on the financial costs of pollution abatement are needed to perform a cost-benefit analysis. Such estimates are usually available, at least to some degree of accuracy. However, the second part of the analysis, the financial costs of the impacts caused by contamination, are more difficult to estimate. One reason for this is that the impacts may be numerous and the data available to evaluate each one of these often are inadequate. Another important reason is that some of the impacts, such as those upon ecosystems or impacts upon areas of cultural and aesthetic importance, are near impossible to evaluate financially (Foster, 1997). For these reasons, such an analysis in the mining district and the Puyango basin, where little or no data on the financial costs of the impacts caused by the contamination can be obtained, are near insurmountable. Instead, the economic analysis proceeds by considering the significance of the income generated by goldmining in relation to a number of economic estimates of: the size of the local economy; the investment represented by the Puyango-Tumbes irrigation project; and the costs of pollution abatement measures.

The mining district's estimated gold production for 1999 was 78 000 ounces. Of this, small-scale and artisanal operators produced about 50 000 oz (1·6 tonnes) and Bira produced about 28 000 oz (0·88 tonnes). Assuming a goldprice of US$ 275 per oz, the total value of the annual gold production in the area during 1999 was US$ 21·5 million (SGAB-Prodeminca, 2000).

Recent population estimates are available for the upper part of the Puyango basin, but not for the whole Ecuadorian part of the Puyango basin. It is therefore assumed that the mean population increase in the upper catchment is representative of the remainder. This gives an estimated 134 000 people living in the area in 1999. Socio-economic indicators suggest that the Portovelo-Zaruma area is socio-economically similarly or slightly less well off compared to average Ecuadorian conditions (Table 1). The GDP per capita for the whole of Ecuador was US$ 1100 in 1999. Using this figure, we arrive at a total annual Gross Product (GP) of US$ 147 million for the whole of the Ecuadorian part of the Puyango basin, and US$ 59 million for the Portovelo-Zaruma district.

The binational Puyango-Tumbes irrigation project aims to irrigate 137 000 hectares of territory and to generate 162 MW of hydroelectricity. A revision of the plans was performed in 1998. The total costs of implementation were then estimated at US$ 2640 million (Predesur, 1998). The feasibility of the project is crucially dependent upon water quality. Chemical analyses of the suspended solids carried by the river suggest that sediment bound metals may represent a significant constraint to the use of the Puyango's water for irrigation. This follows as the suspended solids may accumulate on agricultural land under irrigation. Although the mining contamination is unlikely to completely jeopardise the feasibility of the project, it will prompt an investigation of how to avoid that metal rich sediments are deposited onto agricultural land. In turn, such a study may lead to recommendations for additional infrastructure (filters, settling dams) to be installed. The cost of such studies and/or infrastructure is not known. However, it is a cost that would be avoided if the mining contaminants were adequately confined at source.

An overview of the incomes related to gold sales, the cost of pollution prevention and other pertinent economic estimates are provided in Table 3. From this overview it is possible to make some general and important conclusions. First, the value of the annual production of gold is substantial in relation to estimated regional GP. Thus, the goldmining industry is of vital importance for the well being of the whole area, and its survival is important. Consequently, to stop goldmining completely is not a viable option. Second, the costs of mitigating the pollution generated by the goldmining industry by constructing a communal tailings dam represents 3% of the value of gold sold over a dam lifetime of 27 years or 8% over a dam lifetime of 3·5 years. Thus, the cost of mitigating pollution appear acceptable in the longer term, but somewhat high in the shorter term. Third, the costs of mitigating the pollution caused by goldmining is small in relation to the value of the Puyango-Tumbes irrigation project. Given that the mining pollution may require modifications to this project, investments to solve the environmental problems caused by the mining industry at source may be well motivated. However, some caution attends the latter conclusion as experiences show that investment expenditures can provide erroneous and exaggerated measures of benefits of such irrigation projects (WCD, 2001).

Table 3. An overview of the incomes related to gold sales, the cost of pollution prevention and other pertinent economic estimates relevant for the Puyango river basin (adapted from SGAB-Prodeminca, 2000)

Income		
Estimated value of 1999 gold production		US$ 21·5 millions
Cost of pollution prevention		
Item	Total cost	Annual cost
Initial investment needed for 3·5, year dam life	US$ 3·4 millions	
Total invetment for 27 years (incl. initial investment)	US$ 11 millions	US$ 0·41 million
Operating costs	US$ 6·5 millions	US$ 0·24 million
Closure	US$ 0·46 million	
Tailings confinement (total for 27 years)	US$ 18·1 millions	US$ 0·67 million
Regional Gross Product (GP)		
Estimated 1999 GP of Puyango basin		US$ 147 millions
Estimated 1999 GP of Portovelo-Zaruma district		US$ 259 millions
Puyango-Tumbes irrigation project		
Total investment	US$ 2640 millions	

Constraints on implementation of technical solutions

Baker (1990) proposes two reasons for environmental policy failure: (i) regulatory, when no legal mandate exists for environmental protection; and (ii) enforcement, when the agency charged with environmental supervision and control lacks the infrastructure and/or power to enforce regulations. Given the existence of adequate regulations, it is implied that the failure of environmental regulations and public supervision in the Portovelo-Zaruma area is due to (ii).

However, although a lack of enforcement of regulations is of definite importance, there exists another and possibly more crucial issue which needs to be considered: the miners must co-operate if their environmental problems are to be resolved. The need for joint action follows from two reasons: (i) the vast majority of operators have neither the financial ability nor the technical expertise to implement adequate tailings management facilities; and (ii) the complex topography of the area means that there is no adequate space for tailings confinement for individual operations or even for groups of operators. Hence, a Tailings Management Plan (TMP) for the area must be a communal one. Further, although the cost of such a TMP is shown to be acceptable in the longer term, it is high in the short term. This makes it unlikely that miners will be able to fund such a project, unless it is substantially subsidised. It also implies that miners must initiate long-term, joint planning of their operations.

This need for communal action to solve environmental problems caused by small-scale mining is applicable to other Ecuadorian mining areas. Sadly, experiences gained within Prodeminca indicate that the idiosyncrasies which exist within the Ecuadorian mining community make it very difficult to make miners agree to, and implement, solutions for communal tailings management, even when such measures are subsidised. To date, there exists only one example of miners pooling resources with the government to construct a tailings impoundment, and this is a small and temporary pilot-scale facility, which is constructed in the Ponce Enríquez area, about 40 kilometres north of Zaruma. Here, about two thirds of the mining community has joined a so-called cooperative (the local denomination of the co-operation between a number of small companies). Negotiations between central government, as represented by Prodeminca, and this cooperative are ongoing for the construction of a larger and more sustainable facility in the same area. However, doubts exist as to whether the miners could realistically advance such a project, either with or without technical and financial assistance. The problems relate only in part to a perceived lack of financial resources to construct tailings dams. More important has been the failure to obtain a real commitment among the Ponce Enríquez miners to invest jointly in environmental protection. Furthermore, lack of pressure from government and/or from local communities has encouraged miners to believe that, in effect, they can continue with current practices.

However, there are some indications that the Ecuadorian mining community, as a response to external pressures, may be about to assume a more environmentally responsible position. Some communities living downstream of mining activities have realised that their environment is being degraded. Mining in Ponce Enríquez is being performed upstream of population centres that rely on farming, aquaculture and seafood harvest for their subsistence. Thus, in the year 2000, three cyanidation plants were reported to the MEU and two of them were ordered to close down temporarily. Further, local NGOs are becoming increasingly active in the area, and a build-up of resentment towards the mining activities is evident, as is an increasing awareness on the part of miners to at least be seen to be doing something to limit their impacts upon the environment. Hence the agreement with Prodeminca to construct a pilot tailings impoundment. A similar example is found in the Santa Rosa mining area, about 30 kilometres northwest of Zaruma. Here a vigorous dialogue between communities affected by contamination and the miners have prompted the biggest operator (Eminsa) to considerably improve its environmental performance. This has resulted in a marked improvement in the water quality of two previously severely polluted rivers.

The situation in the Portovelo-Zaruma area is different from that of Ponce Enríquez and Santa Rosa in several ways: (i) there exists no obvious separation between miners and non-miners and although the local population increasingly expresses concern at the contamination caused by mining, the interest is not yet strong enough to make it a crucial issue in local politics; (ii) with the exception of the Peruvian population, very few people live downstream of the mining area and so community pressure for miners to improve their environmental performance is insignificant; (iii) the number of mines and processing plants is much larger in the Portovelo-Zaruma district, which makes negotiations to obtain communal agreements an enormous challenge. Hence, the problems that have been experienced in Ponce Enríquez and Santa Rosa with regards to improving environmental performance among miners are likely to be even more difficult to resolve in the Portovelo-Zaruma area. Suggestions for how these difficulties may be overcome are considered in the next section.

Recommended policy measures

It is indicated that environmental regulations, and the provision of technical solutions, are unlikely to be sufficient to resolve the environmental problems caused by the Portovelo-Zaruma mining activities. However, these actions do form a clear basis upon which further policy measures can be built. This section suggests three main measures that should to be considered.

Improved enforcement and external pressure

Ecuador's environmental regulations were developed and introduced recently. This is typical for many LDCs, where such regulations have often been introduced quicker and more comprehensively compared to the more gradual development experienced in More Developed Countries (MDCs) (Lane *et al*., 1999). However, recent work suggest that the introduction of environmental legislation in LDCs often fails to achieve noticeable improvement in environmental quality. Two main reasons have been suggested, and both are applicable to the Ecuadorian situation. First, the controlling authorities' capacity to enforce regulations has not been given adequate attention (Lagos, 1994; Ongley, 1999; Lane *et al*., 1999). This leads to considerations of how to strengthen administrative and logistical capacity of the controlling authorities. Second, Ecuador is typical for many LDCs in that its environmental regulatory system is based upon a 'command and control' approach, which relies on sanctions and their enforcement to ensure compliance with environmental regulations. Such an approach will work poorly in countries where the legislative system itself is overloaded and/or inefficient, as is the case in many LDCs (Warhurst, 1994; Lane *et al*., 1999). Given this limitation, Lane *et al*. (1999) argue for a more flexible and compliance based approach to environmental supervision and control. Such an approach relies on the setting of environmental goals, and negotiation between the regulator and the regulated to achieve these goals. The overall purpose is to ensure that polluters comply rather than to prosecute deviant activities (hence, the approach is pro-active rather than reactive; Warhurst, 1994). However, Lane *et al*. (1999) acknowledge that the success of such an approach is still reliant upon the efficiency of the authorities charged with environmental supervision and control.

Hence, institutional capacity is crucial whatever approach to environmental control is adopted. This has been acknowledged by the Ecuadorian Ministry of Energy and Mines through Prodeminca. Thus, the MEU has been substantially strengthened during the last five years. The unit now has both trained personnel and adequate instrumentation to undertake environmental monitoring. Protocol, procedures and a database have been set up to ensure that the data collected during such field monitoring are adequately managed. The unit also appears to be coping fairly well with the review of EIAs, audits and other official documents.

In the past, the MEU has experienced trouble in that their directives have often not been implemented. The problem relates in part to the unit occupying a low hierarchical position within its Ministry, and in part to the fact that the central Quito government's control of the southern Provinces has always been somewhat tenuous. Until early 2000, the MEU was entirely based in Quito, and personnel seldom visited the main mining areas except during twice-yearly monitoring campaigns. However, attempts are now being made to locate at least a few officials in regional offices, and in this way to achieve a permanent and more visible presence in the mining areas. The changes of the MEU are clearly in line with current thinking of the need to strengthen the capacity of institutions charged with environmental supervision and control. Further research is needed to ascertain if these developments will lead to improvements in environmental quality in the Ecuadorian mining districts.

Experiences from the oil fields of eastern Ecuador show that central government may intervene to ensure compliance with environmental regulations if environmental and socio-economic problems (e.g. oil spills, displacement of indigenous communities, etc.) become internationally sensitive issues (Hastings, 1999). The contamination of the Puyango river system has the potential to become such a sensitive international political issue, which could motivate central government to intervene. Mining has significant environmental impacts in Peruvian territory, although there seems to be no real recognition of this fact as yet on the part of the Peruvians. However, as bi-national plans for the development and reconstruction of the border regions have been initiated since the peace agreement of 1999, it seems unlikely that a lack of Peruvian awareness will continue for much longer. Hence, central government may soon see itself forced to intervene to stop the pollution of the Puyango river.

Public participation and strengthened capacity for local environmental management

A key issue that needs to be resolved is how to make miners realise that they must invest in environmental protection. One way to achieve this is to promote local government involvement and local public participation in environmental management: once local people find contamination unacceptable, the political will to do something about it will follow, as will the operators' desire to comply with existing legislation. Such a chain of events was evident in the US during the 1960s and early 1970s, when public pressure in combination with new environmental legislation led to dramatic improvements in the environmental performance of mining ventures (Smith, 1987). Similar developments within the mining sector have been noted in LDCs, such as the Philippines (Broad, 1994).

This kind of process has also occurred in Ecuador in the Santa Rosa and Ponce Enríquez districts although environmental improvements are still modest. Further, part of the reason for the good environmental performance of Bira's operations may be caused by the local perception that the operations are run by 'outsiders'. Hence, for Bira's operations to run smoothly, the owners must make sure that local people are given no reasons for complaints. A further probable reason for Bira's good environmental record is an apparent awareness of its owners of the importance of good mining environmental management. However, further research is needed to ascertain the importance of these two factors in explaining Bira's comparatively better environmental performance.

The Law of environmental management and decentralisation (1999) provides a legal platform for meaningful local participation in environmental management. The law also encourages local government to supervise and control activities that may cause environmental impacts. Three main efforts are needed for this to be achieved. First, the capacity of the Portovelo and Zaruma municipalities is severely limited as there exist no properly trained people, nor do the municipalities have the funds to procure equipment to adequately monitor environmental quality. Hence, the municipalities are unable to assume the role that the new law affords them, unless they can be substantially strengthened in terms of both equipment and personnel.

Second, knowledge of environmental legislation and the importance of a healthy natural environment needs to be promoted. Braadbart (1995) found that one reason for the poor environmental performance among water polluting industries in Indonesia was that polluters did not know what to do to become compliant, and were not aware of the costs and benefits of doing so. Several years of Prodeminca activities, and the work performed by a few local NGOs (e.g. Cenda, 1996) have made considerable progress in informing miners of the environmental impacts of their work. Further, Prodeminca's EMP for the district has been presented at several public meetings, and has led to many miners now having a fair understanding of the costs of becoming compliant. However, the almost total reliance of the local economy upon mining in combination with a several century long tradition of mining means that local people (most of whom are in one way or another involved in mining anyway) tend to be more interested in efforts to promote income from mining rather than to curtail activities due to environmental reasons. This mindset is facilitated by the fact that very few Ecuadorians live downstream of the district.

Third, opportunities for the local populace to partake in local decision making should be encouraged and possibly formalised. Both the Portovelo and the Zaruma municipalities are run by popularly elected mayors and their administrations are also partly elected. Hence, avenues exist for the local populace to voice their political views in elections, and by interacting with local administrators. In fact, there are examples of cases were local people have been exposed to pollution, and when popular protest has prompted the municipalities to take action. For example, when mining was initiated near the potable water supply of Portovelo, and when a cyanidation plant was set up in central Zaruma, complaints from the public led to the relevant municipality intervening to stop these activities. This further emphasises the potential power of public involvement in local decision making. This prompted SGAB-Prodeminca (2000) to call for a forum to be set up within the mining district where local administrators and stake-holders may specifically discuss environmental issues.

Restructuring and modernisation of mining activities

Smith (1987) describes how the US mining industry changed after the introduction of environmental requirements in the 1960s and early 1970s. Although the requirements were equal for all mining operations, most smaller-scale operations found it impossible to meet these requirements. Larger companies had the resources necessary for making the changes required. Warhurst (1994) similarly suggests that environmental imperatives have played a part in forcing a reduction in mine production costs, to the advantage of firms that have the resources necessary to develop innovative mining and processing methods.

At present, Bira is alone in achieving an acceptable environmental performance in the area. The Bira operation comprises both mining and processing operations. About 45 000 tonnes of ore were treated in 1999, containing an estimated 28 000 oz of gold (20 $g\,ton^{-1}$). In addition to using reasonably modern mining and processing techniques, it also runs a programme of continuous exploration, so that ore reserves at any one time are guaranteed for at least a few years (SGAB-Prodeminca, 2000). The only other Ecuadorian example of a similarly well-managed operation is Eminsa in the Santa Rosa area. Both Bira and Eminsa are small-scale operations but, in the Ecuadorian context, they are characterised by using more up-to-date technology and being much larger than the typical operations. In the area there exist somewhat larger processing plants which treat in the region of 15 000 to 35 000 tonnes of material annually, whereas most plants treat considerably less than 5000 tonnes annually. This implies that poor environmental performance of the smaller operations may in part be related to the fact that they are small in scale. An additional problem, which relates to being small, is that these types of operators are unable to fund exploration activities or to determine current reserves. This makes any long term planning of their activities impossible. Consequently, if the present state of affairs continues, the day will arrive when the easily extractable ore is mined out. The survival of the two communities of Zaruma and Portovelo will then be in jeopardy, as no proactive planning for new areas of exploitation or a life after goldmining would have been performed.

Hence, a key component in achieving an environmentally acceptable and more sustainable form of mining in the district appear to rest upon promoting a larger scale and more technologically advanced form of mining and processing. Consequently, a clear policy needs to be defined which promotes the reorganisation of small-scale operators into formal companies or cooperatives in order to move away from rudimentary activities that survive on a day-to-day basis, towards bigger and more mechanised operations based on proven reserves. Such scales of operations are more likely to have the knowledge, awareness and financial resources necessary to carry out mining in an environmentally responsible way. Furthermore, through being bigger entities, their compliance with environmental legislation may be more readily controlled and assured.

It is important to acknowledge that although a reorganisation of small scale and artisanal mining activities does not need to negatively affect the size of neither gold production nor tax revenues (in fact, it is probably more likely to do the opposite), it may be detrimental to employment opportunities. Further, the consolidation of mining activities may also lead to the concentration of power and financial resources into fewer hands. Hence, policy measures need to include considerations of how to create alternative job opportunities with the funds generated by mining, and of how to more generally ensure that the benefits created by a consolidated and larger scale mining industry are equitably shared.

Conclusions and wider policy implications

The Portovelo-Zaruma case study provides a good example of the environmental problems that are often associated with artisanal and small-scale mining. Although each operation is small, their large number ensures that cumulative environmental impact are severe. Important impediments relate to the limited economic resources available to each individual miner and the problems of pooling these resources, and to the fact that the main impacts of pollution are suffered downstream of the mining district and, hence, do not affect the miners themselves. Communal solutions may be required, although these are: (i) more costly than necessary due to the complexity and extent of the required collection and transport system; and (ii) difficult to initiate as they will depend upon a large number of individuals and/or companies agreeing to pool their resources to work for the common good. Although solutions to both these problems are theoretically possible, the Ecuadorian experience suggests that they are difficult to implement.

The case of Bira shows that it is indeed possible for indigenous small-scale mining to be performed in both an efficient and less environmentally damaging manner. Here we encounter problems of how to adequately classify mining operations. The Bira operation is small by international standards, and qualifies as small-scale according to available schemes of classification. However, it treats 45 000 tonnes of ore annually and uses up-to-date technology, which makes it much larger and more modern than all other Ecuadorian operations. This reinforces the suggestion that a certain scale and level of mechanisation is required for mining to be performed in an environmentally acceptable manner.

The case study also suggests that the worst environmental offenders are not the artisanal operators who rely on the panning of stream sediments or crushed rock and a subsequent extraction of the gold by means of amalgamation with mercury. Instead, the most significant polluters are plant owners who fall somewhere in the middle of the spectrum in terms of process volumes and level of mechanisation, with the modern Bira operation and the artisanal miners representing two end members. Further, a substantial part of these 'medium-scale' operators are legal operators. Hence, the argument that legal titles and a better environmental performance are related (e.g. Barry, 1996) are not applicable in the Portovelo-Zaruma area in a straightforward manner.

However, evidence also suggests that considerations of technology and scale of operations are not sufficient to ensure a good environmental performance. Social pressure and public participation appear to be vital components for making miners realise that they must invest in environmental protection. This pattern has been observed elsewhere (Smith, 1986; Broad, 1994), and appears to have been a prime motivator for some Ecuadorian operators to ensure that their environmental performance is acceptable to the local community. Hence, the organisation and modernisation of small-scale and artisanal mining activities should be accompanied by efforts to improve public awareness of environmental issues, and of their participation in environmental management decisions.

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