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Effective Monitoring Strategies for Mining-Related Water Pollution

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Effective Monitoring Strategies for Mining-Related Water Pollution

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This work is dedicated to

Rosemary Shoko

an impressive woman and outspoken human rights defender from the village
of Shashachunda in the Hwange District of Zimbabwe,

and to all the other fearless people around the world who never tire of advocating
every day for environmental protection and a more equal society.

* * *

With this dissertation I also commemorate

Käthy Ruppen-Tscherrig
(1926 – 2013)

my brave and bright grandmother, who was born in Switzerland at a time when most
women were denied the opportunity to pursue a path of education and financial independence,
but who eventually managed to live a self-determined life.

Abstract

The ever-growing global economy is driving the extraction of mineral resources at an unprecedented rate, further exacerbating the environmental impacts associated with mining and the disposal of mine waste. Particularly in the Global South, mining-related pollution threatens vulnerable ecosystems and jeopardizes the health and livelihoods of local communities. Surface waters, which are critical for human consumption and agriculture, are especially at risk of short- and long-term contamination from the discharge of hazardous effluents.

However, protection and prevention are inadequate. Governments often lack the financial resources and adequately trained personnel to monitor environmental quality and enforce environmental standards. There is a need to develop alternative monitoring strategies in contexts where mining operators disrespect environmental guidelines and where governmental agencies cannot fulfill their regulatory role. Research on pollution monitoring must therefore go beyond measuring biophysical parameters at different spatial and temporal scales and address the socio-economic drivers of pollution, including the dimension of power.

The goal of this dissertation is to investigate innovative and effective methodologies for monitoring mining-related pollution of surface waters. An analysis of the potential of data acquisition tools aims to contribute to improving resource governance processes in mineral-producing countries in the Global South. To this end, I have investigated pollution incidents in Sub-Saharan Africa at different spatial and temporal scales.

In my first research article, I looked at tailings dam failures. As one of the highest risk factors of industrial mining, they have a low frequency of occurrence, however their impacts on ecosystems and human beings can be devastating. Together with colleagues, we developed a new satellite remote sensing workflow that uses the European Space Agency's Sentinel-2 optical imagery to assess water quality in river systems. This allowed us to track the pollution wave caused by a tailings spill in July 2021 in Catoca, Angola, at the fourth largest diamond mine in the world. In neighboring Democratic Republic of the Congo, residents and the government claimed that they have suffered from large fish kills and serious health concerns. These reports were strongly contested by the mine operator. The turbidity estimates we generated from the remote sensing data identified Catoca as the source of the pollution and showed beyond doubt that turbidity levels were orders of magnitudes higher than usual for several days, which explained the observed fish kills and the health effects on the population. We showed that the pollution signal traveled for over 1400 kilometers from the mine to finally dissipate in the high-discharge Congo River 20 days later. Satellite remote sensing showed to be very powerful in acquiring water quality data for controversial large-scale pollution incidents in the past, where insufficient data was collected in-situ during the event.

In the second research article, colleagues and I addressed another contested pollution case in the coal mining area of Hwange, Zimbabwe. Fish kills have been a regular symptom of contamination in the local river for more than a decade, but the responsibility of industrial players remained highly controversial due to a lack of publicly available data. In this context, we implemented a community-based water quality monitoring scheme involving rural community members that were affected and outspoken against the pollution. In this collaborative effort between community members and academic researchers, close to 800 samples were collected over nearly 1.5 years. This vast dataset depicted the sources and the extent of the pollution. Among other findings, significant public health risks were identified as certain dissolved metals exceeded drinking water standards 70-fold.

Together with another researcher, I demonstrated in the third article how the scientific data from the community-based monitoring was used by local community members to empower themselves against local government representatives and industry. Ultimately, with their self-collected evidence, the community was able to achieve some of their goals such as the drilling of drinking water boreholes. In numerous interviews we tracked the leverage of scientific data through the environmental management agency and showed, based on political ecology theory, how historical trajectories, economic structures, and political dimensions limited the prospects of local accountability initiatives in the mining sector. We identified important stakeholders for environmental benchmarking who support local initiatives, but often go unnoticed in classical social accountability theory. International customers embedded in the supply chain of the mining companies could potentially act as powerful accountability promotors and ally with local communities to improve environmental management in mining.

In this dissertation I argue that monitoring should be designed to provide data that can be trusted by various stakeholders and that additional attention should be paid to the socio-economic context in which pollution occurs. Instead of drafting a one-size-fits-all monitoring where conclusions can be extrapolated from one spatial and temporal scale to another, this thesis targets contextualized strategies that can contribute to ongoing governance processes. There is a need to foster scale-sensitive governance strategies that account for power relations in the extractive sector, especially in contexts where governments do not enforce environmental law, citizen advocacy is ineffective, and companies do not offer transparency to their shareholders or feel pressure from their home markets. Polluters should not be addressed in isolation but with respect to their embeddedness in global production networks to promote positive transformations in the mining sector.

These efforts are not only about improving monitoring of environmental pollution and understanding of the complex socio-political contexts of mining in the Global South, but also about empowering people, holding companies and governments accountable, and improving livelihoods through science.

Zusammenfassung

Die wachsende Weltwirtschaft treibt den Abbau von Bodenschätzen in einem noch nie dagewesenen Tempo voran. Dies verschärft die mit dem Bergbau verbundenen Umweltauswirkungen. Vor allem im Globalen Süden bedroht die bergbaubedingte Verschmutzung empfindliche Ökosysteme und gefährdet die Gesundheit und den Lebensunterhalt lokaler Gemeinschaften. Oberflächengewässer, die für die menschliche Ernährung und die Landwirtschaft grundlegend sind, sind besonders gefährdet, durch die Einleitung giftiger Abwässer kurz- und langfristig verschmutzt zu werden.

Schutz und Prävention sind jedoch unzureichend. Den Regierungen fehlt es oft an finanziellen Mitteln und ausreichend geschultem Personal, um die Umweltqualität zu überwachen und Umweltstandards für den Bergbau durchzusetzen. Es bedarf alternativer Überwachungsstrategien, wenn Bergbaubetreiber die Umweltrichtlinien missachten und die staatlichen Behörden ihrer Regulierungsfunktion nicht nachkommen. Die Forschung zur Überwachung der Umweltverschmutzung muss daher über die Messung biophysikalischer Parameter in verschiedenen räumlichen und zeitlichen Maßstäben hinausgehen. Sie muss sich mit den sozioökonomischen Triebkräften der Verschmutzung befassen und ein spezielles Augenmerk auf Machtstrukturen legen.

Ziel dieser Dissertation ist es, innovative und wirksame Methoden zur Überwachung der bergbaubedingten Verschmutzung von Oberflächengewässern zu untersuchen. Das Potential von Instrumenten der Datenerfassung wird in Bezug auf einen Beitrag zur Verbesserung von Governance-Prozessen in Bergbauländern des Globalen Südens analysiert. Zu diesem Zweck habe ich mich mit bergbaubedingten Umweltschäden in Subsahara-Afrika beschäftigt, die auf verschiedenen räumlichen und zeitlichen Maßstäben auftreten.

In meinem ersten Forschungsartikel habe ich mich mit Dammbrüchen bei Absetzbecken befasst, in denen Erzaufbereitungsrückstände gelagert werden. Als einer der größten Risikofaktoren des industriellen Bergbaus treten solche Vorfälle zwar nur selten auf, doch ihre Auswirkungen auf Ökosysteme und Menschen können verheerend sein. Gemeinsam mit Mitarbeitern habe ich einen neuen Arbeitsablauf für die Satellitenfernerkundung entwickelt. Gestützt auf optische Sentinel-2-Bilder der Europäischen Weltraumorganisation haben wir die Wasserqualität von Flusssystemen bewertet. Auf diese Weise konnten wir die Schadstoffwelle verfolgen, die im Juli 2021 in Catoca, Angola, vom viertgrößten Diamanten-Bergwerk der Welt durch einen Austritt aus dem Absetzbecken ausgelöst wurde. In der benachbarten Demokratischen Republik Kongo behaupteten Anwohner und die Regierung, dass es in der Folge zu einem massiven Fischsterben und ernsthaften gesundheitlichen Problemen gekommen sei. Diese Berichte wurden vom Betreiber des Bergwerks heftig dementiert. Unsere auf Fernerkundungsdaten basierenden Trübungsschätzungen identifizierten Catoca als Verschmutzungsquelle und zeigten zweifelsfrei, dass die Trübungswerte mehrere Tage lang um Größenordnungen über den üblichen Werten lagen, was das beobachtete Fischsterben und die Gesundheitsauswirkungen bei der Bevölkerung erklärt. Wir konnten zeigen, dass sich das Schadstoffsignal über 1400 Kilometer vom Bergwerk fortbewegt hat, um schließlich 20 Tage später im abflussreichen Kongo-Fluss zu verschwinden. Die Satellitenfernerkundung erwies sich als sehr vielversprechend bei der Erfassung von Wasserqualitätsdaten für umstrittene großflächige Umweltschäden, die in der Vergangenheit aufgetreten sind und für die während des Ereignisses keine ausreichenden Daten vor Ort erhoben wurden.

Im zweiten Forschungsartikel behandelte ich mit Kolleginnen und Kollegen weitere kontroverse Umweltschäden im Kohleabbaugebiet von Hwange, Simbabwe. Seit mehr als einem Jahrzehnt kommt es im lokalen Fluss regelmäßig zu Fischsterben. Die Verantwortung der Industrieakteure bleibt

aufgrund des Mangels an öffentlich zugänglichen Daten höchst umstritten. Vor diesem Hintergrund haben wir ein gemeindebasiertes Programm zur Überwachung der Wasserqualität eingeführt, an dem direkt von der Verschmutzung Betroffene beteiligt waren. Im Rahmen dieser Zusammenarbeit zwischen Gemeindemitgliedern und akademischen Forschenden wurden fast 800 Proben über einen Zeitraum von etwa 1.5 Jahren gesammelt. Dieser umfangreiche Datensatz gab Aufschluss über die Quellen und das Ausmaß der Umweltverschmutzung. So wurden zum Beispiel erhebliche Risiken für die öffentliche Gesundheit festgestellt, da gewisse gelöste Metalle die Trinkwasserstandards um das 70-fache überschritten.

Gemeinsam mit einem Kollegen zeigte ich in meinem dritten Forschungsartikel wie die wissenschaftlichen Daten aus der gemeindebasierten Überwachung von den Beteiligten genutzt wurden, um sich gegenüber lokalen Regierungsvertreter:innen und der Industrie zu behaupten. Letztlich konnte die Gemeinschaft mit selbst gesammelten Daten einige Ziele erreichen, darunter auch Bohrungen für Trinkwasserbrunnen. In zahlreichen Interviews verfolgten wir die Hebelwirkung wissenschaftlicher Daten innerhalb der Umweltbehörde und zeigten auf der Grundlage der Theorie der Politischen Ökologie, wie historische Verläufe, wirtschaftliche Strukturen und politische Dimensionen die Aussichten lokaler Initiativen zur Rechenschaftspflicht im Bergbausektor schmälern. Wir haben wichtige Akteure des Umwelt-Benchmarkings identifiziert, welche lokale Initiativen unterstützen, jedoch in der klassischen Theorie der Sozialen Rechenschaftspflicht oft unbeachtet bleiben. Internationale Abnehmer, die in die Lieferkette der Bergbauunternehmen eingebettet sind, hätten mit ihrem Einfluss das Potential Rechenschaftspflicht zu fördern und sich mit den lokalen Gemeinschaften zu verbünden, um das Umweltmanagement im Bergbau zu verbessern.

In dieser Doktorarbeit argumentiere ich, dass die Umweltüberwachung so konzipiert werden sollte, dass sie Daten liefert, denen die verschiedenen Interessensgruppen vertrauen. Auch sollte dem sozioökonomischen Kontext, in dem die Schadstoffbelastung auftritt, zusätzliche Aufmerksamkeit geschenkt werden. Statt eine einheitliche Überwachung zu entwerfen, bei der Schlussfolgerungen von einer räumlichen und zeitlichen Skala auf eine andere extrapoliert werden, sollten vielmehr kontextbezogene Strategien entwickelt werden. Diese sollten darauf abzielen, einen Beitrag zu übergreifenden Governance-Prozessen zu leisten. Es sollten maßstabsgerechte Governance-Strategien gefördert werden, die den Machtverhältnissen im Rohstoffsektor Rechnung tragen. Dies gilt insbesondere für Kontexte, in denen Regierungen das Umweltrecht nicht umsetzen, ziviles Engagement wirkungslos ist und Unternehmen ihren Aktionären keine Transparenz bieten oder von ihren Heimmärkten keinen Druck verspüren. Um positive Veränderungen im Bergbausektor zu fördern, sollten Verschmutzer nicht isoliert, sondern im Hinblick auf ihre Einbettung in globale Produktionsnetzwerke betrachtet werden.

Bei diesen Bemühungen geht es nicht nur darum, die Überwachung von Umweltschäden und das Verständnis der komplexen soziopolitischen Zusammenhänge des Bergbaus im Globalen Süden weiterzuentwickeln, sondern auch darum, Menschen zu ermächtigen, Unternehmen und Regierungen zur Rechenschaft zu ziehen und die Lebensbedingungen der Bevölkerung durch die Wissenschaft zu verbessern.

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1 Introduction

“Sometimes we see water that is green or yellow and we find the fish dead”, reported Londile[1], Nestai and Thokozile on a hot September afternoon in 2019 as they looked at the Deka River. The three women live in villages near this river in the coal mining area of Hwange in Zimbabwe. They regularly observe that the color of the river changes and that many fish float dead on the surface of the water. They report that it takes weeks after these incidents for fish populations to recover, at least partially. The women emphasize the impact that water pollution has on their own lives and those of their families. In the semi-arid region where they live, the river is a lifeline for rural people, whom they depend on to catch fish, weave baskets, feed their livestock and, for the most vulnerable among them, to get drinking water.

When the color of a river changes and numerous fish float dead on the surface, any observer can tell with the naked eye that something is wrong. A degradation of environmental quality that is obviously harmful to aquatic organisms, but whose effects can be even more far-reaching. When a researcher like me encounters such a situation, I must ask myself how to investigate these incidents to understand their nature, extent, and causes. I could focus on numerous different aspects. I could examine the microscopic particles suspended in the water column that may be carrying toxic substances that killed the fish. I could investigate how far down the river the fish died and how often such fish kills have occurred in the past and whether they are related to other events occurring at the same time. I could also analyze whether such incidents have occurred in other rivers in the region or even in other similar areas around the globe. Or I could turn my attention to whether humans caused this damage and, if so, in what way. This would involve investigating, for example, whether an individual made a bad decision that inadvertently led to a fish kill, or whether negligence in management regularly leads to such incidents.

Water color changes and fish kills are phenomena that occur not only in Hwange, Zimbabwe, but also in many other areas of the world where geological materials are extracted from the ground. They are often symptomatic of environmental pollution[2], more specifically water pollution, either directly related to mineral extraction and processing or resulting from the deposition of mine waste (Younger et al., 2002; Kalin-Seidenfaden and Wheeler, 2022). Zimbabwe is a country that is highly dependent on the extraction of its mineral resources. Historically, more than 40 mineral commodities have been mined in the country, and in 2015, the mining sector generated 55% of national exports and 9% of GDP (Mlambo, 2016). Zimbabwe shares this heavy reliance on extractive industries with many other low-income countries in the global South (ICMM, 2018). Here, societies face a major challenge in managing the negative environmental externalities of mining.

To address and understand the root causes of such pollution problems, it would certainly be most comprehensive to consider all dimensions of the problems and ask all relevant questions. However, there are limits to the time and effort that can be invested. Therefore, methodological choices must be made with a clear vision of the type of answer the researcher wishes to obtain. A variety of monitoring tools are used to assess mining-related water pollution. These tools operate at different spatial, temporal, and social/organizational scales – a factor that will critically affect the type of understanding gained.

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[1] The names of community members were changed to protect their identity.

[2] Pollution designates substances that are released to an environment and that can cause harm to living organisms or infrastructure with impacts comprising aesthetic nuisance, economic loss, health damage, death and long-term degradation (McManus, 2009).

In this dissertation, I explore the issue of how to monitor mining-related pollution, considering the needs and challenges encountered in many mining contexts around the world. I initiated and led a community-based water quality monitoring project in Zimbabwe that involved community members and researchers working together to identify the sources and extent of water pollution and assign responsibility to mining operators. In another innovative approach, I used satellite remote sensing to produce water quality estimates and track water pollution caused by a spill at a tailings dam in Angola. To develop appropriate and effective monitoring approaches, I emphasize the importance of scale and focus on what kind of knowledge and data should be produced. This also raises the question of which actor is best able to (co-)produce the data to contribute effectively and positively to the overarching governance process aimed at problem solving.

1.1 Environmental impacts of mining in a nutshell

The extraction and processing of mineral resources impacts the environment and humans on various spatial and temporal scales. From numerous mining contexts around the globe, landscape degradation, air-, soil- and water pollution and related negative effects on human and ecosystem health were reported (Noel et al., 2007; Wood, 2012; Leuenberger et al., 2021; Kalin-Seidenfaden and Wheeler, 2022). Various geological deposits that contain economic valuable portions of base metals like copper lead, zinc, nickel, iron, as well as uranium, precious metals (gold, silver) and coal are also abundant in sulfide minerals such as pyrite. Exposed to the atmosphere in presence of water, oxidation of sulfide minerals produces acidic mine effluents known as Acid Mine Drainage (AMD)[3]. Depending on the mineral deposit type, AMD carries elevated concentrations of iron, sulfates and heavy metals such as copper, cobalt, cadmium, lead, nickel, mercury and chromium (Sheoran and Sheoran, 2006; Jamieson, 2011; Dold, 2017). AMD often causes a serious risk to water bodies (Kuyucak, 2002; Johnson and Hallberg, 2005).

Mining has occupied human kind for tens of thousands of years, but has importantly intensified since the development of the metalworking technology in the Bronze Age around 3300 BC (Gregory, 2021). Industrialization has triggered another boost to extractive activities which have reached unprecedented extents in recent years. Largest open pit mines reach today several kilometers of length and width and over 1 km of depth (Borden, 2003; Plotnikov, 2011; Flores and Catalan, 2019) and underground mines reach depths of over 3 km (Mining Technology, 2019). Extraction rat es are increasing and lead to deforestation in an unprecedented pace, specifically threatening biodiversity hotspots (Sonter et al., 2015; Luckeneder et al., 2021). Contaminated mine water originates from the extraction sites as drainage from underground workings or runoff from open pits, in addition it is generated at ore stockpiles and mine waste structures such as waste rock dumps, or processing waste such as tailings (Dave and Tipre, 2012).

Contamination can go far beyond the lifetime of a mine and impact river estuaries for centuries (Davis et al., 2000; Mead, 2011). Although underground mining might not leave visible traces on the Earth surface, it contributes to long lasting legacies. When the extraction stops, so does the pumping of the underground water. The abandoned pits are subsequently flooded with groundwater which reacts with the rock and leads to acidic and metal rich effluents that find their way to the Earth surface and adjacent water bodies (Wolkersdorfer, 2008). The management of mine- and processing waste is highly challenging. While only a tiny fraction of the extracted material is of economic value, billions of tons of waste are deposited every year, either piled up in mine waste heaps or stored as an aqueous suspension behind dammed tailings storage facilities (Förstner, 1999; Mudd and Boger, 2013;

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[3] The term Acid Rock Drainage (ARD) is alternatively used to describe this chemical process in a broader way (Dold, 2017). I will use the term AMD in this thesis since it is more widely accepted and specifically underlines the role of the extractive process in the acceleration of the weathering of the sulfidic minerals.

Dold, 2014). Average gold ore grade from a representative selection of mines contained around 5 g of gold per ton of rock (Calvo et al., 2016) which relates to close to 200 kg of waste material for each gram of gold produced. For diamonds, this ratio is more extreme. Average grades of around 30 carat per hundred tons of rock are not a rarity (Field et al., 2008). Therefore, 1 carat (200 mg) of jewelry quality diamonds can easily relate to 3.3 tons of mine waste or more.

Between 1985 to 2018, world mining production doubled from 9.6 billion tons to 17.7 billion tons of mineral products, with the highest share related to mineral fuels (Reichl et al., 2020). Mining production will continue to increase in the next decades, also to meet the increasing demand for metals for new technologies for a low-carbon future (Marscheider-Weidemann et al., 2021). Not only is the amount of minerals produced constantly on the rise, but the amount of waste is increasing even faster. Since most high-grade deposits have already been mined, the mining industry extracts geological deposits that contain lower and lower portions of the minerals that are of economic value. This trend of mining decreasing ore grades will become more pronounced in the future and is accompanied by ever increasing waste volumes (Calvo et al., 2016). Most of the residues can be considered as hazardous waste since the contain large amounts of potentially harmful elements and that are easily released to the environment (Mudd, 2004; Dold, 2014). Pollution impacts are not only gradual and visible on the long-term, but they can also be very sudden. Disastrous tailings dam failures that have occurred in the past cost hundreds of human lives, devastated large swathes of land and pollute entire river systems (Roca et al., 2019; Thompson et al., 2020).

Not only so called large-scale industrial mining activities induce important environmental change but also the hundreds of thousands of artisanal and small-scale mining (ASM) sites that are operative around the world. The rudimentary working equipment limits especially the depth of the underground workings. Often they are located in protected and vulnerable forested areas like in the Amazon and Congo Basin where ASM contributes to deforestation, land erosion and river siltation (Telmer et al., 2006; Megevand and Mosnier, 2013). Specifically, artisanal and small-scale gold mining (ASGM) releases an estimated amount of almost 2000 tons of mercury (Hg) per year (Sundseth et al., 2017), a neurotoxin that the international community is determined to eradicate under the Minamata Convention (UNEP, 2013). With close to 40% of the anthropogenic emissions, ASGM is the largest anthropogenic source of Hg to the atmosphere tightly followed by coal combustion (Sundseth et al., 2017). It also importantly concerns water bodies, since through precipitation, the non-degradable mercury ends up in river, lakes and the oceans and is integrated into the food chain where it biomagnifies in the form of methylmercury (Kocman et al., 2017). In this regard, ASGM is not small in scale either in terms of its ecological footprint of mercury pollution or in terms of land cover change.

In summary, mineral resource extraction involves different interrelated spatial and temporal scales. Although the definition of large- and small-scale mining also includes aspects of processing methods, ownership structures and capitalization, the scale aspect is evident in the terminology used[4]. Also, the pollution that is caused by the extractive process manifests on different scales. The scale of surface water pollution depends on how far pollutants can propagate in a river system. Some pollutants might dissipate or settle to the riverbed after having travelled only a short distance from the source. Other pollutants with a more complex biogeochemical cycles, like mercury, are first emitted to the atmosphere, transported for very long ranges before being deposited to water body with rainfall (Selin, 2009). On the other hand, environmental impacts can happen immediately such as a toxic spill linked to a tailings dam failure (Thompson et al., 2020) or the impacts can be long-term such as mine legacies that last for centuries (Davis et al., 2000). Therefore, an understanding of the temporal and spatial dimensions of pollution are key to adequately monitor it.

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[4] For a detailed description and definition of artisanal and small-scale mining, notably in Africa, see AMDC (2017).

1.2 Monitoring environmental pollution and the question of scale

Monitoring in environmental science has since early days been an attempt “to gather information in a systematic way to make a sound decision on the hazard to human health and the environment as a consequence of using a particular chemical or discharging a certain type of waste” (Cairns and Van der Schalie, 1982, p.1180). As environmental awareness grew, systematic assessment and monitoring of rivers, lakes, oceans, soils, forests, and air began in the 1960’s and 1970’s to protect ecosystems and/or reduce the negative effects of pollution (Parker and Vince Howard, 1977; Søndergaard and Mosbech, 2022). Monitoring includes not only the regular sampling and measuring of different physical, chemical and biological parameters but specifically aims at assessing their conformity with regard to specific objectives or standards (Bartram and Ballance, 1996). Therefore, monitoring systems strongly relate to environmental management and (toxicity) risk assessments (Gruiz et al., 2016).

When it comes to monitoring ecosystems, there is a growing understanding that schemes have to operate on different spatial and temporal scales that are adapted to the questions they intend to respond and which, finally, will allow addressing the causes of the pollution (Sparrow et al., 2020). Scale is therefore important to the design and implementation of monitoring schemes. However, scholars so far only take into consideration scale for 1) biophysical parameters and 2) as a kind of unit of analysis. However, the concept of scale is much broader and comprises different definitions that are intensely debated in human geography (Marston, 2000; Marston et al., 2009; Sayre and Di Vittorio, 2009). I argue that there is another dimension of scale, namely power, that must be embedded in monitoring methodologies in order to solve the underlying socio-economic drivers that define a pollution problem.

The most common understanding of scale is the cartographic scale in which an image of the world is reduced in size and diversity to the extent of a map (Marston et al., 2009). In scientific research there are operational scales that refer to the scale at which a process occurs, as well as observational scales that define the extent at which a phenomenon is investigated and also the measurement scales that relate to the granularity, or the finest spatial unit, that is studied (Crawford, 2020). Scientific research questions are necessarily bound to those specific scales of analysis, in the case of this doctoral thesis scales of environmental monitoring. The specific scales which are used include hierarchical levels from the micro to the macro or from the human individual body to the globe (Marston et al., 2009; Crawford, 2020). On the ecological side, scales range from the plot through the field, the landscape, the region, and the globe (Veldkamp et al., 2011). On the social organization it reaches from a human individual through household, neighborhood, city, metropolitan area, province, nation, continent to the globe (Sayre and Di Vittorio, 2009).

Scale is thus concerned not only with hierarchical cascades (Marston et al., 2009), but also with different entities and materialities and enables to connecting seemingly different spaces and objects with each other in an analysis. Scale as defining concept for observations and measurements is therefore relevant for my research. However, another discourse of scale emphasizes the social construction of scale. In this perspective, scale is socially constructed, relational, historically contingent and contested (Marston, 2000; Neumann, 2009). Power is tightly linked to this notion of scale since “as a geographical construction, scales become arenas around which socio-spatial power choreographies are enacted and performed” (Swyngedouw, 2008, p.132). For my research about mineral resources, the extractive sector and related negative environmental impacts, power is indeed a critical dimension to consider.

Power defines not only what is considered as a resource[5] in society in the first place, but power relations between social groups are also decisive when it comes to who has access to and control over resources (Peluso and Watts, 2001). The appropriation, exclusion, control and management of natural resources come with the exertion of administrative and territorial power as it is pointed out by political ecology

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[5] Resources is a term that emerged with capitalism and comprises the social and political relationships through which humans attribute a value to the non-human environment. The latter is separated into valued assets of biological, hydrological and geological processes that serve the needs of human kind and “waste” which is unproductive (Bridge, 2009).

scholars (Vandergeest and Peluso, 2006; Peluso and Lund, 2011). The foundation of large-scale extensive mineral extraction, economic dependency on natural resource exploitation and related environmental degradation and centralized political control in the Global South are intrinsically tied to colonial history and the rise of the industrialized societies in the Global North (The World Bank, 1992; Chachage et al., 1993; Bryant and Bailey, 1997; Ayelazuno and Mawuko-Yevugah, 2019). In post-colonial settings, the management and control practices have been established during colonial times and still define the way natural resources are governed today (Vandergeest and Peluso, 2006; Bebbington and Humphreys Bebbington, 2018; Duffy et al., 2019). Mining in this understanding is linked to historically grown power relations that play out on different scales.

To take into account the social production of scale with a focus on power is also crucial when it comes to environmental degradation and pollution. In various areas around the globe, the environmental burden is carried disproportionally by marginalized and local communities who suffer most from pollution and related health hazard or resource degradation (Carmin and Agyeman, 2011; White, 2013; Martinez-Alier, 2014; Lennon, 2021). Central to the idea of a politicized environment is the recognition that "environmental problems cannot be understood in isolation from the political and economic contexts within which they are created" (Bryant and Bailey, 1997, p. 28). Since resource-related conflicts are considered to reflect imbalances of power and inappropriate governance structures (Baynham-Herd et al., 2018; Purwins, 2020), understanding the interplay between actors of resource governance across scales and the interlinkages between global, national and local dynamics are key to contribute to conflict remediation (Schilling et al., 2018).

As a social production, scale is neither local nor global but rather a shifting, interrelated and nested network that can simultaneously be deeply localized and extensive in its reach (Swyngedouw, 2004). Commodity markets are constantly created and transformed and the access to and control over resources is dynamically negotiated between a set of changing actors and subjects (Escobar, 2006; Peluso and Purwanto, 2018; Purwins, 2020). Economic activities and company networks are becoming simultaneously more localized and more transnational with direct effects on governance. The mining and processing sectors are inserted into global production networks which are complex and "multi-scalar, ranging from the local and regional to the national and global and back again". They "are built-up and transformed over time by a multiplicity of agents with asymmetrical influence and power" (Henderson et al., 2002, p.447).

In terms of governance, scale is crucial since it defines boundaries of decision-making and the allocation of costs and benefits (Blaikie and Brookfield, 1987). Scale concerns the way governance is organized, from jurisdictional, institutional, management, knowledge, and social network scales (Cash et al., 2006). However, especially here, a certain mismatch between scales can be observed (Cumming et al., 2006): Government institutions are actors within the global production networks that are spatially bound to the national and sub-national level while others, especially private actors, transcend political and territorial boundaries (Henderson et al., 2002; Scholvin et al., 2017). Since pollution monitoring is part of broader governance processes of the extractive sector, identifying these scalar mismatches is important to understand limits of governmental pollution control tools.

These different scale dimensions are important for addressing the causal levels of pollution problems, as I will discuss further in Section 1.5. In my research, scale is important for representing space, as I will need to choose and use a scalar lens through which I will view pollution problems from the micro to the macro level. The choice of scale allows for the observation of environmental change, but at the same time will frame my observations. The social construction of scale and its crucial dimension of power will also be important to my work, as they will allow for understanding the underlying socioeconomic drivers of mining-related pollution and enable research to contribute to problem solving and improve environmental conditions in mining areas in the long term. For me, the concept of scale, based on nested and interconnected networks, is critical in examining the power dynamics at play in the mining sector and related supply chains in a globalized economy. This concept of scale clearly overcomes strictly hierarchical spatial scale representations. Nonetheless, I will stick to a representation of separate concentric circles to show how the different chapters of my thesis are positioned in terms of the scale of observation of my research, which ranges from the local to the transnational level (Figure 1).

1.3 Innovative monitoring strategies

Over 50 countries around the world, most of them low-income nations in the Global South, are highly dependent on the extraction of hydrocarbons, minerals and metals since the sector generates over 20% of the export earnings or over 10% of the GDP (ICMM, 2018). Latin America, Asia and Sub-Saharan Africa provide today more than half of all mineral commodities to the world market, whereas Europe, Australia and North America account for less than 30 % of global mineral production (Reichl et al., 2020). Accordingly, mining takes place mainly in the Global South and so does mining-related environmental pollution. The governance of this pollution comes therefore with very context-related challenges and monitoring schemes must be adapted to the specific operational requirements of the mining contexts but also the socio-political context in which the pollution occurs. Monitoring concerns the types of data that has to be acquired and how to operationalize data gathering. Innovative methodologies are needed to assess environmental quality in mining areas and to contribute to problem-solving for achieving what most governments intend to provide for their citizens, a safe and clean environment.

Mostly, trends and seasonality of water quality parameters are understood through targeted monitoring that relies on numerous field measurements of water quality parameters and the collection of water samples which are subsequently shipped to laboratories for analysis (Sparrow et al., 2020). Academic researchers or other trained personnel are conventionally performing the sampling and the subsequent analysis, however in person field work might be partly or fully replaced by automated devices at fixed monitoring stations (Ouyang et al., 2006; Duan et al., 2018). This type of environmental monitoring is generally very costly and criticized as being inefficient (Lovett et al., 2007). In recent years, two new approaches for water quality monitoring have been developed and implemented as a response to some of the requirements encountered in contexts with limited financial capacities and personnel for monitoring. First, spaceborne remote sensing is constantly evolving and allows assessing and tracking water quality parameters based on satellite imagery. This approach covers very large spatial and temporal scales and is cost-effective compared to conventional monitoring. Second, citizen science is an innovative way to monitor environmental quality in collaboration with lay-people which allows operating on a local scale and integrating contextualized knowledge for resolving resource-related conflicts.

In the following, I will give a short literature overview over optical spaceborne remote sensing of water quality (section 1.3.1) and citizen science in the water sector (section 1.3.2) to illustrate the innovative potential of these methods for pollution monitoring.

1.3.1 Spaceborne remote sensing

Since it's developments in the 1970's, satellite remote sensing has become a very promising, cost-effective and widely used tool to detect changes on the Earth surface (Byrne et al., 1980). Land-use or land-cover changes that have initiated in the past and cover different temporal and spatial scales can be studied as far back as satellite imagery is available. This makes it specifically popular for surveilling large areas for deforestation (Hansen et al., 2013; Grecchi et al., 2017) or other long-term ecological monitoring (Pettorelli et al., 2014). Current satellite missions have a relatively high resolution and fast revisit times for monitoring environmental processes at unprecedented detail. Recent advances in remote sensing technologies have a sufficient spatial resolution to assess inland river systems and support water quality databases at the global level (Sagan et al., 2020). Remote sensing analysis of water quality of surface fresh waters relies on optical properties of the water and its constituents. It is based on the relationship of these water quality parameters to light reflectance, which is a function of light absorption and scattering (Dekker et al., 1995; Maul, 1985). Such direct estimation is possible for optically detectable water quality parameters, such as chlorophyll-a, Secchi disk depth, colored dissolved organic matter, total organic carbon, total suspended matters and turbidity (Gholizadeh et al., 2016). Additional spectral bands sensed by newer satellites allow retrieving water quality parameters where prior algorithms failed (Vanhellemont and Ruddick, 2018). The accuracy of the results has been increased by the development of new models and algorithms that operate across different sensors and atmospheric correction processors (Pahlevan et al., 2020, 2022). So far, only few remote-sensing studies addressed water quality issues at mining sites. Telmer and colleagues analyzed the effect of artisanal and small scale mining on river siltation and indirectly estimated mercury loads of a main tributary in the Brazilian Amazon (Telmer et al., 2006). Recent studies used optical spaceborne imagery to assess environmental impacts of large-scale tailings dam failures by showing specific water quality parameters pre- and post-incident (Rudorff et al., 2018; Cheng et al., 2021). However, the potential for inland water monitoring by satellites is far from exhausted, as we will demonstrate in Chapter 2 by tracking a propagating pollution front.

1.3.2 In-situ monitoring via citizen science

Since some years also lay-people are more and more involved in scientific monitoring schemes, creating a new body of literature under the term citizen science. In some citizen science projects, community members have a considerable level of influence over the entire monitoring process, from the conception to the collection and the interpretation of the data. Such approaches are therefore labelled community-based monitoring (Conrad and Hilchey, 2011; Wilson et al., 2018). The participation of the general public in citizen science projects is increasingly used in water research. Especially in research related to ecosystem service management, citizens are encouraged to contribute to the design, collection and interpretation of hydro-chemical data (Buytaert et al., 2014; Breuer et al., 2015; Jollymore et al., 2017).

Community-based participatory research approaches allow for reducing the cost and logistics of periodic sampling campaigns in geographically remote areas on the one hand. On the other hand, proponents claim the virtues of citizen science for increasing scientific environmental literacy and awareness of participants and for having positive effects on community engagement in political processes and public policy implementation (Jalbert and Kinchy, 2016; Kimura and Kinchy, 2016). One aim of citizen science or community-based monitoring schemes is to generate “extramural” knowledge (Lave, 2015), meaning that it is not only accessible to and actionable by academia or experts but also by people affected by the pollution. In mining, participative environmental monitoring has been implemented by different companies as corporate social responsible (CSR) measures in order to reduce resistance to the mining operations, increase trust in the company’s activities and improve environmental knowledge in indigenous communities (CAO, 2008; IFC and ICMM, 2017; Pareja et al., 2018). So far, literature on participatory monitoring focusses on how it can support corporate CSR efforts. Collaborative research between citizens and academia focuses on the creation of high-quality datasets and its usefulness to empower and support research participants in their endeavors for a healthier environment (Wylie et al., 2017b). The potential of citizen science as a collaborative research effort to identify sources and extent of mining-related pollution remains largely untapped.

1.4 Governance processes around mining related pollution

Monitoring is a focused way of collecting data that is linked to a framework of quality objectives and relates to a risk assessment in terms of human and ecosystem health (Bartram and Ballance, 1996).

Monitoring is usually embedded in a broader governance framework regarding pollution control measures. Most mining countries around the world have published regulatory frameworks that set quality standards for air, soil and water which have to be respected by the industry (IGF, 2013; FAO, 2022). Environmental monitoring in the mining sector establishes baseline conditions, determines contaminants and toxic substances that are emitted, discharged, or result from mining operations (Jain et al., 2016b). For governments, monitoring is a regulatory tool for checking the compliance with standards and in case of violation, penalizing the polluter. For the industry, monitoring is a compliance tool for improving internal processes and take corrective action if needed. Monitoring is part of a range of policy schemes to control pollution and to prevent the emergence of externalities or to internalize externalities that have arisen (Perman et al., 2011). Other policy instruments range from the application of direct control on polluters like command-and-control instruments towards incentive-based instruments such as marketable permits and subsidies on 'excess' emissions reduction (McGuire, 2014). The instruments differ in their approach from post-pollution management to pollution reduction targets. All of these policy mechanisms need an active and strong regulator that assures that violators face a high probability to be caught (McGuire, 2014).

Many regulatory contexts in Global South settings have seen traditional mechanisms of environmental regulation and political accountability fail and pollution topics remain unresolved. Over the last decades, initiatives based on civil engagement confronted inefficiencies and shortcomings in formal accountability mechanisms. Civil society and development organizations promoted the concept of social accountability (SAcc) to push governments to respond to citizen's needs (World Bank, 2004). Social accountability is a short route-alternative for citizens demanding accountability from the government when the long route through their (elected) political leaders and public officials does not bring the wished outcome (Joshi and Houtzager, 2012; Brinkerhoff and Wetterberg, 2016).

SAcc initiatives often address public service provisions in the health-, education- and energy sectors. Social accountability also gained momentum in many other sectors, because the private sector embraced environmental and social risk management principles for project financing, such as the Equator Principles which can be considered as an important social accountability initiative of the financial markets (O'Sullivan and O'Dwyer, 2015). Probably the most prominent transparency and accountability initiative in the extractive sector, the Extractive Industries Transparency Initiative, is focused on fiscal transparency, implying new business environments involving corporate social responsibility (CSR) (Sovacool, 2020). The reduction of toxic pollution harming citizens is at heart of numerous social accountability initiatives (Fung et al., 2007; Georgiadou et al., 2014; Perovich et al., 2021). In such a context, citizens and civil society contribute to the governance process for improving environmental conditions in mining areas. As I will develop in the next section (1.5), it is fundamental that academia considers these ongoing governance debates and designs monitoring schemes that support ongoing transparency and accountability initiatives for the extractive industries.

1.5 Research gaps

In low-income countries that highly depend on resource extraction, governing mining-related environmental impacts represent an important challenge. Environmental management authorities often lack financial capacities and trained personnel for performing monitoring independently and fail to put national environmental regulations into practice (Crawford, 2015; NRGI, 2017). Outsourcing this monitoring task to consulting firms is not among viable options because of financial capacity constraints. Regulators generally rely on data from company reports to assess the pollution potential of mining, as deficient Environmental Impact Assessments (EIA) exemplify (Edwards et al., 2014). Governments lack independence in their pollution assessments and monitoring, which further weakens their oversight role (Charles et al., 2022). Also, for civil society organizations, it is highly challenging to foster good governance regarding water pollution. As public platforms testify, water quality data and/or pollutant loads in the aquatic environment are rarely available to the public (GEMStat, 2022).

When mining leads to pollution, causes and responsibilities are often controversial and incidents have a high potential to lead to societal conflict, especially when related to water resources (Pareja et al., 2018; Salem et al., 2018; Smart, 2020). Even though local communities in mining areas are directly exposed to the pollution and suffer from the impacts, the report of their experiences is often not sufficient as proof to trigger improvement of environmental management by the involved companies or corrective action on the side of the government. Policy- and decision makers all over the world tend to rely on scientific proof to validate or discard the request of their citizens with regard to environmental quality (Bencze and Alsop, 2014; Bakker and Ritts, 2018). Such proofs include research studies but most often consist of consultancy reports or company assessments. Mining pollution is debated in multistakeholder arenas with community members, local and international civil society organizations, governmental institutions and private companies. Discussions reach a deadlock because there is a lack of environmental quality data to relate to (Chapter 4 this thesis, Muma et al., 2020). Even if there is a common understanding among stakeholders that there is a need for additional environmental quality data, acceptance and trust in the results depend on the monitoring scheme and on which actor is generating the data (Checker, 2007; Matz et al., 2017). Data can imply a new balance to power asymmetries in specific contexts, however, the credo ‘data is power’ is way too simplistic as information alone is not sufficient to positively influence public sector performance (Fox, 2015). Transparency and access to information does neither automatically induce community engagement nor improve accountability if restrictive government structures discourage citizens to take action (Brinkerhoff and Wetterberg, 2016).

Therefore, there is a need for effective monitoring strategies that provide water quality data for data-scarce regions around the world with limited financial capacities and a lack of equipment and trained personnel. Spaceborne remote sensing has a high potential to fill in the large voids of water quality assessments and to address the large-scale impacts of mining-related water pollution, while importantly reducing monitoring cost. It will also enable to gather water quality data in cases in which field access and in-situ monitoring is restricted. In addition to such instruments that allow assessing large geographic scales, we also need monitoring schemes that consider the governance processes and power dynamics, which structure the pollution problem. Monitoring needs to be scale-sensitive and take into account power relations in the way it generates data. It should provide bases for decision-making and enable mutual learning. These reflections are not considered in conventional monitoring schemes that, instead, focus on biophysical parameters that allow to respond to various degrees – and on various scales – to the questions on what did directly cause a pollution incident and related impacts (in terms of what pollutant was of concern or what biogeochemical process triggered pollution). These schemes consider what substances might be of interest, what the direction and magnitude of change is, where in the landscape the change locates and at which rate it is changing (Sparrow et al., 2020). However, these approaches are ineffective for solving pollution issues for two reasons: They neglect the power dimensions of resource policies, and they disregard local knowledge of the communities affected by mining operations.

The power dimension is missing, because the combination of spatial scales in the observation of biophysical parameters will never reveal the manifold interferences and interlinkages of complex human-environment systems where human decision-making drives pollution. For the mining sector it is crucial to consider interactions and feedback relationships between coupled human- and engineered systems to meet sustainability objectives across temporal and spatial scales (Kunz et al., 2013). Especially concerning water resources management on mining sites, it is important to design stakeholder engagement processes that allow identifying power dimensions between stakeholder groups (Lienert et al., 2013; Kunz and Moran, 2014). It is not sufficient to identify the sources of pollution but necessary to also assess the underlying socio-economic drivers of pollution. To achieve this and better understand human decision making in socio-organizational contexts, qualitative methods such as structural and causal analysis, participant observation and interviews are needed to establish the nature of social objects and relations and identify causal mechanisms (Sayer, 2010). There is need for further research around scale-sensitive environmental governance that integrates disciplinary approaches from natural and social sciences (Padt et al., 2014) in order to address causes instead of symptoms (Karlsson-Vinkhuyzen, 2014). Understanding the nested hierarchies of drivers that operate at different governance levels is a prerequisite for developing more legitimate and more effective governance schemes (Karlsson-Vinkhuyzen, 2014).

It is crucial to integrate local knowledge into environmental quality monitoring to enable communities to participate in natural resources management and to complement data sets with local observations (Nare et al., 2006). Citizens can play an active role to bridge the gaps of traditional monitoring and create trusted data for politicized and conflictual contexts. Collective research in form of citizen science may have an important transformative potential that can lead to improved management of socio-ecological systems (Bela et al., 2016; Kinchy, 2017) and increase decision-making power (Conrad and Hilchey, 2011). Community-based monitoring can contribute to enabling the participants to develop accountability for pollution in a locally configurated way (Pritchard and Gabrys, 2016) and can be considered as an expression of environmental governance rooted in understandings of stewardship, kinship and responsibility (Wilson et al., 2018).

1.6 Objectives and research design

In this dissertation, I propose different monitoring approaches addressing contrasting power dynamics in the extractive sector. These approaches operate at different spatial, temporal and socio-organizational scales to assess and monitor environmental pollution caused by mineral extraction, processing and mine waste management I conceptualize and implement monitoring tools and emphasize on the dimension of ‘power’ in a debate where power is not often thematized.

The overarching goal of this thesis is to investigate innovative and impactful methodologies for monitoring mining-related surface water pollution and to analyze the potential of these data acquisition tools to contribute to resources governance processes in the Global South.

The guiding objectives have two interrelated dimensions. The first relates to the content and design of the monitoring tool and the second to the methodologies of monitoring schemes.

1. Content-related research objectives
    a. to develop and implement adequate and impactful monitoring tools to assess the sources and extent of mining-related pollution and relate it to public health risks
    b. to better understand the socio-economic drivers of the pollution for a given mining context
2. Methodology-related research objectives
    a. to identify potentials and limits of monitoring methods such as citizen science and remote sensing to assess water quality and inform governance processes
    b. to design research methodologies that allow to address the spatio-temporal and the socio-organizational scales of a specific pollution issue and contribute governance processes.

To achieve these objectives, specific cases of mining-related water pollution from mining contexts in Central and Southern Africa are investigated. The main focus is on pollution that is related to mineral extraction process and waste management. There is no specific focus on the step of ore processing, however, the different operational phases often interrelate. (Tailings for example are a waste product from ore processing that is managed at specific waste facilities). Both pollution cases have in common that the issues are of great actuality and have a high social and political relevance.

Each article of this thesis focusses on a different scale when addressing mining-related water pollution (Figure 1). The first pollution case addressed in Chapter 2 consists in a tailings dam incident that occurred at a diamond mine in Angola. This case was brought to my attention in early August 2021, underlined by a request to the academic community to contribute to water quality assessments that would allow to address the pollution situation and attribute responsibilities (CRREBac, 2021). For this case, the local to regional scale of pollution is addressed and methodological transfers to other pollution incidents that occurred in other mining areas around the globe are discussed.

A second case addresses a water pollution problem in a coal mining area in Zimbabwe. At the beginning of the research, I did an extended visit to Zimbabwe to identify the key players in the mining sector and to learn more about the major environmental risks associated with mining. I encountered stakeholders from civil society, the private sector, governmental institutions and universities not only in the capital Harare but in regional centers such as Bulawayo and finally at the local level. This process showed that Hwange was one of the country's main pollution issues with a long-lasting politicized mining conflict and a mediation process that was already ongoing between the local stakeholders. The direct contact with community members and local civil society revealed the potential of implementing a citizen science project there. First, I focus only on developing and implementing a community-based water quality monitoring scheme on the local scale (Chapter 3). For the same case, I further expend the analysis on the socio-organizational scale and how power manifests in governance related aspects, from the local over the national to the transnational scale (Chapter 4).

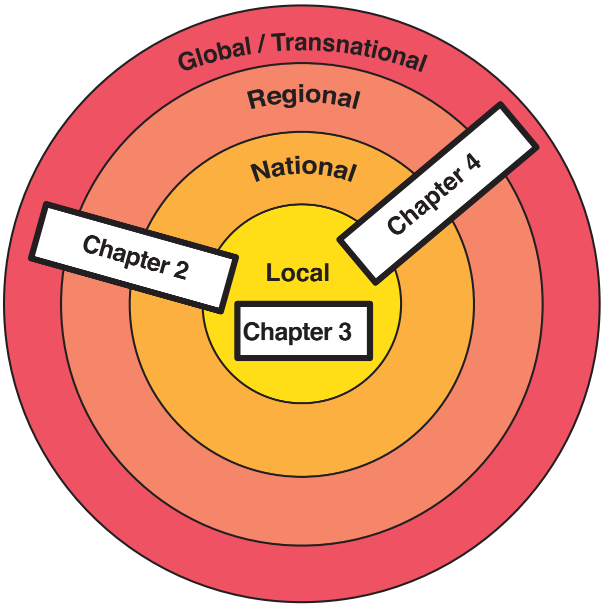


Figure 1 Simplified diagram with concentric circles to illustrate the different scales, from local to global, and the chapters of this thesis that address them (modified after Crawford, 2020; Herod, 2003).

1.7 Thesis outline

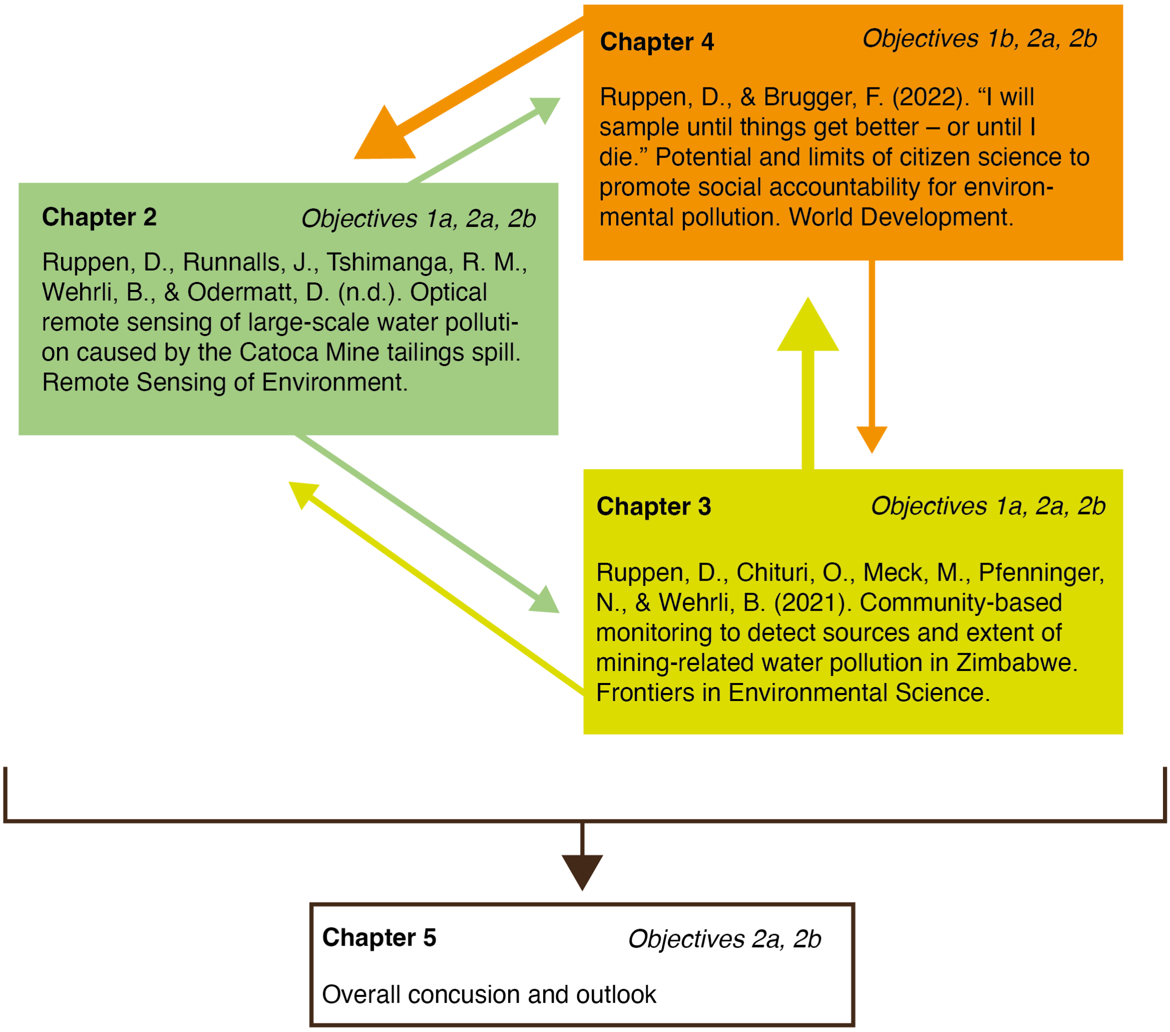
In this thesis, the identified research gaps will be address in Chapters 2 to 4 that consist of three articles where I am the main author. Chapters 2 and 3 focus each on the development and implementation of a monitoring scheme (Objective 1a) and Chapter 4 mainly addresses the socio-economic drivers of pollution (Objective 1b). All three chapters relate to the method-oriented objectives, but the overall conclusion of this thesis in Chapter 5 will provide the main floor for the questions on how to design research methodologies that address a specific pollution issue in a scale-sensitive way and how to contribute effectively to governance processes. Although only Chapter 4 builds directly on Chapter 3, all chapters relate to each other, because research activities timely overlapped and the knowledge that was generated influenced my research perspective continuously (Figure 2).

Chapter 2 includes the first research article that was entitled *Optical remote sensing assesses large-scale water pollution impacts of mining – insights from Catoca's tailings spill affecting Angola and the DRC*. It is currently in preparation by Ruppen, Runnalls, Tshimanga, Wehrli and Odermatt (2022). In this article, we use spaceborne optical remote sensing to monitor large-scale water quality impacts of a tailings dam incident. To develop the methodology, we focused on an incident that had occurred at a diamond mine in Angola in July 2021 and had impacts on communities living in neighboring DR Congo. We present an innovative methodological approach that allows extracting water quality parameters such as turbidity from Sentinel-2 data. With our analysis, we aimed at showing how the pollution propagated from its source and how the water quality parameters during the incident compared to quality from other years. The data allowed clarifying the temporality of this highly controversial pollution incident as well as to attribute responsibility to the mine owner and relate the analysis to the potential health risk for the population. Further, we discussed the applicability on several important spills that have happened in the last six years around the globe. We also discuss the limitations of the imagery provided by the different satellite missions to deliver this analysis.

Chapter 3 encloses the second research article on *Community-Based Monitoring Detects Sources and Risks of Mining-Related Water Pollution in Zimbabwe* that was published in 2021 in Frontiers in Environmental Science (Ruppen et al., 2021). In this article, we focused on a long-lasting and politicized pollution case related to coal extraction and use. Since more than a decade, the Deka River in the rural area of Hwange in Northwestern Zimbabwe increasingly sees fish kills and deteriorating water quality. At project start, the local mediation process came to a deadlock because of a lack of environmental quality data that attributed responsibilities to the industrial players. Together with community members from the rural area, we designed and implemented a community-based monitoring scheme to understand the cause and the extent of water pollution of Deka River. This monitoring covered a period of close to 1,5 years and relied on measuring water quality parameters in situ, collecting water samples, and analyzing them in a laboratory. In contrast to conventional monitoring networks, the scheme was implemented not only by academic researchers but primarily by rural community members. The goal was to examine the causes and the extent of the water pollution, identify pollutants of concern and related public health risk.

In Chapter 4, we, Ruppen and Brugger, present the article *"I will sample until things get better – or until I die." Potential and limits of citizen science to promote social accountability for environmental pollution that was published in May 2022*. Here, we focus on socio-economic dynamics and power relationships that frame and define pollution issues. For the analysis, we zoom again on the pollution case in Hwange, Zimbabwe and take the community-based monitoring (Chapter 3) and its contribution to the local mediation process as a starting point of our analysis. The aim was to understand what happened with the scientific water quality data obtained in the community-based monitoring and how useful the data actually was to improve the environmental condition. By conducting interviews with close to 60 actors from local to national level, we tried to follow the path of the data within formal and informal governance processes. We studied the monitoring and law enforcement capacity of the national environmental regulator and the effectiveness of the industry's environmental management. In our analysis, we take the case of Hwange to focus on the influence of the generated chemical data on the discourse between the stakeholders and the validity of the assumption that 'information is power'. We used not only social accountability theory to frame the civil engagement in Hwange, but also political ecology theory to analyze the coal-mining sector in Zimbabwe and to show how historical trajectories, economic conditions, and political processes define power architectures in Zimbabwe and influence the effectiveness of environmental regulation.

In Chapter 5 I first summarize the key findings of the three research articles with putting them into perspective with regard to the research objectives. I then proceed with broader reflections on the possible transfer of the methodologies and the role of scientist when studying pollution. The chapter concludes with policy recommendations and an outlook to orient further research.



Chapter 4 *Objectives 1b, 2a, 2b*

Ruppen, D., & Brugger, F. (2022). "I will sample until things get better – or until I die." Potential and limits of citizen science to promote social accountability for environmental pollution. World Development.

Chapter 2 *Objectives 1a, 2a, 2b*

Ruppen, D., Runnalls, J., Tshimanga, R. M., Wehrli, B., & Odermatt, D. (n.d.). Optical remote sensing of large-scale water pollution caused by the Catoca Mine tailings spill. Remote Sensing of Environment.

Chapter 3 *Objectives 1a, 2a, 2b*

Ruppen, D., Chituri, O., Meck, M., Pfenninger, N., & Wehrli, B. (2021). Community-based monitoring to detect sources and extent of mining-related water pollution in Zimbabwe. Frontiers in Environmental Science.

Chapter 5 *Objectives 2a, 2b*

Overall concusion and outlook

Figure 2 Thesis outline with research articles in Chapters 2 – 4 and the conclusion in Chapter 5. Arrows illustrate how the chapters relate to each other and the arrow thickness qualitatively shows the influence that one chapter had on the elaboration of the other.

1.8 Research Environment

This doctoral thesis was one of five dissertations that were running within a broader research project named the Swiss Minerals Observatory (SMO). The SMO was established jointly by five professorial chairs at ETH Zurich from September 2017 to April 2022 and situated at the newly founded Institute of Science Technology and Policy[6]. Research activities were motivated by the observation that the harmful environmental externalities that mineral producing countries face were in strong contrast to the good environmental conditions in industrialized consumer countries and trading hubs such as Switzerland. The research project aimed at analyzing the environmental and socioeconomic footprint of minerals mined, traded, and consumed by the Swiss economy and to advocate for responsible extraction and trade of mineral resources. The SMO had the vision to co-shape and support private sector value-chain management and resource policy for the Swiss mineral commodity sector. It was accompanied by a multi-stakeholder advisory board composed of actors from the private sector, government and civil society in Switzerland. The advisory board had the role to enrich and critically review the research process and four meetings between the scientists and the board were held during the project duration.

As outlined earlier, my research focused on extractive activities on the African continent, where mining will intensify in the coming decades. Global demand for mineral and energy raw materials is expected to double by 2050, with the African continent offering enormous supply potential in terms of energy raw materials, metals and industrial minerals (Hartlieb-Wallthor and Marbler, 2017). Sub-Saharan Africa ranks first or second worldwide with regard to the quantity of mineral reserves such as bauxite, chromite, cobalt, industrial diamond, manganese, phosphate rock, platinum-group metals, rutile, soda ash, and zirconium (Yager et al., 2017). Today, Africa produces important shares of the world commodities market such as 61% of cobalt, 51% of manganese, 50% of chromite, 47% of diamond, 21% of gold, and 13% of uranium (Yager et al., 2021). The dependency of the world economy on raw materials from African countries is therefore already very high for specific commodities and is probably increasing in the next decades. Especially for the development of new technologies, mainly for the mobility and energy transition, the demand for lithium, cobalt, manganese, platinum-group metals will double to quadruple until 2040 (Marscheider-Weidemann et al., 2021). This will offer a main growth engine for the African economy (African Development Bank, 2014) but also comes with an enormous challenge for the governance of the extractive sector. The population of Sub-Saharan Africa is predicted to double from 1.07 in 2019 to 2.12 billion in 2050. The region will account for over 50% of the projected world population growth over the next decades (United Nations, 2019). Mining conflicts, especially related to water supply in drought-prone areas, might intensify in the future. Similar risks might develop in other world regions such as Latin America and Asia with increasing resource extraction for meeting global demand (Reichl et al., 2020).

Within the SMO, I collaborated with other doctoral candidates with respect to the gold supply chain. Gold is a commodity that is particularly important for Switzerland, since up to two-thirds of the globally extracted gold is imported into Switzerland for refining and re-exporting (Mariani, 2012; Mbiyavanga, 2019). This strategic role in the global gold market, brings not only economic opportunities to Switzerland, but also important due diligence risks. Some artisanal and small-scale gold (ASGM) supply chains are associated with human rights violations and the financing of armed conflict (Geenen, 2016; Rettberg and Ortiz-Riomalo, 2016). The use of harmful mercury is widespread in the ASGM sector (Boese-O’Reilly et al., 2004; Telmer et al., 2006). Not only might the gold supply from ASGM be problematic for refiners but also business ties to some disputed industrial mines (Geenen and Claessens, 2013; Zaitch and Gómez, 2015). Civil society have repeatedly reported on the lack of transparency and illegal activities in the gold sector and the legal - and due diligence risks that result for Swiss refiners (Global Witness, 2020; Ummel, 2020). From my side, I contributed to the joint SMO

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[6] www.istp.ethz.ch/minerals

research activities by focusing (1) on mercury in ASGM processing and (2) the analysis of the Swiss trade statistics.

In the first collaboration, I contributed to an article of my colleague Antoinette Van der Merwe about the risk perception of artisanal and small-scale gold miners regarding mercury use (Van der Merwe et al., n.d.). I analyzed and interpreted the mercury content of hair samples from 179 miners from several mine sites in Central Burkina Faso to depict the miners' occupational health exposure to mercury. In a second collaboration, my colleague Livia Cabernard and I were looking into the role that Switzerland plays in the precious metals market. We used an improved life cycle methodology and combined databases that were developed in Livia Cabernard's dissertation (Cabernard, 2021) and we studied the Swiss trade patterns and related environmental impacts, in particular biodiversity loss. We were comparing our results with current gold statistics and reports to identify specific gaps and limitations in current reporting of (Swiss) gold trade (Cabernard et al., n.d.).

2 Optical remote sensing of large-scale water pollution caused by the Catoca Mine tailings spill

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Manuscript in review at *Remote Sensing of Environment*

Abstract

Billions of tons of hazardous mine waste are stored in thousands of tailings storage facilities around the world. These impoundments represent one of the most important environmental risk factors of industrial mining, since occasional tailings spills or dam failures cause devastating impacts on human- and ecosystem health, specifically along river corridors. In this study, we developed a satellite remote sensing methodology to assess the impacts of tailings spills on water quality. We focused on the controversial incident that occurred at the Catoca diamond mine in Angola in late July 2021 and that allegedly caused important river pollution in neighboring Democratic Republic of the Congo (DR Congo) and led to public health concerns including the loss of human lives. We processed high resolution imagery acquired by ESA's Sentinel-2 satellites using the Python package Acolite for atmospheric correction and turbidity retrieval. We used a river skeletonizing algorithm to automatically extract turbidity values for the entire river system. This allowed us to track the propagation of the pollution front from the source at the Catoca mine through the Tshikapa- and the Kasaï River during more than one month and across 1400 km, until it finally dissipated after discharging into the Congo River. We further analyzed a 6-year time series of virtual stations in the Tshikapa River located up- and downstream of the effluent discharge, to compare the impacts of the tailings spill to seasonal variabilities of water quality. Turbidity values caused by the spill largely exceeded the seasonal variability in Tshikapa River in recent years. These findings confirm that the Catoca tailings spill has significantly affected water quality of the Tshikapa - and the Kasaï River with total suspended solids concentrations that were several 10-fold above drinking water standards in Lunda Norte Province, Angola and Kasaï Province, DR Congo, making severe public health impacts for residents and fish kills highly probable. We finally discuss the feasibility of transferring this methodology to other tailings dam failures that have occurred since the start of the Sentinel-2 mission in 2015. We identified available data for analyzing other incidents in China, Chile, Peru, and Myanmar. Overall, our new Sentinel-2 workflow represents an opportunity to assess the large-scale impacts of pollution incidents in mining areas around the world at locations where hydrological - and water quality data is scare and monitoring capacities are limited.

2.1 Introduction

On 31 July 2021, local communities in the central Democratic Republic of the Congo (DR Congo) detected tons of dead fish floating on Tshikapa River whose color had turned red. The river is a lifeline to riparian communities and a tributary to the Kasaï River that flows into the Congo River. In the following days, several thousand people in the Kasaï Province requested medical attention for severe diarrhea after consuming river water and 12 people reportedly died (RTNC, 2021). About a month later, the Congolese government held a press conference confirming reports that these events were related to a tailings dam incident that occurred at the Catoca mine, one of the world's largest diamond mines located in neighboring Angola (RTNC, 2021). Subsequently, the Russian-Angolan mine operator broke the silence and published a statement in which the company accepted that a spilling incident had happened at its tailings storage facility but denied that the tailings spill had affected Tshikapa River's water quality exceptionally (Sociedade Mineira de Catoca Lda., 2021).

Unfortunately, the Catoca case is just another recent example on a long list of tailings dam incidents that have occurred in mining history. Comprehensive and up-to-date databases list over 360 tailings dam failures between 1915 and 2020 (Islam and Murakami, 2021; Rana et al., 2021). Tailings are the major waste product from ore processing and consist of an aqueous suspension of a solid phase, mainly with a grain size between silt and sand fraction. At mine sites, operators build dammed impoundments, also known as tailings storage facilities (TSF), to retain and store the tailings. Worldwide, over 18'000 active TFS's exist (Azam and Li, 2010) of which around half are located in China alone (Lepoudre, 2018). An estimated 1.2% of all tailings dams fail over a period of 100 years (Azam and Li, 2010). Globally, the frequency and the severity of the incidents are increasing, because of a growing amount of tailings to be deposited (Mudd and Boger, 2013), a lack of industry standards for TSF design, stability analysis and risk management (Clarkson and Williams, 2021) and the use of outdated dam construction methods and poor monitoring (Azam and Li, 2010).

Tailings dam incidents often have a devastating effect on the environment and humans. Severe incidents resulted in losses of hundreds of human lives and caused dramatic water pollution and biosphere damage. As recent examples, two devastating dam failures in the Minas Gerais State in Brazil have attracted worldwide media attention. The failure of the Córrego de Feijão iron mine in Brumadinho in 2019 claimed 308 human lives and was one of the most deadly tailings dam failures in history (Freitas and Da Silva, 2019). The tailings spilled high loads of turbidity, metals and nutrients into the Paraopeba River with subsequent impacts on the ecosystem. Increased ecotoxicity and fish mortality were documented even months later (Thompson et al., 2020; Da Silva Souza et al., 2021). Located less than 100 km away, the Fundão tailings dam failure of the Germano iron mine in Mariana occurred in 2015. This release of an enormous amount of 60 million m^3 of metal-rich tailings left a track of devastation along more than 600 km of the river and adjacent agricultural land before discharging into the Atlantic Ocean (Rudorff et al., 2018). Several years later, local communities continue to be exposed to high concentrations of toxic metals and related health risks (Cavalheiro Paulelli et al., 2022). Not only mining ventures in the Global South are exposed to risks of such high-magnitude incidents as the dam failure in 2014 at the Mount Polley copper and gold mine in Canada has shown. The discharge of 25 million m^3 of tailings in the Quesnel River watershed resulted in more than one meter of metal-rich sediment burying the former floodplain in the Quesnel River watershed (Hudson-Edwards et al., 2019).

As a result of severe tailings dam failures over the last two decades, new research and political initiatives focused on understanding the causes and reducing the risks of such human and environmental disasters (UNECE, 2014; Roche et al., 2017; Owen et al., 2020). Scientific studies analyzed the mechanisms of historic tailings dam failures and modelled runoff to volume relationships (Rico et al., 2008; Ghahramani et al., 2020). Other researchers provided global reviews and comprehensive databases to better understand the systematics and kinetics of the tailings dam failures

(Islam and Murakami, 2021; Rana et al., 2021). Machine learning was combined with remote sensing techniques to automatically detect tailings pond structures (Li et al., 2020b). In-situ water quality measurements and geochemical analysis allowed assessing direct impact of the failures (Byrne et al., 2018; Queiroz et al., 2018; Guo et al., 2019; Hudson-Edwards et al., 2019) and the success of remediation efforts (Olías et al., 2021). Remote sensing based water quality assessments often complemented in-situ field measurements and mainly focused on turbidity (Rudorff et al., 2018; Teixeira et al., 2021) and suspended sediment concentration (Cheng et al., 2021). Other remotely-sensed products addressed resulting land cover changes of the flooded areas (Syifa et al., 2019; Moraga and Gurkan, 2020).

Specifically, the remote sensing-based assessments offer the potential to map the large-scale extent of the environmental pollution from tailings dam incidents and to establish clear evidence of the pollution sources for controversial cases. Some highly productive mines are located in forested and remote areas that are difficult to physically access due to a lack of road infrastructure. National regulators in the Global South often lack the organizational set up or the financial capacities and personnel to react to those incidents in due time and send sampling teams on the ground. Restricted access to high-security zones in some mining areas present an additional challenge for sampling and analysis efforts by independent researchers. Examples include the notoriously deadly Jade mining sites in the Hpakant area of the Kachin State in Myanmar (Global Witness, 2015), the military controlled Marange diamond fields in Chiadzwa, Mutare District, Zimbabwe (Towriss, 2013) and industrial gold mines being developed in the paramilitary-controlled Antioquia region in Columbia (Zaitch and Gómez, 2015), to mention only a few.

In the remote sensing literature, studies related to tailings dam failures primarily focus on the zone where most of the solid tailings are deposited (Ghahramani et al., 2020). Nevertheless, the mobility of the tailings depends on many factors such as their water content, precipitation intensity at the time of failure, total volume of tailings, dam height, rheological factors or downstream valley topography (Rico et al., 2008; Ghahramani et al., 2020). The solid phase of the mobilized tailings can travel far distances in a river system, while dissolved pollutants move without restriction (Simón et al., 1999; Kraus and Wiegand, 2006). The monitoring of the river water by remote sensing remains challenging because of the mixing conditions and potential methodological limitations such as image resolution (Ghahramani et al., 2020). So far, studies focusing on water quality parameters were limited to the heavily impacted zone, presenting times series of water quality parameters such as turbidity or suspended sediment load index for locations close to the source of the pollution (Rudorff et al., 2018; Cheng et al., 2021; Teixeira et al., 2021).

In our study, we present a methodological workflow that allows extracting water quality parameters of a river system based on multi-spectral Sentinel-2 satellite imagery and relate it to on-the-ground mining activity. A main practical objective of this study is to establish a solid dataset that allows clarifying whether the spill at the Catoca diamond mine in Angola was responsible for the deterioration of the water quality in the Tshikapa River and Kasaï River in neighboring DR Congo. Our approach allows the analysis of turbidity and water reflectance values over a large river reach and consequently track the pollution front. Our approach addresses to the following questions: 1) How far downstream and over which period can we track the turbidity in the river system? 2) And how strong was the impact of the Catoca tailings spill on river water quality in space and time compared to seasonal variations since 2015? After the detailed analysis of the Catoca mine spill, we look into a series of tailings dam failures that occurred over the past 6 years since Sentinel-2 imagery became available. We discuss the potential and limitations of applying our impact assessment to such incidents.

2.2 Study area

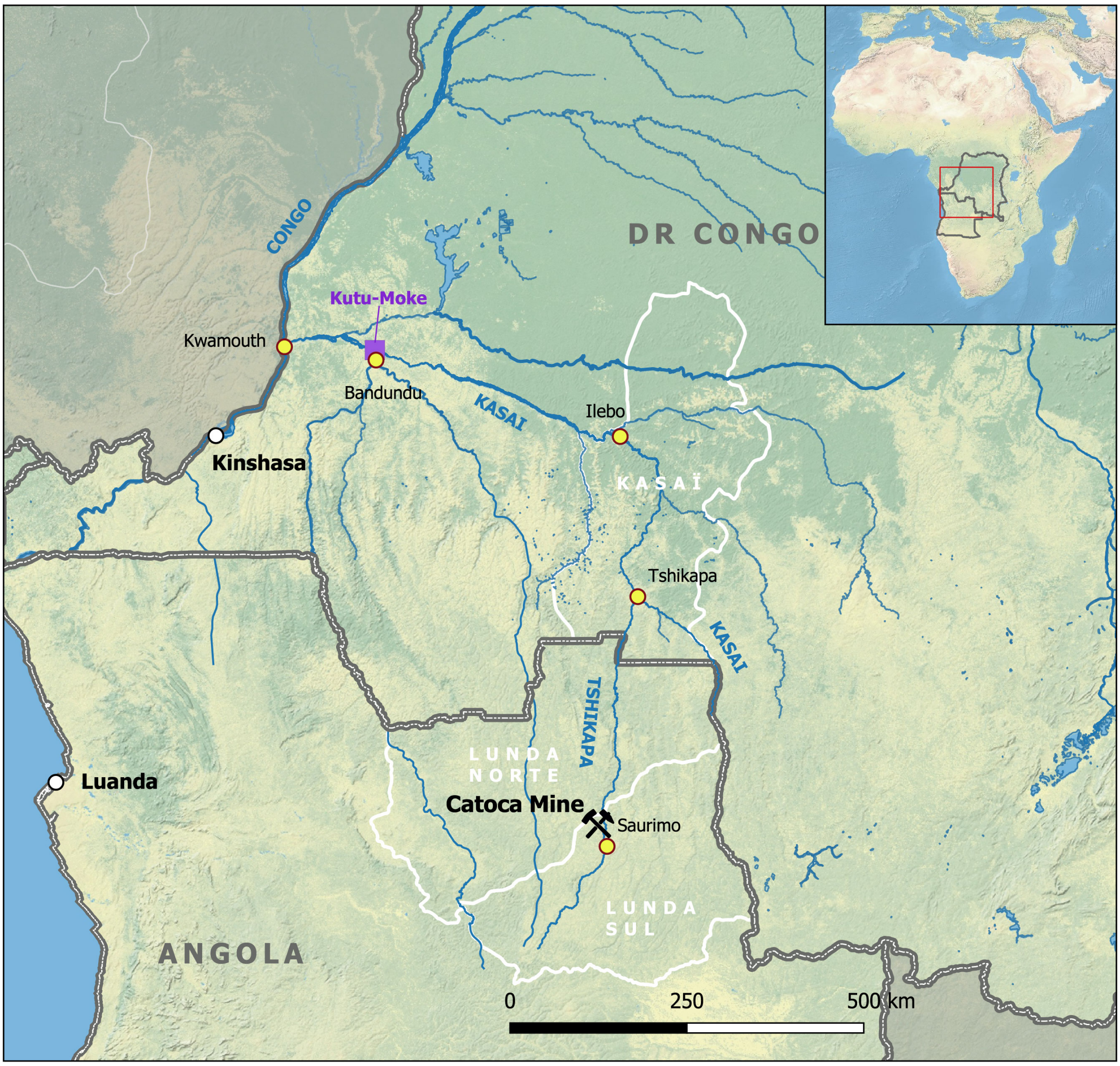

Figure 3 Map of Angola and DR Congo showing the location of the Catoca Mine and illustrating the flow of the Tshikapa River, the Kasaï River and the hydrological features of the Congo Basin. Lunda Provinces (Angola) and Kasaï Province (DR Congo) impacted by the pollution. Hydrological gauging station on Kasaï River is located at Kutu Moke. QGIS maps contain rivers and administrative boundaries from DIVA-GIS (Hijmans et al., 2018), places from Natural Earth (Natural Earth, 2022) and background layer world map (US National Park Service, 2022).

The Catoca diamond mine is located around 30 km North-northwest of Saurimo, the capital of the Lunda Sul province in the northeast of Angola (Figure 3). The mining area experiences a temperate to tropical savannah climate (Köppen, 1936; Huntley et al., 2019; Frazão et al., 2020), with a wet season from October to late April (Mendelsohn et al., 2013). With its recent production of 6.5-7 million carats of high-quality diamonds per year, the Catoca mine ranks as the world's fourth largest diamond mine by production (Cumena et al., 2019; Mining Technology, 2021). The mine is operated by the Sociedade Mineira de Catoca, a joint venture between the largest rough diamond producer in the world, Russian state-owned Alrosa (with a share of 41%), the Angolan Government-owned Endiama (32.8%) and the Chinese LL international Holding B.V. (18%) (Alrosa, 2021).

In Catoca, the ore is extracted at an open pit mine, processed on site and the tailings are deposited in a TSF with a surface of around 11.5 km^2 (Figure 4a). The impoundment stores around 35 Mio m^3 of tailings (Santos, 2021). The spillover from the dam is discharged into the small Lova River, a tributary of the Tshikapa River (spelled Chicapa on the Angolan side) which crosses the area in South to North direction. Discharge data of the Tshikapa River were not available, however, a hydroelectric plant under construction some 20 km downstream of Saurimo (Da Cruz, 2016; Gupta and Shankar, 2022) has a spillway designed for a maximum flow of 467 m^3 s^{-1} (COBA Group, 2015).

The Tshikapa River has its source in the Angolan highlands some 200 km southwest of Saurimo. After passing the Catoca mining area, the Tshikapa River meanders northwards for some 360 km across the Lunda Norte Province where several other industrial diamond mines are operating in vicinity to its course (S&P Global Market Intelligence, 2021). In addition, thousands of *garimpeiros* extract alluvial diamonds in shallow pits or use boats and diving equipment to mine the diamonds from the riverbed (PAC, 2004; AMDC, 2017; Cumena et al., 2019). After setting the border with neighboring DR Congo for around 60 km, the Tshikapa River crosses into the Kasaï Province of DR Congo where it joins the Kasaï River at the town of Tshikapa after another 80 km of flow. The Kasaï River is a main tributary to the Congo River and its sub-catchment drains one fourth of the surface of the 3.7 Mio km^2 large Congo Basin (Mushi et al., 2022). From Tshikapa Town the Kasaï River flows for around 880 km north- and then westwards where it passes the towns of Ilebo and Bandundu before finally discharging into the Congo River at Kwamouth.

2.2.1 Runoff and turbidity

In the Congo Basin, runoff data and water quality measurements are scarce. Hydrological modelling studies of the Congo Basin still use historical gauging data from colonial times (Tshimanga, 2012; Munzimi, 2019). For the Kasaï River, two gauging stations are included in the international database of the Global Run Off Data Centre (GRDC) with data collected between 1932 to 1959 (BFG, 2022). One station was located at Ilebo where the Kasaï River had a mean monthly discharge of 2114 m^3 s^{-1} in the historical dataset (Munzimi, 2019). The second gauging station was located at Kutu-Moke (Figure 3). It was recently renewed with international donor support and is currently managed by the Congolese water research institute *Centre de Recherche en Ressources en Eau du Bassin du Congo* (CRREBaC). Since September 2017 it is an operational hydrological- and sediment monitoring station where turbidity measurements and sediment samples are taken, and river discharge is measured. Between June 2018 and August 2019 the turbidity sensor recorded a median nephelometric front scatter turbidity [FNU] of 124.7, a mean of 281.5 FNU and a standard deviation of 341.7 FNU (Mushi et al., 2022). From August 2018 to August 2019, suspended sediment concentration showed a median of 476.9 mg L^{-1}, mean of 517.8 mg L^{-1} and a standard deviation of 324.7 mg L^{-1}. For the same period of time the discharge of the Kasaï River varied between a minimum in August of 4510 m^3 s^{-1} and a maximum of 12’185 m^3 s^{-1} in March 2019 (Mushi et al., 2022).

2.2.2 Chronology of the pollution incident

Following accounts of concerned residents, the Angolan media reported in early August 2021 the pollution of the Lova River in Lunda Sul Province, the stream into which the Catoca diamond mine discharges its effluents. The Catoca mine management confirmed to the local authorities that on 27 July 2021, the drainage system of their tailings pond had burst, causing the pollution of the river (Figure 4b,c) and adjacent areas (TPA, 2021b). Mid of August 2021, CRREBaC published a leaflet reporting important changes in water quality and vast fish kills in the Tshikapa River in the DR Congo (CRREBac, 2021). The consultancy company Visio Terra visually analyzed satellite imagery and identified signs of water pollution as early as 25 July that they related to a number of mine sites in Angola as being the source of the pollution (Sentinel Vision and Visio Terra, 2021).

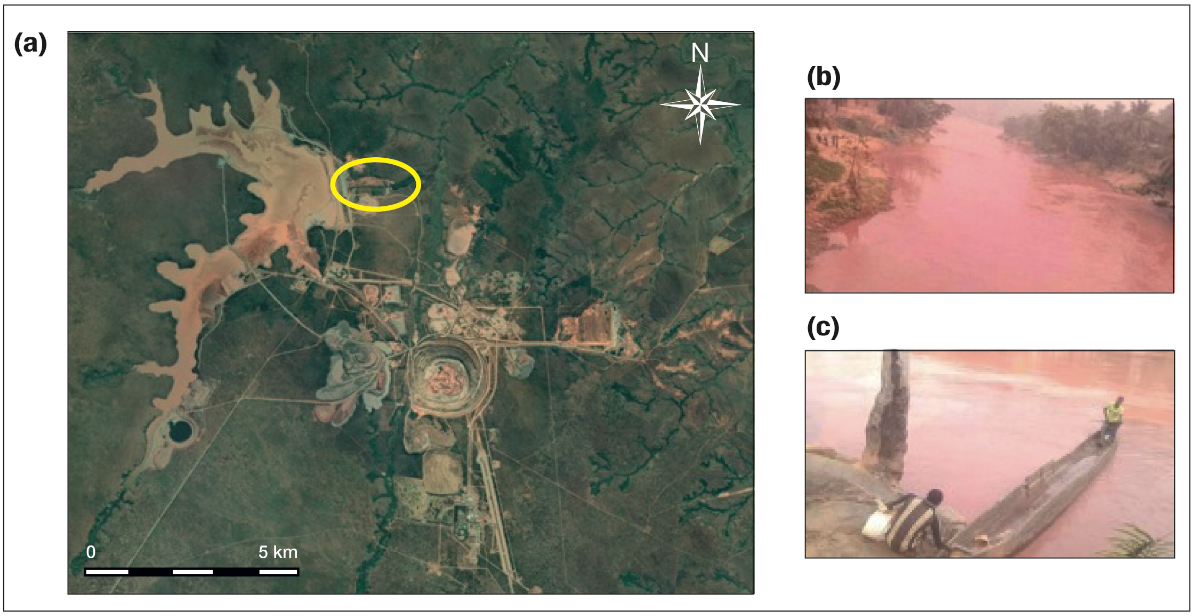

Figure 4 (a) Satellite Image of the Catoca Mine, Angola. Open pit extraction in the center and tailings storage facility in the West of image. Debris flow caused by tailings spill highlighted with yellow circle Google Earth Pro 7.3.4.8248 (1 August 2021). 09° 24' 15.15" S, 20° 18' 06.42" E, Eye alt. 15.76 km. Maxar Technologies 2022. https://www.earth.google.com [14 March 2022]. (b) & (c) Kasaï River close to Tshikapa Town showing red coloring in early August 2021 (Picture credits: Stany Frank).

Roughly 1.5 months after the incident in early September 2021, the Congolese Government held a press conference in the capital Kinshasa with the Vice- Premier Minister and Minister of the Environment as main speaker (RTNC, 2021). The minister reported that from 26 July residents noticed changes in color of the river water and on 31 July 2021 tons of fish and two hippopotamuses were found dead in the Tshikapa River in the Kasaï Province. The minister mentioned that a research team took samples with nickel and iron values above thresholds, but she presented no data. The minister added that 9863 people were affected by the incident in the sanitation zone of Bangalubaka, Territory of Ilebo, Kasaï Province, with 4502 reported cases of diarrhea and 12 deaths (RTNC, 2021). She underlined that the pollution incident in the DR Congo was linked to a mining accident in Angola, more precisely at the diamond mine of Catoca, and mentioned ongoing diplomatic procedures (RTNC, 2021). The pollution of the Tshikapa River attracted vast media attention and was covered internationally (Holland and Reid, 2021; Neto and Maclean, 2021; VoA Português, 2021a).

A day after the Congolese press conference, the Catoca mining company released a statement on their website. A rupture in the pipeline that works as a flood spillway was acknowledged. The statement added that "the tailings basin contains only mixtures of natural rocks, such as sand and clay, and the composition of matter corresponds approximately to the mud flows in the rainy season and does not contain external chemical components, which allows us to state that this situation does not represent risk to the affected populations." (Sociedade Mineira de Catoca Lda., 2021). In several interviews Angolan Provincial government representatives denied that the spill incident had deteriorated water quality in the Lova or Tshikapa Rivers in an unexceptional way and refused that it had caused any health issues to communities neither on the Angolan nor the Congolese side (Santos, 2021; TPA, 2021c, 2021a). The chief of the Provincial Environment Department of Lunda Sul province also highlighted that "the Chicapa and Lova Rivers already have a history of pollution caused by artisanal diamond mining … There have always been abnormal turbidity levels." (TPA, 2021c).

In summary, two events were not contested, the occurrence of a tailings spill at Catoca mine, and the subsequent fish kills. However, the timing of the incident and the causal link between the spill and the deterioration of the water quality remain controversial. This raises the question, whether remote sensing could provide additional evidence.

2.3 Remote sensing data and methodology

We base our analysis on high-resolution optical imagery acquired by the Multispectral Imager (MSI) on the Sentinel-2 (S-2) satellite of the European Space Agency's (ESA). The constellation comprises two polar-orbiting satellites (S-2A and S-2B) in the same sun-synchronous orbit phased at 180° to each other. This allows high revisit times of 5 days at the equator (ESA, 2021b). The imagery contains 13 bands in the visible and near-infrared (NIR) wavelengths with resolutions of 10, 20 or 60 meters, which are provided in 100 x 100 km tiles. Our region of interest extends across 14 such tiles (see also Table 1). Between the Catoca mining area and the Congolese town Ilebo, the Tshikapa River and subsequently the Kasaï River run in South to North direction for 900 km, which falls within a single MSI swath with full coverage every 5 days. By contrast, the Kasaï River between Tshikapa and Kwamouth runs East to West, with a longitudinal extension that is roughly twice the MSI's swath (Figure 5) and full coverage takes three days within the five-day revisit interval. We used the Python package Sencast to download, process and visualize S-2 data (https://gitlab.com/eawag-rs/sencast). In total, we downloaded about 400 S-2 L1C top-of-atmosphere-reflectance datasets (ESA, 2018) from a Copernicus Data and Information Access Service (www.creodias.eu). They include the full region of interest during the dam spill, plus all observations of the Catoca mine perimeter acquired since the launch of S-2A in June 2015.

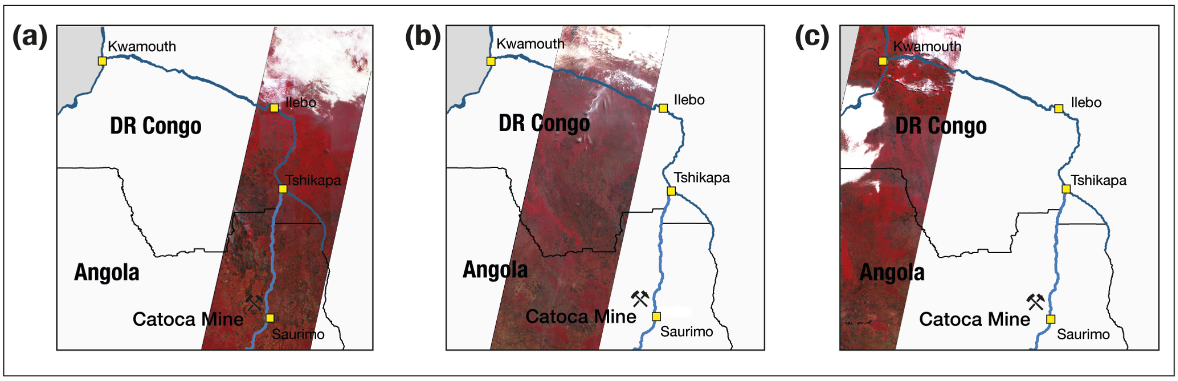

Figure 5 Three MSI swath widths (290 km) were necessery to cover the region of interest: (a) Swath covering the Tshikapa- and the Kasaï River flowing from Catoca Mine to Ilebo (b) Swath that covers the Kasaï River between Ilebo and Bandundu and (c) The Kasaï River between Bandundu and Kwamouth. Swath in false color composite from Sinergise (2022) for 20 July, 23 July and 21 July 2021, respectively. Background map showing locations and rivers of interest, adapted from Figure 3.

To remove atmospheric effects from the radiance signal and convert it to surface reflectance, atmospheric correction was done using release 20211124.0 of the Python package Acolite (Vanhellemont, 2019, 2020) as a subroutine in Sencast. Acolite further allowed us to identify water surfaces by performing non-water pixel masking. Acolite was found to perform best in very turbid optical water types (Pahlevan et al., 2021), and its recommended Dark Spectrum Fitting (DSF) method is useful for atmospheric correction over extremely turbid water, in which case atmospheric optical thickness (AOT) is estimated from dark pixels in the water body's adjacency. Acolite masks non-water pixels with a maximum threshold in L1C top-of-atmosphere reflectance (ρ_t). We used the default 1610 nm band for this task. Due to extraordinarily high aquatic backscattering, the default threshold of $\rho_{t,1610} = 0.0215$ is consistently exceeded in S-2 data of the Tshikapa- and Kasaï Rivers after the spill incident, despite low atmospheric turbidity. We therefore applied a relaxed masking threshold of $\rho_{t,1610} = 0.09$ to all data, and verified visually that both water courses were still adequately masked in data acquired prior to the spill. Likewise, we adjusted the cirrus cloud masking threshold of Acolite, by $\rho_{t,1373} = 0.005$ to $\rho_{t,1373} = 0.009$. The default mask smoothing was disabled.

To correct atmospheric effects, Acolite first corrects ρ_t with regards to atmospheric gas transmittance and the diffuse sky reflectance at the air-water interface. Then, Acolite's DSF algorithm fits an Ordinary Least Squares (OLS) regression through the darkest pixels of each spectral band corrected in such manner (Vanhellemont and Ruddick, 2018). The OLS intercepts yield a representative dark spectrum, which is used to select a spectral band and aerosol model for the estimation of AOT at 550 nm from a Look-Up-Table (LUT). The same LUT accounts for path reflectance, atmospheric transmittance and spherical atmospheric albedo when calculating water-leaving reflectance (ρ_w) from path-corrected reflectance. We used Acolite's default configuration but changed *luts_reduce_dimensions = False* to avoid the 1 m^{-1} AOT limit of the reduced LUT. We harmonized the choice of aerosol models for spatial analyses along the river network, where switching aerosol models lead to stitching artefacts between subsets. Maritime aerosols were chosen by Acolite in 120 of 132 such subsets. We therefore forced the use of maritime aerosols also for the remaining twelve tiles, by using luts = ACOLITE-LUT-202110-MOD2. Sun glint correction was not applied.

Aquatic turbidity is closely related to remote sensing reflectance in red and Near-Infrared (NIR) spectral bands, and the higher the turbidity, the larger the preferred wavelength (Nechad et al., 2009; Odermatt et al., 2012). Dogliotti and colleagues developed a switching algorithm using in-situ measurements in the range 1 — 2000 FNU (Dogliotti et al., 2015). It retrieves low to moderate turbidity using an arithmetic equation for MODIS' 645 nm band, while moderate to high turbidity is retrieved using an analogous equation for MODIS' 859 nm band. The Acolite manual (Vanhellemont, 2021) reports coefficients that Bouchra Nechad calculated in 2016 for using these two arithmetic equations with the 10 m S-2 bands at 665 and 833 nm (Eq. 1, Eq. 2):

Eq 1:

$$T_{665} = \frac{366.14\,\rho_{w,665}}{1-\rho_{w,665}/0.19563}$$

Eq 2:

$$T_{833} = \frac{1913.65\,\rho_{w,833}}{1-\rho_{w,833}/0.1913}$$

which we adopted for use in Acolite's implementation of the switching algorithm by Dogliotti et al. (2015) according to Eq. 3:

Eq 3:

$$\begin{gathered} T(\rho_{w,665} \leq 0.05) = T_{665} \\ T\big(\rho_{w,665} \geq 0.07\big) = T_{833} \\ T(0.05 < \rho_{w,665} < 0.07) = (1-w)\,T_{665} + wT_{833} \end{gathered}$$

It is important to note that both arithmetic equations behave asymptotically when the respective ρ_w approaches the coefficient in the denominator. For Eq. 1 this property is ineffective due to the switching mechanism. But the asymptote at ρ_w (833) = 0.1913 represents a saturation limitation of the algorithm, given that this threshold is reached and exceeded on many occasions after the Catoca dam spill, and under cloud and cirrus free conditions. Using MSI's reference signal-to-noise ratio of 174 in band 8

(ESA, 2015), we estimate that the noise equivalent error due to this saturation increases from 2% at 1000 FNU to 10% at 5800 FNU. We therefore define a calibrated (0 – 2000 FNU), an extrapolated (2000 – 5800 FNU) and a saturated (> 5800 FNU) retrieval range, and we mask all values obtained in the saturated range, as well as values with ρ_w (833) > 0.1913 that yield negative turbidity according to Eq. 2. All estimates masked in such manner are treated as 5800 FNU for further analyses and visualization.

We used the processing pipeline described above to produce turbidity maps covering the Catoca spill area and the river flow path for specific dates related to the incident. We considered satellite imagery that was sensed shortly before the incident and during a month after the incident. The swath coverage of the Sentinel-2 satellites determined the specific sensing dates along the river path (Figure 5). Cloud coverage restricted automatized pixel extraction on several sensing dates. Accordingly, we were able to generate turbidity maps for the different river sections for one satellite image sensed prior to the incident, namely on 20 July 2021, and for eight dates after the incident between 25 July to 30 August 2021 (details in Table 1).

Table 1 List of Sentinel-2 tiles extracted for given dates, MSI swaths relate to Figure 5.

MSI swath	Sentinel-2 tiles	River distance covered	Extracted dates [2021]
A	34 LDQ, 34 LDR, 34 MDS, 34MDT, 34MDU, 34MDV, 34MEV, 34 MDA	Tshikapa River at mine level to Ilebo	20 July, 25 July, 30 July, 4 August
B	34 MCA, 34MBA, 34MBB	Ilebo to Bandundu	17 August, 22 August
C	33 MZS, 33MYS, 33MXS	Bandundu to Kwamouth	10 August, 15 August, 25 August, 30 August

To produce longitudinal sections of turbidity, we required an accurate centerline (one-pixel-wide) of the river system. But the width of the Tshikapa River is at the lowest limit of MSI’s resolution. Which means that mixed pixels from a relatively tolerant land-water mask and uncertainties in geolocation impedes the use of a static river pixel grid. Alternatively, there are a number of published algorithms for extracting a river network from satellite images for example RivWidth (Pavelsky and Smith, 2008) and NRBC method (Zeng et al., 2015). Most involve generating a Boolean map of river pixels, applying a skeletonization or thinning algorithm and then pruning any undesirable branches. For this study, we use the Acolite water classification map to define water pixels in the processed image.

By overlaying the Boolean water matrix with a buffer zone around a rough vector river path that we produced, we could extract a Boolean matrix of river pixels. Since the algorithm determines the shortest route, it occasionally left the main river path and followed a small side branch of the river. In such cases, we manually removed pixels from the river matrix which allowed us to block the side branch and force the algorithm to follow the main river path. We then thinned the river matrix using the scikit-image (Van der Walt et al., 2014) and implemented Zhang and Suen‘s thinning method (Zhang and Suen, 1984). The output river skeleton was abstracted to nodes and edges and the shortest path between the start and end pixels was calculated with the NetworkX implementation (NetworkX, 2022) of Dijkstra’s algorithm (Dijkstra, 1959).

For networks with disconnected start and end nodes, a high-cost edge was introduced between adjacent non-connected nodes. The river skeletons were loaded onto the corresponding Level-2 imagery. For each pixel coordinate of the river skeleton, the turbidity value was extracted from the Level-2 product by aggregating the median based on a 3x3 pixel filter with the given pixel at the center. This filter was used to account for potential mixed pixels along the skeleton, assuming that a minor fraction of the 3x3 pixels is subject to additive (e.g. soil, vegetation) or reductive effects (e.g. shading) at subpixel scale. The complete processing algorithm is available on GitHub (https://github.com/JamesRunnalls/catoca-tailings-failure).

We started the automatized extraction of the water turbidity in the Tshikapa River around 40 km upstream of the inflow to the Lova River. The pixel extraction followed the course of the Tshikapa River for 540 km to the confluence with the Kasaï River near the Congolese town Tshikapa. Automatized pixel extraction was successful for up to 650 km of flow for 20 July 2021 and up to 130 km less for three dates after the tailings spill, namely 25 July, 30 July, 4 August, since extraction ceased towards north due to cloud coverage. For the rest of August 2021, automatized image processing was hindered due to high cumulus cloud coverage or haze on the entire MSI swath. On the second MSI swath to the West, we successfully extracted 17 August and 22 August in this middle section between the towns of Ilebo and Bandundu (Table 1). We also present the values we extracted in a third section covering the last 222 km Kasaï River before reaching the mouth of the Congo River for three dates showing the pollution front (10 August, 15 August, 25 August) and a last date after the pollution front has disappeared again (30 August 2021). The turbidity values were smoothed with a moving average (median) over 300-pixel stretches, in order to remove small-scale variability related to both the actual target parameter (e.g. resuspension) as well as its retrieval uncertainties.

To compare the different river skeletons on a same longitudinal section, we used the river skeleton of the first day which was sensed of the respective MSI swath and compiled for each river skeleton of the other dates a nearest neighbor matrix using the QGIS geographic information system (QGIS Development Team, 2022). For the first 650 km, the river skeletons of 25 July, 30 July and 4 August were projected onto the river skeleton of 20 July 2021. For the section between Ilebo and Bandundu, the river skeleton of 22 August was projected onto the one of 17 August. For the section at the mouth of the Kasaï River, the river skeletons of 15, 25 and 30 August where projected on the river skeleton of 10 August 2021. The distances between the pixels of the reference three river skeletons were calculated using the QGIS field calculator and summed up to display the river flow distance. We used R for data analysis (R Core Team, 2018) and plotted figures using ggplot 2 (Wickham et al., 2019). The Sentinel-Hub EO browser (Sinergise, 2022) was used to visually inspect the Sentinel-2 imagery of the year 2021 and localize the pollution front in true color composite (B4, B3, B2) or in false color composite (B8, B4, B3).

To discuss potential impacts on human and ecosystem health, we used the formula presented by Rasmussen and colleagues that established a linear correlation between suspended solids concentration (SSC) and turbidity values [FNU] for the Little Arkansas River near Sedgwick, Kansas (Rasmussen et al., 2009).

Eq 4:

$$SSC\ [mg\ L^{-1}] = 1.39 * Turbidity[FNU\ ]^{0.943}$$

2.4 Results

In the following, we present the propagation of the pollution front in the Tshikapa and the Kasaï River, as well as a time series of two virtual stations in the Tshikapa River close to the Catoca mine. The Sentinel-2 image of 20 July was the last one documenting the situation prior to the tailings spill. On the next image sensed five days later on 25 July 2021, a debris deposit of 16.75 ha is visible for the first time adjacent to the tailings dam (Figure 4a). The dam wall itself and the extent of the tailings storage facility appear unaltered. The Lova River that receives the mine effluent has a brownish color, which reflects high turbidity levels. The Tshikapa River, which is blue upstream, changes its color to brown after of the confluence with the Lova River. The color change in Tshikapa River after the inlet of the Lova River was not discernable 5 days earlier. (Processed images available on GitHub).

2.4.1 Propagation of pollution front

Prior to the incident, turbidity over the entire river stretch showed an average of 127 FNU and maximum values of 272 FNU in the 300-pixel smoothed median (Figure 6). To explain the turbidity changes, we used high-resolution satellite imagery using Google Earth Pro (Google LLC., 2021) to map mines that operate close to the river course (S&P Global Market Intelligence, 2021) and plotted them with respect to the river course (Suppl.-Table 1 in Appendix A). The effluent of the Catoca mine that joins the Tshikapa at km 40 of the longitudinal profile causes no notable turbidity change on the image of 20 July 2021. The first increase is encountered another 24 km downstream where numerous ASM pits are located along the flow path.

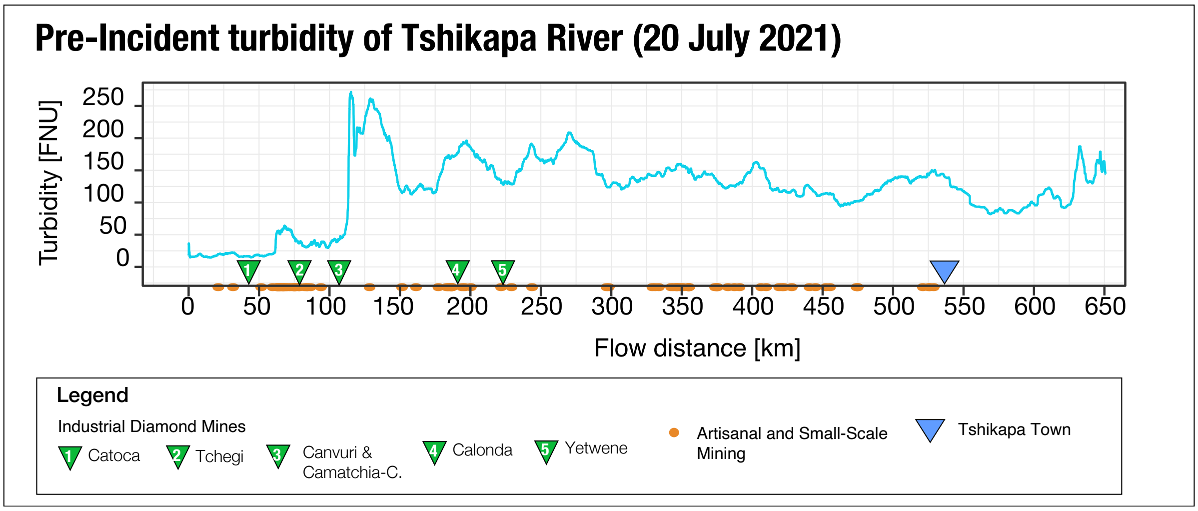

Figure 6 Pre-incident turbidity [FNU] along the Tshikapa River [km]. Values displayed for 650 km starting 40 km upstream of the Catoca Mine.

Here, artisanal miners extract the shallow alluvial deposit on the shores and thereby enhance turbidity. This phenomenon is well known from other ASM contexts (De Lucia Lobo et al., 2017). The turbidity increases nearly 10-fold after the Tshikapa passes the Canvuri and the Camatchia-Camagico mine that are located close to each other. The latter visibly discharges effluent with high sediment load to the Tshikapa River. The turbidity values consequently decrease until the Tshikapa River passes the next extraction site of the Calonda mine, followed by the city of Calonda, and the Yetwene Mine that all discharge effluents into the river. The Tshikapa River joins the Kasaï River at the Congolese town of Tshikapa. At this point, the turbidity decreased close to 100 FNU as the larger Kasaï River dilutes the concentration of suspended sediments carried by the 5-10 times smaller Tshikapa.

Although mining activities affect the turbidity on 20 July 2021, observations after the spill incident reveal a stark contrast (Figure 7). In the scenes from 25 July, 30 July and 4 August that follow the spill, we observe a very abrupt and steep turbidity increase where the Lova River discharges into the Tshikapa River. The water loaded with dam failure debris saturates the turbidity retrieval algorithm (shown as 5800 FNU) consistently and across large areas. We cannot robustly quantify turbidity at such levels, but conservatively estimate an increase that is in the order of 50- to 100-fold the median prior to the incident.

On 25 July, the turbidity values remain at the saturation level for 38 km before rapidly decreasing to pre-incident levels. On 30 July the turbidity remains at saturation level for 306 km before decreasing more slowly and finally reaching pre-incident level after another 159 km of flow. For 4 August, turbidity saturation extends over a distance of 440 km before starting to decrease. The duration of the leaking at the Lova mouth cannot be estimated directly because it extended into the wet season, and cloud-free images are lacking. On 4 August, the pollution front was visually identified through semi-transparent clouds, 201 km North of Tshikapa, at 696 km from the mouth of the Lova River. But no valid pixels are available from Acolite due to the clouds.

In the middle section of the Kasaï River between Ilebo and Bandundu the cloud coverage was high end July and early August. We visually localized the pollution front in the center of this middle section on 7 August. The first date for which it was possible to extract pixels was the 17 August on which turbidity levels were increased with an average of 308 FNU. Five days later, the turbidity was 5-fold lower at 96 FNU, which is presumably the baseline in this section.

In the last section at the mouth of the Kasaï River, we observed the arrival of the pollution front on 10 August. Five days later, on 15 August pollution levels reached a maximum of 320 FNU. Shortly before and a dozen kilometers downstream of the sampling station Kutu Moke (1250 km flow distance), three main tributaries, the Kwango-, the Kwilu- and the Fimi River join the Kasaï (Mushi et al., 2022). Here, the pollution signal decreased to a median of 125 FNU and quickly dropped to levels around 20 FNU when the Kasaï River mixed with water from the Congo River at the town of Kwamouth. Similar patterns were observed on 25 August for the last 100 km. However, median levels dropped by 50% and on 30 August, pre-incident levels of a median of 20 FNU were reached again.

The pollution front was localized on five dates which allowed us to calculate the velocity at which the pollution propagated. These propagation velocities reached for median and average the same value of 0.81 m s^{-1} (Suppl.-Figure 1 in Appendix A). We conclude that the tailings spill started at around midday of 24 July 2021 and the pollution front arrived at the Congo River on 13 August in the early afternoon. The Sentinel-2 image of 15 August confirms that the pollution had reached the Congo River and that the reddish coloring of the incoming Kasaï River water only dissipated after another 20 km downstream in the direction of the Congolese capital Kinshasa.

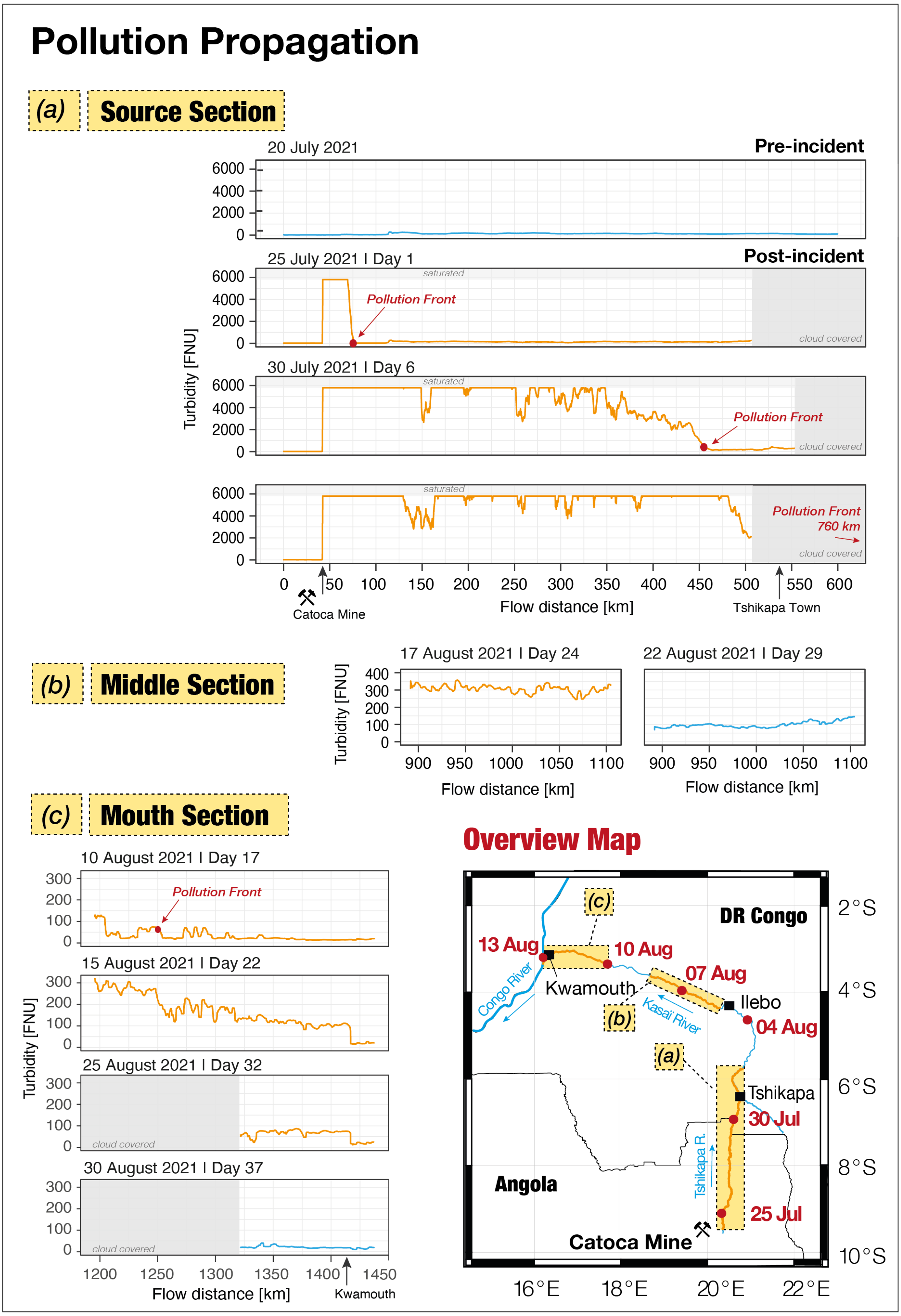

Figure 7 Comparison between pre- and post-incident turbidity [FNU] along the river flow [km]. Moving average over 300- pixel window for different sections of the river system. (a) Source section: first 600 km in Tshikapa River after the Catoca Mine, turbidity values are saturated ≥ 5800 FNU (b) Middle section and (c) mouth section show turbidity in Kasaï River for 860 to 1070 km and 1195 to 1440 km, respectively. (a), (b), (c) Blue color indicates background turbidity and orange color spill-affected turbidity when the pollution front has reached the river section. Scales differ for y- axis. Overview map indicates the three river sections that were analyzed and red points the position of the pollution front for the respective dates based on visual identification on Sentinel-2 imagery.

2.4.2 Time series in Tshikapa River close to Catoca Mine

We defined a pair of virtual stations in the Tshikapa River, where one virtual station was located 5.24 km upstream of the inflow of Lova River and one 4.62 km downstream, respectively (coordinates in Appendix A). For these virtual stations we extracted the turbidity from 382 Sentinel images sensed between October 2015 and December 2021. We calculated the median turbidity obtained from 3x3 pixel boxes in order to avoid mixed pixels. At these two virtual stations, mixed pixel artifacts are minimal, and the time series are the most consistent across all locations we tested. Only three observations were affected by broken clouds, which we removed manually (dates in Appendix A). For the six-year-time series of these two stations, the median from the 3x3 window is available on 184 and 190 dates for the up- and downstream virtual station, respectively (Figure 8). Due to cloud coverage, pixel extraction was less successful during the wet season. Values are available at the upstream virtual stations for 114 dates in dry and 70 dates in the wet season and at downstream virtual stations for 112 dates in dry and 78 dates in the wet season, respectively.

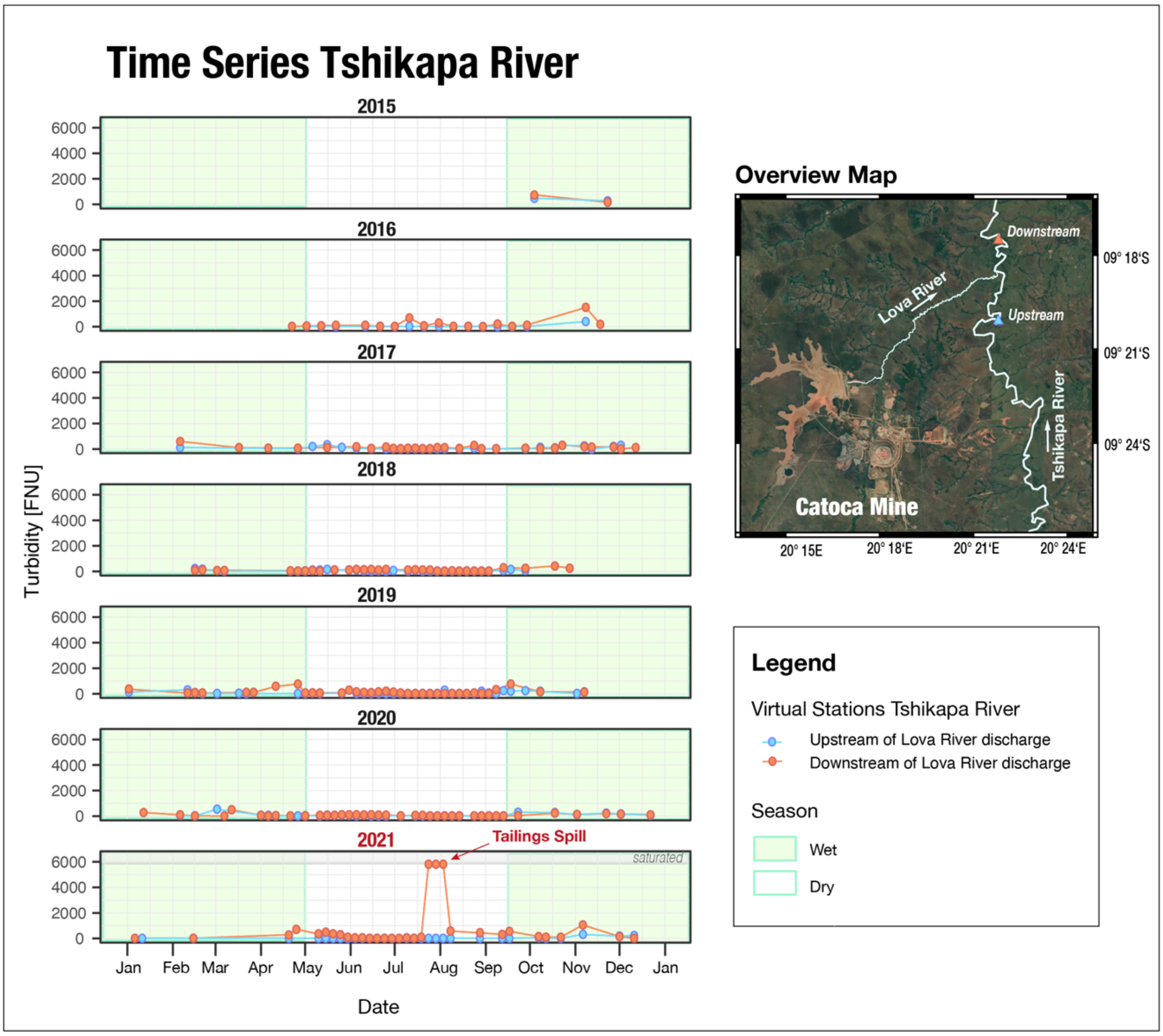

Figure 8 Turbidity from October 2015 to December 2021 for a pair of virtual stations in the Tshikapa River upstream and downstream of Lova River discharge, respectively. Dry- and wet season boundaries are only indicative, the exact onset of the rains varies from year to year. Overview Map: The Lova River which receives the spill-over of the mine and is a tightly meandering for 18.6 km North-East to join the Tshikapa River. Satellite Image of the Catoca Mine, Angola from Google Earth Pro 7.3.4.8248 (August 01, 2021). 09° 24' 15.15"S, 20° 18' 06.42"E, Eye alt 15.76 km. Maxar Technologies 2022. https://www.earth.google.com [March 14, 2022].

In tropical regions, seasonality relates to increased sediment transport from soil erosion and mobilization of bedload during precipitation periods (Mushi et al., 2022). This is reflected by higher turbidity in the wet season than in the dry season at both virtual stations in the Tshikapa River from 2015 to 2020 (for summary statistics see Table 2). Visual inspection of the Sentinel-2 imagery confirms that the turbidity of the river water shows higher values from early October onward since the entire North -South stretch of Tshikapa River shows a brownish color.

Table 2 Turbidity [FNU] of the virtual station upstream-wide and downstream-wide with respect to the inflow of the Lova River respectively. Columns show values for the years 2015-2020 and 2015-2021.

	Upstream				**Downstream**			
	2015 – 2020		2015 – 2021		2015 – 2020		2015 – 2021	
	median	max	median	max	median	max	median	max
Dry Season	22	341	21	341	70	684	71	**5800**
Rainy Season	75	539	57	539	105	1503	112	1503

For 170 dates between 2015 and 2021, turbidity values are available for both stations. In over 80% of the cases, downstream values slightly to moderately exceeded upstream values (Histograms for dry and wet season in Appendix A). In a fifth of the cases, downstream turbidity was lower than upstream which suggest that the Lova River occasionally has a dilution effect on the turbidity in the Tshikapa River, mainly during the rainy season. The highest differences of turbidity between up- and downstream of the Lova inlet can be observed during the spill. On 20 July 2021 upstream turbidity was below 20 FNU while downstream turbidity approached 100 FNU reflecting a usual ratio for the dry season (Table 2). Five days later, on 25 July, turbidity values downstream suddenly jumped to the saturation value of 5800 FNU where they remain until 4 August 2021. These turbidity values represent the maximum of the entire time series and an at least 60-fold increase compared to prior to the spill. For the same time period, values at the virtual station upstream remained stable and below 20 FNU resulting in a difference of two orders of magnitude between upstream and downstream. On 9 August 2021 turbidity values downstream are still elevated, however a magnitude lower than five days earlier. Downstream values reach pre-incident levels only in early October after the onset of rainfall.

2.5 Discussion

2.5.1 Timing and extent of the Catoca tailings spill

The pixel extractions and the visual observations of the Sentinel-2 imagery confirm that the tailings spill occurred between 20 and 25 July 2021. Based on the calculated propagation velocity of the pollution front we date the incident to 24 July 2021. The mine management had initially stated that the incident happened on 27 July (Sociedade Mineira de Catoca Lda., 2021) but in an Angolan television broadcast of late September, another date, namely the 24 July 2021, was mentioned (Santos, 2021). Other researchers also dated the incident to the 24 July 2021 based on composite maps of 1-meter resolution imagery of commercial satellites (Petley, 2021).

The time series of the Tshikapa River at the level of the Catoca mine confirms that, in the 6 past years, there has never been turbidity values as high as the signal sensed from 25 July to 4 August 2021 following the tailings spill. The time-series suggests that the spilling of tailings was not totally stopped by end of July, as the company stated (Sociedade Mineira de Catoca Lda., 2021), but that a high sediment load was discharged into Lova River until mid-September 2021. Our pixel extraction along the river course allowed following the pollution signal from the starting point where the Lova River discharges the mine effluent into the Tshikapa River. The pollution front crossed the border into the Congolese Kasaï Province on 30 July 2021 and, according to our calculations, reached the town of Tshikapa on 31 July 2021. At Tshikapa town, the Tshikapa River discharges into the Kasaï River, a main tributary to the Congo River. Even after the confluence, the pollution signal did not dissipate but the Kasaï River carried the pollution front for another 880 km of flow distance to its confluence with the Congo River where it arrived 20 days later on 13 August 2021. At the mouth of the Kasaï River, the 30 August coincided with the first image where turbidity levels reached pre-incident levels. Thus, our methodology allowed following the pollution signal for over 1400 km and for 32 days, which has a great potential for documenting large-scale pollution incidents caused by failures at tailings storage facilities.

Although we also noticed the impacts of mining activities on turbidity levels prior to the incident, the drastic increase in turbidity after the tailings spill was unprecedented. The dataset showed that median turbidity levels of the pollution wave were several 10-fold higher than prior to the incident. The same large differences appear when comparing pixels along the Tshikapa river path before and after the incident. These observations clearly contradict statements of company representatives and government officials saying that turbidity levels were within usual ranges compared to those caused by other mining activities.

Elevated turbidity levels reflect a higher concentration of suspended particles in the water. Since less light penetrates a turbid water column, aquatic vegetation produces less oxygen through photosynthesis which affects aquatic biota (EPA, 2021). High turbidity has also direct lethal effects on fish by damaging and/or clogging fish gills and leading to asphyxiation (Bash et al., 2001). The mortality of fish depends not only on the concentration of suspended sediments, but also on its particle size, on the duration of exposure and the fish species and its life stage (Bash et al., 2001). Turbidity can be translated into total suspended solids (TSS) concentration via a linear correlation (Eq. 4) (Rasmussen et al., 2009). A median turbidity of around 5800 FNU within the main pollution front translates to TSS concentrations of 4.9 g L^{-1}. This value exceeds the Angolan fresh water standard of 60 mg L^{-1} for TSS (Républica de Angola, 2011) and the Congolese value of 80 mg L^{-1} (Tshamala et al., 2021) by factors of 80 and 60, respectively. Even ten days after the pollution front arrived in the section between Ilebo and Bandundu, turbidity values remained close to 300 FNU, which translates into 300 mg L^{-1} and is still about 4-fold higher than Congolese fresh water reference standards. This means that it is very likely that the spill caused health impacts on individuals who consumed water of the Tshikapa- and Kasaï Rivers between 31 July and 17 August 2021.

These suspended sediment concentrations were also close to 50-fold above the threshold value of 100 mg L^{-1} for healthy fish populations and other aquatic biota in streams (Chapman et al., 2017). Since turbidity remained as high for over 10 days, we must conclude that the tailings spill caused lethal impacts on fish populations in Tshikapa River and Kasaï River as it was reported by the riparian population. Not only is acute mortality of such pollution incidents of concern for aquatic biota, but the particles released during the tailings spill can harm ecosystem for longer time. Particles can clog the stream bed which impacts the breeding sites of fish and benthic macroinvertebrates (EPA, 2021). Also, high flow rates will re-suspend deposited tailings: For the months after the Feijão dam failure in Brumadinho, Brazil, a study demonstrated that a large volume of tailings deposits in the Paraopeba River was resuspended during the rainy season (Teixeira et al., 2021).

Optical remote sensing cannot provide data on metal concentrations, but authors used total suspended solids (TSS) and turbidity as proxies for evaluation of metal transport in river water (Nasrabadi et al., 2016; Swain and Sahoo, 2017). Chemical analyses of mining effluents showed that heavy metals were mostly bound to suspended particles such as iron- and manganese oxyhydroxides and other colloids and that heavy-metal transport was more significant in the suspended than in the dissolved form (Kimball et al., 1995; Telmer and Stapper, 2007; Cánovas et al., 2008; Sracek et al., 2012). Numerous studies revealed a high pollution potential of tailings since the small- sized particles may release high concentrations of toxic metals and acids (Kříbek et al., 2010; Mudd and Boger, 2013; Roca et al., 2019). It is well documented, that diamond mines in Canada, Russia, South Africa with the same ore type as Catoca, exhibit pollution risks with regard to mine waste due to the release of toxic metals such as cadmium, copper, lead, molybdenum, nickel and mercury (Strydom, 2015; Independent Environmental Monitoring Agency, 2019; Legostaeva and Gololobova, 2021). Therefore, it is misleading when the mine operators describe tailings as a "*mixture of natural rocks... that does not represent a risk of life for the affected populations*" (Sociedade Mineira de Catoca Lda., 2021).

For the Catoca spill, the debate on the consequences and the severity of the incidents are still ongoing with the company downplaying the social and environmental impacts and refusing to acknowledge that the spill had any toxic effects (Santos, 2021; TPA, 2021c; VoA Português, 2021b). Since September, no official statements were released, neither by the Congolese, nor by the Angolan government. Neither fishermen nor riparian communities received any compensation for negative health impacts or economic losses to date. However, a trial was initiated on 21 March 2022 against the Sociedade Mineira de Catoca Lda. at the High Court of Tshikapa to seek reparation (Muamba, 2022).

2.5.2 Transfer of the methodology to other tailings dam incidents

In this section, we discuss the applicability of the new methodology to a number of major tailings dam incidents that occurred since the launch of the first Sentinel-2 satellite in June 2015. In recent years, the Sentinel-2 mission became popular for monitoring inland water bodies (Sheffield et al., 2018; Nouchi et al., 2019) and rivers (Warren et al., 2019; Li et al., 2020a; Lu et al., 2020; Wang et al., 2021). Its main advantages are the relatively high resolution of 10 to 20 meters in the visible and near-infrared spectrum, the fast revisit times of five days at the Equator and only 2-3 days at higher latitudes. For comparison, NASA's Landsat 8 (NASA, 2021) satellite mission has only 30 meters resolution in the visible spectrum preventing the analysis of small streams. The slow repeat-cycle of 16 days at the equator also hampers adequate tracking of a water pollution incident with Landsat 8. Restricted access missions such as the Pléiades (1A and 1B) and the SPOT satellites (6 and 7) from the French government space agency CNES were launched a few years earlier than Sentinel-2 and impress with their high spatial resolution of 0.5 m and 1.5 m, respectively, for three visible- and one infrared bands. However, high purchasing costs, inconsistent revisit times and irregular imagery footprints for locations around the globe make these satellites unsuitable for monitoring pollution incidents. Similarly, Planet Labs Inc.'s fleet of over 180 miniaturized and light-weight 'nanosatellites' from the Dove mission and its 5 Rapid Eye satellites offer no valid alternative to Sentinel-2. Not only the small swath of the imagery and irregular revisit times, but foremost the low radiometric quality of the cheaper nanosatellite sensors preclude water quality monitoring (Nagel et al., 2020).

To discuss the potential of transferring the methodology to other tailings dam incidents we made use of the continuously updated online database on tailings dam failures from the WISE Uranium Project (WISE Uranium Project, 2022). The list comprises dam failures or tailings spills at active mine sites and at abandoned workings and includes spills at (aluminum) processing plants and collapses of mine waste heaps that triggered landslides. The reported volume of mobilized tailings is often unknown but ranges from less than 10'000 m^3 to over 30 Mio m^3. The database also contains a qualitative description of the environmental impacts of the tailings spill such as the travel distance of a spill along a river system. For our analysis, we filtered the 26 incidents recorded between the start of the Sentinel-2 mission in June 2015 and August 2021. We classified the incidents based on a simple decision tree: We first selected incidents that occurred at tailings storage facilities in mining areas and that mobilized tailings volumes of at least > 50’000 m^3 and/or where tailings had reportedly affected surface water bodies. For the incidents that fulfill these requirements, we checked the availability of Sentinel-2 data and verified the cloud coverage of each image (Table 3).

The review of the incidents demonstrated that the doubling of Sentinel-2 data availability with the launch of Sentinel-2B in 2017 has significantly improved the mission’s capability to monitor mining incidents. Between 2015 and 2017, the mission relied only on Sentinel-2A, and had therefore revisit times of 10 days at the equator. In addition, only little imagery outside of Europe is available from the first year after launch.

We will briefly discuss three incidents from Table 3 to illustrate this limitation. For the Fundão tailings dam at the Germano mine that failed on 5 November 2015, there is no Sentinel-2 imagery available to cover the incident. Only three weeks after the incident, a first Sentinel-2 image (with high cloud cover) covers the area of interest. Authors that studied this devastating incident mapped surface water turbidity at the mouth of Doce River in the Atlantic Ocean based on lower resolution Landsat TM 5 and Landsat 8 OLI images (Rudorff et al., 2018). For another tailings dam failure at the Antamok mine in the Philippines on 27 October 2016 that reportedly polluted the river system, a Sentinel-2 image of the tile where the mine is located exists close to the incident date, but due to cropping it fails to reveal the area of interest. A third notable example of an incident that falls into the beginning of the Sentinel- 2 mission is the tailings dam failure at Glencore’s Kazzinc Mine in Ridder, Kazakhstan, that occurred on 22 May 2016. The release of nearly 400’000 m^3 of tailings polluted the Filippovka-, the Ulba- and the Irtysh Rivers and allegedly threatened the residents of the metropolitan region of Omsk in neighboring Russia some 1100 km away (Ivanshenko, 2016; Kaparov, 2016; Malikov, 2016; The Siberian Times Reporter, 2016). For this incident, barely any Sentinel-2 imagery exists. For the mine location and surrounding areas until the city of Semey, there is some (cloudy) imagery available prior to the incident, but no other image was sensed during the rest of May 2016. The first post-incident image of the mine and surrounding areas is from early June 2016.

From these observations, we can conclude that Sentinel-2 imagery is only useful for tracking pollution incidents after the mission was fully operational some months after the launch of the second satellite on 07 March 2017. This reduces the initial list of 26 incidents to 15 cases (Table 3). The applicability of our method is not only limited by availability of imagery but also by data quality. Cloud coverage, a known limitation of optical remote sensing, poses a significant limitation to the analysis of many incidents. Not only dense cirrus clouds block the surface reflectance from reaching the satellite sensor but also haze and thin clouds can cause interferences and affect surface reflectance (Pahlevan et al., 2022). This is particularly relevant for tailings dam failures since about 40% of incidents in post-2000 were at least partly triggered by heavy rainfall events (Azam and Li, 2010). Especially in tropical regions with pronounced wet seasons, dense cloud coverage lasts for several weeks to months. This is particularly relevant for areas with monsoon-driven climate such as the Jade producing mines of the Hpakant region in Myanmar, where almost every year a recorded incident was related to precipitations events (Table 3). The steep slopes of the mine waste piles collapsed and triggered flood waves in adjacent pit lakes that buried numerous workers (WISE Uranium Project, 2022). The deadliest event occurred on 2 July 2020 and left more than 175 people dead (WISE Uranium Project, 2022). However, for the Hpakant region, no cloud-free images are available between mid-May and October 2020. Only one incident in Hpakant occurred before the wet season in April 2019 and could potentially be evaluated with the presented methodology.

Table 3 Categorization of 26 tailings dam incidents reported after June 2015 by WISE Uranium Project (2022). Black dots (●) if condition applies, crosses (x) if condition doesn’t apply or (N/A) if information is not available or the condition not applicable. Category of cloud coverage only assessed for S-2 imagery that covers incident. Orange background for incidents with a high potential for analysis with the methodology presented in this paper.

Sentinel-2 satellites	**Date of incident**	**Location**	**Decision tree**			**Imagery**	
			Mine Site	*Volume released > 50’000 m^3*	*Tailings mobilized in rivers*	*S-2 covers incident*	*Low cloud coverage*
A	2015-11-05	Germano mine, Bento Rodrigues, Distrito de Mariana, Região Central, Minas Gerais, Brazil	●	●	x	x	N/A
A	2015-11-21	San Kat Kuu, Hpakant, Kachin state, Myanmar	●	●	x	x	N/A
A	2015-12-14	Lamaungkone, Hpakant, Kachin state, Myanmar	●	●	N/A	x	N/A
A	2016-05-22	Ridder, Kazakhstan	●	●	N/A	x	N/A
A	2016-08-04	Ujina, Pica, Tamarugal Province, Tarapacá Region, Chile	●	x	N/A	x	N/A
A	2016-08-08	Dahegou Village, Luoyang, Henan province, China	x	N/A	N/A	x	N/A
A	2016-08-27	New Wales plant, Mulberry, Polk County, Florida, USA	x	x	x	x	N/A
A	2016-10-27	Antamok mine (inactive), Itogon, Benguet province, Philippines	●	●	●	x	N/A
A	2016-12-28	Satemu, Hpakant, Kachin state, Myanmar	●	●	N/A	x	N/A
A	2017-03-12	Tonglvshan Mine, Hubei province, China	●	●	x	x	N/A
A	2017-06-30	Mishor Rotem, Israel	●	x	x	N/A	N/A
A&B	2017-09-17	Kokoya Gold Mine, Bong County, Liberia	●	x	N/A	N/A	N/A
A&B	2018-02-17	Barcarena, Pará, Brazil	x	●	●	N/A	N/A
A&B	2018-03-03	Huancapatí, Recuay province, Áncash region, Peru	●	●	●	●	x
A&B	2018-03-09	Cadia, New South Wales, Australia	●	x	x	N/A	N/A
A&B	2018-06-04	Cieneguita mine, Urique, Chihuahua, Mexico	●	●	●	●	●
A&B	2019-01-25	Córrego de Feijão mine, Brumadinho, Minas Gerais, Brazil	●	●	●	●	x
A&B	2019-03-29	Machadinho d'Oeste (inactive), Oriente Novo, Rondônia, Brazil	●	x	x	N/A	N/A
A&B	2019-04-09	Muri, Jharkhand, India	x	N/A	x	N/A	N/A
A&B	2019-04-22	Hpakant, Kachin state, Myanmar	●	●	N/A	●	●
A&B	2019-07-10	Cobriza mine, San Pedro de Coris District, Churcampa province, Huancavelica region, Peru	●	●	●	●	●
A&B	2019-10-01	Nossa Senhora do Livramento, Mato Grosso, Brazil	●	x	x	N/A	N/A
A&B	2020-03-28	Luming Mine, Tieli, Yichun City, Heilongjiang Province, China	●	●	●	●	●
A&B	2020-05-01	San José de Los Manzanos, Canelas, Durango, Mexico	●	x	N/A	N/A	N/A
A&B	2020-07-02	Hpakant, Kachin state, Myanmar	●	●	●	●	x
A&B	2021-07-27	Catoca mine, Saurimo, Lunda Sul, Angola	●	●	●	●	●

Climatic conditions also limit the potential to track tailings dam incidents in other mining regions in the world. Among the intensively mined areas in Latin America, the southern extent of the 5000 km long Andes Cordillera is known for intense precipitation and high cloud coverage (Barrett et al., 2009). A case in point is the dam failure of the Huancapati mine in Chile on 3 March 2018, for which no acceptable imagery exists. In addition, the devastating incident of the Brumadhino tailings dam in Brazil of 25 January 2019 disappeared under dense clouds for more than a month after the incident.

In addition to the Hpakant incident, we identified three other tailings dam failures that have a potential be studied using our Sentinel-2 workflow (Table 3). 1) the Cobriza copper mine in Huancavelica region, Peru (10 July 2019), 2) the Cieneguita gold and silver mine in Chihuahua, Mexico (4 June 2018) and 3) the Luming molybdenum mine in Heilongjiang Province, China (28 March 2020). We recommend analyzing water quality impacts of those four tailings spill incidents with the Sentinel-2 workflow presented in this study.

Overall, the Catoca tailings incident was a highly suitable case for pollution tracking regarding the availability and the quality of Sentinel-2 multi-spectral imagery to cover the first few hundreds of kilometers along the river system. First, the incident happened at the end of the dry season where cloud coverage generally was low. In the weeks that followed the spill, the climate transited to the rainy season and cloud coverage increased. Especially in the North of our region of interest closer to the Equator, there was a lot of haze on the imagery. Further, the pollution propagated in river system, which was oriented mainly in a South to North direction for over 780 km, from the Catoca mine to the town of Ilebo. This perfectly suited the path of the polar-orbiting Sentinel-2 satellites, which means that, for each sensing day, a coherent compilation of juxtaposed tiles in North- South direction was available which significantly reduces the workload for image mosaicking. The continuity in image coverage for the same day becomes trickier if the pollution would rather propagate in longitudinal direction. We observed this additional challenge when monitoring the flow of the river in East to West direction between the city of Ilebo and Kwamouth, the mouth of the Kasaï River reaching the Congo River. For the last 620 km of flow distance, we had to switch MSI swaths twice which comes with a considerable effort of mosaicking and the difficulty in plotting the data chronologically.

2.6 Conclusion

Strong global economic growth continues to stimulate the demand for manufactured goods and fossil energy carriers and therefore thrives the extraction of mineral resources in an unprecedented pace (Reichl et al., 2020). The tendency to extract lower and lower ore grades leads to an ever-increasing amount of ore processing waste that is deposited every year within over 18’000 dammed tailings storage facilities (TFS) around the world, of which 0.12 ‰ fail (Azam and Li, 2010). Large amounts of tailings are released with devastating consequences on the environment and human health (Cheng et al., 2021; Rana et al., 2021). Water bodies are affected the most, but human and financial capacities in producer countries are often inadequate for assessing the large-scale impacts and incidents remain highly debated. Here, we demonstrated how remote sensing supports the assessment of large-scale water quality impacts of tailings spills and adds to the evidence base in data-scarce regions where riparian communities still wait for the recognition and the compensation of damage. We presented a satellite remote sensing workflow to analyze the magnitude and the extent of a pollution incident where tailings polluted a large river system.

We applied this new workflow to the controversial tailings spill at the Catoca diamond mine in Angola, that caused a diplomatic incident between Angola and DR Congo following accusations of fatalities as a consequence of the pollution. We used high-resolution satellite imagery of ESA’s Sentinel-2 mission to extract turbidity as a water quality parameter for the river system. Although, the tailings spill at the

Catoca mine had left only minor land-cover changes in the Lunda Sul Province in Angola, our data illustrates that the incident had major and far-reaching impacts with regard to water quality. We were able to clear controversies about timing of the incident, dating it to midday of 24 July 2021. A 6- years-time series of the turbidity at the level of the mine showed that the values exceeded anything previously measured. Turbidity values increased up to several orders of magnitude, which evidenced that the impacts of the spill were severe. We were able to track the pollution signal downstream from Angola into the DR Congo for over 1400 km until it reached the Congo River 20 days after the spill had started. The high turbidity values left no doubt that this tailings spill caused large fish kills. It is highly probable that human beings who consumed the river water in Lunda Norte Province, Angola between 25 July and 10 August and in the Kasaï Province, DR Congo between 30 July and 17 August suffered severe health effects.

In addition to our in-depth analysis of the Catoca spill we studied the feasibility of applying the methodology to other tailings dam failures that occurred since the start of the Sentinel-2 mission. We illustrated the data limitations before the Sentinel-2 mission was fully operational in 2017, problems caused by cloud cover but also opportunities to apply our workflow to learn more about the dynamics and extend of tailings dam failures. Finally, we identified four tailings-related pollution incidents in Peru, Mexico, China and Myanmar, where the new workflow could be used for assessing water quality impacts.

2.7 Data availability statement

The code and imagery supporting the conclusions of this article are available under the following link: https://github.com/JamesRunnalls/catoca-tailings-failure

2.8 Acknowledgment

We thank Stany Frank for providing photographs of the Kasaï River after the pollution incident. Heresh Fattahi from Jet Propulsion Laboratory at Caltech is acknowledged for the discussions about satellite technologies. Francesco Wyss from Swisstopo National Point of Contact provided information on commercial satellite imagery. We thank Rosi Siber for compiling the hydrologic map of the study area.

2.9 Author contributions

DR designed and implemented the study under the guidance of DO. JR programmed the river skeletonizing algorithm and DO and JR performed the atmospheric correction of the satellite imagery and the pixel extraction. DR analyzed and interpreted the dataset and wrote the manuscript. RT was involved in the conception of the study. BW has provided support to orient the study and to edit the manuscript. All authors discussed the results and commented on the manuscript.

3 Community-Based Monitoring Detects Sources and Risks of Mining-Related Water Pollution in Zimbabwe

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Abstract

Although mining and mineral processing are vital for many economies in the Global South, they are associated with enormous challenges of managing potentially devastating environmental impacts. In contexts where environmental oversight agencies often lack financial and personal capacities to fulfill their role, community-based monitoring might be a valid alternative to monitor potential environmental impacts. In this study, we present the setup and the implementation of a citizen science project to monitor water quality parameters in a river downstream of a coal mining area in Hwange, Western Zimbabwe. In a joint effort over 1.5 years, community monitors and scientists took close to 800 water samples in the Deka River and effluent channels. The data allowed identifying sources of pollution and relating these to past and present mining activities. The primary source of acid mine drainage came from abandoned underground mine sites. Illegal mine water dumping from active mine sites accentuated the problem and resulted in fish kills and food risks for the local population. Concentrations of manganese, nickel and arsenic were exceeding national fresh water guidelines and international drinking water standards. Manganese concentrations exceeded guidelines by a factor of 70 resulting in a public health risk. In this study, we showed that community-based monitoring offers a promising approach to establish a high-quality dataset for assessing mining-related risks if the implementation of sampling protocols is followed tightly. The monitoring scheme significantly improves the collection and interpretation of water quality data in challenging contexts where governmental institutions and industrial players are not enforcing environmental standards.

3.1 Introduction

Mining and mineral processing are vital for many economies in the Global South. In 2018, over 70% of minerals and metals were produced in developing and transition countries. Their share of the global mining output is increasing every year as mineral demand is growing while the production of developed countries flattens since more than a decade (Reichl et al., 2020). Mining and mineral processing come with enormous challenges of managing potentially devastating environmental impacts such as atmospheric emissions, soil contamination, land disturbance, biodiversity loss and water pollution (Azcue, 1999; Jain et al., 2016a). Areas with highest extraction growth rates per year are as well primarily located in low and middle-income countries of the Global South where mining intensification hotspots enhance water scarcity and/or threaten species-rich biomes and vulnerable ecosystems (Luckeneder et al., 2021). As average ore grades of industrial mining production are declining over time (Mudd, 2010, Calvo et al., 2016), the proportion of waste rock per unit of commodity produced is steadily increasing, and with it the challenge of managing and disposing the billions of tons of mine waste generated each year around the globe (Jones and Boger, 2012). Mine tailings and abandoned mines specifically affect water resources far beyond the lifespan of a mine via acid mine drainage (AMD) produced by accelerated oxidation and weathering of sulfide-rich ore deposits and mine waste. This results in acidic effluents with elevated concentrations of metals (Sheoran and Sheoran, 2006; Jamieson, 2011). AMD remains an important water pollution problem of the mining industry around the world (Clarke, 1996; Kuyucak, 2002; Johnson & Hallberg, 2005). In mineral-rich countries of the Global South, environmental management authorities often lack financial and personal capacities for performing periodical sampling and analysis independently and fail to enforce national environmental regulations (NRGI, 2017).

In research related to ecosystem services, citizen science projects encourage the general public to contribute to the design, collection and interpretation of environmental quality data (Buytaert et al., 2014; Commodore et al., 2017; McKinley et al., 2017). In Northern America, volunteer-based water quality monitoring is renown and hundreds of such environmental monitoring projects are on-going (Carr, 2004; Conrad, 2007; Stepenuck and Genskow, 2019). U.S states such as Maine and Wisconsin have made volunteer engagement an integral part of their natural resources' governance approach (VLMP, 2013; DNR, 2022). In addition, citizen science was recently promoted by the United Nations as a way to reach the sustainable development goal on water and sanitation (UN-Water, 2020). Although the number of citizen science projects in water research in the Global South is constantly growing (Walker et al., 2021), we are not aware of such projects focusing on mining-related water pollution. Sure, participative monitoring has been promoted by the World Bank and the International Council for Mining and Metals to avoid or reduce mining conflicts and increase trust between communities and mining companies (CAO, 2008; ICMM, 2015). In the Athabasca Basin in Canada for instance, a uranium mining company finances a participative environmental monitoring scheme where members of local communities take water and sediment samples in collaboration with a local environmental consultancy company (CanNorth, 2015, 2016). For the mining company, the project mainly aims at reducing resistance to the mining operations and increasing trust in the company's activities.

Citizen science networks in general and community-based monitoring schemes in particular, could offer a complementary framework to fill the gaps of institutional monitoring and contribute to the improvement of natural resource governance in mineral producing countries with weak oversight agencies. Here, we present a citizen science approach that addresses the need for an innovative monitoring scheme with high spatial and temporal coverage demonstrating cause and effect of mining-related pollution. To this end, we focus our study on the case of the coal mining area of Hwange in Northwestern Zimbabwe where the water quality of the local river, Deka, is deteriorating and numerous fish kills afflict the river each year. Villagers reported livestock allegedly dying after herding around the Deka River. Pollution issues in Hwange allegedly related to coal mining and processing reached broader general public attention in 2011 after a newspaper reported "Stop coal miners or see Hwange die" (The Zimbabwean, 2011). Affected by the worsening environmental condition of the Deka River, communities started to mobilize against the pollution and express grievances towards the mining and processing companies in 2017. This led to an ongoing multi-stakeholder mediation process with government, industry and civil society organizations. Even though the Deka River pollution is broadly accepted by the industrial stakeholders, the contribution of each player to the overall pollution remained unclear and highly debated. Two studies of the Deka River's water quality identified some violation of Zimbabwe effluent standards. However, due to the one-shot nature of the analysis and other methodological shortcomings, these studies were neither able to identify the pollutants causing the loss of aquatic life and livestock nor pinpoint sources to find the culprits on the side of the companies (Nhiwatiwa, 2014; Yalala, 2017).

In this highly polarizing context, we started a community-based water quality monitoring scheme that aimed at achieving three goals 1) to examine the impacts of coal mining activities on river water quality, 2) to identify potential public health risks related to river pollution and 3) to assess the effectiveness of current mine management practices. Citizen scientists took grab samples to capture spatial relationships between sources and environmental impacts and helped to install and maintain automated sensors in order to assess potential relationships between acute pollution events and the hydrological dynamics. Trained scientists complemented the dataset by sampling additional locations. We analyzed the resulting dataset to address the concerns about potential mining impacts on the environment and community health. Based on those outcomes, we further evaluated the effectiveness of community-based monitoring for mining areas in developing countries. We describe qualitatively how to set-up such a co-production of science (Nowotny et al., 2013) between an academic institution and local communities in order to overcome systemic barriers for citizen science schemes.

3.2 Study Area

Hwange District, with its economic center Hwange Town, is located in Northwestern Zimbabwe, at the boarder to Zambia and Botswana (Figure 9). The Deka River has its source some 80 km Southwest of Hwange Town in the pristine environment of the world renown Hwange National Park. After crossing Hwange town, the river flows northeastwards into the Zambesi River passing several villages in the rural area. In this subtropical climate, rainfall is scarce with an average annual precipitation of around 700 mm (Moyo et al., 2012) and 98 % of the rainfall occurs from October to April (Chamaillé-Jammes et al., 2007). Due to climate change, the onset of the rains has significantly shifted to the end of the year (Dervieux and Belgherbi, 2020) and the region is regularly prone to severe droughts with El Niño as the major driving force for interannual climate variability (Gore et al., 2020). Community members from the villages close to Deka use the river water for catching fish as their main source of protein, breeding baskets, feeding their livestock and also as a direct source of fresh water due to lack of functioning drinking water boreholes.

In and around the town of Hwange, bituminous coal has been mined and processed since colonial times. Shortly after the discovery of the rich coal seams at the end of the 19th century, the colonial administration granted a concession of over 1000 km^2 to the Wankie (Rhodesia) Coal, Railway and Exploration Company that started producing coal in 1903 (Palloks, 1987). This mining company has been restructured several times but is still operating currently. In recent years, half a dozen other mining companies have been granted concessions to extract coal in Hwange District. Although extensive areas have been mined underground in the past, open pit mines dominate today. The largest share of Hwange's thermal coal is locally combusted at Zimbabwe's largest thermal power plant producing 40% of the country's electricity. For several decades, industrial effluents from coal mining and processing operations are channeled into the Deka River system via the main Sikabala channel (Figure 9). Currently, the activities of three coal mining companies and the thermal power plant mainly contribute to the discharge into Sikabala. The channel originates at the thermal power plant that continuously releases cooling water. Along its way, Sikabala is joined by a complex network of smaller effluent channels.

Map Study Area

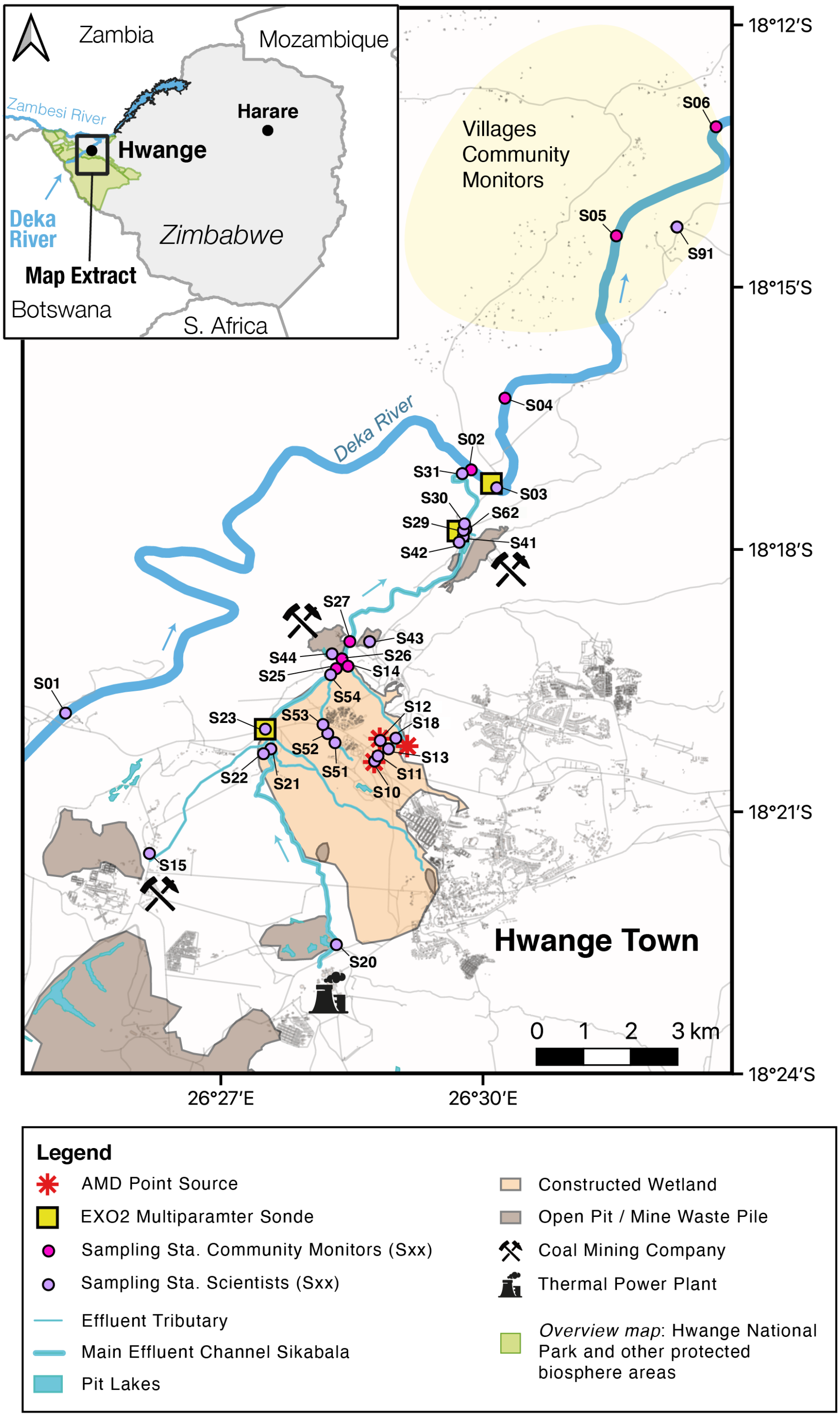


Figure 9 Overview map illustrating coal mining concessions and protected natural reserves in the Hwange District, Western Zimbabwe (top left). Detailed map of Hwange Town and surrounding villages with the Deka River, industrial sites and locations of the sampling station for the water quality monitoring and the placement of the in-situ sondes (center). QGIS maps contain administrative boundaries from DIVA-GIS (Hijmans et al., 2018) and infrastructure, buildings, and roads from (Open Street Map, 2021). Shapefiles of the protected biosphere areas were provided by the Protected Planet Initiative (UNEP-WCMC and IUCN, 2021). Some sampling stations are located outside the map extent and are not included in this figure. Coordinates of all sampling stations are listed in the Supplementary Material.

The entire system is embedded in a patchwork of several hectares of constructed wetlands, where reeds partly treat the effluent. In between, there are areas with standing water that exhibit typical field indicators for AMD such as disturbed biota and “yellow-boy” mineral precipitates that cover stream beds and banks (Lottermoser, 2010). These areas are located on top of underground mines that have been closed in the 1960’s to 1970’s. Here, acidic groundwater reaches the surface through former service- and exploration boreholes. In recent years, artesian wells with water fountains of several meters’ height have built up. The boreholes have been unsuccessfully plugged and the groundwater is still reaching the surface, accumulating in small lakes. After crossing the wetlands, Sikabala episodically receives additional mine water from current open pit activities and, especially during rainy season, wash out of coal particles from mine waste heaps. After heavy rainfall events, spontaneous overflow of strongly acidic water accumulated in pit lakes or even illegal pumping of this pit lake water might significantly add to Sikabala effluent volume and contaminant load. Sikabala and the entire effluent drainage network is not fenced and is regularly accessed by the population living and working nearby. From the source to the confluence with the Deka River, Sikabala flows for around 20 kilometers. It joins the Deka River just a few meters downstream of a small dam that was constructed during colonial times. The river upstream of the inlet of Sikabala channel runs dry approximately from July to October and therefore Sikabala is the only water feeding Deka in that period. (Pictures of the Sikabala effluent channel and Deka River are provided in Suppl.-Figure 15 to Suppl.-Figure 38 in Appendix B).

3.3 Materials and methods

In total, 13 community members from four different villages located along the Deka River participated in the community-based monitoring. They self-identified as “community monitors” and chose to group in 4 teams. On a weekly to bi- weekly frequency, they sampled 8 spots along the Deka and the Sikabala tributary. Regularly, two trained scientists conducted sampling campaigns taking samples at another 28 locations in the study area. Researchers also installed multiparameter in-situ probes to record water quality parameters. In a joint excursion, community monitors and scientists sampled five drinking water boreholes in the broader Hwange District. (The chemistry of the drinking water boreholes is presented in Suppl.-Figure 12 in Appendix B).

3.3.1 Community-Based Environmental Quality Monitoring in Hwange

Training

On 14 December 2018, researchers conducted a sampling training workshop at the primary school in the village of Mashala. The training introduced community members with limited formal education and scientific literacy to fundamental knowledge about water quality and sampling. Using an illustrated training manual (Suppl.-Figure 3 and Suppl.-Figure 4 in Appendix B), the training focused on measuring pH by using test strips and taking water samples while minimizing sample contamination. The community monitors were also encouraged to store the samples safely in dry and dark places in their houses. During this training meeting and subsequent test sampling, the community members and the scientist jointly decided where to locate the sampling spots in the Deka River. We advised community monitors to catch dead fish if a fish kill occurred (Demography of the community monitors and further information on the collaboration is documented in Suppl.-Table 4 in Appendix B).

Sampling

Community monitors took unfiltered 50 mL water samples in polyethylene falcon tubes provided by the project. In total, they collected 420 grab samples in the time span of December 2018 to March 2020.

Three sampling stations were located on the Deka River downstream of the confluence with the effluent channel Sikabala while another station was situated upstream. In addition, three sampling stations were located along the Sikabala and one at a main AMD tributary (coordinates of all sampling stations in Suppl.-Table 6 in Appendix B). Community monitors rinsed sampling tubes three times with the test water before taking the sample. They measured pH in the flowing water using test strips (Merck pH-Indicator strips pH 2.0 – 9.0 MColorpHast™) and recorded data in their notebooks including date and time of sampling, weather condition, water color, observations about the ecosystem condition such as presence of fish and insects (Suppl.-Figure 5 and Suppl.-Figure 6 in Appendix B). Their notes were later digitized. Community monitors labelled the samples with a code, including the initials of each community monitor and continuous numbers (Suppl.-Figure 7 in Appendix B). In order to minimize contamination and health risks, community monitors took unfiltered and unacidified grab samples. While taking acid-free samples is not a standard procedure, it has been successfully used for sampling and analysis of trace metals in stream water (Erel et al., 1991). In the rainy season of 2019/2020, community monitors agreed to record rainfall data in order to fill the gap of missing rainfall records. Community monitors mounted conical rain gauges (plastic, max holding capacity 100 mm, electrosales, Zimbabwe) at three locations in the Hwange District and recorded daily precipitation.

Follow-Up Meetings

Every few months, researchers organized meetings in the rural area to exchange experiences and challenges of the sampling, to ensure continuity and maintain the motivation and quality of the effort (Meetings are listed in Suppl.-Table 5 in Appendix B). Scientists reported and explained the chemical results of laboratory analysis of previous water sample shipments and related them to potential health impacts. Community monitors handed their water samples to the scientists for subsequent shipment and analysis in the laboratory in Switzerland. Scientists took photographs of the sampling notes in the personal notebook of each community monitor. Difficulties with regard to the sampling protocol were discussed and additional training exercises implemented. At each meeting, community monitors decided together with the scientist about the sampling day and frequency. After some meetings, the group decided to name group leaders for each sampling team in order to ease communication between scientists and community members. In between the physical meetings, scientists and community monitors kept continuous exchange via phone calls and text messages. Community monitors received 1 to 2 USD phone credit per month to their mobile phone in order to facilitate communication.

3.3.2 Trained Scientists Environmental Quality Monitoring

Two trained scientists collected another 354 water samples, mainly quadruplicates with different sample treatments, covering additional 28 sampling locations. They occasionally took samples to compare their results to the ones from the community monitors. However, they mainly focused their sampling campaigns on spots that were not covered by the community-monitoring scheme. This consisted in AMD point sources, minor tributaries to the Deka River and other pollution hot spots in the mining area. Further the researchers took upstream samples that were too distant from the villages of the community monitors. At sampling locations, they measured in situ parameters (pH, water temperature (°C), conductivity (μS cm^{-1}), dissolved oxygen (mg L^{-1}) and redox potential) using a handheld WTW Multiprobe 340i. They took 15 mL water samples in polyethylene falcon tubes and used four different sample treatments per sampling location: 1) unfiltered, unacidified, 2) filtered, unacidified, 3) unfiltered, acidified and 4) filtered, acidified. The filtered samples were immediately filtered using a pre-rinsed syringe and a 0.45- μm Millipore membrane filter mounted on the syringe. For acidification, they added a few drops of ultrapure nitric acid (69%) to the sample. Scientists also sampled AMD-related colorful yellow-white precipitates that coated the rocks.

Automated Multiparameter Sondes

With the support of the community monitors, scientists installed three YSI EXO2 Multiparameter Sondes in September 2019. The installation aimed at complementing the community monitoring with additional parameters. The sondes recorded water quality parameters chlorophyll a (Chl a), conductivity, temperature, fluorescent dissolved organic matter (fDOM), turbidity, pH and dissolved oxygen (DO). Before the probes were installed, the sensors were calibrated using water-saturated air for the DO sensor and pH buffer solutions (pH 4.01 and pH 7 Merck Supelco ®) for the pH sensor respectively. Readings were cross-checked with those of the handheld WTW Multiprobe 340i. One probe (named ZIM 1) was installed in Deka River downstream of the inlet of Sikabala (Figure 9). Two of the devices were placed in Sikabala effluent stream, one before (ZIM3) and one after (ZIM2) receiving the main share of the mine waste water. ZIM2 was fixed to a small bridge around 2 km before Sikabala reached the Deka River. Unfortunately, there was no opportunity to install a probe upstream. The battery-powered probes recorded water quality parameters every 30 min and where recalibrated and redeployed after 2 months of continuous measurement. We dispatched the three probes on 21/22 September 2019. On 18 January 2020 a flood event ripped off ZIM1 and ZIM3 from their anchor at concrete bridge pillars. After this loss, we removed probe ZIM2 in February 2020. The data series for all three sondes covers the period between the installation on 21/22 September to the last calibration on 8 November 2019. Only ZIM2 recorded the period between 8 November 2019 to 13 February 2020 (Data presented in Suppl.-Figure 13 in Appendix B).

3.3.3 Laboratory Analysis in Switzerland

The samples were shipped to Switzerland for chemical analysis and filtered with 0.45- μm nylon membrane filters. We diluted the samples in ratios between 1:10 and 1:1000 with 1% HNO3 in distilled de-ionized (DDI) water depending on the metal concentration. For the chemical analysis, we used the Inductively Coupled Plasma Mass Spectrometer (ICP-MS) facilities at ETH Zurich and Eawag: Agilent models 7500, 8900 and 7900. In the majority of the measurement series, we determined the concentration of 29 elements: Li, Be, B, Na, Mg, Al, Si, K, Ca, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Mo, Cd, Cs, Ba, Tl, Pb, Bi and U using multielement standards (ICP-MS Multielement Standard Solution ROTI®STAR by Carl Roth, Art No 6802.1 and Multielement-Standard 21 Elemente by Bernd Kraft; Art No. 32195.0000). To estimate the limit of detection (LOD) and limit of quantification (LOQ) we measured a set of 12 blank samples (1% v/v HNO3 69% in DDI water). Merck X Multi element standard was used as reference standard for digestions of water samples and NIST 1643 f reference standard was used as a quality check for ICP-MS measurements. To evaluate total metal concentration, we additionally digested 231 samples using 2 mL of sample and adding 3 mL of HNO_3 69% and 1 mL of H_2O_2. The samples were transferred into MLS-Ultraclave for microwave digestion under a pressure of 160 bar and a temperature of 200°C. For a series of 144 samples, we measured the concentration of anions such as sulphate, fluoride and chloride using Ion Chromatography (Metrohm 930 Compact IC Flex, AuA Laboratory, Eawag Dübendorf, Switzerland).

3.3.4 Data Treatment

We used R for data analysis (R Core Team, 2018) and plotted figures using ggplot 2 (Wickham et al., 2019). R scripts and primary data are publicly available under https://www.research-collection.ethz.ch/handle/20.500.11850/535761. The sampling points of the Deka River upstream run dry during later dry season between July and October 2019 and we excluded stagnant water data because Deka upstream was not feeding Deka downstream anymore. For our analysis, we use the rain fall recordings of the Agritex (Ministry of Agriculture) in Hwange Town to define the duration of the rainy season: 1 November 2018 to 11 April 2019 and 12 November 2019 to 16 April 2020 (Data is included in Appendix B).

3.4 Results

3.4.1 Water Quality of Deka River

Our water quality data shows dramatic increases in the concentrations of many elements in the Deka River as it crosses the point of mining discharge (Figure 10). Conductivity averaged 465 μS cm^{-1} upstream and jumped to a mean of 1140 μS cm^{-1} at the first sampling location downstream. Upstream pH was 6.98 compared to average readings via pH meter of 5.56 downstream. The pH measurements of community monitors using test strips showed a similar pattern, but appeared to be biased toward more acidic values, with a minimum of pH 5 upstream during flooding and 4.5 during late rainy season at the first community monitoring sampling station downstream (Figure 10A). The pH values downstream of the effluent canal were regularly well-below fresh water guidelines of the national environmental management agency (Zimbabwe Government Gazette, 2007) and the WHO drinking water regulations (WHO, 2017) of pH 6 and 6.5 respectively. The change of water quality in the Deka River could occasionally be observed with the bare eye since its water color changed from its usual state of blue-brown to a milky blue-green color (see Suppl.-Figure 20 and Suppl.-Figure 21 in Appendix B).

Many metals and main anions show a similar behavior, jumping in concentration after passing the effluent canal Sikabala (Figure 10B). Most trace elements, however, remain below water quality thresholds with concentrations in μg L^{-1} range. Manganese (Mn), nickel (Ni) and arsenic (As) are notable exceptions. We detected downstream concentrations of Mn of up to 6.8 mg L^{-1} and many additional measurements in excess of the EMA guidelines of 0.1 mg L^{-1}. Ni values reached up to 95 μg L^{-1} downstream and were sporadically above the recommended WHO drinking water values (70 μg L^{-1}) but below national EMA river water standards (300 μg L^{-1}). Overall, most elemental concentrations are continuously decreasing in flow direction with distance from the inlet of the effluent channel.

As values did not follow the pattern of other elements and do not appear to be related to the effluent canal, but are notably high throughout the surveyed area, especially during the peak of the rainy season in February and March. We observed the highest As value in the Deka upstream of the mine discharge, reaching up to 31 μg L^{-1} in March 2019 while downstream values remained below 17 μg L^{-1}. These values did not exceed EMA fresh water standards (50 μg L^{-1}) however, they were above WHO drinking water guidelines (10 μg L^{-1}). The geogenic background level of fluoride reaches high levels of 2.2 mg L^{-1} in drinking water boreholes of the Hwange District (see data in Appendix B). Sulfate concentrations, a key indicator of acid mine drainage related sulphide-weathering (Dold, 2014), exceed national and international water guidelines downstream in the Deka River around 2-fold.

Community monitors reported fish kills on several occasions, among which 5 January 2019, 25 September 2019, and 13 October 2020. Dissolved aluminum (Al) concentrations in the Deka downstream reached up to 2 mg L^{-1}, total concentrations even up to 5.3 mg L^{-1}. Al is known for its toxicity to fish in acid to circumneutral water conditions. The phenomenon has been studied intensively during the fresh water acidification and decline in fish populations in Scandinavia (Poléo et al., 1997). At acidic pH values, Al has an effect on the ion regulation in the gills whereas at neutral to alkaline pH condition it has physical effects resulting in asphyxiation once coating happens at respiratory membranes with Al hydroxides (Exley et al., 1991; Gensemer & Playle, 1999; Rodriguez et al., 2019).

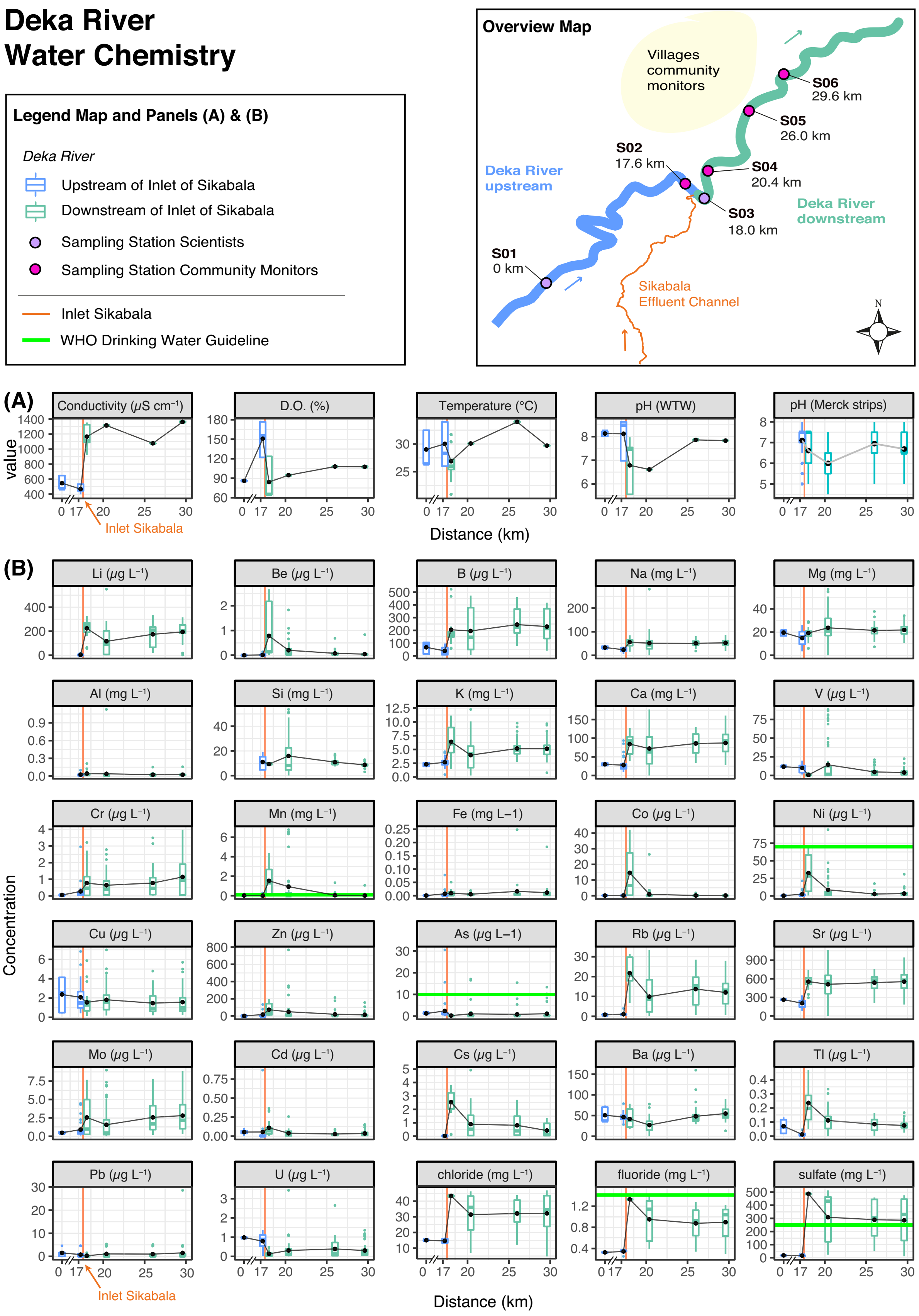


Figure 10 Overview map shows sampling locations in Deka River upstream (blue) and downstream (green) with respect to inlet of Sikabala effluent channel (orange). (A) Boxplots of field parameters of Deka River. (B) Boxplots of dissolved metal concentrations from 298 unacidified samples (out of which 276 grab samples) taken between 14 December 2018 and 31 March 2020 in Deka River. WHO water quality thresholds (WHO, 2017) are shown as horizontal green lines if exceeded. Black dots represent average values and black lines indicate trend between them. X-axis is discontinued between 0 and 17 km tick, namely between the two Deka River upstream sampling stations. Orange vertical line indicates position of Sikabala inlet.

3.4.2 Main Effluent Channel Sikabala and Source Attribution of Tributaries

The industrial effluents in Hwange form a complex network of channels which is partly embedded into a constructed wetland. Sikabala is the main channel that discharges effluent into Deka, and it drains various potential sources from different coal mining and processing activities. We monitored metal concentrations in different sections of the Sikabala channel to estimate the relative contribution of the tributaries on pollutant loads (Figure 11, pictures of different Sikabala sections provided in Suppl.-Figure 28 to Suppl.-Figure 39 in Appendix B). In Section A, Sikabala is mainly carrying cooling water from the thermal power plant. Afterwards tributaries add discharge from concessions of three different coal mining companies which are labeled as Section B, C and D respectively. A selection of elements for the dry and rainy season illustrates the seasonal effects on water chemistry (Figure 11).

At the source of Sikabala where the thermal power plant released cooling water (S20), we observed low transition metal concentrations, with Ni 5.1 μg L^{-1}, iron (Fe) 14 μg L^{-1} and Mn 41 μg L^{-1}. Other elements are comparably low with calcium (Ca) 34 mg L^{-1}, magnesium (Mg) 5.9 mg L^{-1} and sulfate 99 mg L^{-1}. The pH values are in the lower alkaline range (average pH 8.41) and conductivity was comparably low with an average of 410 μS cm^{-1}. After some flow distance in NE direction, Sikabala enters a constructed wetland and is joined by partly treated sewage from Hwange Town and partly attenuated waste water from industrial processes such as the coal preparation plant. As the other sampling stations of Section A, notably S23 and S25, illustrate, this has a minor impact on the dissolved metal concentration in Sikabala. The pattern changes at sampling station S26, when specific metal concentrations shoot up, most notably Mn and Ni. The sampling station S26 is located after the most important AMD tributary, the outlet from a constructed wetland of the largest mining company in the area, joined Sikabala. This channel has high metal concentrations reaching up to Mn 11.6 mg L^{-1}, Fe 1.7 mg L^{-1} Ni 539 μg L^{-1}, sulfate 1.4 g L^{-1} and showing pH values as low as 3.28 and conductivity as high as 2630 μS cm^{-1}. Pollutant concentrations in Sikabala remain at high levels and tend to increase in flow direction. In the rainy season, we observed a slight attenuation linked to a dilution effect downstream of this AMD tributary. Section C receives non-point discharges from a second mining operator with open pits close to Sikabala. Here, rainwater washed out coal fines from waste heaps during the wet season. Within the 500 m flow direction that separate S27 and S29, a third mining operator episodically discharges effluent. This operator was on halt at the beginning of the community-based monitoring and resumed operations in September 2019. The discharge of that mine episodically doubled the concentration of specific metals such as Mn, Ni, zinc (Zn). The Sikabala collected all mining effluents in Section D, where the runoff estimated via a mobile-phone app in mid- September 2019 (late dry season) was around 650 L s^{-1} (Information about mobile-phone app in Appendix B).

3.4.3 Sources of Metal Pollutants

At AMD point sources, electrical conductivity reaches close to 4000 μS cm^{-1} with pH values as low as 2.54. Dissolved metal concentrations at the sources are up to 13 mg L^{-1} for Mn and 160 mg L^{-1} for Fe (S12) and episodically exceed EMA Red Effluent standard (Zimbabwe Government Gazette, 2007) by factors of 30 (Mn: 0.5 mg L^{-1}) and 20 (Fe: 8 mg L^{-1}), respectively. Because of low pH at AMD sources, total concentrations of Fe and Mn are close to dissolved ones, which also holds for aluminum concentrations of up to 60 mg L^{-1}. The Fe data illustrate the attenuation effect of the artificial wetlands, where cations are removed from the water by adsorption, co-precipitation, or sedimentation. The concentration of total Fe was as high as 160 mg L^{-1} at specific point sources and after passing the reeds, they dropped by almost two orders of magnitude to 1.7 mg L^{-1}. The neutral cooling water from the upper Sikabala diluted the Fe load by another order of magnitude to 0.12 mg L^{-1}.

Chemistry Sikabala

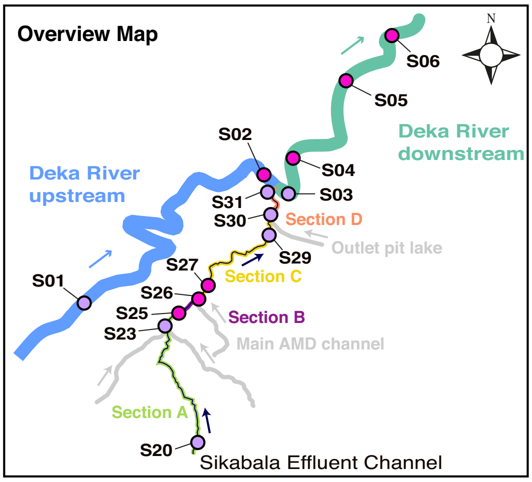
Legend Map and Panels (A), (B), (C), (D)

- ○ Sampling Station Scientists
- ● Sampling Station Community Monitors

Deka River
- Upstream of the inlet of Sikabala (S01, S02)
- Downstream of inlet of Sikabala (S03 to S06)

Main Effluent Channel Sikabala
- Section A (S20, S23, S25)
- Section B (S26)
- Section C (S27, S29)
- Section D (S30, S31)

Tributaries to Sikabala
- Effluent Tributaries joining Sikabala



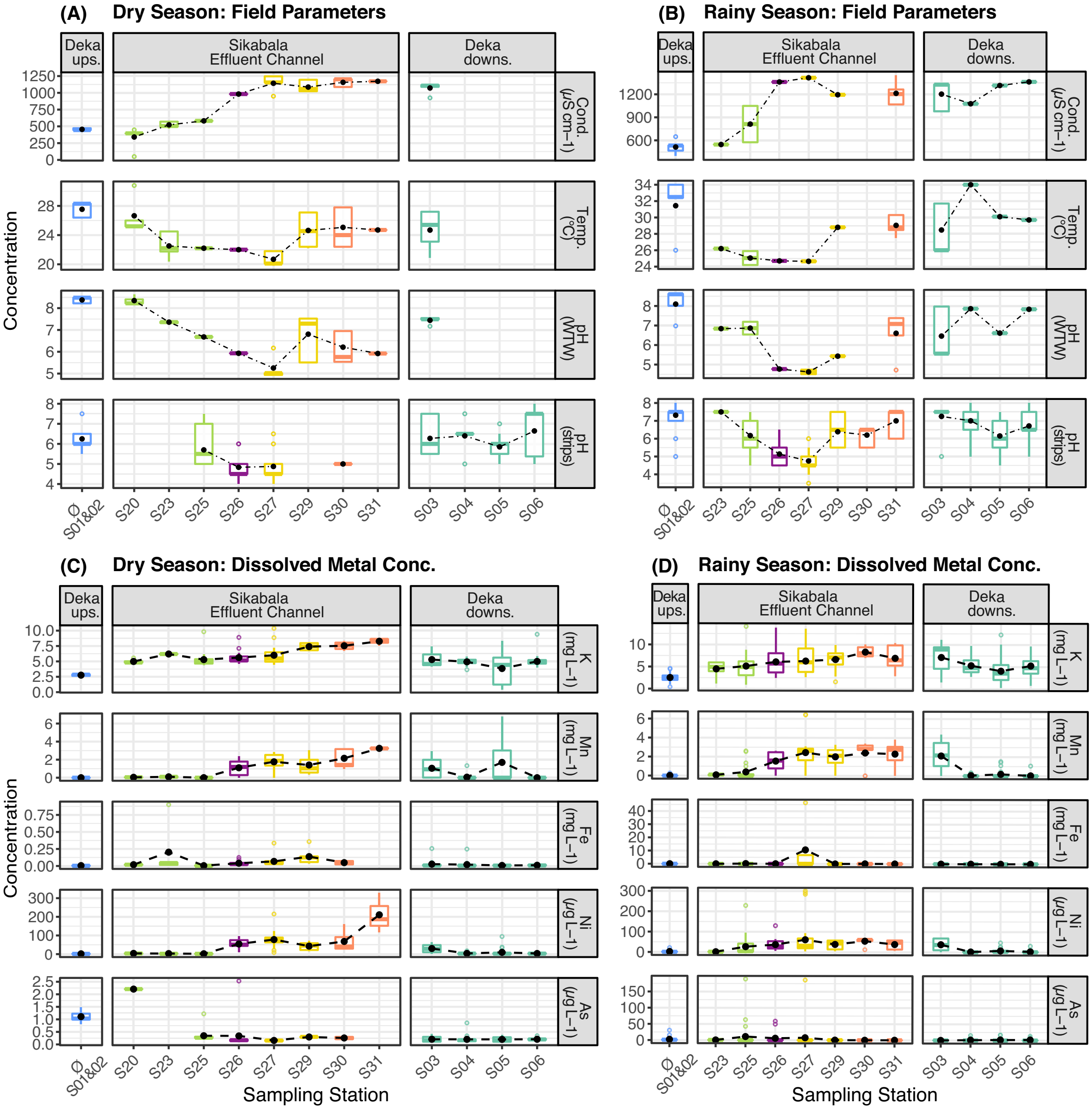


Figure 11 (A,B) Boxplots of field parameters in the dry and rainy season, respectively. (C,D) Boxplots of dissolved metal concentrations for the dry and rainy season, respectively. Water sampled between December 2018 and March 2020: 379 grab samples from community monitors, 173 triplicates from scientists (filt./acid.; unfilt./unacid.; filt./unacid.). Black dots represent average values and dashed lines show trend between them. In each panel, the first and last facet show data in Deka River up- and downstream of the inlet of effluent channel Sikabala, respectively. The middle facet shows data of sampling stations within Sikabala. Color code relates to the different sections in Sikabala. Concentrations of Deka River upstream are depicted for comparison by averaging the data measured at sampling points S01 and S02 (Ø S01 & 02). Scale of Y-axis varies between dry (A,C) and rainy season (B,D).

High concentrations of ferric iron are usually hydrolyzed and precipitated at pH > 2 , as different ochreous minerals such as jarosite (pH 2), schwertmannite (pH 2.5–4), or ferrihydrite (pH 5) form (Sánchez España, 2008). Precipitates have the characteristic yellow-red coloring at point sources of AMD also known as “yellow-boy” (Lottermoser, 2010). Whitish precipitates coated the rocks of the streambed of Sikabala at sampling station S27 (see Suppl.-Figure 34 to Suppl.-Figure 37 in Appendix B). Those efflorescences consist of Al-(oxy)hydroxides (data in Appendix B) that precipitate at pH > 5 and that were observed in other AMD environments after Al- rich acid waters reach more neutral pH levels through dilution or neutralization (Nordstrom, 2011). The precipitation of nanocrystalline Al-phases as white coatings on the bedload has also been observed in undisturbed alpine environments where acidic metal-rich mountainous streams are neutralized after mixing with neutral tributaries (Wanner et al., 2018).

Secondary Al-phases would therefore explain the milky white color that the Sikabala sporadically takes after the acidic AMD effluent channel mixes in (see pictures in Appendix B). In contrast, iron precipitates within the wetland and along Sikabala, with new secondary minerals precipitating each time at the confluence with a more neutral effluent. This results in rather low iron concentrations in the Deka River downstream of Sikabala. Copper (Cu) concentrations decreased by about 5 times after passing the constructed wetland and lead (Pb), molybdenum (Mo), caesium (Cs) and Ni were reduced by a factor of 2. Mn, however, remained almost as high as at the source. We observed no major dilution effect at point sources during the rainy season. Mn concentrations at the point sources of AMD were only about a tenth of iron concentration, but after reaching the Deka River, Mn exceeded the Fe concentrations about 1000-fold. Pit lakes, where mine water accumulates in mined-out pits, show similar values, but with even more extreme maxima. One deep red colored pit lake (S44) showed pH values as low as 2.65, conductivity of 4180 μS cm^{-1} and dissolved concentrations reached 3 g L^{-1} sulfate, 250, 200 and 30 mg L^{-1} Fe, Al, and Mn, respectively, while Zn, Ni and Cu were at 40, 6, and 3 mg L^{-1}, respectively.

As described above, the source of mine water is much more concentrated than Sikabala. Pollutants such as Fe, can strongly be attenuated via the wetlands or the dilution with less polluted waste water streams. Without the mitigation effect of the wetland for instance, concentrations in Sikabala could possibly be an order of magnitude or more higher. In the Hwange area, hundreds of thousands of cubic meters of highly concentrated mine water reside in pit lakes that are potential sources for future river pollution.

3.4.4 In-situ Sensors Combined with Community-Based Monitoring Data

The YSI EXO2 Multiparameter Sondes recorded data every 30 min and provided a clear picture of the dynamic range of water quality parameters and the dramatic effects of illegal mine water pumping. During the first days after the deployment, ZIM1 (Deka River downstream of inlet of Sikabala) and ZIM2 (Sikabala) show a perfectly parallel behavior for pH and conductivity (Figure 12). In the morning of 25 September 2019, ZIM2 measured an abrupt drop from pH 7.39 to 4.0, lasting only about 1 hour before recovering to pH values above 7. Simultaneously, conductivity values shot up to over 5000 μS cm^{-1} (Figure 12).

The probe located in the Deka River (ZIM1) also recorded a drop in pH, but the values took several days to recover. These changes were not recorded by the sonde located upstream in Sikabala (ZIM3). For the same date, community monitors and government officials reported that the recently reopened coal mine had illegally pumped old pit water for several hours into Sikabala resulting in a fish kill in the Deka River.

Several thousand cubic meters of contaminated pit water reached the Sikabala just a few meters downstream of the probe ZIM 2. The inflowing pit water created a backflow and ZIM2 recorded the change in water quality. A few days later on 30 September 2019, the environmental management of the concession owner attempted to stabilize pH by with adding bags of lime to the Sikabala stream. This neutralization attempt was recorded by the pH signal at ZIM2 shooting up from 7.47 to 9.17 and ZIM1 at Deka River climbing up to pH 8.06.

3.5 Discussion

3.5.1 Geochemistry

Analyzing the water quality of the Deka River before and after the inlet of the main effluent channel Sikabala proves that the Deka River's water quality is satisfactory upstream of the inlet of Sikabala and clearly deteriorates afterwards. Generally, the more mine water enters the Sikabala, the higher the pollutant concentrations. The water chemistry data allowed to trace the parameters from the actual sources of metal pollution to the channels and ultimately to the Deka River. We followed a variety of specific metals and field parameters such as pH and conductivity from the mining concessions all the way to the river evidencing cause and effect. The water chemistry of Sikabala and of the confluence with the Deka River reveals the presence of a broad range of metals that are characteristic of acid mine drainage of coal seams. Here, bivalent cations such as Mn^{2+}, Fe^{2+}, Ni^{2+} are main indicators and can be followed along flow direction documenting that mine drainage contaminates the Deka River and violates drinking water regulations during the dry and wet season. Our data provides strong evidence that the pollutant concentrations in Deka River attenuate with increasing distance from Sikabala, which supports the assertion of the community members that Sikabala is the main source of pollution.

Manganese and Arsenic as Public Health Risks

Specifically, Mn exceeds national and international water standards by almost two orders of magnitudes. Manganese causes major challenges in the treatment of acid mine waters: In contrast to Fe^{2+} (Singer and Stumm, 1970; Wehrli, 1990), the oxidation of dissolved Mn^{2+} proceeds extremely slowly at low pH (Diem and Stumm, 1984; Morgan, 2005). The kilometers-long transport of Mn from AMD sources over Sikabala to the Deka River is illustrative to the difficulty of removing it from mine waters and its persistence as a metal pollutant. Precipitating manganese requires either high pH values (Morgan, 2005) or the presence of strongly sorbing mineral particles or active bacteria (Davies & Morgan, 1989; Friedl et al., 1997).

As mentioned previously, the Deka River is also used as source of drinking water for community members that do not have access to functioning boreholes. Although manganese is an essential nutrient that is relevant for bone formation and for amino acid, cholesterol and carbo-hydrate metabolism, excess Mn can have adverse effects on the central nervous system with lesions and symptoms similar to those of Parkinson's disease (Russell et al., 2001). In the Deka River downstream of Sikabala, concentrations of Mn episodically reached close to 7 mg L^{-1}. These elevated concentrations of Mn represent a public health risk for communities who regularly drink this water.

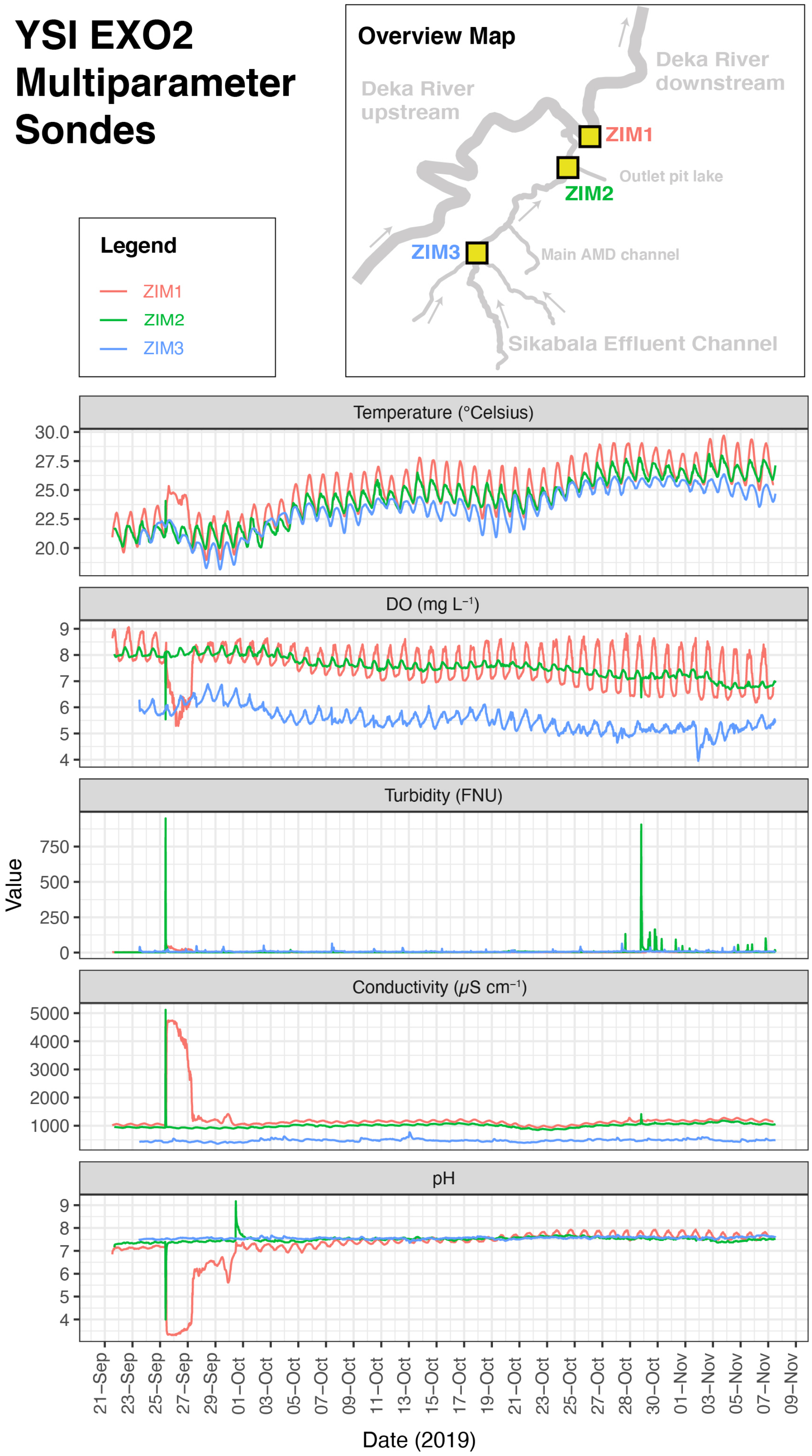


Figure 12 Temperature, dissolved oxygen (DO), turbidity, conductivity and pH measured by the YSI EXO2 Multiparameter Sondes (ZIM1, ZIM2, and ZIM3) from 23 September to 8 November 2019. Overview map shows probe locations: ZIM1 monitored the Deka River downstream of the Sikabala inlet. ZIM3 was located in Sikabala upstream of the main inflow of mine water and ZIM2 downstream of it.

Unlike many of the other compounds of interest, arsenic showed roughly equal and elevated concentrations throughout the local waterscape. Values are highest before the mine water mixes and they largely exceed concentrations measured at AMD point sources. The peaks in As concentrations in the upstream Deka and in the Sikabala River coincide with periods of abundant rainfall and flooding (see rainfall data in Appendix B). Therefore, atmospheric deposition is more likely to be the process driving the concentration of the metalloid in the Deka River. Geogenically, the occurrence of arsenic is mainly linked to the abundance of pyrite in the coal and adjacent lithologies (Yudovich and Ketris, 2005). Our results indicate that arsenic might enter the environment through the combustion of coal at the thermal power plant. Analyses of wet deposition would be required to test this hypothesis. The share of arsenic released to the atmosphere at thermal power plants depends on the combustion regimes and efficiency of pollution control systems and might reach up to 50% of the total arsenic present in the coal (Yudovich and Ketris, 2005). Hwange Power Station was designed to utilize low- grade high- sulfur coal which was discarded as waste prior to the thermal power plant's commissioning in 1983 (Palloks, 1987). According to a local professional, a lack of investment and maintenance caused a failure of the pollution control systems of the Hwange Power Station. Therefore, large pollutant loads were emitted to the atmosphere potentially causing human health risks for chronic As exposure.

Effectiveness of Environmental Management

In contrast to manganese, iron is effectively removed from the Sikabala before reaching the Deka River. The results of the Fe chemistry show the importance of the constructed wetland system for attenuating the total metal load before reaching the Deka River. These removal processes can be observed comparing the concentration of metals at AMD point sources with respect to values after the wetland. Iron oxyhydroxides such as goethite are important secondary minerals formed in AMD environments and important sink for various other elements: Nickel does not form discrete secondary nickel hydroxide or oxide phases but the bulk of Ni^{2+} is co-precipitated along with goethite (Alpers, et al., 1994). Surface adsorption of Ni^{2+} on the other hand, is most effective at $pH > 5$ (Senthil et al., 2010). At the time of our field study, the wetland had a reduced removal capacity compared to the initial state. Constructed wetlands need maintenance and among other factors, weed invasion, loss of plants and bank erosion should be monitored and managed (Beharrell, 2004), which was not the case. To the contrary, around a third of the wetland area had dried up because a coal mining company constructed a road through the wetland. The remaining wetland is fragmented, and its patches sum up to an area of around 1.3 km^2 on the northern side of the main road (Figure 9). At known AMD point sources, we observed that the mining company in charge regularly performs liming by throwing bags of lime into the effluent without estimating the necessary buffer capacity.

The artificial wetlands successfully remove a major part of the Fe load and other metals that coprecipitate with iron hydroxides, but the neutralization capacity is not sufficient and effluents downstream of the wetlands were not attenuated. When acute mine water spills happened, concession owners proceeded to liming without dosing system.

3.5.2 The Important Contribution of Local Knowledge in Co-production

The weekly to biweekly sampling over 1.5 years in a dozen locations was only possible in a team effort between community monitors and scientists. With 420 water samples, the community monitors collected most of the water samples covering the entire hydrological year. Together with the samples from the scientists, this effort resulted in a rich dataset on water quality of the Deka River and its seasonal dynamics. This outcome would not have been possible in a classic international scientific project with short sampling campaigns. Community monitors were able to react to observed changes in their environment and sample spontaneously. During their numerous field visits, they took notes about environmental conditions and contextualized the changing water quality in the Deka River with their valuable long-term experience. This allowed scientists to interpret peak events in the water chemistry. This local point of view was especially valuable for interpreting the continuous data of the YSI EXO2 probes in the river. These devices allow to recording water quality parameters remotely. However, in a complex system where biogeochemical processes overlap with human activity such as illicit mine water pumping, every field observation is valuable to interpret automatic recordings.

3.5.3 Challenges and Limits of the Community-Based Monitoring

Data Quality

Citizen science literature suggests that knowledge and data collection experience figure among decisive success factors of projects (San Llorente Capdevila et al., 2020). Community members in rural mining communities mainly have a low education level and poor scientific literacy related to elevated poverty rates (Castañeda et al., 2016). This suggests the need of an in-depth training that is adapted to the competences of the citizens. Our experiences support not only the need of such in-depth training, but specifically a tight follow-up on the sampling protocol to identify potential errors. Although most community monitors had a similar level of basic formal education, for some of them it was easier to follow the sampling protocol than for others. Once for instance, the scientists delivered another type of pH strips with an alternative color-coding. This led to confusion among some of the community monitors and resulted in incorrect pH measurements. During the following project meeting, scientists discussed sampling challenges with the community monitors and identified these mistakes. This allowed excluding the invalid data.

Therefore, physical encounters and face-to-face discussions were key to judge the personal capacities of each community monitor and eased the interpretation of the community monitors' notebook observations. Overall, pH strips are valuable indicators but have a limited accuracy. In the field, scientists compared pH measurements from test strips with the digital multimeter and detected that users of pH strips (both, scientists and community monitors) tend to underestimate pH in the circumneutral range by around 1 pH unit. pH strips are interpreted more accurately in the acidic range of pH 3 to 4.5 (Data comparison provided in Suppl.-Figure 8 in Appendix B).

Communication Equipment

In many rural areas of Sub-Saharan Africa, poor service provision from lacking mobile phone network coverage (GSMA, 2021) to inexistent electricity grids (Arderne et al., 2020) are prevailing. Only 20% or less of the population of Sub-Saharan Africa have access to modern smartphone- or other information technologies (Poushter, 2016). In our citizen science project, these boundary conditions shaped communication and observations protocols limiting the response capacity of the community-based monitoring during acute pollution events. At specific occasions when community members observed peak pollution events like fish kills, only few community monitors spontaneously went sampling but they failed to alert others. This missing coordination was related to a lack of mobile phone equipment, phone credit and insufficient network coverage. Some community members did not have a phone at the beginning of the project and only two members had smartphones and access to internet messaging. We decided to work only with the resources available to the local community instead of providing additional electronic equipment. Since communication via internet was limited, a direct contact person in Hwange or at least in Zimbabwe had the important role to keep regular phone contact with community monitors to stay informed.

Lack of Local Laboratory Infrastructure and Role of Scientific Partner

Like in most developing countries, local universities in Zimbabwe often lack analytical equipment for trace element analysis and commercial laboratories delivered poor quality results at a comparatively high cost (data comparison provided in Suppl.-Figure 11 in Appendix B). Shipping samples abroad for analysis, as performed during this project, is logistically challenging and costly. In addition, it was not possible to find a strong partner, in civil society or else, with enough interest, scientific literacy and financial resources to continue to manage the monitoring project. In the multi-stakeholder meetings, no participant questioned the quality of the community-based monitoring data and the impartiality and fairness of its interpretation. We assume that the close support and lead of the community monitoring by a case-independent scientific unit fulfilled the role of a “honest broker” (Pielke, 2007) and was key for the acceptance of the monitoring results in such a politicized context.

Short- and Long-Term Outcomes

The data generated in the community-based monitoring was presented by researchers and community monitors in a multi- stakeholder meeting in April 2019 and in the following, new insights from the monitoring have regularly been exchanged with various stakeholders from local government and mining industry. Most outspoken community monitors formed a pressure group and used the chemical data to advocate for their grievances, which reactivated the mediation process. About a year after the onset of the community-based monitoring, one company had finally sunk three boreholes in the villages affected by the pollution and another company had commissioned a feasibility study. These measures at least partly responded to the main grievances of the community monitors. The requests of drilling additional boreholes and the long-term objective of improving mine management remain open.

Even though the monitoring project was able to fulfill its key objectives of identifying the sources of pollution and evaluate health risks, the long-term improvement of the pollution situation in Hwange would need a commitment that exceeds the time frame of a research funding scheme. In Hwange, some highly motivated community monitors wanted to continue sampling after the official closure of the project, but we could not provide the analytical infrastructure any longer, which illustrates the limitations of short-term research projects.

3.6 Conclusion

Based on the data of the community-based monitoring, we showed that coal mining and combustion are degrading the water quality of the Deka River. The main effluent channel Sikabala that joins Deka River carries along a variety of metals that relate to those found in very high concentrations at the point sources of acid mine drainage (AMD). These AMD sources are mining legacies from former underground mines. Our findings show that AMD formation is mainly responsible for critical loads of Mn^{2+} and other bivalent transition metals in the river downstream of the inlet of the main effluent channel Sikabala. The constructed wetlands remove a major part of the iron load and other metals that coprecipitate with Fe, but the neutralization capacity is not sufficient. Active open pit mines located along Sikabala add to the pollution concentration of this main effluent tributary by punctually discharging additional mine water. These sources emit effluent after the wetlands and subsequently metal concentrations are poorly attenuated. Pollutants are most probably also entering the river system via the atmosphere, as punctually high arsenic concentrations during rain events suggest. A potential source of these emissions is the thermal power plant.

Since the Deka River also provides drinking water, mainly manganese and to a lesser degree nickel and arsenic are of concern for a human health perspective. These elements regularly exceed drinking water standards, with manganese being the most drastic case, surpassing standards around 70-fold. We suggest commissioning a public health study in the Hwange District to determine potential health effects related to high manganese exposure. We also recorded illegal pumping of pit water that deliberately violate environmental emission standards and reflect worst mining practice. Therefore, the strongly acidic pit lakes in the Hwange area present a high- risk factor for Deka's ecosystem health if mine managements continue to neglect environmental issues. Our results suggest that the practice of coal mining and power generation in Hwange need improvement on each level, from dealing with AMD mine legacies over mining practice for active open pit mines to limiting toxic atmospheric emissions.

The community-based monitoring in Hwange proved that citizen science works in a low-resource setting, including taking water samples in a technically correct manner, measuring quality parameters, and reporting field observations. It also showed that a science-society collaboration is a promising approach to establish an extended dataset in a remote area over a longer period. A tight follow-up on the sampling protocol via personal encounters and an in-depth training of community monitors with low formal education were crucial to ensure satisfactory data quality and the success of the project. Regular meetings are not only key to re-iterate training, identify low quality or biased data and adapt sampling protocols, but also to deepen trust relationships and keep motivation levels high. We conclude that community-based monitoring can be a valuable scientific scheme that allows collecting and interpreting data in challenging contexts where governmental institutions and industrial player are not fulfilling their role of monitoring environmental quality, enforcing environmental law and protecting the environment.

3.7 Data availability statement

The raw data from the chemical analysis and all field measurements supporting the conclusions of this article are available under the following link:
https://www.research-collection.ethz.ch/handle/20.500.11850/535761

3.8 Acknowledgment

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3.9 Author contributions

DR designed the project under supervision of BW, DR directed and implemented all stages of the project in Zimbabwe and in Switzerland and wrote the manuscript. OC performed additional field sampling and assisted the community monitoring in Hwange. MM was involved in planning and implementing the field work in Zimbabwe. NP performed ICP-MS analysis at the Eawag Dübendorf. BW aided in interpreting the results and editing the manuscript. All authors discussed the results and commented on the manuscript.

4 «I will sample until things get better – or until I die» Potential and limits of citizen science to promote social accountability for environmental pollution

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Abstract

Mining can cause harm to both human health and ecosystems. Regulators in low-income countries often struggle to enforce decent environmental standards due to financial, technical, and personal capacity constraints and political capture. In such settings, social accountability strategies are often promoted through which citizens attempt to hold governmental and private actors directly to account and demand better governance. However, social accountability initiatives are rarely effective. We demonstrate how political ecology analysis can inform social accountability theory and practice by identifying the power structures that define the potentials and limits of a social accountability strategy. We study the coal mining area of Hwange in Western Zimbabwe, where mining not only supplies coal to power plants and factories of multinational companies but also pollutes the Deka River. Together with local community monitors, we implemented the first citizen science project conducted in Zimbabwe and identified the sources and extent of the pollution. The scientific data strengthened the community monitors' advocacy for a cleaner environment and empowered them in their exchanges with the companies and the environ- mental regulator. However, only some of their demands have been met. The political ecology analysis, spanning from the local to transnational levels, reveals why local social accountability initiatives are insufficient to spring the low-accountability trap in a state captured by a politico-military elite, and why corporate governance regimes have not been successful either. We argue that pro-accountability networks are more effective when they include complementary players such as multinational enterprises, provided their responsible procurement approach moves from a corporate risk management to a developmental logic.

4.1 Introduction

On a hot September morning in 2019, three community members from the Hwange District in Matabeleland North province, Zimbabwe, stand in the knee-high water of the Deka River and complain: “Sometimes we see water that is green or yellow, and we find the fish dead” (ID01). They share their concerns about water pollution with around 2000 other residents. They all live downstream of the industrial town of Hwange, where coal has been mined and processed for over a century. The arid climate and frequent droughts make the perennial Deka River a lifeline for the subsistence farming families, providing fish as main protein source and river-borne reeds to weave baskets for income generation. Some villagers even depend on the Deka River as a source of drinking water since the few boreholes fail to provide sufficient water. Other villagers illegally tap the pipeline carrying water from the Zambezi River to the thermal power plant, where it is used for cooling. This causes conflict with the company. Pollution in the Deka River has gained nationwide attention (The Zimbabwean, 2011; Mungazi, 2018) and numerous large fish kills have occurred in recent years (ID02). In September 2017, 21 cattle reportedly died after grazing near the river (ID03).

What is happening in Hwange is no exception. Mining regularly leads to negative impacts on water, soil, and air quality and impacts human health (Noel et al., 2007; Wood, 2012). In developing countries, which include 90% of mining-dependent economies (Hartlieb-Wallthor and Marbler, 2017), regulators often struggle to set and enforce environmental standards due to financial, technical, and human capacity constraints and political capture (NRGI, 2017). Where the government fails to protect the environment in mining areas, conflicts are more likely to occur (Salem et al., 2018).

To compensate for the malfunction of formal accountability mechanisms, development agencies promote the concept of social accountability (SAcc) as part of their good governance agenda. The idea of SAcc is that citizens hold state actors directly to account and demand better governance (Joshi and Houtzager, 2012; Brinkerhoff and Wetterberg, 2016). The success of SAcc interventions depends both on citizens’ ability to engage with state actors and challenge their performance and on state actors’ willingness and ability to respond to such demands (Bukenya et al., 2012).

Hwange community members started complaining to the traditional chief and the local administration about river pollution in 2011. They also called on the companies that they considered polluters to install safe drinking water boreholes (ID4, Mungazi, 2018). To assist the community, a local NGO supported by an international donor initiated multistakeholder meetings in early 2018 involving the local government, the government’s Environmental Management Agency (EMA), community representatives, the coal mining companies, and the power station (ID04, ID05). The companies agreed that the Deka River is severely polluted by industrial effluents, but the individual contribution of each industrial player to the overall pollution remained contested. EMA stated that it was unable to determine the type or origin of the toxic pollutants (ID06); studies commissioned by civil society also failed to provide clarity (Nhiwatiwa, 2014; Yalala, 2017). The companies initially committed to drilling drinking water boreholes but did not do so. By the end of 2018, negotiations had reached a deadlock.

The first author noticed the impasse when she attended a multistakeholder meeting in October 2018 and proposed that the four community members who attended the meeting start community-based water quality monitoring. The four saw the opportunity to restart the stalled negotiations, to back up their claims, and to better understand their environment. Soon, they had recruited nine more friends and family members in four villages. Eight women and five men, ranging in age from youths to over 65 years, received training in technical water sampling and measuring water acidity. Together with two scientists from ETH Zurich and University of Zimbabwe, they collected almost 800 water samples over 15 months, which were taken to ETH in Switzerland for analysis.

This first citizen science[7] project in Zimbabwe (for project set- up and implementation see Appendix C) identified the chemical elements that exceed drinking water quality limits, the main sources of pollution, and the individual contribution of the major industrial players. The pollution is largely related to acid mine drainage (AMD)[8], a legacy of underground mining operations abandoned by the government-owned company. Surface erosion and the illegal pumping of acidic mine water by private sector Sino-Zimbabwean mining companies contribute further to the high pollutant load, as does coal combustion at the thermal power plant (for details see Chapter 3)

The citizen science project has produced comprehensive evidence on the extent and sources of pollution. The results have been shared with and acknowledged by all stakeholders. Nevertheless, few issues have been addressed, and the pollution issues in Hwange remain unresolved. In this paper, we ask why the initiative has been only partly successful despite clear data demonstrating the pollution. Further, we assess the potential and limits of citizen science as an instrument for promoting SAcc. To do so, we use political ecology scholarship to expand the institutionalist underpinning of SAcc theory. Political ecology describes how historical trajectories, economic conditions, and political processes influence the effectiveness of environmental regulation. We analyze how politics and power dynamics from local to global levels constrain state and private actors to respond to citizen demands, through, for instance, colonial configurations, identity politics, and embedment in global production networks. Our results suggest that SAcc and citizen science initiatives will benefit from political ecology analysis as it provides more strategic approaches to overcoming supply-side accountability constraints.

4.2 Literature review and theory

4.2.1 SAcc Literature: The short route to accountability

Through SAcc initiatives, citizens seek to improve the functioning of the public sector. Examples include increasing the effectiveness of service delivery in health care and education, improving the quality of governance and democracy, and reducing corruption (McNeil and Malena, 2010; Joshi and Houtzager, 2012; Brinkerhoff and Wetterberg, 2016).

Citizen-led demand for accountability and good governance operates bottom-up, building on civic engagement (Malena et al., 2004). SAcc interventions center around two core ideas: improving transparency and access to information, and strengthening citizens' voices so that they can use the information available to confront public officials (Booth, 2012).

Supporting demand-side SAcc initiatives, dubbed the "short route" to accountability, has become an important part of the World Bank led good governance agenda since the late 1990s (Levy and Kpundeh, 2004; The World Bank, 2004). It is seen as a promising alternative when the "long route" to political oversight and accountability via elected politicians and public officials fails to deliver results (The World Bank, 2004; Joshi and Houtzager, 2012).

The effectiveness of SAcc interventions depends on citizens being able to articulate their claims to state actors; this is labelled the demand side of social accountability. Yet, success also hinges on the

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[7] Citizen science broadly refers to the engagement of the general public in scientific research activities (Vohland et al., 2017). In water research specifically, citizens are involved to various degrees in the design of the monitoring scheme and the collection and interpretation of water quality data (Buytaert et al., 2014; Jollymore et al., 2017; San Llorente Capdevila et al., 2020). Community-based monitoring is one form of citizen science in which community members have a considerable level of influence over the monitoring process and its outcomes (Conrad and Hilchey, 2011; Wilson et al., 2018).

[8] AMD refers to acidic effluents caused by accelerated weathering of sulfide-rich ore deposits and is an infamous water pollution problem known to the mining industry around the world (Clarke, 1996; Kuyucak, 2002; Johnson and Hallberg, 2005).

responsiveness of state actors: the willingness of authorities to take claims seriously and develop effective responses. This is termed the supply side of accountability (Bukenya et al., 2012).

SAcc initiatives show mixed results so far. Greater access to information alone is not enough to trigger public officials to action and improve governance outcomes (McGee and Gaventa, 2010; Georgiadou et al., 2014; Fox, 2015; Reed et al., 2018; Hernández et al., 2019). "Whether and how new information is used to further public objectives depends upon its incorporation into complex chains of comprehension, action, and response" (Fung et al., 2007, p. 53). One group of authors disentangles the reaction chain from the demand side to the supply side and analyzes how the alignment of the two sides furthers or hinders the success of SAcc initiatives. In essence, for a SAcc reaction chain to work, citizens need to be able to transform data into information, make sense of the information, formulate demands, and present them to the responsible entity in public institutions or in the private sector. These actors have to appreciate the evidence and requests presented, need the competence and willingness to take decisions, and finally, require the resources and capacity to act (Dewachter et al., 2018). For this process to work, the state needs the capacity to engage with citizens and the willingness to provide a civic space in which social accountability outcomes are negotiated (Brinkerhoff and Wetterberg, 2016).

Another group of scholars challenges the very basis of social accountability and the neo-institutionalist thinking on which SAcc theory and the good governance agenda are modeled. Neo-institutionalism is criticized for prioritizing institutional design over the engagement with context, power, and interests (Joshi, 2014). Bukenya and colleagues conclude from their review of 90 SAcc programs that SAcc needs to be reconceptualized "in ways that better reflect its deeply contextualized and political character" (Bukenya et al., 2012, p. 5). However, SAcc initiatives have rarely explored how political analysis might inform engagement strategies (McNeil and Malena, 2010).

Finally, scholars suggest that the prevailing SAcc conceptualization is not only apolitical but also simplistic. They go beyond the dichotomy of supply versus demand and state versus citizen to think more broadly about pro-accountability actors. These actors can be found embedded in both state and society. A coordinated approach between them enables a sandwich strategy that is more likely to spring low-accountability traps (Booth, 2012; O'Meally, 2013; Fox, 2015).

We add to this critique two more limitations. First, the state–citizen-centered focus of SAcc excludes the proliferation of actors participating in governance over the last two decades, in particular in the private sector. This is all the more surprising as the same donor agencies that promote SAcc and good governance also promote private sector participation in public services and public policy more broadly.

Second, SAcc theory has a national focus that neglects the extent to which national-level governance is intertwined with regional and global governance dynamics. With good reason, global governance is considered to form a patchwork because it consists of a multitude of regimes with varying scope, coverage, overlap, and underlap and is sponsored by various combinations of public, private, and civil society stakeholders (Weiss and Wilkinson, 2014; Thérien and Pouliot, 2019). The extractive sector is a case in point: mining is bound to geological deposits and thus to specific jurisdictions, yet mining companies constitute a part of global production networks involving a host of private sector actors, third party jurisdictions, and global governance regimes (Henderson et al., 2002; Bridge, 2008; Coe et al., 2008). Examples of global governance frameworks include the OECD Guidelines for Multinational Enterprises on Responsible Business Conduct in the environmental and social spheres (OECD, 2011) and the International Finance Corporation (IFC) Environmental and Social Safeguards (IFC, 2022). A private sector equivalent of the latter, the Equator Principles, was established in the financial industry in response to civil society pressure. The Equator Principles consist of a myriad of sustainability frameworks to manage environmental and social risk in large projects such as mining (EP Association, 2022). Accordingly, international governance dynamics and market forces interact with local governance and, hence, with the prospects of local SAcc initiatives.

We contend that SAcc-inspired initiatives can only be fully effective when they abandon the apolitical attitude of standard SAcc and account for the interconnectedness of local governance with its global counterpart.

4.2.2 Expanding social accountability with political ecology

To overcome the lack of political sensitivity and the narrow focus of SAcc theory, we turn to political ecology (PE) scholarship. Central to the idea of a politicized environment is the recognition that "environmental problems cannot be understood in isolation from the political and economic contexts within which they are created" (Bryant and Bailey, 1997, p. 28). Early PE scholars studied environmental degradation by, for instance, linking the phenomenon of soil erosion to the political and economic conditions in which agricultural activities were performed (Blaikie & Brookfield, 1986; Blaikie, 1985). Others analyzed struggles over access to and control of natural resources, including forests (Agrawal and Chhatre, 2006; Vandergeest and Peluso, 2006; Lukas and Peluso, 2020), land (Leach et al., 1999; Seter et al., 2018; Franco and Borras, 2021), water (Johnston and Fiske, 2014; Rodríguez-Labajos and Martínez-Alier, 2015; Cairns, 2018), wildlife (Neuman, 2001; Peluso and Watts, 2001; Duffy et al., 2019), mineral deposits (Richards, 2001; Bebbington and Humphreys Bebbington, 2018; Purwins, 2020), and energy carriers (Watts, 2001; Labban, 2010; Lennon, 2021). PE focuses on the power dynamics underlying struggles over natural resources and shows how race, class, and gender structures create inequality, marginalization, and injustice in access to and use of resources (Bryant, 1998; Peluso and Watts, 2001; Tschakert, 2012; Martinez-Alier, 2014; Perreault et al., 2015; Lennon, 2021).

Political ecologists engage with power at the levels of decision making and implementation, as well as of knowledge generation and the legitimization of decisions (Rodríguez-Labajos and Martínez-Alier, 2015). First, power relations are constructed and maintained through the commodification of natural resources along the logic of the capitalist economy, including socially produced scarcity that excludes people from accessing resources (Le Billon, 2000; Vandergeest and Peluso, 2006; Purwins, 2020). Markets are constantly created and transformed, and access to and control over resources is negotiated dynamically between changing actors (Escobar, 2006; Peluso and Purwanto, 2018; Jalbert et al., 2019). Examples include smallholder farmers who are integrated into global carbon compensation forestry and tied to influential transnational players (Osborne, 2011) and migrant workers whose remittances change the mechanisms of land control in distant home markets (Peluso and Purwanto, 2018).

Second, patterns of resource use and control are also determined by discursive, symbolic, and cultural identity politics, including religion, gender, and ethnicity (Turner, 2004; Peluso and Lund, 2011). PE recognizes the importance of the creation and legitimization of knowledge to resource control and challenges the hegemony of expert claims about environmental issues. Recent examples include oil extraction (Wylie et al., 2017a) and hydraulic fracturing (Willow and Wylie, 2014).

Historical trajectories reveal how power has been gained and used to shape environmental transformation (Peluso and Lund, 2011; Walter, 2014). For example, management and control practices established during colonial times may still determine how natural resources are governed today (Vandergeest and Peluso, 2006; Duffy et al., 2019). Many approaches to planning and managing nature are rooted in a capitalist logic and ignore cultural differences in the ontology of nature (Escobar, 1996, 2006). The power to set boundaries and assign rights determines where resources are extracted and where nature is conserved (Corson, 2011; Bebbington and Humphreys Bebbington, 2018; Purwins, 2020). This leads to territorialization of natural resources, with permanent exclusion and dispossession for some people and rights of use and control for others (Peluso, 2008; Peluso and Lund, 2011; Perreault, 2013).

Another concept important to PE is that of scale, because it defines the location and scope of decision making and the distribution of costs and benefits (Blaikie and Brookfield, 1987). Economic activities and company networks are simultaneously becoming more localized and more transnational, and the nation-state is embedded in a complex web of multilateral, private, and nonstate actors. Interpenetrating scales have direct implications for environmental struggles and governance patterns (Swyngedouw, 2010). Consequently, identifying scale interdependencies is fundamental to understanding resource-related conflicts and their resolution (Corson, 2011; Schilling et al., 2018).

Finally, PE is concerned with practice and political action, with a growing body of PE research around civic engagement and environmental activism (Loftus, 2015). This research benefits from PE's methodological openness. Qualitative methods such as ethnography, discourse analysis, process tracing, and content analysis are used in PE research designs (Demeritt, 2015; Zimmerer, 2015). In addition, natural science methods are frequently used, above all in citizen science projects for environmental monitoring related to extractive industries (Jalbert and Kinchy, 2016; Wylie et al., 2017b). PE also critically discusses the political dimension and limitations of the generation and use of citizen science data (Brombal, 2020; Blacker et al., 2021; Nost and Goldstein, 2021).

In summary, SAcc theory tends to focus on the demand side of accountability, whereas PE is crucial for understanding its supply side. PE therefore provides a useful framework for analyzing the power dynamics of society that shape the Hwange pollution case and the limited success of citizen science interventions through historical trajectories and multi-scalar linkages (Joshi, 2014; Dewachter et al., 2018).

4.3 Methodology

4.3.1 Framework

Citizens demanding accountability from authorities rely on evidence to convince decision makers of their concerns and to persuade them to take action (Hernández et al., 2019). Building on Fung et al.'s (2007, p.7) idea of the "chains of comprehension, action and response" upon which SAcc outcome is contingent, we detail the concept of the social accountability value chain and embed it in a political ecology context. This provides the methodological framework that guides our research (Figure 13).

4.3.2 Methods

On the demand side of SAcc, community monitors have created evidence following citizen science methods. The citizen science process is described and discussed in Appendix C and more extensively in Chapter 3. This paper focuses on the SAcc engagement process by which community monitors strategize potential alliances and tactics to make use of the evidence established and collaborate with pro-accountability actors to convince decision makers to respond to their demands.

To situate the agency and advocacy of the community monitors in the broader political ecology context, we apply qualitative historical-materialist analysis (Davis, 2015). We collected and analyzed primary data in regulatory documents (acts, provisions, and policies) and newspaper articles. Further, we conducted semi-structured interviews (Section 4.3.3). As secondary literature, we used peer-reviewed articles and reports from NGOs and think tanks.

To examine which response the citizen science-supported advocacy has elicited on the supply side of SAcc, such as government agencies and mining firms, we use the process tracing method (Beach, 2017; Collier, 2011; Mahoney, 2010). This allows us to identify mechanisms that link actions and interventions to the outcomes of SAcc initiatives at different scales. At the local level, we trace how the results of the citizen science intervention and the community members' advocacy campaign were received by local mining companies, local government representatives, and the local Environmental

Management Agency, what actions they responded with, and their rationale (Section 4.5.2). At the institutional level, we trace how the information presented in Hwange passed through the EMA system to the decision level in Harare and back to the local officers in Hwange, and how the information interacted with the political ecology dynamics (Section 4.5.3). At the global level, we trace potential links between sourcing commitments in global production networks and local level struggles to assess the coherence and potential synergies between neoliberal global governance mechanisms addressing the same problem (Section 4.5.4).

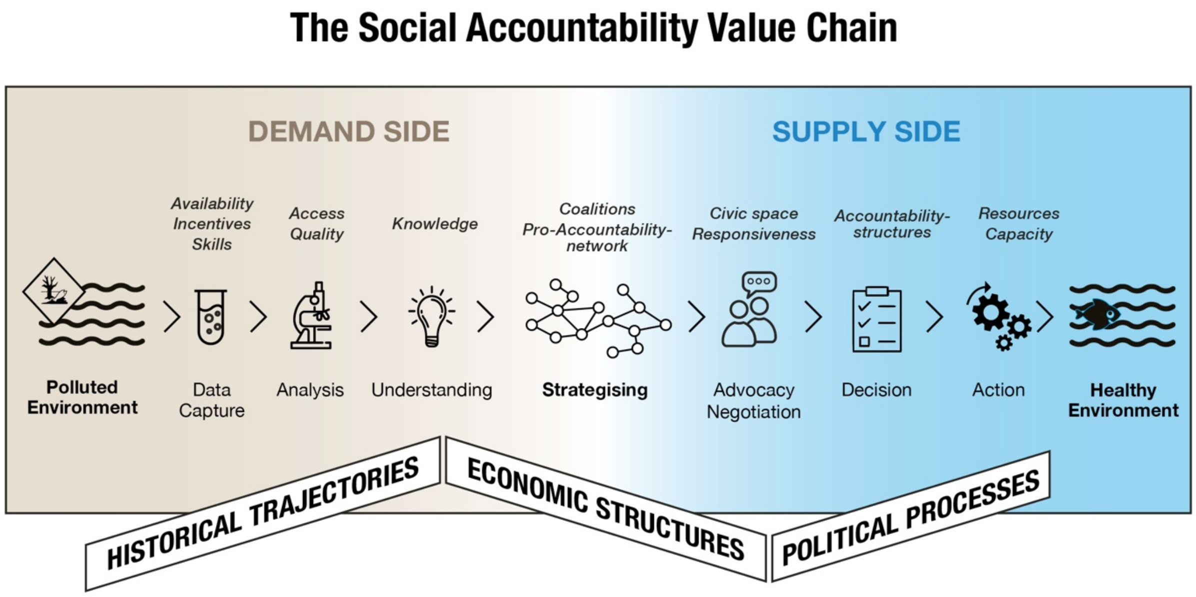

Figure 13: The social accountability value chain illustrates a social accountability initiative in environmental governance expanded by a political ecology perspective. Symbols and the labels in roman font below them indicate the various stages along the demand side (left) and the supply side (right) of a social accountability initiative that aims to transform a polluted environment into a healthy one. Labels in italic font above the symbols show the required capacities and resources for the respective stages. The political ecology dimensions are depicted as flags and apply to the entire value chain. (Source: authors, based on Fung et al., 2007 and Dewachter et al., 2018).

4.3.3 Data collection

Between March 2018 and November 2019, we conducted semi-structured and conversational interviews with 58 stakeholders in the Hwange area, in the provincial center, Bulawayo, and in the capital, Harare. About half of the participants were interviewed multiple times. Interview quotations used in this article are listed in Appendix C. Sampling was purposeful (Patton, 1990), selecting stakeholders who either had a direct connection or expertise either to the pollution case in Hwange or were representatives of various levels of the hierarchies of the public institutions and private companies involved. At the beginning, we also applied the snowball sampling technique (Patton, 1990) to better grasp the historical background of the Hwange pollution case. Due to political sensitivity, it was not possible to record the interviews; we took extensive notes that were later thematically coded and examined with qualitative content analysis (Mayring, 2000). In addition, we took field notes, collected observational data, and made photographs. We also used audio recordings by a staff member from Switzerland who visited the project and produced a short project documentary. He interviewed five community monitors in September 2019 about their motivations for participating in the community-based monitoring project. Following the supply chain, we conducted an interview with the international coal buyer Holcim Zimbabwe in Harare in October 2019. Nestlé Zimbabwe, another buyer, did not respond, but we interviewed representatives at the European headquarters of both Holcim and Nestlé in May 2021.

4.4 The political ecology of coal mining in Zimbabwe

To understand the extent and nature of the challenges the community monitors faced in their advocacy for a cleaner environment, we have to acknowledge the complexity of the extractive cluster in Hwange, where coal mining determines all aspects of public life. We begin this section by recalling how postcolonial identity politics in Zimbabwe brought about today's extractive landscape and how international politics and global production networks influence power and dependency.

4.4.1 Coal mining in Hwange: a colonial legacy

Hwange town is located around 80 km south-east of the Victoria Falls and has roughly 40'000 inhabitants (ZimStat, 2013) (Figure 14). It was established as a mining town by the Wankie Coal, Railway and Exploration Company Limited after it acquired a 1000 km2 coal concession in 1901 (Palloks, 1987). Wankie soon became one of the largest mining operations in Southern Rhodesia, supplying neighboring colonies and Atlantic seaports through its rail network (Shumba, 2016). It is a textbook example of how today's economic dependency on and centralized control of natural resources is intrinsically tied to colonial history and Europe's quest for minerals, metals, and cheap energy to power its own industrialization (Chachage et al., 1993; Bryant and Bailey, 1997; Meredith, 2007; Walter, 2014; Ayelazuno and Mawuko-Yevugah, 2019). After independence, Wankie was nationalized and converted into the state-owned, stock-listed Hwange Colliery Company Limited (HCCL) in 1986. At around the same time, the largest coal-fired powerplant of the country, with a capacity of 920 MW, was built adjacent to HCCL to burn its coal and produce electricity. Due to lack of maintenance, this subsidiary of the parastatal Zimbabwe Electricity Supply Authority (ZESA) currently runs at less than the half of its full capacity yet still produces around 40% of the electricity in Zimbabwe (Altana and Kojo, 2008; ZAIDG, 2011; Zimbabwe Power Company, 2019).

Today, Hwange town is still under the administration of the mining company. Most residents live in compounds initially built for the mine workers, close to former underground mines and surrounded by coal waste dumps, processing facilities, and the thermal power plant. People are exposed to air and noise pollution and endangered by underground coal fires (Centre for Natural Resource Governance, 2017). The industrial effluents are carried away by the Deka River, which passes the Hwange coal cluster as it flows from its source in the world-renowned Hwange National Park, the largest wildlife conservation area in the country, to the Zambesi River bordering Zambia.

Despite its strategic importance, Hwange District is primarily a site of extraction with low political standing. This is also because it is in Matabeleland, home of the Ndebele people, and thus remains a stronghold of opposition to the ruling party (Gaidzanwa, 2020). Notwithstanding the official doctrine of national unity, relations between the Ndebele minority and the Shona majority remain dire. After independence, ethnic hegemony was violently enforced by Shona-led ZANU-PF until the Unity Accord of 1987, and the Shona continue to dominate the hierarchy of political leadership (Muzondidya, 2010; Gumbo, 2020). The Ndebele remain marginalized with lower levels of development and fewer job opportunities, especially at higher positions (Rwodzi, 2018; Mpofu, 2019; Hadebe, 2020).

4.4.2 Looking East

Over the last 20 years, the government has granted mining and explorations licenses on the vast HCCL concession and beyond, some even in the Hwange National Park. The Zimbabwe Environmental Law Association (ZELA), an NGO, has successfully challenged the prioritization of mining over conservation in court, and the government revoked the exploration licenses in 2020. However, both the Mines and Minerals Act of 2001 and the Parks and Wildlife Act of 2002 continue to allow mining in national parks (BBC, 2020; Dhliwayo, 2020).

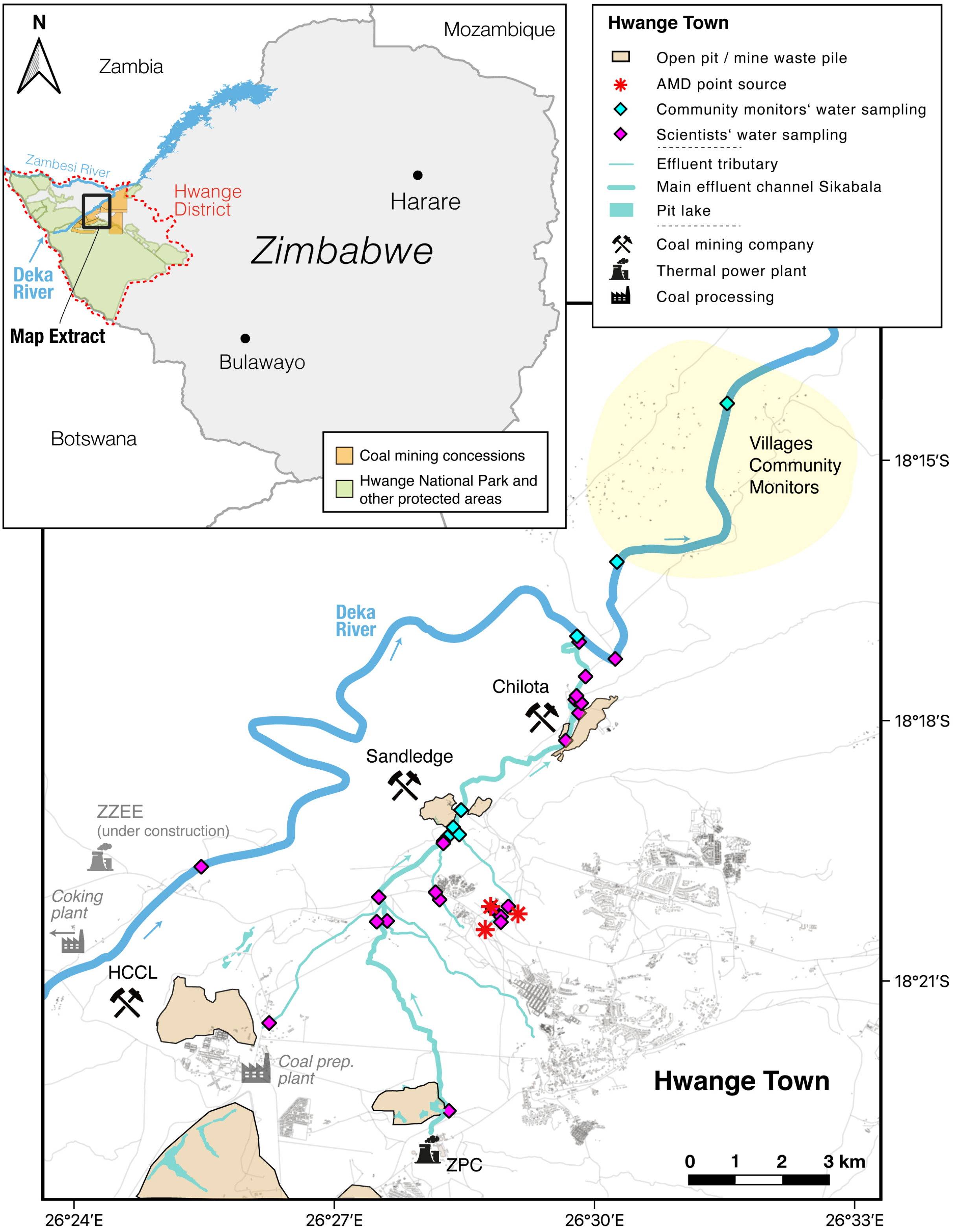

Figure 14 Overview map illustrating coal mining concessions and protected natural reserves in Hwange District, Western Zimbabwe (top left). Detailed map of Hwange Town and surrounding villages with Deka River, industrial sites and sampling locations of the community-based water quality monitoring (bottom). QGIS maps contain administrative boundaries from DIVA-GIS (Hijmans et al., 2018) and infrastructure, buildings and roads from https://www.openstreetmap.org/, made available under the Open Database License: http://opendatacommons.org/licenses/odbl/1.0/. Shapefiles of the protected biosphere areas were provided by the Protected Planet Initiative (UNEP-WCMC and IUCN, 2021) and mining concessions obtained at the drawing office of the Zimbabwe Geological Survey (Zimbabwe Geological Survey, 2019).

Most new concession holders, as well as HCCL and ZESA, are partnered with Chinese firms. The country has pursued a Look East policy since the United States, European Union and other Western states imposed sanctions over the human rights situation and the government's controversial land reform program in 2001 (Nsingo, 2016; Ojakorotu and Kamidza, 2018; Moyo and Musarurwa, 2019). In a racial-nationalist move to consolidate the power of the ruling ZANU-PF, the Fast-Track Land Reform Program (FTLRP) was passed in the early 2000s to expropriate white landowners. Similarly, the Indigenization and Empowerment Act of 2007 forced foreign companies to transfer 51% of ownership to locals (Mkodzongi, 2013; Nyahunzvi, 2014; Chigumira, 2018; Gumbo, 2020).

Chinese firms are extending their activities in the Deka River basin beyond mining, further complicating environmental management. Since the end of this study's community-based monitoring, for example, the Zimbabwe ZhongXin Coking Company (ZZCC) has begun producing coking coal for export, and its subsidiary Zimbabwe ZhongXin Electric Energy (ZZEE) has begun building the first phase of a 300 MW power plant to feed the national grid (The Chronicle, 2020; The Herald, 2021).

4.4.3 The politico-military complex

The businessmen holding the new mining concessions in the Hwange area are Zimbabweans, predominantly members of the politico-military elite and their patronage networks. A high-profile case is the late war hero and former Midlands Provincial Governor Cephas Msipa. He was the owner and CEO of a mining operation, which the citizen science project identified as contributing to the pollution of the Deka River. The company, now led by his eldest son, expelled its South African business partner in 2017 under the Indigenization and Empowerment Act and created the Sandledge joint venture with the Chinese firm Zimberly in 2018 (ID07, ID08, Business Reporter, 2013; Laiton, 2019; The Herald, 2012).

The position of war veterans and the military must be understood in the context of the liberation entitlement doctrine. This doctrine portrays the ruling ZANU-PF and its liberation war veterans as the sole givers and guarantors of independence. The country's sovereignty is constantly threatened by imperialist forces against whom the legacy of the liberation must be defended (Gumbo, 2020; Ruhanya, 2020).

The effect is a partisan and politicized role of the military and other security services and a militarization of political and economic affairs (Masunungure, 2011; Shumba, 2016; Gaidzanwa, 2020). Increasingly, strategic public positions are held by individuals who come from or have close ties to the security sector, including in the judiciary, the Electoral Commission, and local government institutions (Ndawana, 2020; Noyes, 2020; Kufakurinani, 2021; Maverick Citizen, 2021). The militarization of public institutions also extends to the state enterprises and parastatal organizations (SEP), which number over one hundred. In many, the military is a shareholder, and military personnel serve as directors or senior managers (Moyo, 2016). Such "military commercialism" creates both predatory commercial opportunities for military officials and opportunities to set aside "secret budgets" for covert and extralegal activities (G. Moyo, 2016, p. 354).

Notoriously mismanaged SEPs, including HCCL, successfully fended off reform attempts during the Inclusive Government period (2009–2013) (Moyo, 2016). Nevertheless, HCCL's debts and salary arrears continued to pile up, and a business irregularity scam involving the then-chairman of the board and now Minister of Mines led to HCCL going into administration in 2018 (ID09, Kunambura, 2019; Langa, 2019). A medical doctor with a military career has been appointed as Acting Managing Director (HCCL, 2019).

The mismanagement at HCCL has had an unmistakable impact on operations. Production levels are far below actual capacity because equipment is outdated, and infrastructure is dilapidated (ID10). The environmental management unit has no equipment to monitor water quality (ID11, ID12). It is for similar reasons that Hwange Power Station runs at about half of its capacity (ID13).

4.5 Effectiveness of citizen science in fostering SAcc

From December 2018 to March 2020, community monitors collaborated with scientists and implemented a thorough water quality monitoring campaign. They mainly collected the samples in groups of two to three monitors “to ensure proper sampling” (ID14) and repeatedly reminded each other of the importance of what they were doing. They had gained a basic understanding of water chemistry, pollutant transport, and the measurement and meaning of water quality parameters. Community monitors collected robust evidence on the sources and extent of the water pollution and were able to explain basic facts (Appendix C; Chapter 3). Throughout the process, they kept their community informed and met the village elders and the village chief in order “not to hide anything” (ID12) and to secure their support. Their commitment to the public cause and the knowledge they acquired has empowered them and enhanced their reputation within the community (ID15). Towards the end of the project, a community monitor expressed his uninterrupted motivation by stating: “I am not tired. I will sample until things get better … or until I die” (ID16).

With meaningful data, however, the next question arose: How can community monitors best use their evidence to press their claim and at the very least obtain drinking water boreholes for their communities? The community monitors tried to advance their cause in two ways: (1) by underlining their grievances with chemical data at a multistakeholder meeting with stakeholders and (2) by directly confronting and engaging with mining operators through a pressure group.

4.5.1 Navigating the civic space

In late April 2019, when the first laboratory results were available after 4.5 months of sampling, the local NGO that had previously supported the community members reconvened the multistakeholder platform. The community monitors presented preliminary monitoring results with the support of a scientist. They provided information on the harmful pollutants found in the river and the contribution of each industrial operator to the pollution in the river catchment. The official reception of the community monitoring findings was surprisingly positive. Neither the quality of the data nor the impartiality or fairness of their interpretation was questioned. HCCL was the only company represented, and the environmental manager said, “We are satisfied with your work” and promised to fulfill the communities’ request for drinking water boreholes, saying: “You can make a tick on this one.” (ID17). The EMA representative welcomed the initiative as “a unique case in Zimbabwe that also allows trust to deepen between the government and the community members” (ID18). Another EMA officer later added: “We didn’t know the culprit. Your facts now show who the culprit is. It is very clear now. When we have the facts, we can get the polluters to come up with a plan.” (ID06).

As a follow-up, community monitors formed a three-member delegation they called the “pressure group” (ID15). This group engaged directly both with the mining company that attended the multistakeholder meeting and with the other industrial stakeholders that were not present. They also visited the local government. In bilateral meetings, they used the results of community monitoring to demonstrate the companies’ responsibility to drill drinking water boreholes so that communities have long-term access to clean drinking water. They also called on the companies to improve the health of the river’s ecosystem by properly treating mining wastewater.

4.5.2 Local-level corporate response

The long-term monitoring of water quality and the pressure group's persistent advocacy work triggered several reactions from the companies. At HCCL, the measurement results raised the interest of the environmental manager. He saw it as an opportunity to strengthen his internal position and used the results "to convince management to procure equipment... We are very open to learning and improving." He also emphasized that he used the results to lobby management to make well drilling a corporate social responsibility priority (ID17). HCCL indeed hired a company to identify suitable locations for water boreholes. However, by the end of 2021, only one borehole had been drilled (ID14).

We also learned that HCCL acquired ISO9001:2015 certification in 2019, which specifies requirements for a quality management system, and HCCL is also seeking ISO14001 certification, which specifies the requirements for an environmental management system (ISO, 2015a, 2015b). The adoption of the standard is incentivized by its international clients (ID17) as is the case for export-oriented firms in general (Liston-Heyes and Heyes, 2021). HCCL supplies coking coal to the ferrochrome industry in Zimbabwe, South Africa, Zambia, DRC, and Malawi. The company also delivers thermal coal for processing heat to the Zimbabwean subsidiaries of Holcim for cement and Nestlé for food products such as instant coffee, milk powder and cereals. These last two require certification with international environmental management standards. The HCCL environmental manager views multinational companies with headquarters in the West as the main benchmarking authorities for environmental standards and product quality: their "integrated management is super strict," and they also have "influence on regulatory bodies such as EMA" (ID17). It is important to note that although ISO 14001 compliance is key to maintaining business relationships with multinational companies, it does not specify environmental performance criteria; thus, certification can signal environmental responsibility to clients but says nothing about the level of ambition in environmental performance.

The governmental operator of the thermal power plant, Zimbabwe Power Company (ZPC), withdrew from the multistakeholder process in mid-2018 and did not reengage after the onset of the community-based monitoring project. Even though the water quality data indicated that airborne particles from coal combustion also polluted the Deka River, ZPC expressed no concern with water pollution. Contrary to their initial admission, they refuse to drill any boreholes and refer to their plans to renew the 40km long Zambesi pipeline and incorporate some points from which local residents can fetch water (ID04). We were neither granted access to the premises of the high security zone of Hwange Power Station nor received any opportunity to interview the environmental management.

The Sino-Zimbabwean joint venture Sandledge reacted differently to the advocacy and sent a delegation to discuss with community monitors and village representatives. A year later, the company had sunk two boreholes in affected villages (ID14). However, no measures were taken to improve the environmental management or deal with the AMD. While the community monitors were positive about the water boreholes, the explanation of the operations manager for the absence of any measure to reduce pollution was sobering: "No funds are reserved for environmental management and there is also no important decision taken in Hwange, everything is resolved in Harare." Therefore, "pollution problems cannot be addressed at the local level" (ID08). This is consistent with the assessments of other interviewees working in the sector who observe that "there is a tendency to extract and go" (ID19). Chinese investors "are here for money, they are not strong with sustainability. You have to push them seriously to comply" (ID17).

Located close to the Deka River, a second Sino-Zimbabwean mining company named Chilota paused operations at the beginning of the community-based monitoring project and therefore did not take part in the multistakeholder meeting in April 2019. Under the management of a new Chinese partner, the company resumed operations in September 2019 (ID07, ID18). Shortly after mining activities restarted, the company illegally pumped highly polluted mine water into a tributary and caused a major fish kill in the Deka River. The monitoring data gave clear evidence of the pollution, but Chilota, which was renamed Sunrise Chilota in 2020, did not engage with the community monitors about the evidence that they had assembled. The example of Chilota illustrates how quickly the mining landscape in Hwange changes. Emerging companies tend to neglect environmental standards and are difficult counterparts for communities also because of their opaque business structures.

4.5.3 Institutional level: the EMA

Community-based monitoring identified HCCL as the main polluter of the Deka River. Following the presentation at the multistakeholder meeting, the local Environmental Management Agency (EMA) office acted. In early May 2019, it sent a letter to HCCL requesting it to submit an action plan detailing short- and long-term measures to mitigate pollution. The local EMA office also duly reported the monitoring results to its superior office. For more decisive action, as the community monitors hoped for, the local EMA office would need authorization to issue an order with binding targets and enforce its implementation. In this section, we trace the information that EMA Hwange sent to Harare and how it was absorbed and processed by the formal administrative channels. Before we do so, we outline how EMA is set up and how it functions in the prevailing political dynamics.

The EMA's organization

The EMA was established in 2006 as a regulatory agency responsible for ensuring sustainable management of natural resources and protecting the environment (EMA, 2019). The agency emerged from a major donor-sponsored reform of the water sector in the early 2000s. The reform redefined roles and responsibilities and introduced concepts of integrated water management and the polluter-pays principle (Naome et al., 2012; Manzungu and Derman, 2016). However, the merging of departments from various ministries into the EMA led to data loss, the discontinuation of some monitoring programs, and overlap and competition with the Zimbabwe National Water Authority (ZINWA) (Murwira et al., 2014, ID20–22). Others also question the competence of EMA officers, saying that "many former policemen were appointed there" (ID23).

Companies are obligated to report effluent water quality to the EMA on a quarterly basis, and the EMA takes monthly samples of mining effluents and river water. According to an EMA employee, sampling sites are identified jointly with the companies based on physical accessibility and proximity to the city rather than scientific criteria (ID18). The EMA office in Hwange does not possess a vehicle ("In 2014, the car left") nor technical instruments (ID18). Water samples are analyzed in the EMA laboratories in the capital, and the results are sent back to Hwange (ID24, ID25). There is a widespread perception among the private sector, civil society, and other government institutions that "the sampling by EMA is weak" (ID04, ID23, ID26, ID27).

The polluters-pays principle uses market mechanisms for environmental regulation by making it economically attractive to minimize wastewater and prevent pollution (The World Bank, 1992). A company pays a fixed and a volume-based fee for the effluent volume discharged into the environment. However, the fees are too low to incentivize wastewater volume reduction; this has been exacerbated with the onset of hyperinflation in 2018. Fines up to a maximum of an equivalent of 1500 US dollars are equally insufficient to deter pollution, incentivize investment in wastewater treatment plants, or encourage remediation. Rather, as an industry representative stated: "You pay EMA to be able to pollute" (ID23). The same view was expressed by two people from mining companies and the government (ID28, ID29).

Finally, the transformation of the EMA into a parastatal organization introduced commercial objectives that compromise the EMA's mandate as an independent regulatory authority. The EMA receives only minimal core funding and must raise around 80% of its annual budget through licenses, fees, and fines from companies, which the EMA calls "clients" (ID06, EMA, 2017, 2016). This combination of regulation with revenue generation means that the EMA remains weak by design. While EMA officers complain that environmental legislation does not provide incentives for companies to reduce pollution, companies note that the EMA also has no incentive to reduce pollution and “fines to generate revenue” (ID25). The low accountability equilibrium appears to serve both sides (Manzungu and Derman, 2016).

The EMA’s response

The EMA is organized in a rigid top-down hierarchy. Monthly reports are written at the district level and sent to the provincial office. There, these reports are converted into thematic reports for each organizational unit at national headquarters in Harare. Provincial managers supervise district offices and are themselves supervised by the national director. The director himself reports to the Minister of Environment, Water and Climate (EMA, 2020). All decision-making power is centralized at the Harare headquarters, and decisions are communicated from the top down through the same system.

A few months after the presentation of the results at the multistakeholder workshop in Hwange, we followed up on the information that the local EMA office had fed into the official regulatory system. We followed the EMA’s official line of communication from Hwange to Bulawayo and Harare by visiting each office and interviewing at district, provincial, and national levels. Our inquiry started in Hwange, where we consulted the internal reports from EMA Hwange to the provincial office and saw that the report contained the information in full detail. Yet, when we knocked on the EMA door at the provincial office and at headquarters, nobody seemed to be aware of the community monitoring results (ID30, ID31).

Two complementary potential explanations emerged from interviews. First, the EMA was withholding information because it feared that “the information might end up in a newspaper, … [could] be used to destabilize …[and] that people see that they are not doing their job” (ID18). This pattern of withholding information has been used before. Initially, the EMA Hwange office told us that the regular fish kills remained “a mystery” (ID06). Later, we were allowed to view the internal EMA reports. The January 2016 report describes some of the chemical parameters negatively affecting effluent quality at the various mining companies and proposes remedial actions. The January 2018 report addresses a fish kill that occurred in late December 2017 and links it conclusively to environmental management failures by the coal mine operators.

Although the results of the community-based monitoring did not reach the top hierarchy through formal channels, our interviews revealed that EMA headquarters was well informed about the environmental problems in Hwange. The head of the environmental management department, who is supposed to receive the reports of the Hwange District Office, including the information on the community monitoring, told us that he had written his master thesis on AMD-related problems, mine management, and water treatment options in Hwange (ID31). Another environmental quality officer at the headquarters confirmed the need for remedial action in Hwange but said that HCCL lacked the financial capacity (ID32). The economic argument for noncompliance with EMA orders was also mentioned in discussions with the provincial supervisor, who indicated that we have to “appreciate the current economic situation” (ID30).

The second explanation is that parastatals and private companies controlled by powerful members of the politico-military elite cannot be touched. Interlocutors at the national level repeatedly pointed out that high-ranking government officials and politicians undermine enforcement of the Environmental Management Act because of conflicts of interest or because profiting from mining takes precedence over environmental compliance (ID32). A rationalized version of this elite capture we often heard runs: “Large state-owned companies are trying to improve. It is hard to shut them down when they try.” (ID30). When asked why the EMA does not enforce environmental regulations when evidence of pollution is on the table, the provincial supervisor in Bulawayo replied heatedly: “Communities should take action themselves and confront the companies… They can go to litigation.” (ID30). Whether this was done to defend EMA or out of frustration over the agency and hoping for a push from outside could not be elicited.

EMA officials in Hwange were not surprised that they were not allowed to impose remedial action or shutdowns, even though they correctly reported the causes of the fish kills back in 2016 and the results from the community monitoring now: “Reasons why nothing is happening in Hwange are political. EMA officers are held back from above. Information does not get through to the top, but restrictions quickly reach the local level. … Everything comes from the top.” (ID33). No action is taken unless the pressure “comes from a high political level and is applied top down directly from the Director General to the local offices” (ID18). Meanwhile, EMA officials in Hwange try their best to improve the situation through local arrangements. By requesting an action plan, they made full use of the means at their disposal. Finally, and against all the odds of an institution captured by the elite, HCCL submitted an action plan to EMA on 4 June 2019 that identifies short- and long-term measures to improve effluent quality.

4.5.4 Global governance level

As HCCL is integrated into global production networks, we sought interviews with those international clients that HCCL mentioned as points of reference for environmental management. Both Holcim and Nestlé supply national and regional markets through production facilities in Zimbabwe with energy-intense processing, for which they procure coal from HCCL. Multinational companies can exert pressure on their suppliers through their position as customers and through their international reputation. At the same time, procurement obligations make multinational companies vulnerable to pressure from activists in their home markets and from shareholders. Voluntary sustainability policies and guidelines for responsible sourcing are routinely promoted and adopted to manage upstream supply chain risks and protect companies from stakeholder pressure. Typically, suppliers are divided into risk categories, and the human rights and environmental requirements for each category are defined, as is how compliance is to be reviewed.

Holcim and Nestlé have responsible sourcing guidelines in place at the corporate level (Nestlé, 2018; LafargeHolcim, 2020). Nestlé’s sourcing standard prioritizes agricultural commodities; engagement with energy suppliers is limited to ensuring acceptable working standards. Holcim requests that coal suppliers conduct a self-assessment for sustainable procurement and relies on the ISO certification of the supplier company (ID34). The next step in compliance verification is that “suppliers of extractive raw materials in high-risk countries are to be audited annually or bi-annually” (LafargeHolcim, 2021). In the event of noncompliance, the company has the option to assist the supplier in taking corrective action to “avoid jeopardizing supplier relationships” (ID35); this is particularly relevant for strategic suppliers.

The low level of engagement with HCCL is explained by the fact that the roll-out of the code of conduct currently lags in Africa and the Middle East. The company further argues that there are suppliers with whom “we have no bargaining power—it is the government” (ID35). Beyond that, at least one Zimbabwean state agency is a shareholder of Holcim’s local subsidiary: the National Social Security Authority (Lafarge Cement Zimbabwe Ltd, 2019). Similarly, Nestlé claims that “there are certain markets where you can’t choose where you buy nor what price you pay” (ID36). These statements demonstrate a defensive posture towards the government. Obviously, this has paid off, as both companies succeed in maintaining good relationships with the government. They have managed to retain full control over their subsidiaries despite the Indigenization Act, a law that was eased for the extractive sector in 2018 following the business paradigm of the Mnangagwa leadership (Chinamasa, 2017).

Multinational companies must simultaneously satisfy their international stakeholders and protect their business interests. Risk-based supplier policies and reliance on certification standards such as ISO14001:2015 allows the company to serve this purpose. In contrast, cooperation with local communities, for example through citizen science initiatives, does not help. The two multinationals see such cooperation as a task for their suppliers (ID35).

4.6 Discussion

Our study explored the strength of a political ecology (PE)-expanded social accountability (SAcc) theory to explain success factors and hurdles of a social accountability initiative and examined how PE can better inform SAcc strategies. At the theoretical level, an PE-expanded SAcc theory overcomes the institutionalist-inspired citizen–state dichotomy. PE-expanded SAcc recognizes that citizen-led initiatives confront historically evolved power distributions and dependencies at the national level that interact simultaneously with international political developments and the dynamics of global production networks.

We applied the PE-expanded SAcc to local communities' longstanding struggle against water pollution in the coal-mining area in Hwange. Together with 13 community members, we implemented the first citizen science project in Zimbabwe. Community members and scientists took close to 800 water samples over 15 months to create robust evidence of the extent and sources of pollution (Appendix C and Chapter 3).

This project has demonstrated the potential of citizen science to produce reliable environmental data in a logistically challenging and highly politicized mining setting in Sub-Saharan Africa and with participating community members who have low levels of formal education. The citizen science project has empowered community monitors and reinforced their advocacy. They were able to present and explain the results at public events and when lobbying companies, which illustrated that the data produced were understandable and the information was actionable. Scientific evidence and cooperation with universities were important to open doors, facilitate a fact-based discussion, and build credibility through the efforts invested (Chapter 3). Beyond Hwange, the citizen science initiative allowed community monitors to strengthen their advocacy network and build new alliances (Appendix C).

However, the potential of using citizen science to strengthen SAcc is limited by the lack of affordable quality laboratory infrastructure in Zimbabwe and in most sub-Saharan African countries. This lack, combined with the high costs associated with sample shipping, makes such initiatives dependent on external partners and funding (see Chapter 3).

The current setting and configuration of actors in the coal supply chain in Zimbabwe make it impossible for community monitors to fully develop strategies, build networks, and thus deploy smart tactics to increase accountability while an entrenched elite uses power and instrumentalizes institutions to advance its partisan interests. Potentially powerful alliances between multinational companies and local communities remain largely elusive today. Although HCCL's multinational clients and local communities share the goal of responsible environmental management and are proud of their responsible sourcing commitments, forging powerful alliances with communities is not an option that the multinational companies currently consider. The difficulty for community monitors in contacting firms they do not know is just one problem. More importantly, European headquarters set procurement guidelines as part of their corporate risk management strategies and target an international audience of civil society and investors. According to this logic, it is more purposeful for the MNE to require suppliers to comply with ISO standards than to lobby the EMA or support local communities, which might undermine attempts to maintain a business-friendly environment and navigate the political economy of the host country. The implementation of a light-touch supplier due diligence and noninvolvement in 'internal affairs' maintains the status quo at the expense of local communities.

Instead of basing environmental management principles on a logic of risk management, the corporate sector could follow a developmental approach and focus on environmental quality assessments. An example would be joint water quality monitoring between mining companies and local communities as the IFC Compliance Ombudsman has called for years (CAO, 2008; IFC and ICMM, 2017). It has seen limited adoption in the industry, foremost in Peru (Pareja et al., 2018) and Canada (CanNorth, 2016). Given the lack of incentives and capacity for community-based monitoring of the state-owned

HCCL and Sino-Zimbabwean joint ventures, multinational companies would do well to follow international best practice.

These considerations highlight not only the potential but also the difficulty for local communities in forging strong alliances with actors that support accountability. A strategic approach is critical to success; it is the linchpin between the demand and supply sides of SAcc (Figure 13). Local communities in Hwange have done their best to form such alliances. They have activated pro-accountability actors at the operational level of the companies and at the local EMA office. Yet, the range of options they are able to access beyond Hwange is limited.

Accordingly, the changes that the community monitors could effect are limited to what can be achieved through voluntarism at the local level and in the shadow of a captured system by mobilizing local pro-accountability actors in local government agencies and companies. Notably, the most tangible results were produced with Sandledge, a Sino-Zimbabwean joint venture, whereas HCCL remained at the planning stage of drilling the boreholes for a long period before finally realizing one of them. ZPC, the governmental thermal power plant operator, took no action and no longer responds at all. More responsible environmental management will require more than perseverance in community-based monitoring and advocacy. More decisive action is needed using insights from PE to spring the low-accountability trap of a deliberately weak regulatory authority and a hegemonic politico-military elite. In this sense, the work of advocacy has only just begun.

4.7 Conclusion

Our research has engaged critically with SAcc, and we have developed a more solid foundation for SAcc theory by introducing PE thinking and analysis into the logic of the demand for and supply of accountability. On the demand side, we have demonstrated that citizen science is an effective way to empower marginalized communities in mineral-producing low-income countries and objectify debates about environmental management. This research has also confirmed the limits of institutionalist SAcc initiatives that rely on the ‘power of data’ and underestimate the inertia of structural power serving elite interests. On the supply side, recourse to PE to expand SAcc theory has proved critical in several ways: First, PE strengthens our understanding of the supply-side dynamics of social accountability. Secondly, such analysis reveals a broader range of actors involved by connecting local polluters to global production networks, which can, thirdly, open more diverse strategic options for the creation of alliances.

We advise donors and development agencies to incorporate explicitly political ecology analysis in SAcc strategies. Similarly, our research findings indicate that it is appropriate for donors to support citizen science as a significant component of SAcc initiatives. Yet for environmental citizen science to thrive, support needs to include functioning laboratories at local universities and the capacity to operate them. Without a minimal institutional and technical ecosystem to support it, citizen science cannot create sustainable empowerment but introduces new dependencies to external science players.

Finally, this analysis has also highlighted the inconsistency inherent in the patchwork architecture of global governance. SAcc initiatives by local communities and voluntary responsible sourcing guidelines by multinational companies may both aim at promoting good environmental management, but they follow different logics and thus set different, sometimes even incompatible priorities. As our case shows, this can frustrate the development of synergies and undermine improvements in effective environmental management on the ground.

If voluntary corporate regimes are to advance sustainable development independently of the corporate risk calculus, a fundamental conceptual revision of developmental logic is necessary. One way to achieve this would be to modify corporate responsibility regimes so that compliance is evaluated against internationally agreed environmental benchmarks for water, air, and other essential environmental parameters rather than against procedural criteria. This can be reinforced by moving local civil society from remote beneficiaries to active participants in global governance in their own right, as joint monitoring initiatives exemplify. Such a developmental turn in how corporate responsibility is conceptualized and evaluated will unlock synergies, make SAcc initiatives more impactful, and thus advance the responsible management of natural resources.

4.8 Acknowledgment

We would like to thank the large number of people who participated in this research and shared their knowledge and experience. Particular gratitude goes to the 13 community members from the rural area of Hwange District who have implemented the community-based water quality monitoring project and thus, have laid the foundations for this study. We further thank the colleagues from the Department of Geology, the Department of Mining Engineering and the Institute of Mining Research at University of Zimbabwe, Harare, who have inspired and supported this study. We are grateful to Owen Chituri from University of Zimbabwe for the technical assistance and to Christian Dinkel from Eawag for sharing audio recordings. We acknowledge Dr. Laura Perler for the valuable discussions about the manuscript and Dr. Christopher Humphrey and Dr. Simon Milligan for proofreading.

4.9 Author contributions

DR designed the study under supervision of FB. DR implemented all stages of the project in Zimbabwe and Switzerland, conducted most semi-structured and conversational interviews and wrote the manuscript. FB supported the interpretation of the results and importantly contributed to the writing of the manuscript.

5 Overall conclusion and outlook

Managing environmental impacts of mining is highly challenging for many mineral producing countries, especially in the Global South. Extraction rates thrive and mining activities threaten vulnerable ecosystems and biodiversity hotspots (Luckeneder et al., 2021). Governments often have difficulties to monitor environmental pollutants and execute environmental law due to limited financial capacities, equipment and a lack of trained personnel (Crawford, 2015). Not only the extraction process comes with a large variety of environmental externalities but also mine waste disposal and legacies around abandoned mines can be highly problematic. As average ore grades of industrial mining production are declining over time, the proportion of waste rock per unit of commodity produced is steadily increasing (Jones and Boger, 2012; Mudd and Boger, 2013), and with it the challenge of managing and disposing the billions of tons of mine waste generated each year around the globe. Fine-grained ore processing waste from hydrometallurgy known as tailings are stored in dammed impoundments of which some are at a permanent risk of failure, due to climatic factors, poor construction and managerial shortcomings (Azam and Li, 2010).

Monitoring schemes for the extractive industries should aim at localizing the sources of pollution, identifying pollutants of concern and assess potential health risks. However, this is not sufficient. Pollution does not take place in a vacuum. It has a societal and political dimension and is often situated in conflictual settings. It is crucial that the data and knowledge from monitoring schemes can be 1) trusted by various stakeholder groups and that 2) they are actionable by the parties that are invested to improve the situation. Monitoring for mining-related pollution should inform policy- and decision makers and should contribute to governance processes with the vision of problem-solving. To achieve this, it is important to identify the socio-economic drivers of pollution and the historical trajectories that frame pollution cases. On top of understanding biophysical parameters, it is key to focus the analysis of pollution issues regarding the underlying power dynamics between individuals and social groups. A special attention should therefore be put on scale since power manifests through scale (Swyngedouw, 2004) and also sets the boundaries of how environmental change is observed, measured and possibly understood.

The concept of scale overcomes disciplinary boundaries (Cumming et al., 2006), as does this thesis in which I developed and implemented effective approaches to monitor mining-related pollution that are adapted to the specific context and potentially transferable to other settings (Chapter 2 and 3). I identified, the socio-economic drivers of a pollution case (Chapter 4). In doing so, I focused on different pollution issues that took place in two different locations in Sub-Sahara Africa (Table 4).

Within the Swiss Minerals Observatory research group, my fellow doctoral students, our project coordinator, and I met weekly to monthly to identify common research interests and to reflect upon our own research by adopting other (disciplinary) perspectives. We were able to develop research collaborations where each of us could bring in our disciplinary expertise and address multidimensional aspects of the mineral supply chains with an interdisciplinary approach[9]. Three co-authored articles directly resulted from this coordination effort, two of which I contributed to (Van der Merwe, et al., n.d., Cabernard et al, n.d.).

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[9] For further information, see the synthesis report about the Swiss Minerals Observatory (Brugger et al., 2022).

Table 4 Overview of scale, aim and methodology in the different chapters

	Chapter 2	Chapter 3	Chapter 4
Place	Catoca Mine, Lunda Norte-, Lunda Sul-Province (Angola), Kasai-, Kwilu-, Mai-Ndombe-Province (DR Congo), other areas around the world	Hwange District (Zimbabwe)	Hwange District, Bulawayo, Matabeleland South, Harare (Zimbabwe), Zug, Nyon (Switzerland)
Scale	local/regional/global	local	local to global/transnational
Aim	Assessing large-scale water quality impacts of tailings dam incidents	Assessing mining-related environmental pollution and potential health hazards of residents and ecosystem	Analyzing the potential of collaborative in-situ-monitoring to support social accountability initiatives
Methodology	Remote sensing of water quality parameters	In-situ sampling in collaborative citizen science framework	Interviews with stakeholders from coal supply chain from Hwange to Harare and Europe

5.1 Potential of analyzing pollution and its socio-economic drivers

In Chapter 2 we analyzed a tailings dam incident that occurred at a diamond mine in Angola in 2021. According to the government and civil society in neighboring DR Congo, it had devastating impacts on water resources and public health. The large fish kills threatened the livelihoods of fishing communities and thousands of people who consumed the river water fell sick and 12 died. The mining operator contested these reports and refused all responsibility. In our study, we used remotely sensed high-resolution satellite data to assess water quality parameters for the area of interest in this period to identify the sources and the extent of the pollution. Our methodological approach allowed tracking the pollution wave from the source at the Catoca diamond mine all the way to the mouth of the river system when it reached the Congo River 20 days later and after over 1400 km of flow distance. The pollution wave reached turbidity levels that were punctually up several magnitudes higher than pre-incident values and exceeded Angolan and Congolese water quality standards by two orders of magnitude. We illustrated the temporal evolution of water quality parameters over 6 years at two virtual stations upstream and downstream of the point where the mine effluent reached the river, which enabled us to show that the pollution incident exceeded seasonal variability. With this contribution, we revealed the high potential of multi-spectral spaceborne remote sensing to track pollution in inland water bodies after a tailings dam failure. As we discussed for the tailings spill in Angola, responsibilities remain contested with the outcome that communities that suffer from the impact of pollution receive no compensation at all.

In Chapter 3, we showed that community-based monitoring can be an opportunity not only for producing an extensive dataset on water quality but also for enabling disenfranchised citizens to become active players in the stewardship of the water resources of their communities. In Western Zimbabwe, the Deka River is negatively impacted by coal mining; however, the mining industry rejects any responsibility. In the citizen science project, rural community members that were affected by the pollution were trained for technical water sampling. Over a period of close to 1.5 years, the community monitors took water samples and measured pH at specific sampling spots on a weekly to bi-weeks frequency. Academic researchers complemented the sampling and together with the community monitors, collected close to 800 water samples which were shipped to Switzerland for further laboratory analysis. With the data, we were able to pinpoint the pollution sources and to show that coal mining and combusting in Hwange were degrading water quality. The dataset showed that past mining activities from colonial times still affect the area. Acid mine drainage from abandoned underground mines cause a large share of pollution from the concessions that are today in the hands of the governmental mining company. Not only ill-managed mining legacies pose problems, but also everyday environmental management is unsatisfactory. We provided evidence that the Sino-Zimbabwean joint venture companies illegally pumped pit water, which caused pollution peaks in the Deka River and resulted in fish kills. This makes acidic pit lakes in the area a large environmental risk. Our study indicates that specific metals such as manganese, nickel and arsenic exceed drinking water guidelines, with arsenic probably emitted via coal combustion at the local thermal power plant. The scheme allowed identifying a public health risk especially regarding manganese since values exceeded drinking water standards by a factor of 70. The community-based monitoring had important advantages with regard the quick deployment of the community monitors in cases of acute pollution incidents. Community monitors not only went sampling at the agreed weekly to biweekly frequency. When observing something irregular like a fish kill, some community monitors took water samples and measured pH. This was important to cover the high variability of pollution in a dynamic setting. Around 10 months after the onset of the community-based monitoring, we installed three measurement devices, on in the river and two in the effluent channel. It was of great help to relate to the observations and contextual knowledge of the community monitors to interpret the readings of the measurement devices and the chemical data.

Dying fish and water quality parameters that exceed guideline values can be considered as a symptom of much broader underlying governance challenge. In Chapter 4 we presented an in-depth political ecology analysis of the underlining political, historical and economic conditions that frame the long-lasting pollution case in Hwange, Zimbabwe. With our analysis of the power dimensions that are involved in the coal supply chain in Zimbabwe, we showed how the elite capture of the state and industry in Zimbabwe was limiting the prospects of social accountability initiatives to local levels. This explained why the community monitoring was only partly successful in demanding accountability and remedial action from the side of the industrial stakeholders. The local social accountability initiative was successful in empowering community members towards power holders in Hwange and getting concessions from them (such as drinking water boreholes) but limited to trigger higher-level reactions for remediating the pollution.

We linked local polluters to global production networks and thus identified important powerful stakeholders in the system that remained undetected: the international clients of Hwange coal. Our analysis showed that involved stakeholders in the Hwange coal supply chain cover various scales ranging from local through national to the global level. These scales do not necessarily connect through the hierarchical order since in a globalized capitalist world economy the local level can directly interfere with transnational structures and vice versa (glocalization, see also Swyngedouw, 2004). We contributed to social accountability theory by underlying the important role of the private sector that goes beyond the citizen-state dichotomy of classical social accountability theory. We highlighted how the right alliances between local communities and global private actors could improve the effectiveness of social accountability (see Section 5.7 for detailed policy recommendations).

Overall, community-based monitoring and other citizen science frameworks have a high potential for environmental quality assessments and for fostering the collaborative process. Citizen science offers a monitoring strategy with the advantage that local communities can be taken on board. To involve local communities is the first step to engage with stakeholders on the ground. With this involvement of stakeholders, the monitoring activity has a direct connection to the context and ongoing governance processes. In Hwange, the community-based monitoring was a new approach that the local communities used to improve their environmental conditions. It faded into the ongoing social accountability initiatives that civil society started two years before. That the community members got involved in research activities had an educational effect that allowed them to acquire the necessary knowledge and vocabulary to better confront representatives from the government and private sector and level out some of the power asymmetries. Community monitoring acknowledges local expertise and empowers local communities to stand in for their environment.

5.2 Limitations of monitoring tools for water quality

In Chapter 2, we showed how powerful satellite remote sensing can be to monitoring pollution impacts in a context with a lack of personnel and financial capacities to deploy monitoring teams to the ground in case of sudden pollution incidents. Nevertheless, satellite remote sensing methodology fails to offer a cheap and simple alternative to in-situ sampling.

Although software kits from Space Agencies like the ESA and NASA or cloud-based services such as the Google Earth Engine (Gorelick et al., 2017) did facilitate the access to and analysis of satellite imagery, atmospheric corrections remain challenging depending on the specific end use. Water quality monitoring with satellite remote-sensing is certainly comparably cost-effective for large areas but comes with important (financial) requirements for hardware and high prerequisites for user expertise specifically if no ready-to-use toolboxes are available (see Section 5.7.2). To cover the vast spatial dimension of the Catoca incident we analyzed fifty 100 km^2 Sentinel-2 image tiles. By performing the atmospheric correction and extracting the water quality parameters for those tiles, we generated over a terabyte of data. Such a task requires not only powerful processors in personal computers, but also stable and high-speed internet connections to download and/or share imagery. These are important (cost) factors that may limit the development and implementation of space-born water quality monitoring in many countries of the Global South. Such a strategy requires some additional support from the private sector, as I will propose in Section 5.7. In addition, the resolution of publicly available satellite imagery such as Sentinel-2 represents still a limiting factor for specific water pollution cases in mining areas (Section 5.3). In a societal context, the main limitation of remote sensing methods is the complete isolation of data creation and interpretation from the governance processes on the ground. In our study on Angola, we created a valuable data source that clearly illustrates the devastating effects of the Catoca tailings spill, however, the creation of this data is detached from the ground, and it will be highly challenging to introduce this data into an ongoing governance process, especially on the local level.

A community-based monitoring scheme is strongly rooted in the local context, however, there are important logistical challenges. This reaches from the continuous supply of adequate sampling tubes to a remote field area to the availability of local laboratory infrastructure. These logistics are not only highly demanding regarding the administrative load but also cost intense. Private laboratories in Zimbabwe proved to be inappropriate to the needs of trace metal analytics. Even researchers at local universities in Zimbabwe tend to ship their samples abroad to laboratories in the Global North if their funding schemes allow it. This limited laboratory facilities at local universities and costly alternatives are a boundary condition that is also encountered in other Global South contexts and that will constrain not only the ability of local scholars but also to shape such collaborative research initiatives. Nevertheless, data quality is not only an issue of accurate laboratory analysis but is also dependent on a rigorous data collection. Community-monitoring schemes need a stringent follow-up from the professional side to ensure that data quality remains high. Group discussions and field visits are key for professional partners to identify errors and ensure that the community implements the sampling protocols correctly. A sensitive design of a community-based monitoring scheme is crucial also regarding its embeddedness in an overarching governance process. Experiences from other contexts have shown that citizen science alone not always leads to the intended political outcome (Brombal, 2020). Even worse, citizen science is sometimes exploited to maintain harmful industrial practices (Blacker et al., 2021).

5.3 Reflections on the scale of pollution monitoring

The choice of scale affects how a researcher can evaluate environmental change in an area. Thus, scale creates a certain bias in the analysis (Turner, 2006). Observational and measurement scales restrict the understanding of the complexity of the underlying relationships between the physical and the social dimension (Rindfuss et al., 2012). To construct a causal interference simply based on spatial correlations of a set of variables is not only risky, but can lead to wrong interpretations and sustain simplistic environmental and social narratives of change (Turner, 2003, 2016). The famous physicist Philipp Anderson noted 50 years ago in his essay that at each level of complexity new properties appear. He underlined that physical laws were not universal: if a law applies to a particle, it may not be applicable for describing the behavior of many particles interacting with each other (Anderson, 1972). There is no general linearity across time and space that would allow extrapolation of conclusions across and between scales (Sayre, 2017). Research on land-use and land-cover change regarding pastors and herders (Brottem et al., 2014; Sayre, 2017; Hopping et al., 2018) and conservation (Turner, 2006; Dufour et al., 2018) impressively demonstrated that observations made in one scale cannot be applied across and in between other scales without possibly misinterpreting certain facts. It is difficult to get from local to global level and vice versa without running the risk of ignoring important phenomena (Dufour et al., 2018). Complex and non-linear behavior is observed in fields from forestry, through biodiversity to population dynamics and make the choice of the geographic and temporal scale of observation and measurement highly relevant for the understanding of patterns in land-use and land cover change (Rindfuss et al., 2012). Choosing adequate time frames in the observation of the Earth system is also crucial for identifying nonlinear switches in states and related components that are reaching a tipping point due to anthropogenic climate change (Lenton et al., 2008).

Scales therefore frame problems but it can also be the other way around. Based on their (political) interests, social actors can also choose specific scales to frame issues of climate change, water protection and forest conservation. For instance, they may try to scale up or scale down issues, which implies that some actors may define issues as global or local depending their political interest (Gupta, 2014). This is also important with regard to narratives around environmental pollution, degradation and scarcity or ecological marginalization where blame is often ‘localized’ to marginalized communities instead of analyzing the driving factors that reach up to global networks of multinational extractive companies (Hartmann, 2001). Environmental impacts and negative health effects often have drivers that are scattered on a multitude of layers and situated within nested power hierarchies (Karlsson-Vinkhuyzen, 2014). In Chapter 4, we showed these interrelated connections between the local and the global through the business relationships between Hwange coal miners and multinational enterprises that buy the coal for manufacturing their products in Zimbabwe. These international companies are in a powerful position that would allow them to support local communities and act in favor of social accountability to change the underlying socio-economic drivers of the pollution (see also Section 5.7).

In Chapter 2, I showed how the use of remote sensing substantially increased the spatial scale of monitoring activities for mining-related pollution, but this large-scale approach brings challenges. As often observed in conservation and forestry studies, scalar choices in monitoring include or exclude observable patterns that will shape political and ecological practices (Read, 2006; Turner, 2006). The scale of analysis influences what kind of environmental changes can be monitored, but the scale for best governing the issues might be different (Turner, 2006). Jurisdictional scales are defined by boundaries and organized administrative units (Cash et al., 2006). However, structures of social organization often mismatch in scale with the ecological processes they intend to manage which leads to inefficiencies or disruption of ecosystem services (Cumming et al., 2006).

As it is not meaningful to generalize through scales by extrapolating a conclusion from one level to another, the question remains how researchers can combine different scales in a methodological approach to achieve a transformative effect. Already in the early 1980’s, Cairns and Van der Schalie (1982) stated that no single monitoring tool would ever be able to provide all the information necessary about the condition of an ecological system. In recent years, scholars of ecological sciences argue for an integration of different monitoring types that are operated on different geographical scales and temporal spans, insisting that each of the different types have strengths and drawbacks, depending on the questions asked (Sparrow et al., 2020). Traditionally, this consists of linking in-situ data to remote-sensing data, thus remaining on the different scales of biophysical parameters. Integrative land-use science went a step forward by combining different types of datasets and methods. Especially in studies related to deforestation and land degradation it became imminent that social science expertise was necessary for the analysis, especially to better understand the drivers of change and human decision making about land (Turner, 2003; Dennis et al., 2005).

For the Hwange area, the question seems at hand why we did not link the chemical in-situ data from the citizen science project to aquatic parameters obtained from optical remote sensing satellite data. The U.S. state of Wisconsin, for instance, works with a thousand volunteers in an initiative that was initiated 1999 to collect on-the-ground data and to combine it with remote sensing to monitor the water clarity in the 8000 lakes of the state (DNR, 2022)

To answer this question, I would like to draw the attention on two important aspects that are both context-related: First the feasibility for implementing the monitoring and second the purpose of implementing it. On the level of data acquisition, there are some important drawbacks for using spaceborne imagery for water quality monitoring in mining areas. The visible range of the electromagnetic spectrum on Sentinel-2 imagery has a 10 meters resolution, but other bands needed to compile water or vegetation indices have a higher resolution of 20 meters. Effluent channels are often relatively small and are only between a few and to a dozen meters wide. For most of them, the spatial resolution of the imagery is simply too low. One pixel on the sensed images would therefore blend in not only the water surface of the effluent channel, but the shores and the vegetation that surrounds it, which prohibits sensible interpretation. The Deka River for instance, is perennial and runs partly dry during several months per year. The river has only a few pixels covered by water all year and that can constantly be classified as water pixels. This makes a water quality analysis through spaceborne remote sensing highly demanding and results would have very limited informative value.

In addition to operational challenge for combining the monitoring methods, we have to ask if, in the case of Hwange and the specific societal and political context, it makes any sense to add another source of data generated through spaceborne remote sensing. What type of important data would the remote sensing produce that the community-based monitoring was not able to provide? Monitoring has to be purposeful and, in this case, I come to the conclusion that it would not only be highly challenging to realize a water quality monitoring based on Sentinel-2 imagery but that the benefit for problem-solving would probably be limited. The political ecology analysis of the coal sector in Hwange (Chapter 4) clearly showed that the environmental governance is not hindered (anymore) by the lack of data but by political and economic structures that influence governance processes. We could show how power dynamics limited the potential of community-based monitoring to trigger a transformative moment. Our research confirmed the limits of institutionalist social accountability initiatives that rely on the power of data and underestimate the inertia of structural power serving elite interests (Fox, 2015). Based on the experiences in Hwange and the results of our political ecology analysis (Chapter 4), the prospects of remotely sensed data to contribute to the governance process in Zimbabwe are low. Nevertheless, if a governance process could be initiated at the global level by involving the multinational enterprises that are clients of Hwange coal and their staff at the European headquarters, remotely sensed data might help to illustrate pollution impacts and strengthen the message to convey. Currently national governments in the Global North and multilateral institutions are taking into account to implement higher level governance schemes for the resource sectors that touch also on the environmental dimension of extraction and trade. In Europe, responsive sourcing standards and corporate due diligence are gaining momentum as the Commission of the European Union has presented a proposal for binding obligations for companies involved in global supply chains to respect human rights and the environment (European Commission, 2022).

Conclusively, it is important to highlight that it is not a pure question of technical feasibility whether monitoring tools should be combined or not but rather a context-related decision that should focus on what type of data is needed in a specific situation and in which way this data can be introduced into a governance process.

5.4 Reflections on the role of trust in pollution monitoring data

Participatory monitoring is a widely accepted instrument to build trust between communities and stakeholders such as (mining) companies and the government (Fernandez-gimenez et al., 2008; Bebbington and Bury, 2009; Pareja et al., 2018). However, trust is also important at another level, namely for the trustworthiness of the data obtained in the context of a participatory monitoring scheme. In this section, I will focus on the issue of trust in surveillance data by discussing experiences from Zimbabwe and providing an outlook on the potential use of remote sensing data by stakeholders.

In the Chapters 3 and 4, we highlighted that the data obtained from community-based monitoring in Hwange, Zimbabwe, was deemed trustworthy by various stakeholders, including mining industry representatives. This became evident during the multistakeholder meeting end of April 2019 where preliminary data was presented: Two community monitors explained the process of sampling, and I presented the chemical data, showing graphs and explaining causal relationships and the scientific interpretation. In the subsequent discussion, the audience acknowledged and welcomed the data, although I was prepared for a debate on data quality and the validity of our interpretation (see Section 4.5.2). This surprisingly broad acknowledgement of the data became also obvious during the numerous stakeholder visits and the bilateral interviews I had conducted throughout the project.

In my experience, the debate on trustworthiness of data is to a large extent a debate on data quality. Various scientific studies have been dedicated to the question of data quality in citizen science projects by comparing the data collected by citizen scientists with the data collected by professionals (Crall et al., 2011; Herman-Mercer et al., 2018; Balázs et al., 2021). Among other factors, these authors highlight the importance of a tight follow-up on the sampling process to ensure high-quality standards, as well as a rigorous setting of data validation to increase trustworthiness. Our experience in Zimbabwe confirmed the conclusions of these studies and demonstrated the importance of tight follow-up of the data collection process by community to detect errors in the sampling and keep high standards of data quality (Section 3.5.3). This follow-up was conducted through numerous meetings and conversations with community monitors, during which they also explained their approach to sampling (e.g., the decision not to sample alone) and the care they took in handling samples, which allowed me to further build confidence in their sampling approach. In addition, because of the hundreds of samples and the wide range of chemical elements we analyzed in the laboratory, we were able to identify doubtful samples and confront the community controllers with questions about the circumstances of the samples. When in doubt, such samples were removed from the dataset (Section 3.5.3).

For various stakeholders, trust in data is also tightly linked with the reputation of the data collector (Hunter et al., 2013) and to the overall accountability system of science (Baert and Shipman, 2005). In participatory monitoring, the party supporting the community observers or other lay people is the one providing such guarantees. In the case of Hwange, ETH Zurich and less prominently the University of Zimbabwe acted as scientific partners in this participatory monitoring program and therefore had the critical role of ensuring scientific standards and data reproducibility. In the eyes of company representatives and government officials, the trustworthiness and credibility of the data were strongly linked to these academic partners in the project. The fact that the main academic partner was a prestigious university in the Global North most likely reinforced the subjective sense of trust in the data (see also Section 5.5 about the role of the scientist). Another factor in the acceptability of the data was also that government officials and company representatives were well aware of the problems on the ground and had also collected their own data that led to similar conclusions. During the two-year experience in Hwange, it became clear to me that the government and industry were well aware of the major problems but withheld information from the public for political reasons (Section 4.5). In the bilateral meetings I had in Harare with national representatives, no one openly expressed distrust of the data, even as its existence was denied by government officials (Section 4.5.3). Overall, I estimate that the more adversarial the environment in which the data are presented (e.g. in court), the more the quality of the data is doubted. I conclude that open communication towards all stakeholders also positively contributed to the reception of the data. I informed all stakeholders bilaterally that community monitoring would begin and regularly updated them on the project outputs and preliminary results. During the technical training of the community monitors, a representative from the Environmental Management Agency was present and followed the process. The involvement of a scientific partner therefore stands in contrast to other participatory monitoring schemes that do not fulfill any quality standards and are not trusted by the industry. As an interview partner from a Canadian mining company underlined, the company funds a participatory monitoring between community members and a consultancy company as a trust building measure for the community members, but the mining company implements another additional monitoring with the consultancy company that fulfills their own requirements (personal communication Inglis-McQuay, C., 03.11.2017). This suggest that the company doubts the trustworthiness of the community data.

Especially for the communities, an academic partner is often welcomed and widely accepted, when community members or civil society cannot detect a particular self-interest or apparent conflict of interest (Resnik et al., 2015). However, it also will depend about how the specific partner will behave in questions of lobbying for a specific outcome (see Section 5.5; Pielke, 2007). Further, it was shown that communities generally have higher trust in data that was collected by other community members, especially in pollution setting (Wilson et al., 2018). Also in Hwange, other community representatives have trusted the data because members of their communities have not only collected the majority of the samples, but the regular meetings in Hwange also helped them to understand and relate to the process that followed the sampling collection on the local level. With images from the laboratory, we have illustrated the different steps of the analytical process that was ‘out of their hands’ and of data that they didn’t understand (Bebbington and Bury, 2009).

Overall, trust in science is a complex issue and depends on the type of science being done and the political status of the individuals who trust or distrust the science (McCright et al., 2013). To date, it remains to be seen how the results of the remote sensing analysis in Chapter 2 will be received by stakeholders once they are published. Although remote sensing imagery is informative and provides an objective analysis that is attractive to many (international) stakeholders, there is still the question of trustworthiness of the data. The issue of trust in remote sensing products is generally one of reliability of the data, bias in estimates, and spatial distribution of patterns (Weerasinghe et al., 2020).

For the Catoca study, only one Congolese scientist, who is a nationally known and consulted water expert, co-authored this study. No other stakeholder in Angola or DR Congo was involved in the data generation and analysis process and therefore has knowledge of the data. I judge it necessary that the study, once published, would be presented in person and explained to stakeholders that were involved in the pollution case at the Catoca mine and that their concerns about data interpretation and validity can be clarified. Accuracy of remotely sensed products in water quality monitoring is one specific concern of users outside academia (Schaeffer et al., 2013). Other studies have shown that the uptake of remote sensing results also highly depends on the overall stakeholder engagement process (Beveridge et al., 2020). The translation and communication of remote sensing data is critical to contributing to an environmental management process (Heremans et al., 2021). Otherwise, there is a great risk that the spaceborne water quality data will not be taken up by decision-makers on the ground and that its potential will not be exploited.

5.5 Reflections on the role of the scientist in pollution monitoring

Choosing a certain scale to analyze a problem brings a scientist in a powerful position, since, as developed in Section 5.3, scale defines how environmental change is understood. This leads to the important question of the role of the scientist on which I will reflect in relationship to my experiences using different monitoring tools.

Satellite imagery for instance is sensed by a device that orbits in space in over 700 kilometers in altitude from the Earth surface. The researcher that analyses the data, can be located anywhere on the planet. Not only is the sensing instrument disconnected from the ground, but also the researcher does not necessarily have a personal and physical connection to the area of interest that is analyzed. This importantly abstracts the researcher and the research from the material and historical context of the landscapes that is studied (Robbins, 2003; Turner, 2003; King and Tadaki, 2018; Braun, 2021). This detachment from the ground can be interpreted in different ways. It might be tempting to believe that remote sensing allows working with a neutral data set and with objective evaluation criteria with a view from ‘nowhere’. However, knowledge is situated and embodied (Haraway, 1988). At every step a scientist makes, she[10] is moved by her own norms and perspectives, which affects her research process, from the choice of data and methodology to the data interpretation and beyond. The scientist is situated, and her researcher’s positionality doesn’t only have a scientific, i.e. disciplinary, dimension, but also a (geo)political one. Remotely sensed data “should not assumed to be ‘raw’, fundamentally objective, and detached from the observer but rather both a product and a part of contextually specific political negotiations and sociotechnical systems” (Alvarez León and Gleason, 2017, p. 1087). Researchers indulge in the idea that that remote sensing data is ‘unbiased’, however often forget that the understanding of the relationships between reflectance spectra and biogeochemical processes in ecosystems is still limited (Read, 2006) and has led to misleading interpretations around ecosystem’s management (Hopping et al., 2018). Also, the greater the distance, the higher the risk that certain kinds of knowledge go unnoticed or are even excluded (Lane et al., 2018). Categories of analysis such as forestry typologies, ecological classifications, or hydrological units used in remote sensing and geographic information systems (GIS) do not necessarily match with local categories of foresters and herders and therefore ignore local realities (Robbins, 2003). The detachment from the ground should therefore rather been considered by academia as an additional challenge for impactful research than an advantage. In addition, the trustworthiness of the remotely- sensed water quality analysis will be perceived differently by the various stakeholder groups and, accordingly, is factored differently into their decision making (Schaeffer et al., 2013, for details on trust in data see Section 5.4).

Science traditionally adheres to the norms of neutrality and objectivity, however cultural, historical and social contexts shape the way in which science and technology are created and used, as scholars from the field of Science and Technology Studies highlight (Lave, 2012; Lennon, 2017; Nost, 2022). Donna Haraway for instance considered the claim of objectivity in sciences as a key tool to exert social control, since “knowledge from the natural sciences has been used in the interests of domination” (Haraway, 1991, p.8). Other scholars provocatively expressed that all science is political since “science is mobilized in the name of particular interests, or in public debates, or for specific projects, all of which involve political boundary work and social constructions, and all of which are contingent and situated” (Isopp, 2014, p.319). Therefore, the positioning of the scientist is complex, and the debate should rather focus on which role a scientist can consciously take when getting involved in a problem. Researchers that are confronted with environmental degradation often have to ask themselves which role to take in problem-solving (Pielke, 2007). Concerning pollution in particular, research outputs might have a juridical component. The right to a clean and safe environment is anchored in many national constitutions and in the UN Charta of human rights, which means that cases of pollution have the potential to be debated in front of the courts. In Hwange for instance, civil society considers its options of civic engagement exhausted (Chapter 4) and designs a strategy for legal action (personal

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[10] Generic femininum is used

communication Muzamba, P., 12.08.2021). In the DR Congo, a trial has been initiated against the mine owner in Angola that has caused the tailings spill and polluted the water resources (Muamba, 2022).

Challenges related to the researcher positionality and its role became very apparent to me during the four extended stays I spent in Zimbabwe from early 2018 to end of 2019. During those periods, that sum up to about one year, I was confronted with the political realities of the country that not only impacted the way citizens were able to engage with the pollution in the civic space, but also for the work as a scientist regarding freedom of speech, of movement and security. Each of the ten times I visited Hwange over the nearly two-year period, I spend several weeks in the study area. In addition to collecting samples and meeting with the community monitors, I interviewed stakeholders and participated in the mediation meetings, as part of the audience or presented data together with community monitors. I developed social relationships with various stakeholders, and it became evident to me that I was also perceived as an actor since I was contacted and included by stakeholders who referred to me while debating about the pollution. The impact that field work and personal relationships have on the researcher's perspective and on the research is also highlighted by other scholars (Law, 2018). It is important to notice, that, as a researcher I was not perceived in an abstract way, but in my own socio-cultural and political situatedness: I was perceived as a white woman from a high-income country in Western Europe that represented a prestigious university. In post-colonial locations, it of course plays a significant role in which ways researchers produce knowledge (Jazeel and McFarlane, 2010). In Hwange, the factors related to my positionality also influenced how the results of the community-monitoring were perceived, involving dimensions of credibility, trust and reliability, among others.

As involved researcher, I could choose – as Pielke provocatively proposed – to become an advocate 'lobbyist' or honest broker to foster policy implementation (Pielke, 2007). This specifically also influenced the numerous exchanges I had with government representatives. Here it was important not to lobby for change, since, in the post-colonial political understanding in Zimbabwe (see Chapter 4) this would have been perceived as paternalistic and morally charged with a Western hegemonic viewpoint and white supremacy thinking. Overall, the cooperation with the different stakeholders was more straightforward on the local level in Hwange were the numerous personal encounters allowed me to a built a common trust level. On the national level in Harare, by contrast, I only punctually met with government- and industry representatives for interviews and therefore I encountered more reluctance by them to share information with me (Chapter 4).

5.6 Potential for method transfer

For methodologies developed in a specific context, the question arises whether they can be transferred to other contexts. This concerns not only the transfer to other geographic areas, but also includes the applications to the mining of other types of raw materials. For both monitoring approaches developed in this thesis, the potential exists to be transferred to other contexts, but I acknowledge that many factors must come together for this transfer to be successful and for the data generated to be credible. This is true for both the citizen science project implemented in Hwange (Chapter 3) and the remote sensing methodology used to track the impacts of tailings dam failures (Chapters 2).

5.6.1 Citizen science for Hg pollution

In the following, I will focus the discussion whether citizen science could be reproduced for other pressing problems in the mining sector in Zimbabwe. As I identified in the literature and in numerous interviews during my stays in Zimbabwe, there are many other pressing issues all over the country. Zimbabwe is one of the countries worldwide with the largest ASGM sector per capita and among the ten biggest ASGM mercury polluters in the world (Shoko and Veiga, 2004; Telmer and Veiga, 2009;

Mawowa, 2013). The use of mercury amalgamation for the mineral processing in many gold mining sites is a potential risk to surface water quality (Shoko and Veiga, 2004). Zimbabwe has signed the Minamata Convention on the phase-out of Hg (UNEP, 2013). Therefore, the question would be if a citizen science project could support the assessment of the mercury pollution in surface waters in Zimbabwe and support the implementation of the Minamata convention. Based on my experience, I consider it very difficult to directly assess and monitor mercury in water via a citizen science scheme. As we have seen in Hwange, trace element chemistry is challenging regarding the laboratory infrastructure the monitoring relies on. For main pollutants of concern, like manganese for instance, test strips were not available. Mercury analytics for liquid samples are even more complex as it is not included in the lists of regularly analyzed trace metals by specialized laboratories. Mercury is highly volatile which comes with a delicate water sampling technique relying on the adequate procedures from the sampling (glass) bottles to the preservation and storage of the sample. Mercury is also a difficult substance to sample for lay-people. In contrast to AMD, mercury pollution is not associated with changes in pH or water color. Although chronic exposure is very harmful to human health, effects are appearing on the long-term and in the experience of people, they cannot be directly linked to (water) consumption. Instead of sampling water, an alternative for a community-based monitoring could be to sample fish species that are locally consumed. This would make sampling protocols easier and reduce the risk of contamination and would allow assessing the bioaccumulation of mercury in the food chain and directly relating it to public health risks for elevated fish consumption.

Further, the success of citizen science highly depends on the motivation of the participants. Without the openness of community members in Hwange to participate in the project, we would not have been able to implement this project. Community monitors felt personally concerned by the environmental pollution and some of them had already been outspoken against it for years. Not only is the personal involvement a key issue but also trustful relationships between academic researcher and the community monitors and within their group. Family ties and friendships made the Hwange community monitoring successful. People motivated and trusted each other. The two factors – concern and trust – are much harder to find in gold mining communities. Gold mining communities, notable in Zimbabwe, tend to have more disrupted social tissues because of intense migration pattern and higher potential for violent conflict (Mkodzongi, 2020; Mkodzongi and Spiegel, 2020).

5.6.2 Monitoring tailings dams by remote sensing

In many cases of mining-related pollution, civil society, and media report on the negative impacts whereas governments or mining operators tend to be silent or deny that any short- or long-term harmful effects have occurred (Chapters 2 and 4, this volume). Satellite imagery might be a strategic tool for investigating pollution incidents where only little information is available or that are highly controversial. This is specifically relevant for pollution incidents that have occurred in the past or in mining where physically access is highly restricted (see also Chapter 2). For tailings spills or -dam failures for instance, large-scale water quality impacts have not been assessed and residents have not been compensated for their economic losses and health impacts. In Chapter 2 we presented a new workflow to assess water quality impacts of tailings spills using Sentinel-2 imagery. We also studied the feasibility of transferring the methodological to other tailings dam failures that have occurred since the start of the Sentinel-2 mission in 2015. Our review showed that the data availability is only satisfactory for monitoring pollution incidents some months after the launch of the second Sentinel-2 satellite in March 2017. Further, optical remote sensing relies on passive sensors that measure the reflectance that is scattered back from the Earth Surface. Therefore, the methodology is highly sensitive to cloud coverage and other atmospheric disturbances. The prospects of applying a Sentinel-2-based pollution monitoring to other tailings dam failures depend therefore also on the climatic conditions during which the incident occurs. We nevertheless identified other tailings dam failures in China, Mexico, Peru, and Myanmar where the workflow could be applied with a high probability of assessing water pollution. In addition, I recommend developing user friendly Sentinel-2-based toolboxes for large-scale water quality surveillance in mining areas (see Section 5.7.2).

5.7 Policy recommendations

The common denominator for the various temporal scales of water pollution, whether long-term contamination or acute incidents, is often the lack of accountability on the part of the polluters. To provide a nudge for improving environmental management and governance in mining, the focus should not only be on the mine operator at the local level, but also consider its embeddedness in a global economy. Here, international commodity customers in the supply chain and/or industry associations might be able to set benchmarks for higher environmental standards and form alliances with local actors aimed at improving the situation.

5.7.1 Long-term water pollution

Environmental pollution has a price, but in many places around the world, this price is paid primarily by poor and marginalized communities who are directly exposed to the pollution (Carmin and Agyeman, 2011). As the Hwange case has shown, government- owned companies in an elite-captured state do not have to fear anything substantial from the side of governmental authorities (Chapter 4). Foreign mining companies often operate under political protection and do not feel any pressure from their home markets, like the Chinese firms we encountered in Hwange. For these industrial players, the environment has no real price, yet. That Hwange is heavily polluted is known all the way up the hierarchical ladders of the political institutions in Zimbabwe. Also, the pollution has been mediatized since over a decade (The Zimbabwean, 2011) and therefore this pathway for creating public concern and pressure is exhausted.

What could be a nudge for mining companies in such contexts to improve their environmental management? As described in Chapter 4, it is crucial to search the right alliances to improve accountability deadlocks. We have shown that multinational enterprises (MNE) have an important stake in the supply chain, not only as producers but also as clients. They are listed in the Global North, which makes them sensitive to shareholder attitudes. The value of equity shares of a listed company is highly sensitive to reputational risks, as the recent examples of the financial sector have shown once again (Son, 2022). The sincerity in which MNE's implement their due diligence guidelines is key to move forward. Our results have clearly shown what important role corporate responsibility can play even in local contexts that superficially have little to do with the main activities of the international company (Chapter 4). This holds true not only if the company is a direct producer of a commodity but, as we have seen, also as a stakeholder within the supply chain. International companies are powerful, whether the power is apparent or real. Concerning Nestlé and Holcim, however, it is not surprising that such MNE's make an impression to local business partners. The sales volumes of Holcim and Nestlé exceeded Zimbabwe's gross domestic product of 16.77 Mia USD in 2020 by 1.5 to 5 times, respectively. Their size allows the companies to develop thorough due diligence guidelines and sustainable procurement principles, however the implementation comes with important challenges considering that these MNE's have over hundred thousand suppliers around the world (LafargeHolcim, 2021; Nestlé, 2021). In certain Global South contexts, MNE's encounter difficulties in pushing the standard forward without taking a political stake that could transform in a severe business risk. Especially energy carriers like coal suppliers are challenging since the mining companies often figure among the strategic suppliers with a high market share and a high importance for the MNE's activities (Chapter 4). In such cases, it is difficult to disengage if the MNE wants to continue operating in that market. To push the implementation of the procurement guidelines forward and to promote other due diligence principles we suggest that MNE's foster the support of environmental monitoring (Chapter 4). Such an engagement could support local communities in the implementation of a community-based monitoring like the one in Hwange (Chapter 3). Here the MNE would have more opportunities to allocate budget expenditures since the support of civic engagement for cleaner water might also be part of the corporate social responsibility endeavor. MNE's could thus contribute to improve environmental management of their suppliers substantially without financially involving with them.

To operationalize this, it might be difficult for an MNE to find a counterpart for engagement on the side of the communities to set up a community-based monitoring. Rural community members that affected and engaged against the pollution might only loosely be organized and MNE's run at a risk of ending up in a formal arrangement with local elites. We therefore suggest that the MNE mandate and financially support a local academic or technical institute to set-up a collaborative research framework and implement a community-based monitoring scheme. Local universities have a positive reputation that could allow them to fulfill the role of a honest broker (Pielke, 2007), a role that was key for welcoming the community-monitoring data in Hwange (Chapter 3). Especially in highly politicized contexts, it is key to engage a player that has no direct stake in the pollution and is considered as impartial as possible. For local research institutions this could be a win-win scenario to develop a community-based monitoring that enables on the one hand to increase their own research activities in form of citizen science and on the other hand to have additional funding source for research. Regarding the lack of laboratory infrastructure for chemical analysis that are a limiting factor for community-monitoring schemes (Section 5.2), MNE's could also provide support, from sample logistics to the establishment of local laboratory infrastructure. This might exceed funding opportunities of a CSR engagement, but MNE's could seek to find synergies with development agencies and other donors, that are interested in improving environmental issues and that could consider local research institutions as an appropriate counterpart to (indirectly) support grass roots civic engagement.

5.7.2 Accidental water pollution

In the event of accidental spills, in-situ sampling teams must be deployed quickly. This is only possible if emergency structures are in place and trained personnel are available. Otherwise, it is very difficult for local government, scientific or civil society representatives to respond appropriately to pollution disasters. Complementary to in situ sampling, satellite remote sensing methods could be a way to provide transparency for controversial environmental incidents, assess their impacts, and clarify responsibilities on the part of potential polluters, as we showed in Chapter 2. In what follows, I formulate some policy recommendations that are based on the lessons learned in Chapter 2 but do not derive directly from the research findings as do the recommendations in Section 5.7.1.

Publicly available high-resolution data such as Sentinel-2 offer new opportunities for monitoring waters. The Sentinel-2 space mission will continue to provide data with a short repeat time in the coming decades as the satellites currently in space are replaced at the end of their lifetime (ESA, 2021a). It would therefore be worthwhile for Sentinel-2 to develop user-friendly toolboxes for water quality monitoring-an effort that might otherwise be avoided given the limited lifespan of satellites.

For the agricultural sector, the European Union funded research to provide a close-to-market tool for monitoring growth stages and yields that incorporates automation through artificial intelligence neural networks (Karagiannopoulou et al., 2020). In the mining sector, machine learning facilitates the detection of land cover changes. Currently, tools such as ASMSpotter are being developed with pilot implementations for Peru, Suriname, and Guyana to automatically detect new artisanal and small-scale mining (ASM) sites based on Sentinel-2 imagery (Dida, 2022). Policy makers such as the German Federal Institute for Geosciences and Natural Resources (BGR), which advises various mining authorities in the Global South, support the development of such tools. BGR believes that such automated data analysis can help government agencies and other stakeholders monitor the spread of ASM and develop appropriate governance measures (personal communication Schütte, P., 22.03.2022).

In this sense, developing a toolbox for local universities to monitor turbidity in streams around active mines, as shown in Chapter 2, could prove very useful. A similar technique for satellite-based monitoring of suspended sediment concentrations in large rivers has been implemented by researchers in collaboration with government agencies in Bangladesh (Beveridge et al., 2020). The analysis can be run on two platforms, one using Google Earth Engine and the other using a local desktop server and the Google cloud. Such toolboxes could be developed for the mining sector and complemented by new applications of the ever-evolving remote sensing technology, not only optical remote sensing, but also Synthetic Aperture Radar (SAR), which overcomes the limitations of cloud coverage. A consortium of North American and European space agencies is currently developing a new radar mission, Surface Water and Ocean Topography (SWOT) (JLP, 2022). SWOT will provide estimates of water elevation and other parameters and will further expand the use of satellite remote sensing in water research. In the case of tailings impoundments, this will allow estimation of the volume of tailings released during a spill, which is not possible with current satellite radar imagery (personal communication Fattahi, H., 09.11.2021).

Industry associations could play an important role in developing such tools and bringing the data into a governance process at the global level. Industry associations could 1) push for higher standards related to dam safety, and 2) work with their members and involve local research institutions in producer countries to support the development of ready-to-use toolboxes. It is important to emphasize that these toolboxes should be adapted to the needs of users in producer countries and that they can be linked to national management systems, including emergency response structures. One option would be to establish national points of contact (NPOCs) for remote sensing. They could aim to share imagery and expertise with government agencies, businesses, and other users of satellite data, as the Swiss Confederation has done (Swisstopo, 2022). Local universities or research institutions, such as the Department of Geography and Environmental Sciences at the University of Zimbabwe or CREEBaC in DR Congo, could host such structures and become NPOCs for remote sensing for their countries. As highlighted earlier, it is important to contextualize remote sensing data by researchers who have on-the-ground knowledge to avoid the risk of misleading interpretations (Section 5.5) and to create and maintain technical expertise in extractive countries.

For example, the International Council on Mining and Metals (ICMM) is a major mining association and benchmarking body. Its 26 members include leading mining companies such as AngloAmerican, Barrick, AngloGold Ashanti, BHP, Glencore, Gold Fields, Newmont, RioTinto, and Vale, as well as more than 35 national organizations and international commodity associations, from the Mining Association of Chile to the World Coal Association (ICMM, 2022). Recently, a consortium around the ICMM published the Global Industry Standard on Tailings Management (ICMM et al., 2020), demonstrating the association's ability to set higher standards for tailings management. In the flow failure scenarios that the standards include, I think it would be important to explicitly address the large-scale impacts to water bodies. On a broader scale, the ICMM could also take on the role of a benchmarking authority to promote environmental standards in other related transparency and accountability initiatives in the extractive sector. For one of the most recent examples, consider the Catoca diamond mine: It is the fourth largest in the world and supplies about 6% of the world's diamond production to the international market (Mining Technology, 2021). Angolan diamonds are also included in the existing Kimberley Certification Scheme, which aims to ensure that diamonds do not finance armed conflict (Cumena et al., 2019).The Kimberley Certification Scheme does not include environmental standards. Here, the ICMM could take a leading role in supporting the revision of standards to include environmental and social aspects.

Therefore, the private mining sector could support local academic institutions in developing remote sensing research capabilities that would enable monitoring of water resources for emergency response and public warning. This is particularly important for transboundary watersheds where management units do not match the spatial scale at which water pollution manifests itself and traditional management mechanisms fail.

Appendices

A. Optical remote sensing

List mines

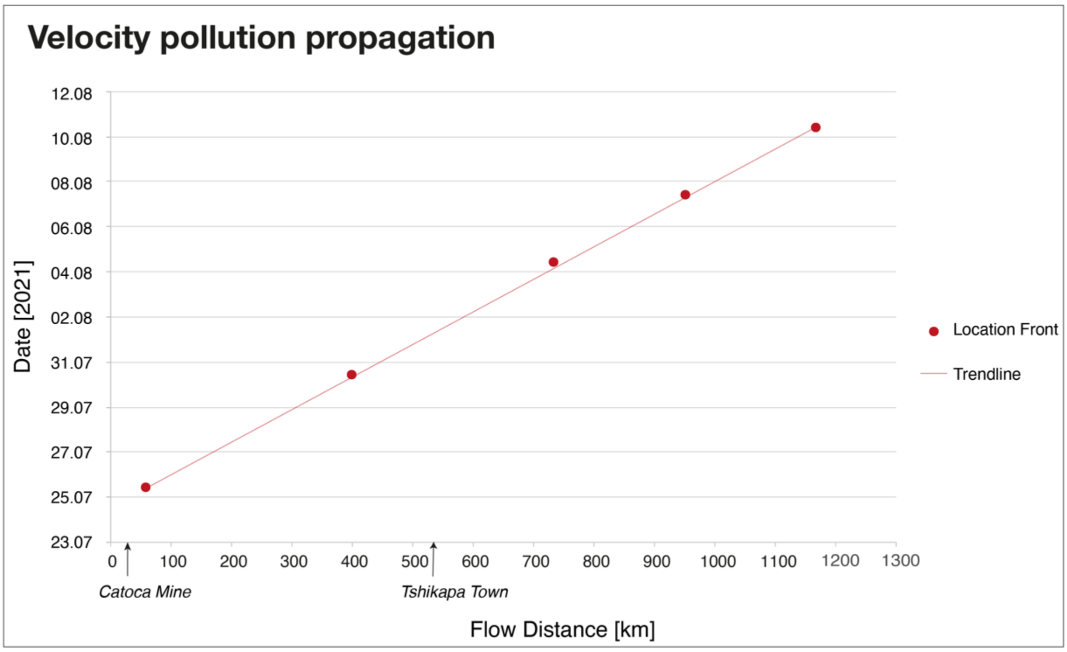
Suppl.-Table 1 Mines operating currently close to Tshikapa River, extract from SNL database (S&P Global Market Intelligence, 2021)

Mine Name	Current Stage	Current Status	Latitude	Longitude
Catoca	Operating	Active	-9.39889	20.30083
Kamachia-Kamajiku	Limited Production	Inactive	-8.94671	20.47628
Calonda	Operating	Active	-8.515	20.543
Canvuri	Operating	Active	-8.963	20.423
Tchegi	Operating	Active	-9.12	20.35
Yetwene	Operating	Care And Maintenance	-8.29458	20.5082

Propagation velocities

Suppl.-Table 2 Calculations propagation speed of pollution front based on visual identification of pollution front on Sentinel-2 imagery (Sinergise, 2022)

Date	Latitude	Longitude	Pollution front [km]	Distance Lova Inlet [km]	Time span to previous [s]	Speed [m s^{-1}]
25.07.21 08:36:01	-9.128601	20.344405	83.106	60.4	**76249.9**	na
30.07.21 08:35:59	-6.939499	20.621618	425.4	402.7	431998	0.792
04.08.21 08:36:01	-4.622282	20.942001	759.5	736.8	432002	0.773
07.08.21 08:46:01	-3.939503	19.428108	977.3	954.6	259800	0.838
10.08.21 08:56:01	-3.322016	17.712536	1193.2	1170.5	259800	0.831
Lova Inlet to Tshikapa [km]	41.3				Arithmetic mean	0.809
Distance Lova to Tshikapa River [km]	18.6				Median	0.812
Start Pollution Front Catoca Mine	**24.07.21 11:51:56**					
Arrival Pollution Front Congo River	13.08.21 13:34:09					
Total distance to Congo River [km]	1402.5					
Travel time (days)	20.01					

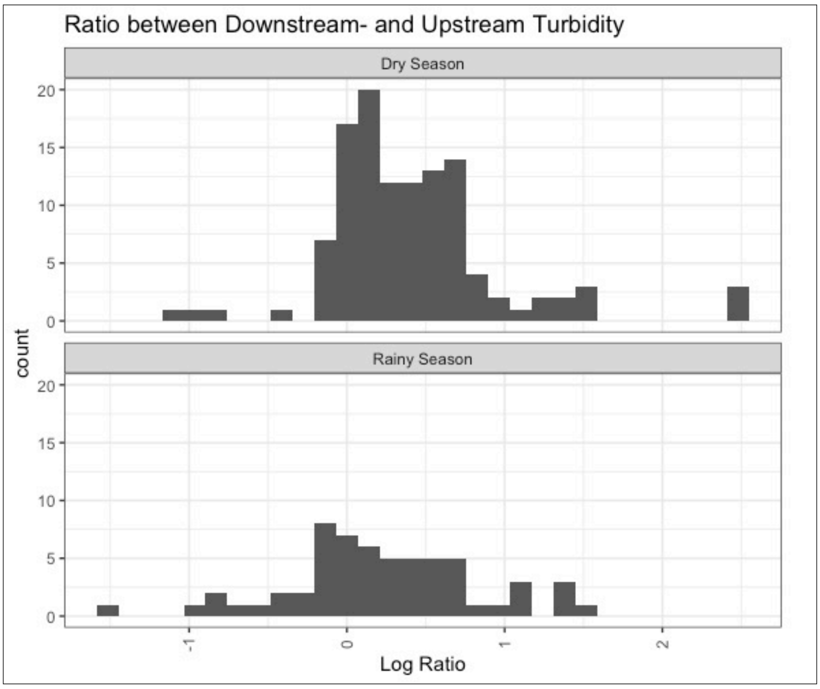


Suppl.-Figure 1 Plotting of location of pollution front (coordinates in Suppl.-Table 2) results in an almost linear ($R^2 = 0.9998$) propagation speed with median and arithmetic mean of 0.81 m s^{-1}

Virtual stations

Suppl.-Table 3 List of coordinates of the virtual stations in Tshikapa River close to Catoca mine

Virtual Station	Longitude [degrees]	Latitude [degrees]	Distance to Lova River Inflow [m]	Dates manually removed
Upstream	20.363238	-9.334211	-5251	23.11.2018
Downstream	20.363316	-9.291250	4604	09.10.2018, 24.10.2019



Suppl.-Figure 2 Histogram of point-to-point ratios of turbidity values between up- and downstream of virtual stations of Figure 8. In logarithmic scale.

B. Community-based monitoring

Demography of community monitors

During one of the pollution mediation meetings organized by a local civil society organization in October 2018 in Hwange Town, we approached the community members with the idea of building a community -based water monitoring scheme to overcome the lack of publicly available environmental quality data. The four community members present showed a deep interested in the proposition. Back in their villages, they recruited other interested individuals. In total 13 community members from four different villages along the Deka River, representing a total population of around 1500 people, participated in the community-based monitoring (Suppl.-Table 4). Family ties and private trust relationships formed the basis of the group which was diverse in age and included young adults and elderly persons above 65 years. Some of the teenagers still attended government school whereas older members lived mainly on subsistence agriculture. Two- third of the community members in the group were female. Along the project duration of 1.5 years, the participation and motivation of the community monitors remained comparably high. Only two young adults dropped out of the sampling scheme because of work related migration and one older member because of advanced age.

Suppl.-Table 4 List of community monitors and sampling stations

Nr	Acro-nym	Village	Stations sampled	Sampling Group	Sex	Age	Occupation	Comment
1	SC	Zwabo/ Makuyu	S004	2	F	45-55	Farmer / housewife	
2	SD	Zwabo/ Makuyu	S006	1	F	40-50	Farmer / housewife	
3	OM	Shashachunda	S005	3	M	18-25	Student	Drop-out (work migration)
4	MN	Mashala	S004	2	M	55-65	worker	Coordinator Group 2
5	LN	Shashachunda	S005	3	F	40-50	Farmer / housewife	
6	RN	Champepo Area	S025, S026, S027, S014, S002	4	M	40-50	Technical worker	Coordinator Group 4
7	PS	Mashala Down	S006	1	F	18-25	Student/ Primary school teacher	Coordinator Group 1
8	RL	Shashachunda	S005	3	F	55-65	Farmer / housewife	Coordinator Group 3
9	RS	Mashala Top	S006	1	F	16-25	Farmer / housewife	
10	HT	Zwabo/ Makuyu	S004	2	F	16-25	Student	Temp. drop-out (school)
11	SZ	Mashala Down	S004	2	F	40-50	Farmer / housewife	
12	PD	Mashala Down	S004	2	M	16-25	Student	Early Drop-out (work migration)
13	CN	Mashala Top	S006	1	M	65-70	Farmer / village elder	Early drop-out (age)

Training Manual

For the training of the community monitors, we produced a two- page training manual printed out in A4 format (Suppl.-Figure 3 and Suppl.-Figure 4). The manual illustrated in 11 steps how to take water samples and how to measure pH using test strips.

Hwange District

Community-based water quality monitoring

ETH zürich

1 Prepare your sampling kit

2 Open a clean sampling tube

3 Rinse the tube three times

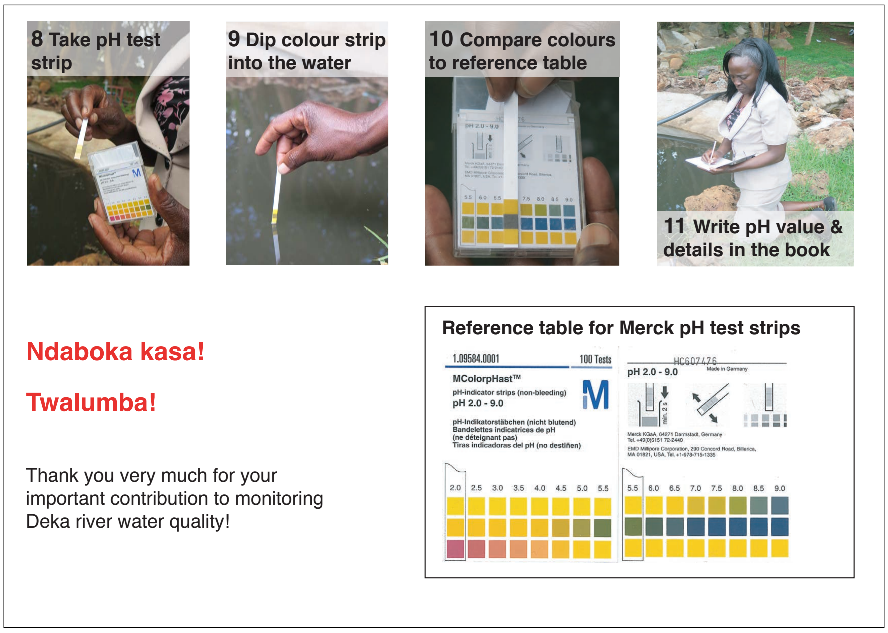
4 Fill the tube entirely up to the rim

5 Rinse the cap with test water

6 Close the tube thoroughly

7 Write location, date, time and sample number

Suppl.-Figure 3 Front page of sampling manual for community monitors. Printed in A4 landscape



8 Take pH test strip

9 Dip colour strip into the water

10 Compare colours to reference table

11 Write pH value & details in the book

Ndaboka kasa!

Twalumba!

Thank you very much for your important contribution to monitoring Deka river water quality!

Reference table for Merck pH test strips

1.09584.0001 100 Tests

MColorpHast™

pH-indicator strips (non-bleeding)

pH 2.0 - 9.0

pH-Indikatorstäbchen (nicht blutend)
Bandelettes indicatrices de pH
(ne déteignant pas)
Tiras indicadoras del pH (no destiñen)

HC607476

pH 2.0 - 9.0 Made in Germany

min. 2 s

Merck KGaA, 64271 Darmstadt, Germany
Tel. +49(0)6151 72-2440

EMD Millipore Corporation, 290 Concord Road, Billerica, MA 01821, USA, Tel. +1-978-715-1335

Suppl.-Figure 4 Rear page of sampling manual for community monitors. Printed in A4 landscape

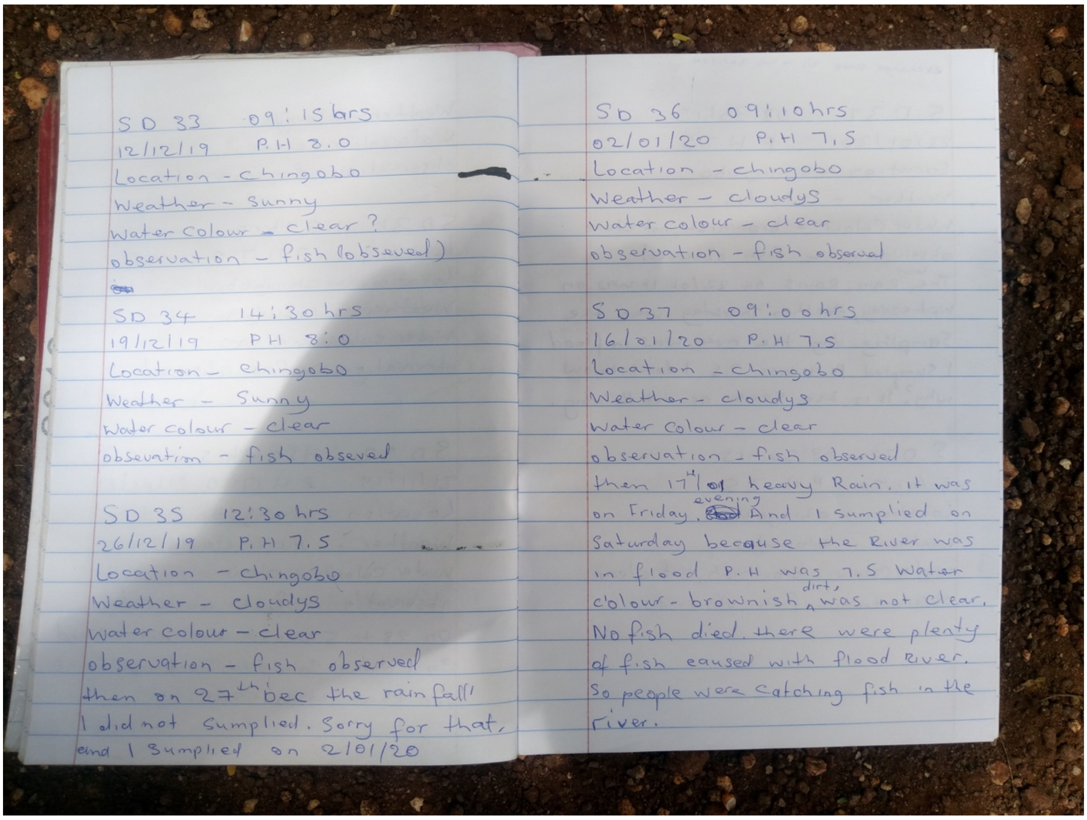
Meeting chronology

During the project, scientists and community monitors met on numerous occasions (Suppl.-Table 5). During the meetings scientists and community monitors co-decided on when, where and what to sample and to adapt the sampling protocol if necessary. Scientists shared results and discussed results from the chemical analysis personally at the meetings as soon as the data was available. The meetings helped to identify points of concern and of interest to the community monitors such as water quality in boreholes or food-safety of fish. The tight feedback loop allowed improving the data quality by adapting the sampling protocol and repeating training sessions. Occasionally, members from local civil society organization and from the environmental management agency participated in the meetings. After the technical part of the half-day meetings, community members and scientists shared drinks and food provided by the project.

Suppl.-Table 5 Group meetings with community monitors. Bilateral meetings not listed.

Date	Occasion	Place	Community monitors present	Attendance science	Attendance other stakeholders
14.12.2018	Training Sampling	Primary School, Mashala Village	11	Désirée Ruppen	representative Environmental Management Agency
02.02.2019	Monitoring Meeting	Primary School, Mashala Village	13	Désirée Ruppen, Owen Chituri	representative local NGO
30.04.2019	Mediation Meeting	Hwange District Administration, Hwange	4	Désirée Ruppen	Multistakeholder group
04.05.2019	Monitoring Meeting	Private Homestead, Mashala Village	11	Désirée Ruppen, Owen Chituri	
03.09.2019	Group coordinator meeting	Private Homestead, Mashala Village	4	Désirée Ruppen, Dr. Fritz Brugger	
14.09.2019	Monitoring Meeting	Primary School, Mashala Village	9	Désirée Ruppen, Owen Chituri, Christian Dinkel	
19.09-21.09.2019	Zimbabwe Alternative Mining Indaba	Holiday Inn, Bulawayo	4	Désirée Ruppen	
11.11.2019	Monitoring Meeting	Primary School, Mashala Village	10	Désirée Ruppen, Owen Chituri	Two representatives NGO Basilwizi
13.02.2020	Group coordinator meeting	Private Homestead, Mashala Village	3	Owen Chituri	
22.10.2020	Group coordinator meeting	Private Homestead, Mashala Village	3	Owen Chituri	

Notebook Recordings



SD 33 09:15 hrs
12/12/19 P.H 8.0
Location - chingobo
Weather - sunny
Water Colour - clear?
observation - fish (observed)

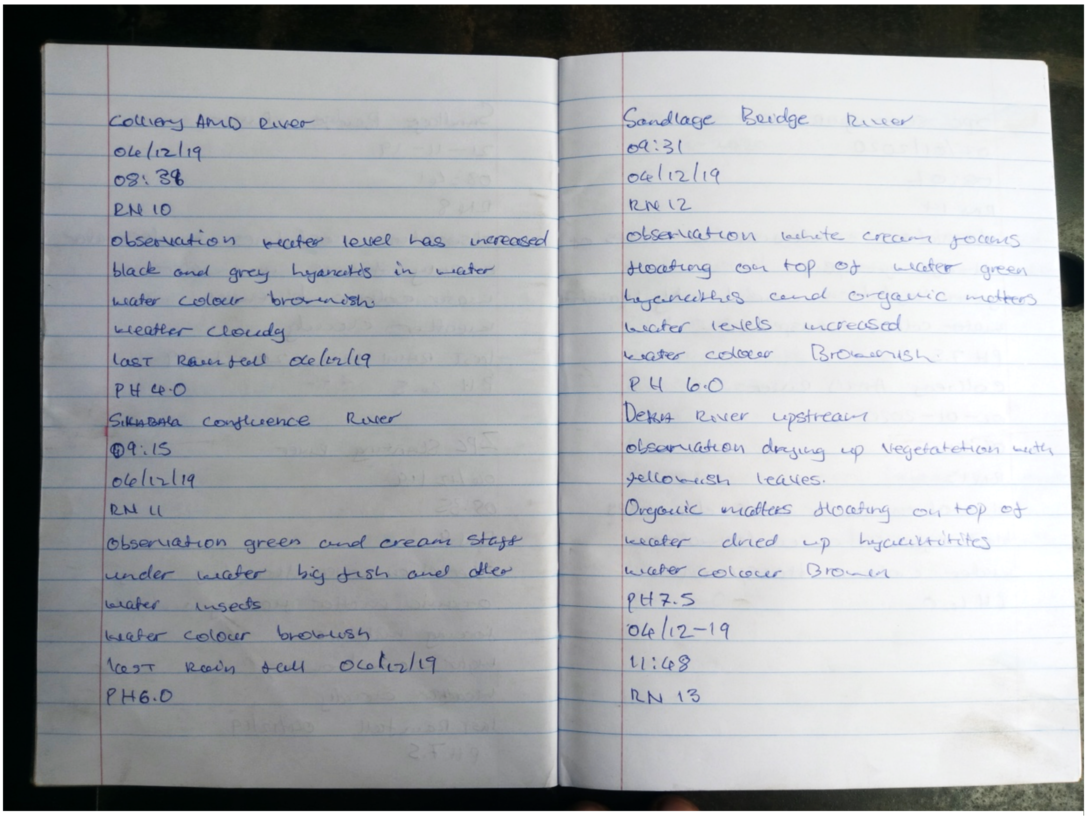
SD 34 14:30 hrs
19/12/19 PH 8:0
Location - chingobo
Weather - Sunny
Water colour - clear
obsevation - fish obseved

SD 35 12:30 hrs
26/12/19 P.H 7.5
Location - chingobo
Weather - cloudys
water colour - clear
observation - fish observed
then on 27th Dec the rain fall
I did not sumplied. Sorry for that,
and I sumplied on 2/01/20

SD 36 09:10 hrs
02/01/20 P.H 7.5
Location - chingobo
Weather - cloudys
water colour - clear
observation - fish observal

SD 37 09:00 hrs
16/01/20 P.H 7.5
Location - chingobo
Weather - cloudys
water Colour - clear
observation - fish observed
then 17th/01 heavy Rain. It was
on Friday, evening And I sumplied on
Saturday because the River was
in flood P.H was 7.5 Water
colour - brownish dirt, was not clear.
No fish died. there were plenty
of fish caused with flood River.
So people were catching fish in the
river.

Suppl.-Figure 6 Example of notebook recordings from community monitor SD. Notes were digitized by scientists



Colliery AMD River
06/12/19
08:38
RN 10
observation water level has increased
black and grey hyancits in water
water colour brownish
weather cloudy
last Rainfall 06/12/19
PH 4.0
Sikabala confluence River
09:15
06/12/19
RN 11
observiation green and cream staff
under water big fish and other
water insects
water colour browish
last Rain fall 06/12/19
PH6.0

Sandlage Bridge River
09:31
04/12/19
RN 12
observation white cream foams
floating on top of water green
hyacinthes and organic matters
water levels increased
water colour Brownish
PH 6.0
Dekra River upstream
observation drying up vegetatetion with
yellowish leaves.
Organic matters floating on top of
water dried up hyacintitites
water colour Brown
PH7.5
04/12-19
11:48
RN 13

Suppl.-Figure 5 Example of notebook recordings from community monitor RN. Notes were digitized by scientists.

Sampling tubes and labeling

Suppl.-Figure 7 Sampling tubes and labeling used by community monitors

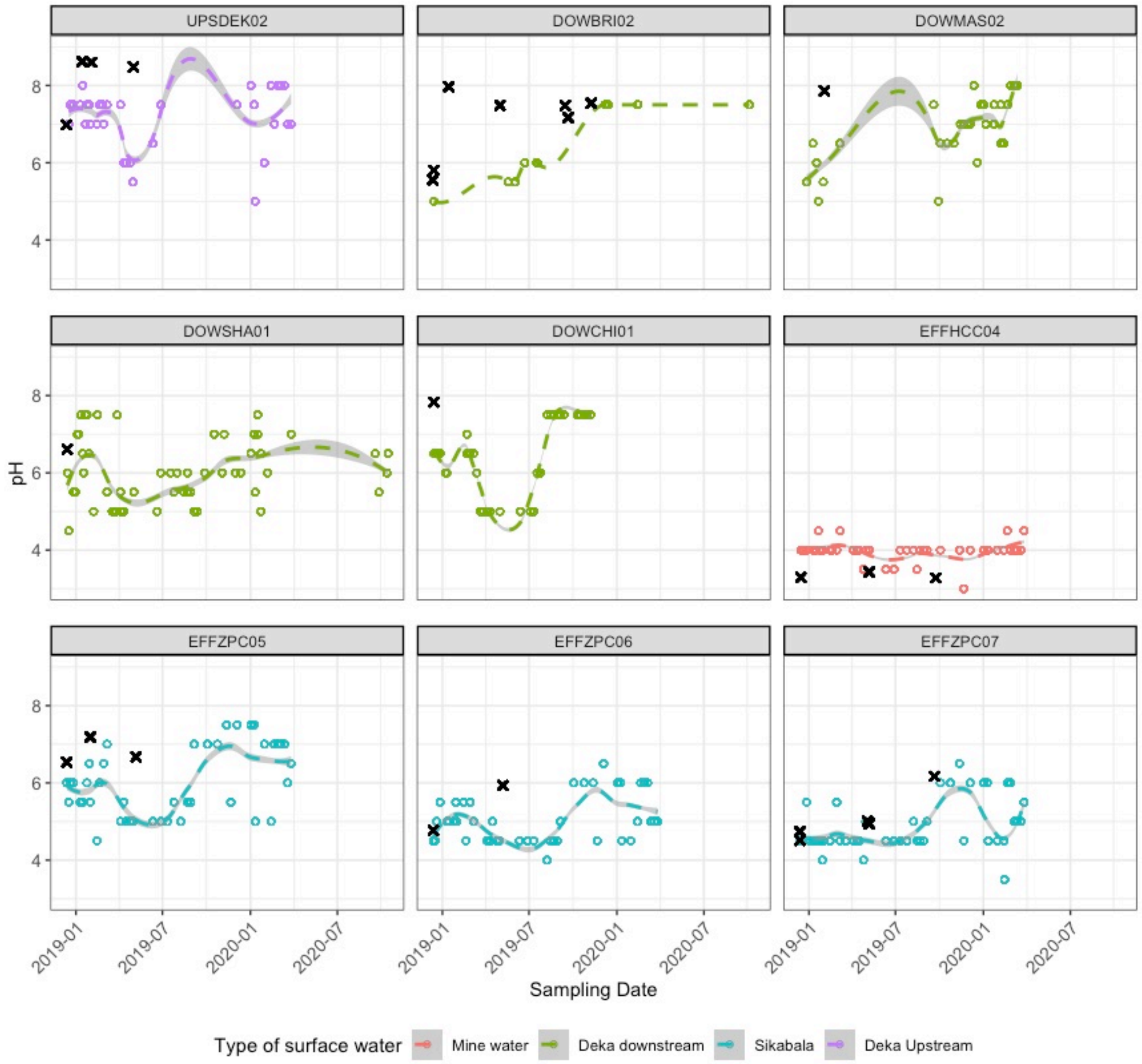
List of sampling stations

Suppl.-Table 6 Coordinates of Sampling Stations

	Name Alias	Name Sampling Station	Latitude	Longitude
1	S1	UPSDEK01	-18.33122	26.42036
2	S02	UPSDEK02	-18.2848	26.49751
3	S03	DOWBRI02	-18.28862	26.50217
4	S04	DOWMAS02	-18.24018	26.52519
5	S05	DOWSHA01	-18.27113	26.50394
6	S06	DOWCHI01	-18.21939	26.54421
7	S07	DOWBIN01	-18.10119444	26.71947222
8	S10	EFFHCC00	-18.34038	26.47932
9	S11	EFFHCC01	-18.33938596	26.47995302
10	S12	EFFHCC02	-18.33645497	26.48040103
11	S13	EFFHCC03	-18.33804703	26.48196702
12	S14	EFFHCC04	-18.32223499	26.47400698
13	S15	EFFHCC05	-18.35797501	26.436375
14	S18	EFFHCC08	-18.335999	26.48336898
15	S20	EFFZPC00	-18.37536897	26.472027
16	S21	EFFZPC01	-18.33875899	26.46010299
17	S22	EFFZPC02	-18.33896301	26.45812696
18	S23	EFFZPC03	-18.33428	26.45848
19	S25	EFFZPC05	-18.32269	26.47176
20	S26	EFFZPC06	-18.32083597	26.47285799
21	S27	EFFZPC07	-18.31753	26.47436
22	S29	EFFZPC09	-18.29638	26.49626
23	S30	EFFZPC10	-18.29513	26.49646
24	S31	EFFZPC11	-18.28556	26.49603
25	S41	EFFSAN01	-18.29756	26.49624
26	S42	EFFSAN02	-18.29865	26.49543333
27	S43	EFFSAN03	-18.31759722	26.47836667
28	S44	EFFSAN04	-18.31992603	26.47119904
29	S51	EFFCIN01	-18.33686099	26.47176297
30	S52	EFFCIN02	-18.33512	26.47038
31	S53	EFFCIN03	-18.333397	26.46947597
32	S54	EFFCIN04	-18.32390802	26.47093099
33	S62	EFFCHI02	-18.29614598	26.49672504
34	S71	EFFCON01	-18.44533104	26.46747102
35	S72	EFFCON02	-18.40740301	26.418831
36	S81	EFFCIT01	-18.33067297	26.422051
37	S91	WATBOR01	-18.23854697	26.53699304
38	S92	WATBOR02	-18.34022398	26.40532097
39	S93	WATBOR03	-17.99443603	26.36633104
40	S94	WATBOR04	-18.071357	26.484437
41	S95	WATBOR05	-18.06780702	26.50576198

Measurements of pH by community monitors and scientists

Measurements of pH were taken using a handheld WTW Multiprobe 340i and pH strips (Merck pH-Indicator strips pH 2.0 -9.0 MColorpHast™). Comparing the two types of measurements, we observed that pH values in circumneutral range were underestimated by pH strips (Suppl.-Figure 8).

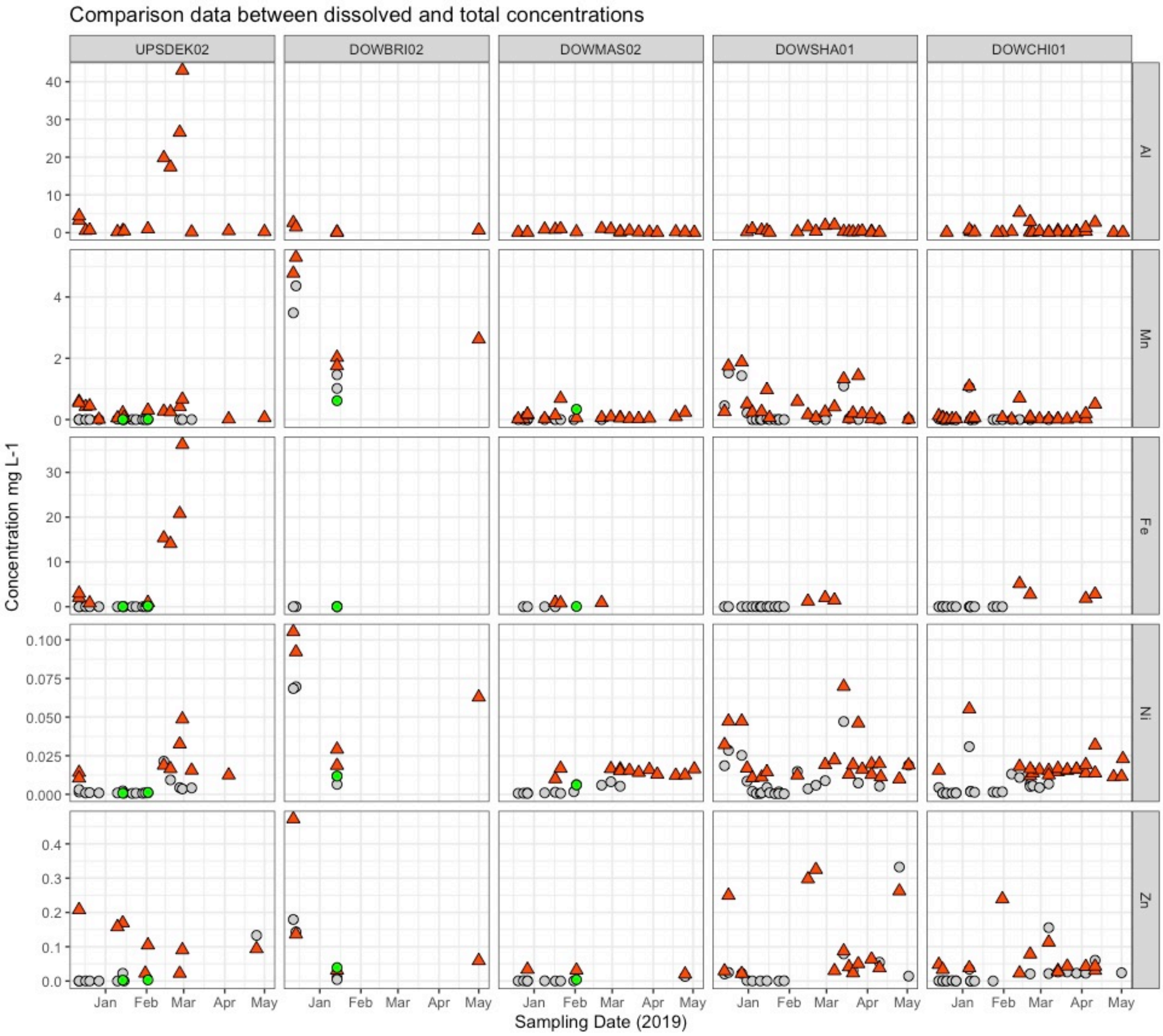


Suppl.-Figure 8 Comparison and trends of pH measurements at specific sampling location. Circles for community monitors using pH strips; crosses for scientists using WTW multimeter. Dashed line shows trend strip measurements. Based on smoothed conditional means (R/geom-smooth.r) with loess smoothing method and span=0.4 for smoothing.

Sample treatment

In the monitoring scheme, community monitors took unacidified and unfiltered water samples in order to minimize contamination risks. We acknowledge that guidelines advise to filter and acidify water samples at the time of collection in order to preserve the chemistry and later evaluate dissolved metals. For comparison, scientists took samples with different field treatments: unfiltered/unacidified, filtered/unacidified, acidified/unfiltered, filtered, acidified.

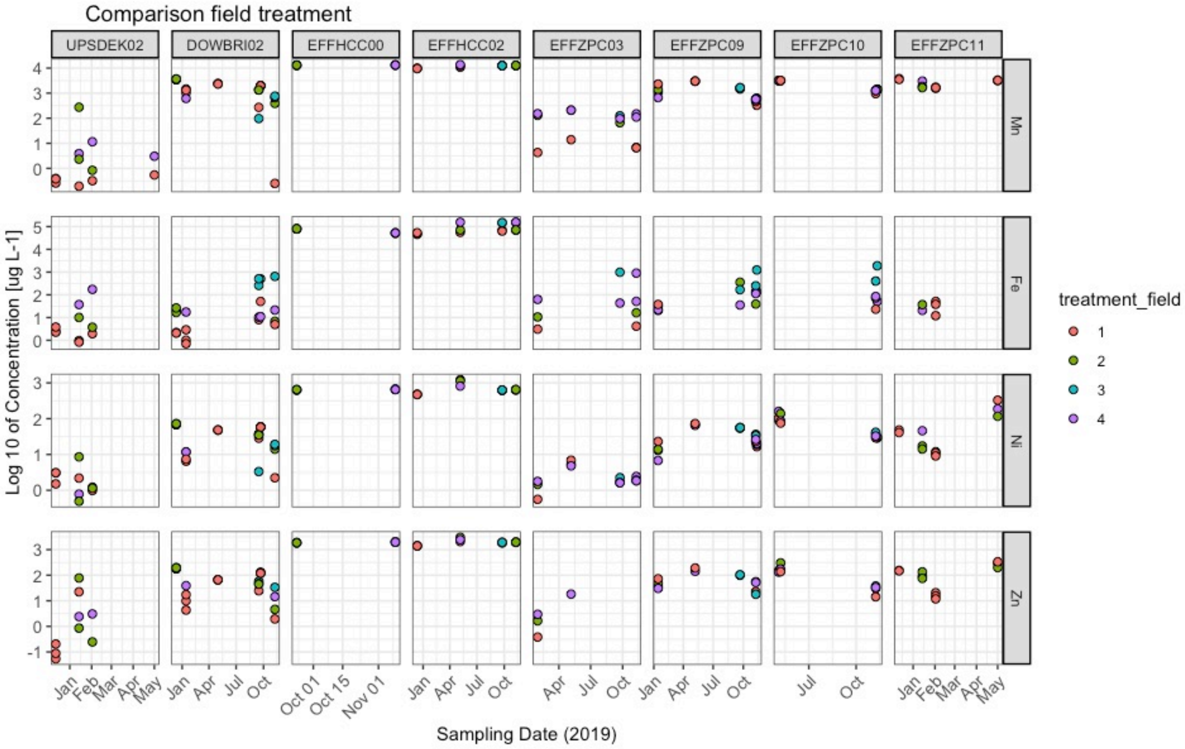
Especially dissolved iron concentration was under detection limit for a large share of the grab samples from the Deka River. In Suppl.-Figure 9 we compare the dissolved and the total concentration of a series of grab samples. In addition to this, the dissolved concentration of a filtered and acidified sample was plotted in the same figure.



Suppl.-Figure 9 The same 112 grab samples from Deka River were analyzed for their dissolved (grey circles) and total concentration (red triangles). For 4 samples, a filtered and acidified sample was plotted for comparison (green circles)

For most sampling stations in the Deka River, the chemical results of the digested samples illustrate that we tend to slightly underestimate Mn concentrations by using the dissolved concentration of the grab samples but that these differences are not in orders of magnitude. Further, Fe concentrations are under detection limit for both digested and undigested samples. In February, dissolved concentrations of Fe in four samples of the sampling station S02 were under detection limit in Deka upstream, but for the same samples they range between 14 and 36.2 mg L^{-1} for the total concentration in the digested samples. These samples were taken during a period when Deka River was flooded (mid and end of February 2019) and they contained a lot of suspension. The community monitor (RN) who took those samples noted in his notebook that the river was “brown and flooded with dirty water. Green hyacinths, big and small fish and many water insects were present.” Therefore, the extra load of suspension of these samples explains the high total concentrations that we measured.

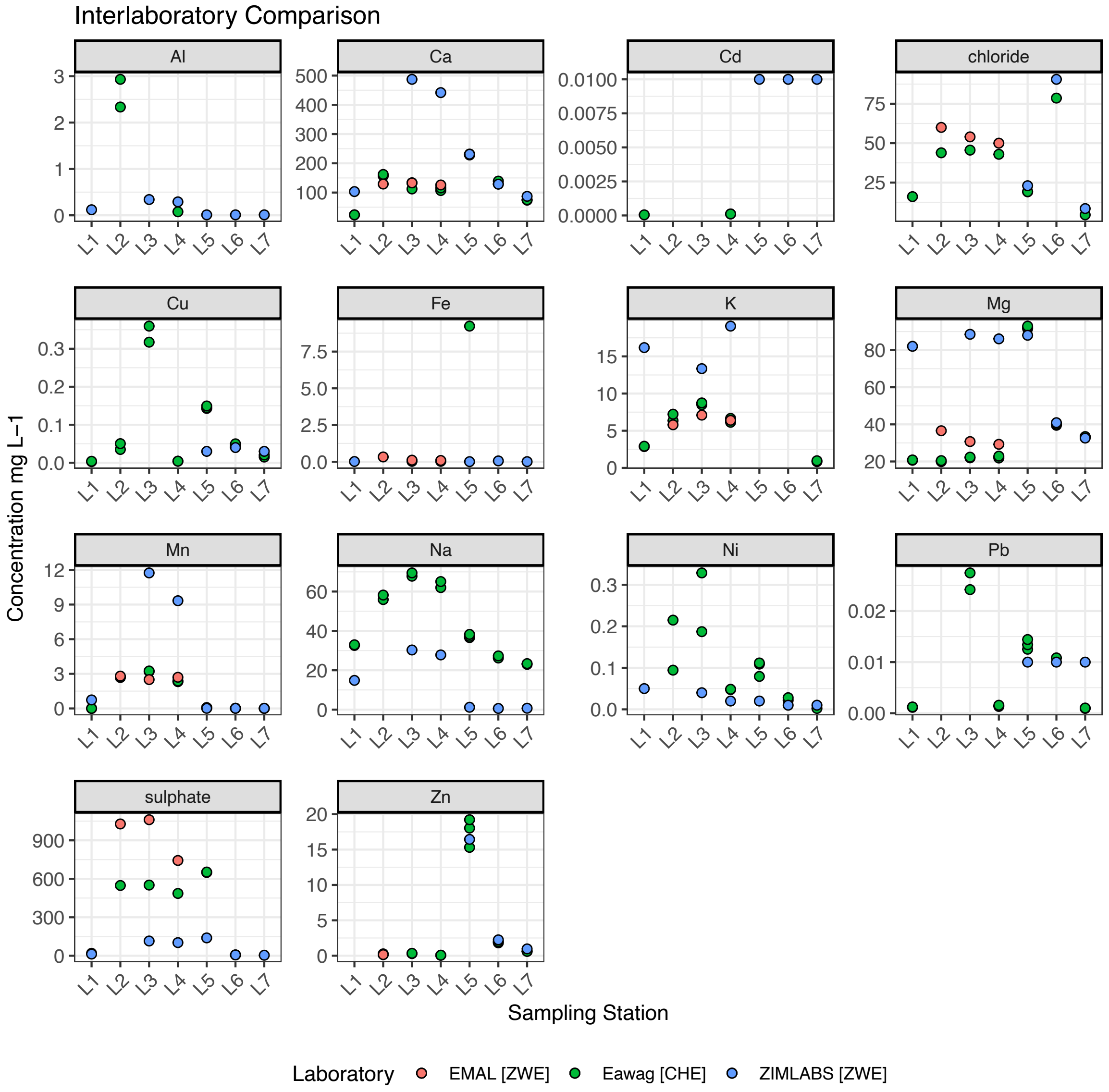
We also compared field treatments of samples that a scientist took at the same sampling location and date (Suppl.-Figure 10). First of all, it can be observed that differences between triplicates with same sample treatments can be as large as the variance between different sample treatments (see difference between grab samples at same location The concentration differences between the treatments vary strongly depending on the type of surface water sampled. The treatment differences are largest and up to two magnitudes for all plotted metals of the samples that were taken in Deka River (UPSDEK02, DOWBRI02), this most notably during rainy season. Like noted previously, the river was flooded in February 2019 after heavy rainfalls and carried a lot of suspension that ended up in the unfiltered grab samples. Differences at the point source of AMD are low (EFFHCC00, 02). This can be explained by the pH that is acidic (2.6 to 3.1) which well conserves the samples. Within Sikabala, differences are highest for Mn and Fe. However, we can see that variations between different samples with same treatment can be as high as differences between treatment.



Suppl.-Figure 10 Comparison of field sampling treatment for Fe, Mn, Ni and Zn at two stations in Deka River (UPSDEK02, DOWBRI02), 1 station at AMD point source (EFFHCC00,- 02) four stations in Sikabala effluent channel (EFFZPC03, -09, -10, -11). Color indicates the field treatment (1: unfiltered/unacidified, 2: filtered/unacidified, 3: unfiltered, acidified, 4:filtered/acidified). All samples from one scientific sampler (DR). X axis shows sampling dates in 2019 and Y logarithm base 10 of concentration [µg L-1]

Commercial labs compared to own measurements

In our study, we tested two laboratories in Zimbabwe, notably EMAL and ZIMLABS. EMAL is the laboratory of the Environmental Management Agency (EMA). Besides the chemical analysis for the nationwide monthly monitoring of the authority, the laboratory operates also commercially. Overall, the data from EMAL agreed well with our results, notably for cations such as Ca, K, Mg, Mn and for chloride (Suppl.-Figure 11). Concerning trace elements such as Ni, detection limits of flame AAS were too high to measure these potentially toxic elements. This reveals a serious limitation for the governmental monitoring mandate of EMAL. In addition, commissioning EMAL as the main laboratory for an independent citizen science project could trigger conflicts of interest, since it is managed by EMA, the governmental oversight agency in charge of issues related to environmental management.

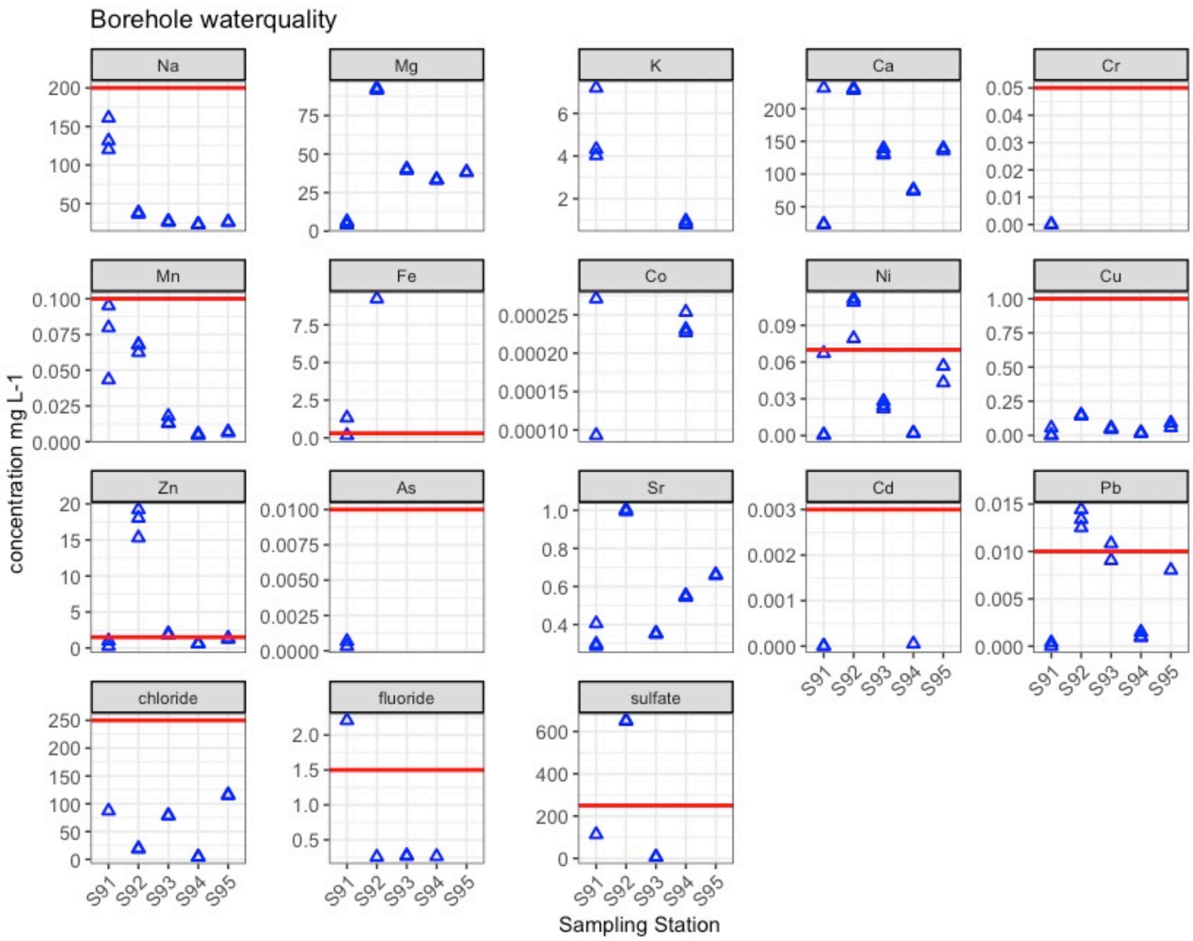


Suppl.-Figure 11 Interlaboratory comparison for filtered and acidified samples from early May 2019. The Zimbabwean laboratory of the Environmental Management Agency (EMAL) analyzed L2, L3 and L4. The Zimbabwean laboratory ZIMLABS measured the samples L1, L3, L4, L5, L6, L7. The Swiss laboratory Eawag (our laboratory) measured all of the samples.

As Suppl.-Figure 11 indicates, the quality of the fully commercial and certified laboratory ZIMLABS was poor, although the prices for analysis were approx. three times higher than those of EMAL. After the laboratory had completed the analysis, it first delivered a data sheet where technicians had confounded samples. Even in the corrected data sheet, the analysis differed by factors of more than 3 from ours, especially for cations like Na, K, Mg, Mn. For Cd, our results were below detection limit using ICP-MS (BEC 0.0044 μg L^{-1}) and ZIMLABS reported concentrations of 0.01 mg L^{-1} for all WATBOR samples (LOD 0.003 mg L^{-1}). For cation measurements, the laboratory reportedly used acid digestion with Flame AA Spectroscopy (method CHW101).

Borehole water quality

Community monitors were specifically interested to sample boreholes that serve as their drinking water sources. Borehole water quality was mainly within acceptable ranges (Suppl.-Figure 12). Drinking water borehole S91 had fluoride concentrations of 2.2 mg L^{-1} and therefore exceeded the WHO guideline value of 1.5 mg L^{-1}. Hwange District is known to have geogenic groundwater fluoride (Interconsult, 1985; NUST, 2019). High fluoride concentrations have been observed in different parts of Africa and Asia and linked to different health risks (Bretzler and Johnson, 2015). In Hwange, we observed moderate to severe forms of dental fluorosis with several community members that consume this water. The drinking water borehole S92 was above drinking water guidelines for Pb (14.4 μg L^{-1}), Fe (9.3 mg L^{-1}), Ni (111 μg L^{-1}), sulfate (652 mg L^{-1}) and most notably for Zn (19.2 mg L^{-1}). This borehole is located at around 1.5 km distance from a coal preparation plant and sources groundwater with high concentrations of dissolved metals.

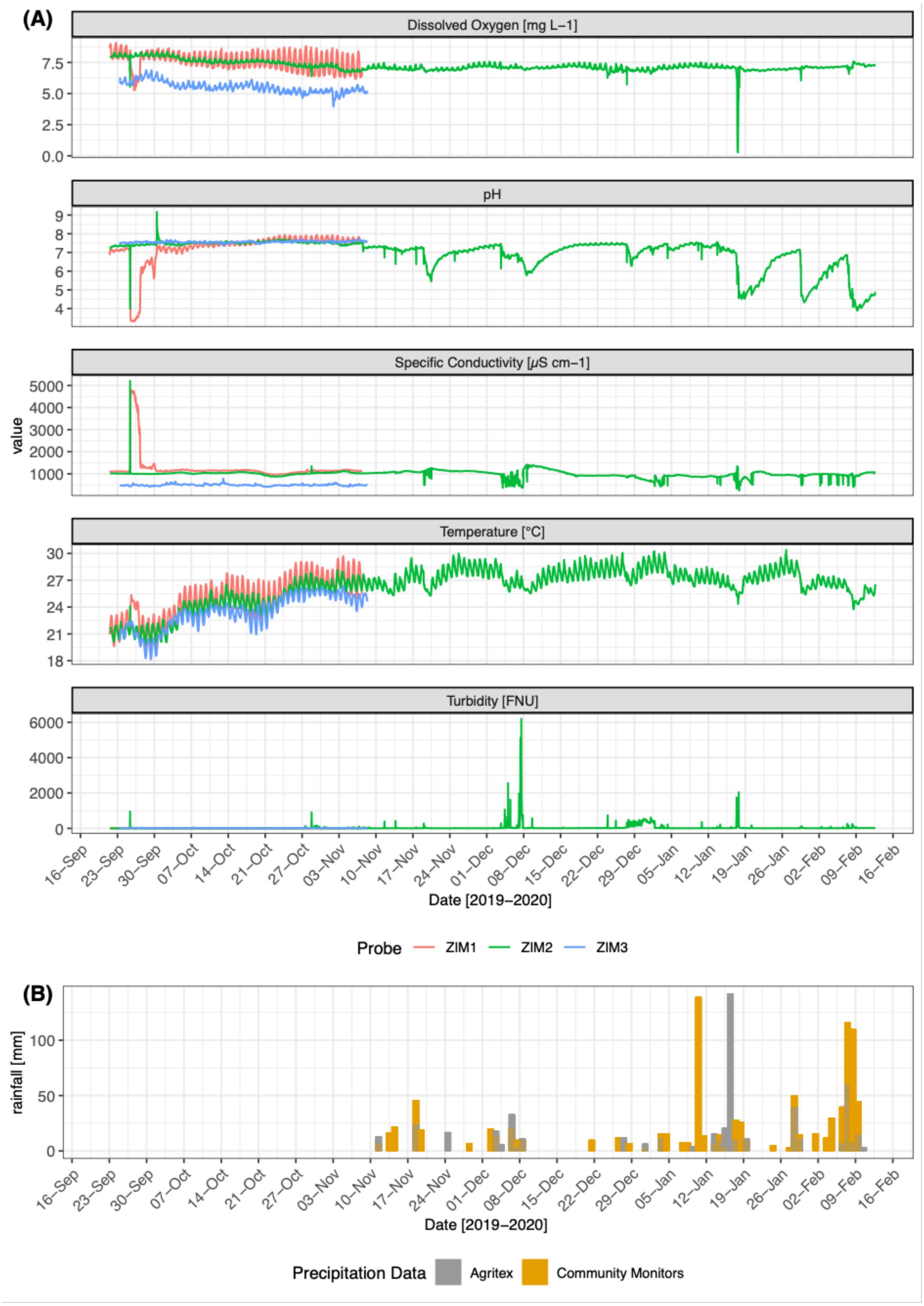


Suppl.-Figure 12 Elemental concentrations for 5 drinking water boreholes in Hwange District. WHO drinking water guideline values are indicated with a horizontal red line. The drinking water boreholes S91 and S92 exceed guideline values.

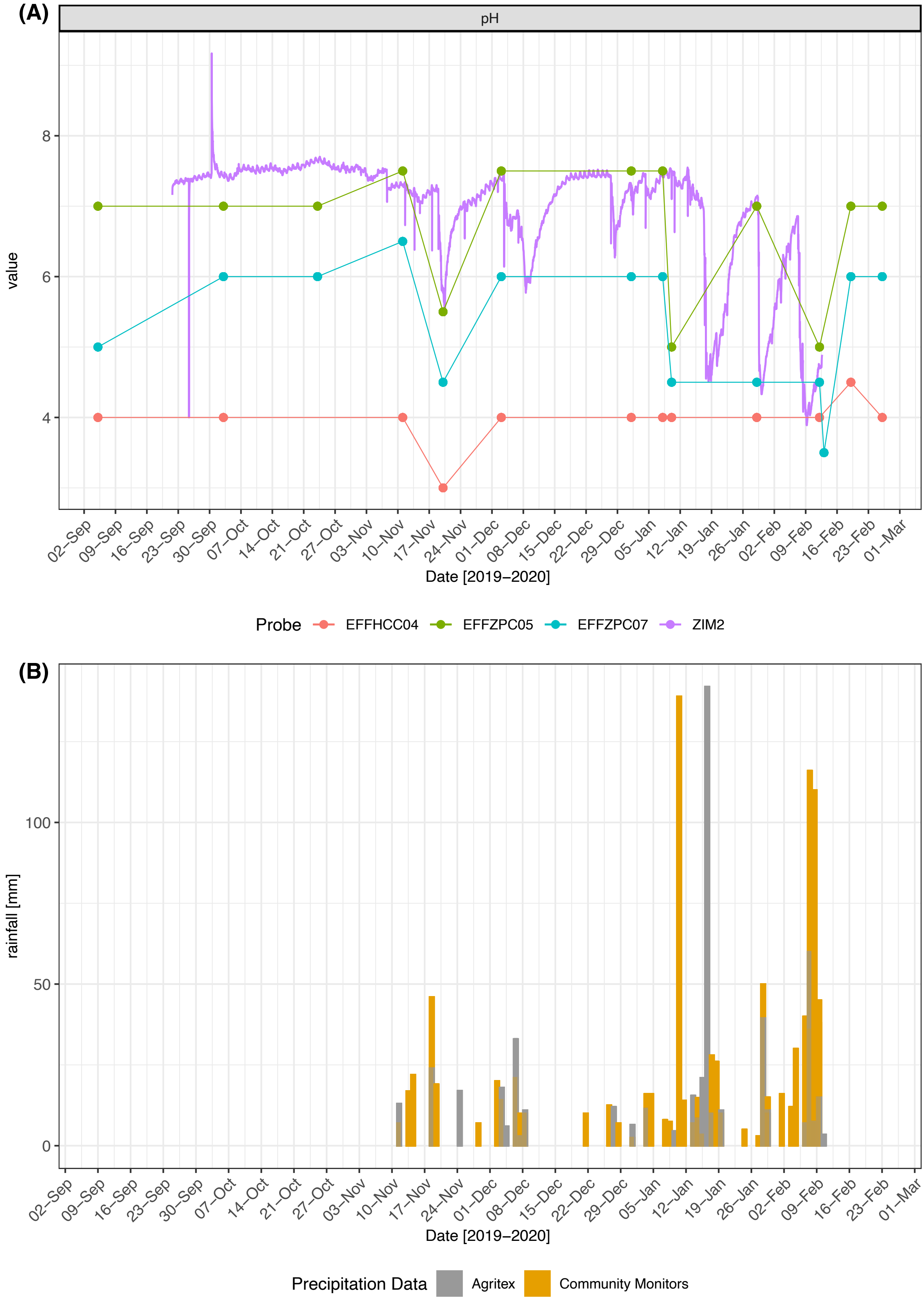
In-situ sensors combined with community-based monitoring data

ZIM2 was the only EXO-probe that documented the remaining period from 8 November 2019 to 13 February 2020. In this period, ZIM2 showed some very steep decreases of pH followed by a quick pH recovery within hours (Suppl.-Figure 13). The observed pattern indicates that the reopened mine downstream discharged mine water, and the backflow reached the probe. From 20 November 2019 onwards, we observed another, slower decrease of pH that took several days to arrive at a minimum before pH recovered to a more neutral level. This behavior was repeatedly observed after mid- January 2020. The downward trends in pH correlated with sharp drops in electrical conductivity while dissolved oxygen remained constant. In addition, peaks of turbidity coincided with stronger rainfall events.

We suggest that the slower downward trends in pH were an effect of the mixing with rainwater. Rainwater generally has a pH in the range of 5 to 6. Due to the heavy atmospheric load of sulfurous and sulfuric acid caused by the combustion of high S coal at the thermal power plant nearby (Palloks, 1987; Mapani et al., 2013), we expect a low pH of rainwater in Hwange as it is known from many other contexts with coal-fired power plants (Hao et al., 2000). The rainfall, however, causes an overall dilution of the metal load in the water reflected in the electrical conductivity measurements. In addition, rain events might activate non-point sources by mobilizing coal fines in the poorly management mine waste heaps located in vicinity of Sikabala. The overall effects of these processes of acidification, dilution and mobilization are hard to quantify but a more targeted monitoring could reveal main sources and pathways. The data of one community monitor (code-name RN) who sampled effluent stations in Sikabala (EFFZPC05, EFFZPC06, EFFZPC07) consistently showed a drop on 21 November 2019 (Suppl.-Figure 14) and expanded the in-situ observations of the EXO probe.



Suppl.-Figure 13 (A) Measurement series of dissolved oxygen [mg L^{-1}], pH, specific conductivity compensated to 25°C [µS cm^{-1}] and turbidity [FNU: Formazine nephelomitetric units] for the three YSI EXO2 Multiparameter Sondes ZIM1, ZIM2 and ZIM3 recorded from 21 Sept 2019 to 13 Feb 2020. Only ZIM2 recorded the continuous series. (B): Rainfall [mm] recorded for the same time period by the Ministry of Agriculture (Agritex) in Hwange Town and the community monitors in the rural area of Hwange respectively



Suppl.-Figure 14 (A) pH measurement series for ZIM2 (pink line) from 21 Sept 2019 to 13.02.2020. pH measurements of community monitor RN at specific dates (circle) connected with solid lines. RN sampled two stations in Sikabala, EFFZPC05 before mine water joins, EFFZPC07 after mine water joins. EFFHCC04 main wetland discharge (B): Rainfall [mm] recorded for the same time period by the Ministry of Agriculture (Agritex) in Hwange Town and the community monitors in the rural area of Hwange respectively.

Analyses of white precipitates

In September 2019, we sampled rock specimen from Sikabala effluent stream coated with white precipitates at the sampling station S27. The rock specimen were air-dried and the precipitates were subsequently scratched of the rock samples using a stainless steel spatula. The precipitates were analyzed at the University of Bern. 50 mg of the sample was digested with 5 mL 65% HNO_3 (Carrero et al., 2017; Wanner et al., 2018). In the digested solutions, the concentrations of Al, S, Si, As, K, Na, Fe and Ca were determined by inductively coupled plasma optical emission spectroscopy (ICP-OES) using a Varian 720-ES ICP spectrometer. Sulfur concentrations were converted to SO_4^{2-}. Samples were exposed for 2 hours to 1050 °C (i.e., loss on ignition) to determine the H_2O and OH^- content.

During the digestion, the samples were not dissolved completely. This explains why the sum of the elements doesn't sum up to 100% (Suppl.-Table 7). Based on this observation and the high Al/SO4 ratio, we assume that the high Al- contents are mainly present as Al hydroxides (e.g. $Al(OH)_3$) and only subordinately as Al sulfates.

Suppl.-Table 7 Results of ICP-OES measurements of digested white precipitates from Sikabala effluent stream

		Sample Sik-1	**Sample Sik-Y**
	Weigh-in (mg)	50.32	50.07
	Digested solution (mL)	50.00	50.00
Aluminum (Al)	wt%	20.64	13.16
Calcium (Ca)	wt%	0.30	0.31
Iron (Fe)	wt%	2.75	3.15
Silica (Si)	wt%	0.13	0.12
Sodium (Na)	wt%		0.07
Sulfate (SO_4)	wt%	4.48	3.48
H_2O + OH (Loss of ignition 1050 °C)	wt%	44.66	34.751
Sum	**wt%**	**72.95**	**55.04**

Discharge measurement app

To our knowledge, governmental monitoring of Deka River discharge stopped in 1996. We tested a mobile phone application named *Discharge* to estimate the discharge of Deka river and some spots in Sikabala. Based on the structures present at the surface of the water bodies, an algorithm infers a velocity profile and relates it to the discharge (Photrack AG, 2021). Scientists set up discharge measurements points following the software description and personal advice of the developers. For the cross section of Deka river or Sikabala, they used a DistoS910 from Leica. Since at most spots, discharge or flow velocity was too small the mobile phone application, they only achieved to make occasional discharge measurements of discharge at one specific spot in the effluent channel Sikabala.

Only at sampling station S30 (Latitude: -18.29512599, Longitude: 26.49645799), we successfully measured the discharge of Sikabala on 14. Sept and 17. Sept 2019, resulting in an average of 652.2 L s^{-1} (Suppl.-Table 8).

Suppl.-Table 8 Discharge measurements using the mobile phone application Discharge.

Date	time	Water level [cm]	Velocity [m s-1]	Discharge [L s-1]	Daily mean
14.09.19	15:07	75	0.33	607.95	722.98
14.09.19	15:04	78	0.46	909.38	
14.09.19	15:01	66	0.44	651.62	
17.09.19	11:46	60	0.47	588.71	581.41
17.09.19	11:42	51	0.47	461.07	
17.09.19	11:40	61	0.5	694.46	
Mean of 14. 09 and 19.09.20198					652.20

Pictures of Hwange Area

Scenes along Deka River

Suppl.-Figure 15 Deka Upstream close to S001/UPSDEK01. Picture taken from bridge on main road with little water flowing to the right. (Picture oriented downstream towards north- east, taken on 30.01.2019 at 18°19' 57.98''S, 26°25'06.49''E

Suppl.-Figure 16 Deka Upstream close to S001/UPSDEK01. Picture taken from bridge on main road with little water flowing at the left. (Picture oriented upstream towards south- west, taken on 30.01.2019 at 18°19' 57.98''S, 26°25'06.49''E

Suppl.-Figure 17 Deka River at S002/UPSDEK02 showing dam upstream of confluence with Sikabala channel. Picture oriented North, taken on 02.02.2019 at 18.2848 S, 26°29'51.03"E

Suppl.-Figure 18 Deka River at S002/UPSDEK02 similar location as Suppl.-Figure 17 but water not flowing during late dry season. Picture oriented North, taken on 15.09.2019 at 18.2848 S, 26°29'51.03"E

Suppl.-Figure 19 Deka just after confluence with Sikabala showing a weir. Location 18°17'07.96''S, 26°29'57.36''E, taken on 02.02.2019

Suppl.-Figure 20 Deka River at bridge downstream of confluence with Sikabala Water has light blue-green color at right and white foam to the left of the bridge (Picture from 14.12.2018 at Sampling Station DOWDEK02 at 18°17'19.03"S, 26°30'7.82"E

Suppl.-Figure 21 Same site as Suppl.-Figure 20, but water has usual brown-blue coloring (Picture from 15.09.2019 at Sampling Station DOWDEK02 at 18°17'19.03"S, 26°30'7.82"E))

Suppl.-Figure 22 Deka River at level of villages at the sampling station DOWCHI01 at 18°13'9.82"S, 26°32'39.17"E. Picture taken on 14.12.2019 looking downstream in Northeastern direction

Suppl.-Figure 23 Deka before joining Zambezi River at 18° 05'53.11"S, 26°43'12.76"E

AMD point sources

Suppl.-Figure 24 Main point source of acid mine drainage on top of an abandoned underground mine at sampling station S010/EFFHCC00 at 18°20'25.38"S, 26°28'45.54"E. The area is not fenced. This cow got stuck in the mud and had to be rescued afterwards. Picture taken on 23.11.2018

Suppl.-Figure 25 Sampling Station S012/EFFHCC02 at a main AMD point source. Picture taken on 06.05.2019 at 18°20'11.24"S, 26°28'49.44"E

Suppl.-Figure 26 Effluent channel close to AMD point source on top of abandoned underground mine at S062/EFFCHI02 at 18°20'6.45"S, 26°28'13.37"E. Picture taken on 23.09.2019

Suppl.-Figure 27 Plugged former service borehole, AMD effluent reaches the surface. Picture taken 21.03.2018 at 18°20'14.96"S, 26°29'7.04"E

Wetlands and effluent channels

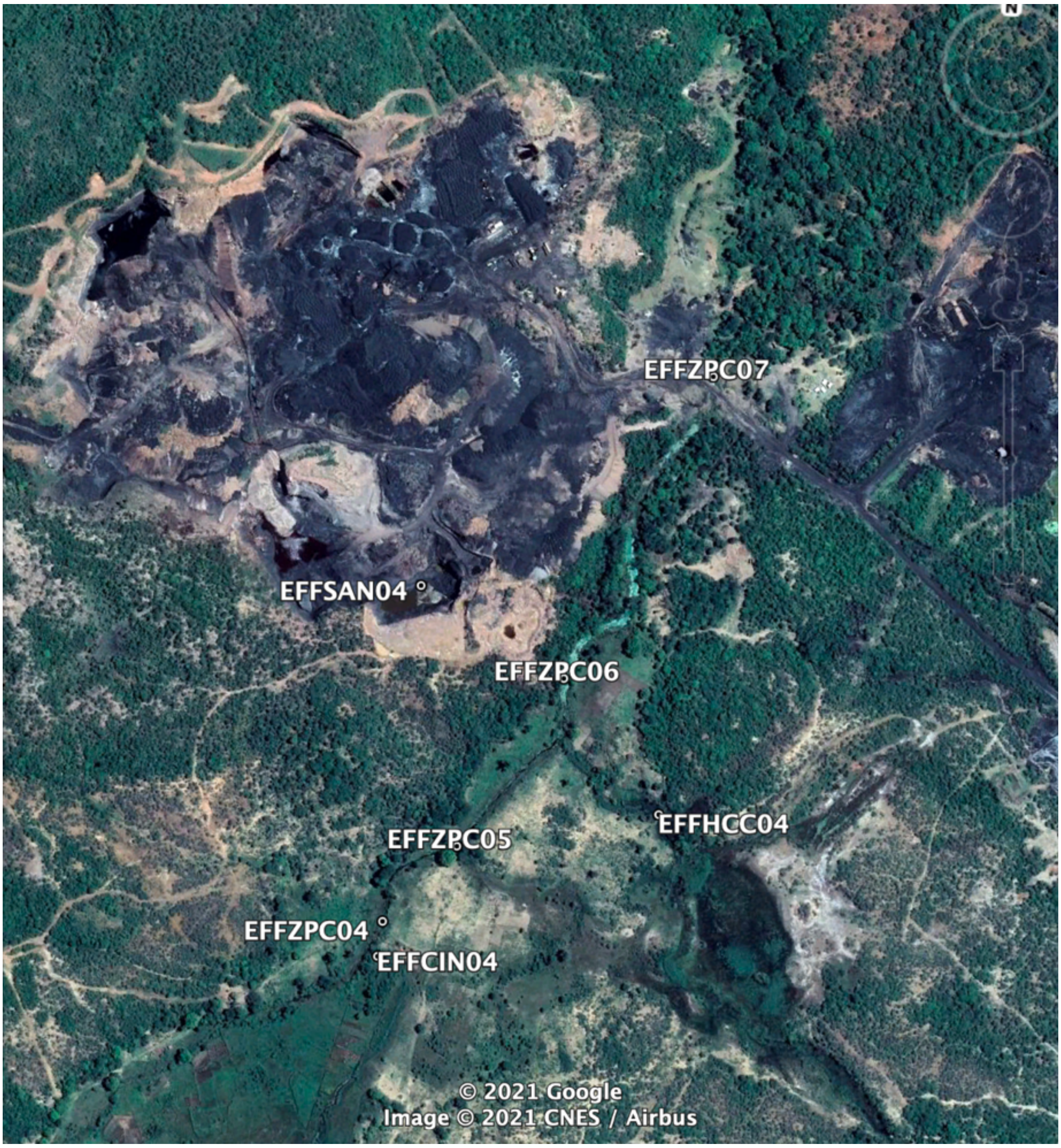
Suppl.-Figure 28 Road constructed in 2011 that cuts main wetland into two parts, Picture from 06.05.2019 at S018/EFFHCC08 (18°20'16.97"S, 26°28'55.08"E)

Suppl.-Figure 29 Artificial Wetland partly dried up. Looking from road towards west. Picture taken on 06.05.2019 at 18°20'16.97"S, 26°28'55.08"E

Suppl.-Figure 30 At S018/EFFHCC08, planted wetland showing one main channel 30.01.2019 at 18°20'9.60"S, 26°29'0.13"E

Suppl.-Figure 31 Starting point of Sikabala channel close to ZPC showing cooling tower in the back (Picture oriented upstream 30.04.2019 at 18°22'31.33"S, 26°28'19.30"E)

Suppl.-Figure 32 Main outlet of the wetland just before joining Sikabala River. (S014/EFFHCC04 at 18°19'20.05"S, 26°28'26.43"E). Picture taken on 15.12.2018



Suppl.-Figure 33 Effluent channel Sikabala (Sampling Stations EFFZPC04, 05, 06) showing clear water color change at EFFZPC06 after wetland discharge joins from east (EFFHCC04). Google Earth Pro 7.3.3.7786 (64-bit) (22 February 2019). Hwange, Zimbabwe.18°19'15.01"S, 26°28'22.29"E, Eye alt 1.12km. Borders and labels; places layers. Google, CNES Airbus 2021. http://www.google.com/earth/index.html (Accessed 15 June 2021)

Suppl.-Figure 34 Sikabala showing a blueish coloring because of Al-hydroxide precipitation at Sampling Station S026/EFFZPC06 at 18°19'15.01"S, 26°28'22.29"E. Picture taken on 13.12.2018

Suppl.-Figure 35 Sikabala at S027/EFFZPC07. Picture taken on 13.12.2018 at 18°19'3.11"S, 26°28'27.69"E

Suppl.-Figure 36 White precipates on rocks in Sikabala at Sampling Station S027/EFFZPC07 at 18°19'3.11"S, 26°28'27.69"E. Picture taken on 14.09.2019

Suppl.-Figure 37 Close up of precipitates on rocks in Sikabala at Sampling Station S027/EFFZPC07 at 18°19'3.11"S, 26°28'27.69"E. Picture taken on 03.05.2019

Suppl.-Figure 38 Pumped mine water enters Sikabala effluent channel at 18°17'42.45"S, 26°29'47.25"E. Sampling Station S030/EFFZPC10. Picture taken on 08.11.2019

Suppl.-Figure 39 Pit lake next to Sikabala, Sampling Station S042/EFFSAN02 at 18°17'55.81"S, 26°29'49.03"E. Picture taken at 03.05.2019

Mining site, mine waste heaps and thermal power plant

Suppl.-Figure 40 Open pit extraction close to Sikabala effluent channel. Picture taken at 18°18'6.72"S, 26°29'39.53"E on 14.09.2019

Suppl.-Figure 41 Mine waste heaps at Sandledge mine 17.09.2019. Picture taken at 18°18'56.11"S, 26°28'18.84"E looking South

Suppl.-Figure 42 Pit lake at mining concession close to Sikabala effluent channel showing deep red colored water with high metal concentrations and pH around 2.6 at EFFSAN04 at 18°19'11.73"S, 26°28'16.32"E. Picture taken on 07.05.2019

Suppl.-Figure 43 Mine waste heap in a neighborhood in Hwange Town at 18°21'48.39"S, 26°29'29.81"E. Picture taken on 02.05.2019

Suppl.-Figure 44 Thermal power plant in Hwange with mine waste heaps in front. Picture taken on 30.04.2019 from 18°20'39.93"S, 26°30'12.07"E looking South West

C. Social Accountability

Set-up and implementation of community-based water quality monitoring

During a multistakeholder mediation meeting in Hwange Town in October 2018, we approached community representatives with the idea of developing a community-based water monitoring scheme to overcome the lack of publicly available environmental quality data. The four community members present showed a deep interest in the proposition. Back in their villages, they recruited other interested individuals. Thirteen community members from four different villages along the Deka River, representing a total population of around 2000 people, participated in the community monitoring. Family ties and private trust relationships formed the basis of the group, which was diverse in age and included youths and elderly people above 65 years. Some of the teenagers still attended government school whereas older members lived mainly on subsistence agriculture. Two thirds of the community members in the group were female. Throughout the project duration of 1.5 years, the participation and motivation of the community monitors remained comparatively high. Only two young adults dropped out of the sampling scheme because of work-related migration and one older member because of advanced age.

In mid-December 2018, the first author trained 13 community members, who had rudimentary formal education, for technical water sampling and introduced them to the sampling protocol. Community monitors were trained from a two-page training manual with pictures illustrating the 11 steps for taking water samples and measuring pH using test strips (for details on methodology and results, see Chapter 3). During the training and subsequent meetings, community monitors acquired a basic understanding of water chemistry, pollutant transport, and the measurement and meaning of water quality parameters such as pH. For the subsequent 15 months, community monitors took biweekly to weekly water samples and measured pH of Deka River. Volunteers organized and sampled on a weekly to biweekly frequency for over 1.5 years and would have been motivated to continue sampling. The community monitoring was a collective process that was neatly integrated into existing local society and culture.

Between December 2018 and April 2020, community monitors and scientists collected, analyzed, and interpreted close to 800 water samples. Community monitors made observations about the environmental condition of the river and the weather in notebooks. Scientists from ETH Zurich and University of Zimbabwe supported community monitors with reminder messages and logistic support. At the beginning of the month, each community monitor received phone credit of 1-2 USD to facilitate communication with their peers. In the 15 months that the community monitoring took place, scientists and community monitors met at least 10 times. In these joint meetings between community monitors and scientists, the team discussed the last sampling period and field observations and shared social moments around a meal. The new samples were collected, registered, and subsequently transported to a chemical laboratory in Switzerland. At the subsequent meeting, scientists presented the results of the previous analysis and discussed them with community monitors. This tight feedback loop helped improve data quality by, for instance, modifying the way notes were taken and samples were labeled and identifying errors in the way pH was measured. The meetings were also instrumental in keeping monitors motivated because they saw the fruits of their labor.

Community monitors used the results to update their neighbors on the water quality and whether fish were suitable for eating. Especially younger, female community monitors stated that they were now “more respected in their community” and that, in village meetings, they were “consulted from the elders on the water quality of Deka River” (ID15). Community monitors were invited to human rights defender workshops to present their initiative (ID07) and presented their case at a national dialogue platform on the mining sector (ZELA, 2019).

List of interview quotations

Suppl.-Table 9 List with interview quotations

ID	Institution type	Location	Gender
ID01	Civil society	Hwange District	female
ID02	Civil society	Harare	male
ID03	Civil society	Hwange	male
ID04	Government	Hwange	male
ID05	Private sector	Hwange	male
ID06	Government	Hwange	male
ID07	Private sector / civil society	Hwange	male
ID08	Private sector	Hwange	male
ID09	Academia	Harare	male
ID10	Academia	Harare	male
ID11	Private sector	Harare	female
ID12	Private sector	Hwange	female
ID13	Private sector	Hwange	male
ID14	Civil society	Hwange District	female
ID15	Civil society	Hwange District	female
ID16	Civil society	Hwange District	male
ID17	Mining company	Hwange	male
ID18	Government	Hwange	male
ID19	Private sector	Harare	male
ID20	Government	Harare	male
ID21	Government	Bulawayo	female
ID22	Government	Bulawayo	male
ID23	Government	Harare	male
ID24	Government	Harare	female
ID25	Government	Harare	male
ID26	Government	Hwange	male
ID27	Private company	Bulawayo	male
ID28	Private sector	Mutare	male
ID29	Private sector	Mutare	male
ID30	Government	Bulawayo	female
ID31	Government	Harare	male
ID32	Government	Harare	male
ID33	Government	Hwange	male
ID34	Private sector	Harare	male
ID35	Private sector	Switzerland	female
ID36	Private sector	Switzerland	male

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Curriculum Vitae

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Education

2017 - 2022	**Doctor of Sciences, ETH Zurich, Switzerland** Doctoral thesis supervised by Prof. B. Wehrli, Aquatic Chemistry Group, Institute of Biogeochemistry and Pollutant Dynamics, Department of Environmental Systems Science Thesis title: Effective Monitoring Strategies for Mining-Related Water Pollution Methods: 2 years field study in Zimbabwe; inter- and transdisciplinary research including chemical analysis, a political ecology study and remote sensing
2009 – 2011	**Master of Sciences in Earth Sciences, Major in Geology and Geochemistry, ETH Zurich** Specialization: geochemistry, sedimentology, structural geology Thesis Title: Reconstructing the geodynamic setting of the Late Paleozoic northern active continental margin of the Mongol-Okhotsk Ocean, Mongolia Methods: 4 weeks field study in Mongolia; geochemical and palaeomagnetic sample analyses
2006 – 2009	**Bachelor of Sciences in Earth Sciences, ETH Zurich** Bachelor Thesis Title: Changes in the Fluorescence Spectra: A Possible Earthquake Precursor? The Case of the Thermal Spring of Val d'Illiez, Switzerland Erasmus exchange semester in 2008 at the Università degli Studi di Perugia, Italy
2000 – 2005	**Swiss Federal Maturity, Lycée-Collège des Creusets, Sion VS, Switzerland**

Work experience

September 2017 – June 2022
ETH Zurich, Institute of Science, Technology and Policy (ISTP), Universitaetstr. 41, CH-8092 Zurich
Research associate (doctoral candidate)

- established a research collaboration with the University of Zimbabwe
- conceptualized and implemented a citizen science project for water quality monitoring in a mining area in Zimbabwe and participated in a multi-stakeholder process on environmental pollution
- developed new methodology to track large-scale water pollution incidents using optical remote sensing
- worked in interdisciplinary research group with engineers, natural- and social scientists, supervised students and taught seminars

February – June 2017
Sanu durabilitas, foundation for sustainable development, CH-2502 Biel/Bienne
University of Lausanne, Faculty of Geosciences and the Environment, Industrial Ecology Group, CH-1015 Lausanne

Research associate in the project *Laboratory for Applied Circular Economy – LACE*

- recruited industry partners and wrote the proposal for the transdisciplinary research project on circular economy accepted for funding within the Swiss science program NRP 73 (1 million CHF)

October 2013 – October 2016
German Federal Institute for Geosciences and Natural Resources (BGR), Mineral Resource Group, DE-30655 Hanover

Project geologist in the mineral certification project of the Democratic Republic of the Congo (DRC), seconded to Bukavu, Eastern DRC

- designed and implemented capacity building courses for the Congolese Mining Ministry, mining cooperatives and civil society on HSE, such as transparency and traceability of the supply chains of tin, tungsten, tantalum (3T) and gold from artisanal mining
- led mine site inspections and coordinated 3rd party audits in Eastern Congolese mining provinces
- harmonized project activities with other international donors and due diligence initiatives (ICGLR, OECD, etc.) and represented the project at international commodity conferences in Sub-Saharan Africa and the Middle East

January 2012 – August 2013
ETH Zurich, Institute for Environmental Decisions, Chair for Natural- and Social Science Interface, CH-8092 Zurich

Research associate in the project *Vulnerabilities and Potentials of the Swiss Energy Supply Security (VPA)* with the Swiss Federal Office of Energy

- developed a method for jointly quantifying the probability of natural, technical and socio-economic hazards in relation with the European gas network and participated in energy expert group meetings
- analyzed the exposure of the European gas infrastructure to incidents and hazards, compiling hazard maps with geographic information system (GIS)

Project manager of *Global TraPs (Global Transdisciplinary Processes on Sustainable Phosphorus Management*)

- managed activities of an international transdisciplinary project on the phosphorus supply-demand chain; with experts from science, the mining- and fertilizer industry, recycling companies, international organizations, NGO’s and farmer cooperatives
- organized a workshop with 90 international experts in El Jadida, Morocco in March 2012 and created communication material (newsletters, reports, posters and handouts)

February – April 2011
ETH Zurich, Geological Institute, Earth Surface Dynamics Group, CH-8092 Zurich

Research assistant in the project *Inferring global erosion rates from low temperature thermochronology*

- analyzed extensive database on tectonic uplift and erosion patterns for a global erosion model and computed topographical maps displaying radiogenic ages

June – July 2008
Geoplan AG, CH-3940 Steg

Intern at the natural hazard division of a geotechnical firm

- evaluated the risk of natural hazards based on field observations and created hazard maps with GIS, monitored drinking water resources, communicated risks to stakeholders

Other activities

since 2022	**Volunteer teacher for languages and maths** supporting migrants, *Croix-Rouge Suisse, CH-2504 Biel/Bienne*
Nov – Dec 2016	**Production assistant** for the drama «*Egoisten*», a play of the independent theatre company *Schauplatz International*
since 2016	**Founder and co-president** of the non-governmental organization *Neno Association, CH-3000 Bern* supporting civil society from the DRC with a focus on resource governance and culture
2000 – 2005	**Music teacher for flute** tutoring music theory, harmony and playing technique to pupils within *Tambouren- und Pfeiferverein, CH-3922 Stalden*

Language skills

German mother tongue
Italian intermediate (limited working proficiency)
Arabic elementary (level A1 in 2012)
French fluent (bilingual)
Russian basic (level B1 in 2010)
Portuguese elementary (A1)
English fluent (full working proficiency)
Kiswahili basic (level B1 in 2016)
Spanish elementary (A2)

Computer skills

Data- and Image Processing	Geographic Information Systems (QGIS, ArcGIS), R programming language, Latex, Microsoft Office, Adobe Illustrator

Publication List

Articles included in this thesis:

- Ruppen, D., Chituri, O. A., Meck, M. L., Pfenninger, N., & Wehrli, B. (2021). **Community-Based Monitoring Detects Sources and Risks of Mining-Related Water Pollution in Zimbabwe**. Front. Environ. Sci. 9, 599. doi:10.3389/fenvs.2021.754540.
- Ruppen, D., & Brugger, F. (2022). **"I will sample until things get better – or until I die." Potential and limits of citizen science to promote social accountability for environmental pollution**. World Development, 157, 105952, doi: 10.1016/j.worlddev.2022.105952
- Ruppen, D., Runnalls, J., Tshimanga, R. M., Wehrli, B., & Odermatt, D. (n.d.). **Optical remote sensing of large-scale water pollution caused by the Catoca Mine tailings spill**, in review at Remote Sensing of Environment

Articles related to this thesis:

- Cabernard, L., Ruppen, D., Pfister, S., (n.d.). **Biodiversity loss related to precious metals supply chains in Switzerland**. In preparation
- Van der Merwe, A., Ruppen, D., Wehrli, B., Brugger, F., Moussa, H. & Günther, I. (n.d.). **Constraints to protective behavior against mercury on artisanal gold mines: knowledge, risk perception and access**. In preparation

Further publications:

- Ruppen, D., Knaf, A., Bussien, D., Winkler, W., Chimedtseren, A., von Quadt, A. (2013). **Restoring the Silurian to Carboniferous northern active continental margin of the Mongol–Okhotsk Ocean in Mongolia: Hangay–Hentey accretionary wedge and seamount collision**. In: Gondwana Research, Volume 25, Issue 4, p.1517–1534
- Baltensperger, T., Blumer, Y., Ruppen, D & A. Spoerri (2013). **Analyse der Schweizer Energieversorgungssicherheit. Eine Abschätzung der Verwundbarkeit des Energiesystems**. Bern: BFE., 109 pp.
- Sterbik, N., Vasters, J., Ruppen, D. & G. Franken (2015). **Business plans for small-scale mining in the Democratic Republic of the Congo**. In: AIMS, 5th International Symposium on Mineral Resources and Mine Development, Vol. 14, p.163-172
- Barume, B., Naeher, U., Ruppen, D., & Schütte, P. (2016). **Conflict minerals (3TG): Mining production, applications and recycling**. Current Opinion in Green and Sustainable Chemistry, 1, 8–12. https://doi.org/10.1016/j.cogsc.2016.07.00
- Barume, B., Neumann, M., Ducellier, B., Ombeni, A., Näher, U., Schütte, P., Von Baggehufwudt, Ulrike, Ruppen, D. (2018). **Responsible Gold from Artisanal and Small-scale Mining in the Democratic Republic of the Congo Lessons learned from the Kampene Gold Pilot**, Hannover, Germany: Federal Institute for Geosciences and Natural Resources, BGR

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Book cover:

Milky blue wastewater of the Sikabala effluent channel at the Sandledge coal mine, Hwange District, Zimbabwe, September 2019 (Photo: Désirée Ruppen)