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Investigating Conflicts between Gold Mining and Water Protection by Remote Sensing Imagery

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Content

Abstract

Water is a scarce resource and is therefore subject to manifold competing interests and conflicts. This is exemplified best by the mining sector which requires large quantities of water and can make it unusable for other purposes. This is an important aspect, especially in developing countries, as our research in Ghana shows. We investigated how space technologies and optical remote sensing can be used to determine surface water quality from space and to track pollution in areas affected by mining. In addition to a technical report, we analysed the existing public policies in Ghana regarding safeguarding water quality using remote sensing. Based on an intensive literature review, the analysis of policies, expert interviews and an exhaustive search for available datasets we identified several loopholes and pitfalls that hamper the usage of remote sensing: Firstly, there is a clear lack of readily available datasets allowing fast analysis of surface water bodies and their quality. Secondly, in-situ reference data required for calibrating and validating workflows and algorithms based on remote sensing are hardly available for developing countries such as Ghana since existing governmental data is not freely available. Especially in Ghana we can see that practitioners and policy makers are aware of the potential of space technologies and remote sensing because they are cost effective and comprehensible. In practice, however, these technologies are hardly used due to the limitations described. In addition, remote sensing-based approaches to water quality assessment and pollution tracking have to take into account complex interference effects between the local population, legal and illegal mining activities, which makes in-situ references and local expertise indispensable alongside the use of these technologies. We therefore recommend the development of in-situ reference and knowledge databases for managing space-borne water quality retrieval. Thus, we strongly advice expert knowledge about local conditions to be systematically recorded and to make data available to the public using standardised web services and data exchange formats.

Introduction

Water is arguably among the most important natural resources, as life directly depends upon the availability of water and most economic activities, to some degree, exploit this invaluable resource. Consequently, competing interests in the usage of water resources cannot be avoided. This issue and its drawbacks are best exemplified by the mining industry. Minerals sector is characterized by a manifold and complex interrelationship with water management and protection in a given region (Mudd, 2008; Kemp et al., 2010; Laurence, 2011). In mining, water acts as a transport and process medium. Furthermore, water is usually the carrier of pollutants into the wider environment. Thus, mining activities could directly affect water quality and gain access to freshwater resources in a given region.

Access to water, especially clean drinking water, is a universal human right acknowledged by the UN General Assembly (Resolution A/RES/64/292) and, in consequence, water quality is explicitly addressed within the Sustainable Development Goal number 6 (UN General Assembly, 2015). Moreover, the World Health Organization (WHO) clearly emphasized the strong linkages between water quality and human health. For this reason, the adoption of water quality standards by the member states was enforced (WHO Assembly Resolution WHA64.24). The effective and efficient enforcement of such regulations requires traceable and accurate near real-time retrieval methods of water quality.

We hypothesize that **space technology by means of remote sensing can be used to gain valuable information regarding water quality and its conflicts with mining activities**. This is because changes in the physical and chemical properties of surface water bodies directly affect their spectral behaviour by means of changed reflection and absorption patterns of electromagnetic energy (Ritchie, Zimba and Everitt, 2003). Thus, we assume that conclusions about water quality can be drawn by recording the spectral properties of surface water bodies.

To test our hypothesis, we have chosen the Western African country of Ghana as a case study. With a population of about 30 million inhabitants (WBG, 2018) over a 238,533 km^2 of territory, in which 11,000 km^2 makes up the area covered by surface water bodies (World Atlas, 2018), Ghana is a bustling country with a developing economy ranked 83rd on the world market (Statistics Time, 2019). As of 2018, the country was dubbed the fastest growing economy in the world which was spurred mostly by the mining industry, followed by the oil sector and the agriculture sector (WBG, 2018). Ghana is the second-largest producer of gold in Africa and, thus the mining sector is of great importance to the economy and livelihood of many of its citizens.

As of 2004, only 16% of Africans had access to safe drinkable water (Lewis, 2019) and the number will drop as the century goes, despite the gains made during the era of the Millennium

Development Goals (MDGs) (PACN, 2010). This drop is due to the rise in temperature in the region which caused many surface waters to dry-up, and through contamination from various harmful activities such as illegal mining and the use of hard metals and chemicals like mercury and cyanide (Sarpong, 2017). In a 2017 press release by UNICEF, it was purported that there were huge gaps in the drinkable water distribution services between urban and rural areas on a global scale. The release further stressed that in urban areas, two out of three people have access to safely managed drinking water and three out of five people with safely managed sanitation services (UNICEF, 2017). This distribution inequality is present in Ghana but on a lower scale per UNICEF indicators (UNICEF, 2015).

As of 2015, the UNICEF water management index stated that only half (~53.93%) of the drinking water in urban communities globally are from safely managed water supply. In rural areas, the number is an abysmal 9.78%. Surveillance of basic drinking water quality observed 37.85% in urban communities and 56.25% in rural areas (UNICEF, 2015). The rural areas received 12.37%, 6.65%, and 14.94% for limited water service level, unimproved water service level and direct surface water supply, respectively (UNICEF, 2015). The figures are smaller in urban areas whereby 5.64% and 2.85% received access to water with limited service level and unimproved water service level, respectively. No one had to use direct surface water in the urban areas (UNICEF, 2015). Undoubtedly, water plays a crucial role in the daily lives of Ghanaians, especially for rural settlers who are predominantly farming communities. They rely most times on poorly treated water supply or surface water and/or underground water to help cultivate their crops, and sometimes also for domestic usage in the absence of treated tap water supply.

Ghana’s rapid economic growth, the country’s lack of proper policies to protect the environment, and the West African gold rush of the 21st century reaching its peak in 2015, was a defining period in the history of the nation’s environmental challenges. The authorities and local population in the rural areas of the country found themselves battling against illegal artisanal and small-scale mining (ASM) activities (IGF, 2019), otherwise known by locals as “Galamsey”. The unregulated mining process and harmful chemicals used by the illegal miners, such as mercury and cyanide (Sarpong, 2017), has polluted and muddied many large freshwater sources in the country. These activities are taking place in the forest and water belt zones and are threatening access to drinkable surface and underground water (Lewis, 2019). This in turn creates a negative chain effect such as reducing the productivity of the farmable lands thereby leading to a reduction in agriculture production (National Geographic, 2018) that will subsequently impact negatively on the GDP of the country and possibly plunging the economy down the hill. As these harmful chemicals find their way into the food chain through the water supply system, the many health challenges associated with this menace cannot be overemphasized.

However, despite the awareness of the challenges and damages the act of “Galamsey” and some ASM operators causes to the environment and livelihood of the settlers in these regions, many culprits willingly sell-off farmlands and join in the illegal act in order to get a reliable source of income. These impoverished farmers now turned miners consider the illegal mining activity to be more lucrative than their regular farming activities. The Human Rights Watch (HRW) indicated in a 2015 article that families engaged in the act also get their underage children involved in the practices leading to the exploitation and usage of child labour in this field (HRW, 2015). Many of these child labourers engaged in “Galamsey” get involved on their own without any guardian permit, indicating the lack of guardianship from society and the state to protect the rights of these children (HRW, 2015).

The act of “Galamsey” does not just spell doom to the water, environmental and food security of the country, but it also brings to light the many policy weaknesses and possibly the lack of full coverage of the social welfare system across the country to cater for most of the basic needs of these rural folks and their families. It also indicates the lack thereof in the implementation of already existing policies regarding small scale mining activities, environmental protection and social benefits such as the free school policy from primary to the senior high school level. And finally, it reveals the looming threat of quality of life for the teaming youth and underage children engaged in this illegal activity while working under life-threatening circumstances.

The long-term consequences of the negative impact “Galamsey” activities and some ASM entities have on the water and food security of the state and in other countries facing similar problems is a good enough reason to seek alternative sources of solution that merges science and public policy together such as the usage of remote sensing imagery.

Research Questions and Purpose

In our research project on water protection by remote sensing imagery concerning Ghanaian gold mining, we studied two main aspects that we think could improve and, to a certain extent, solve the detrimental environmental change and societal losses brought by gold mining in Ghana. As such, these main aspects are assigned as the following scientific inquiries:

- **How can we extract information about the effect of gold mining activity on water quality using remote sensing imagery?**
- **How will this extracted information support policy-making in developing areas to protect water sources?**

To investigate these aspects in detail, we focused on small- and large-scale gold mining in Ghana considering both their legal and illegal forms. Some of the small-scale mining groups are not registered officially. This leads to further problems in terms of controlling the social and environmental impacts beyond the general harm of mining (Banchirigah, 2008). Since our research paper is purposed to look at space technology to address these problems, the technology has to be readily available and easily accessible. On this backdrop, the aims of this research paper are:

Aim I

To investigate to what degree space technologies could contribute to understanding the role of illegal mining activities in affecting the quality of surface water sources in rural areas.

Aim II

To identify the available space technology or tools to help identify and track polluted surface water sources and most of the key chemical pollutants.

Aim III

To identify and address the policy gap in the protection of water sources and usage of space-technology in resolving water quality issues related to mining.

Identified Gaps

In the process of understanding the subject matter and its various intricacies, a couple of research gaps were identified. Our relevant findings can be found in the Results section. The following questions outline the identified research gaps:

- **What are the available space technologies to investigate the conflict between water quality and mining in developing countries?**
- **Are there easily accessible data from space-based technologies concerning water quality (directly and indirectly)?**
- **What is the actual usability ratio of the data by local policy makers in the policy-making processes regarding water and its accompanying issues?**
- **What is the level of awareness, and policy implementation of governments in affected regions regarding the importance of space technology in the protection of water bodies?**
- **And finally, what are the policy recommendations to be proposed in combining data gained from space-based technologies with National Water Policies in helping address the negative effects of mining activities on the quality of surface water?**

Taking all this into account, and considering the main scientific questions, two main findings resulted from this research are:

- **A detailed technical summary of the available state-of-the-art remote sensing data sources and analysis techniques on water quality assessment related to gold mining.**
- **Detailed findings related to our case study in Ghana with specific recommendations on how these results can be used in local, national or international policy-making not just in regulating mining activity but also to maintain good quality water sources for local residents.**

Theoretical Framework

Overall Theoretical Framework

The theoretical framework of this study is bounded by three aspects of space-based technology assessment of inland water quality due to illegal mining activities: 1) space technology for assessment and information delivery, 2) policy framework and 3) socio-economic impacts. This is clearly illustrated in Figure 1 whereby water quality and quantity are placed as central elements that are influenced by mining activities on different spatial and temporal scales. The interrelationship between mining and the availability of fresh drinking water is mainly controlled by national and supra-national regulatory frameworks and policies (Figure 1, bottom left). Institutions such as public state authorities as well as non-governmental organizations (NGOs) can be identified as the main actors that take information on mining activities and related impacts on surface water quality into consideration for developing, adopting and monitoring policies accordingly.

Figure 1: Theoretical framework of space-based technology for water quality assessment upon mining activities in the context of public policy and socio-economic factors.

Moreover, mining activities are not only controlled or favoured by the legal situation, but also by the behaviour of individuals – especially when it comes to small-scale mining that is mainly practiced by the local communities (Bansah, Yalley, & Dumakor-Dupey, 2016; Hilson & Potter, 2005). Thus, mining activities and subsequent impacts on water quality are also subject to socio-economic relationships that are essentially reciprocal in their nature (Figure 1, bottom right). The economic situation influences individual decision making. An important example, which captures the aspect of socio-economic transformation in sub-Saharan Africa, is to start small-scale mining and abandon traditional forms of land management (Banchirigah, 2008; Hilson, 2009). On top of that, the local population is directly affected by negative impacts, such as deterioration in the quality and availability of water resources and health effects, which can hamper further economic development and thus create a self-enforcing feedback loop. Space technologies are used to asses these impacts and deliver the information to policy makers and decision makers (Figure 1, upper).

Required Concepts and Definitions

To address the theoretical framework denoted in the previous paragraph, the most important concepts and definitions are described here to allow for a sound and concise assessment of the individual aspects:

1. Space Technologies

The term “space technologies” outlined in Figure 1 is very broad and lacks a uniform definition. Therefore, in accordance with the scope of this analysis it was decided to focus on optical remote sensing that is part of space-based technologies. In general, remote sensing means the “technology of obtaining, analysing, and displaying the information about an object or a phenomenon through remote detection of its reflected and emitted electromagnetic energy” (Chen, 2014). Often remote sensing is used to study the surface of the Earth from space, using satellite-based sensor technologies. The main principle of optical remote sensing is to associate changes in the spectral properties of an object (mostly changes in reflection) with changes in other physical or chemical properties of the object. This can either be determined by empirically determined relationships or modelled by a system of physical equations (Lillesand, Kiefer & Chipman, 2014). Furthermore, differences in spectral reflectance properties (i.e. spectral signatures) work as distinct fingerprints to differentiate surface types from remotely sensed optical imagery (Liew, 2001). For instance, the spectral signature of water can be used to detect water bodies. Gholizadeh, Melesse, & Reddi (2016) argued that the assessment of water quality from space could effectively address the main restrictions of in-situ measurements which are mainly laborious, time-consuming and cost-intensive. Another disadvantage includes poor data reproducibility especially when the investigation of spatial patterns and dynamics is carried out over longer time frames.

2. Water Quality

Water quality considers the chemical, physical, biological and radiological properties of water. The most common standards used to assess water quality relate to the health of ecosystems, safety of human contact, and drinking water (WHO 2004, 2013). By means of optical remote sensing the most frequently analysed parameters include total suspended solids (TSS), chlorophyll-a concentration, turbidity and temperature of water bodies, as well as nutrient indicators (e.g. total phosphorus) that are important factors determining water quality (Gholizadeh, Melesse, & Reddi, 2016). However, the spectral and spatial resolution of the used sensors/satellites often limit the effective application (Ritchie et al. 2003) as well as unintended side-effects such as atmospheric disturbance, cloud coverage and adjacency effects.

3. Illegal Mining

Mining activity – that is about the extraction of mineral resources from the Earth's crust - can be classified into two groups: Legal and illegal mining, depending on whether companies are registered and follow national (or international) regulations. In most countries, underground mineral resources belong to the state. However, many governments in sub-Saharan Africa have loosened national mining investment codes, in the hope that this will attract foreign investment and contribute to domestic economic development (African Union, 2009). The expansion of the large-scale mining projects fuelled by foreign investment has displaced rural mining communities, many of which revert to illegal mining on concessions given to the formal mining sector (Banchirigah, 2006, 2008).

4. Galamsey

Galamsey is a local Ghanaian term describing the act of illegal mining activities (Mensah, 2018). The expression "artisanal mining", which is used by some scholars, represents an alternative term. This has been the main damaging activity leading to the pollution of surface water and underground water bodies in the rural areas of the country. Various activities at the government level have been initiated to tackle this menace with prominent mention being a joint intergovernmental initiative between Kenya, Senegal, Sierra Leone, Ghana, and Tanzania to create the Africa Regional Data Cube (ARDC) to create a pool of data resource derived from Earth observation and satellite technology to help combat activities leading to water access, among many others (see http://www.data4sdgs.org/ARDC). The argument of this paper is that Galamsey imposed adverse impacts on the environmental, economic and social fabric of Ghana.

5. Public Policy

As explained by Hassel (2015), public policy is a set of decisions by governments and other political actors to influence, change, or frame a problem or issue that has been recognized as in the political realm by policy makers and/or the wider public. Furthermore, public policy is a fundamental part of the policy decision making process because it "provides signals and sets the regulatory and institutional framework that influence the actions of all actors, including private investors and consumers" (Qureshi, 2015). Consequently, public policy will be an important concept in the assessment of the policy-related aspect of this research.

Research Design and Methods

Research Workflow

In accordance to the framework denoted in Figure 1, the **workflow approach** proposed by Chen, Zhang & Martti (2007) is applied in this study. Originally developed to analyse the contribution of remote sensing to water policies in Finland, their four-step workflow is adjusted to meet the requirements of this study. A summary of the workflow is provided in Figure 2. Moreover, it is important to note here, that the procedure we listed follows the standardized evaluation process of the European Space Agency ESA for the scientific assessment and development of new remote sensing satellites.

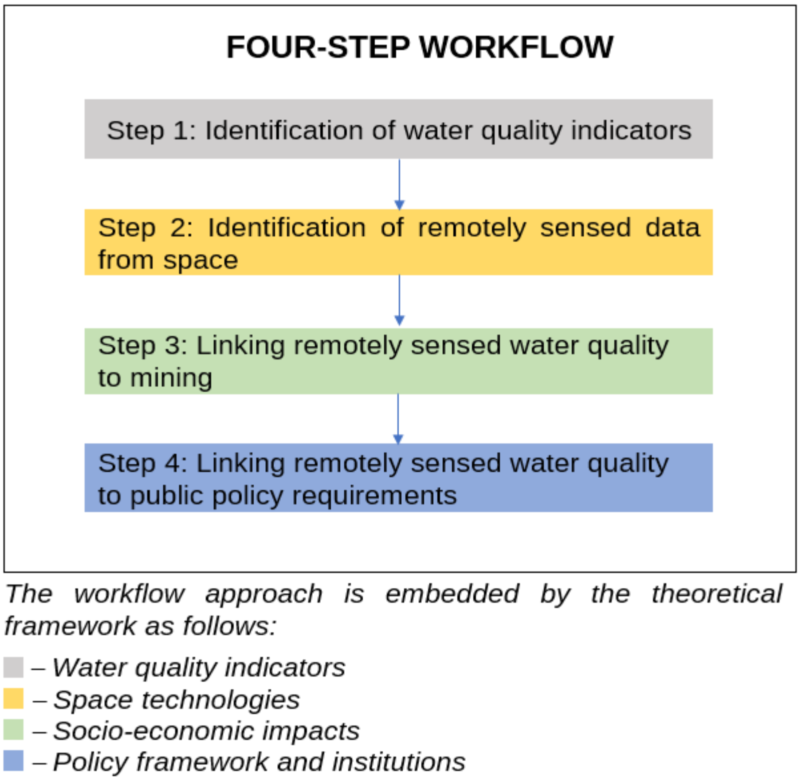

Figure 2: Workflow approach adapted from Chen, Zhang and Martti (2007) and adheres to the standardized evaluation process of the European Space Agency.

Details of Research Workflow

Step 1: Identification of water quality indicators

The first step is to investigate which indicators are available for the investigation of water quality. From this list, a formalized scheme is used to assess which of these indicators are particularly important for the study of Galamsey. In detail, it is decisive whether the signal (e.g. a change in water turbidity) can be clearly attributed to illegal mining activity or whether it is superimposed with other natural effects. Table 1 shows the rating scheme which contains three categories ranging from "+" (a clear relationship between the indicator and Galamsey exists) to "-" (no relationship could be identified or established).

Table 1: Rating scheme for evaluating available water quality indicators to Galamsey.

Rating	**Explanation**
+	The indicator can be directly linked to Galamsey. It is unlikely to be superimposed with other effects of a natural and/or anthropogenic nature.
o	The indicator can be directly linked to Galamsey. However, there is a chance to be superimposed with other effects making the indicator thus less suited for assessing the spatio-temporal characteristics of Galamsey.
-	A direct linkage between the indicator and Galamsey cannot be established. This might be because no relationship exists at all, or the superimposition with side-effects is too complex to make a distinct statement about the appropriateness of the indicator.

Step 2: Identification of remotely sensed data sources from space

Those water quality measures that exhibit at least an indirect link to Galamsey are analysed regarding the available optical remotely sensed data and state-of-the-art retrieval algorithms. Firstly, it is evaluated whether an indicator can be spectrally examined. Those indicators that meet this requirement will be assessed in terms of spatial and temporal resolution, accuracy, transferability and uncertainties of the approach. Moreover, data availability is considered.

Step 3: Linking remotely sensed water quality indicators to mining activities

The interpretation of the outcomes of Step 2 is conducted regarding the anticipated effects of mining activity on socio-economic conditions (Figure 1, bottom right). Therefore, it is necessary to develop an understanding of the potential impacts of Galamsey on aquatic ecosystems and the environment in terms of water quality. It is examined whether the spatio-temporal scales of the effects correspond to those that can be obtained from the remote sensing data, as this has a decisive influence on the usability of the data.

Step 4: Linking remotely sensed water quality indicators to public policy requirements

Finally, the remote sensing derived water quality indicators are contrasted with identified policy requirements in the study area, Ghana. The policy requirements are analysed based on identified policy gaps (see paragraph about data evaluation) in the existing water and mining policies. At this level, the process of understanding data derived from Earth observation and satellite technology will provide clear indicators with actual figures that we assumed cannot be disputed in the political discourse. This should facilitate the design of regulative measures by using legal instruments to guide the activities surrounding mineral explorations and/or to protect water bodies from harmful activities such as Galamsey. In short, we claim for a firm scientific background to provide the data in order to create the needed ethical and political grounds for consensus among the various political groups and key stakeholders.

A rating scheme is employed to determine whether a distinct policy requirement is “fully covered” or “not addressed at all” by means of the identified remote sensing techniques. The spatial and temporal resolution are considered important as they mainly determine if the scale of analysis matches the anticipated scale of the policy requirements. Moreover, it is analysed whether the provided retrieval accuracy and transferability of the remotely sensed approach are suited for informed decision making.

Study Area

With a surface area of more than 8000 km², Lake Volta is the largest artificial reservoir in the world in terms of surface area. In addition to generating electricity, the lake is also used for fishing (Tschakert, 2010). Tschakert (2010) reports that the fish population in the lake is not conspicuous by elevated mercury levels as the lake is not directly influenced by mining activity. In addition, it should not be forgotten that the density of mercury is significantly higher than that of water and mercury due to the high surface tension tends to drop formation. It is therefore questionable whether the findings of the study prove a lack of influence of gold mining on the lake. This is because the lake absorbs water from several tributaries that are in areas with active gold mining. Therefore, we assume that at least sediment inputs influence water turbidity.

Data Evaluation

The main part of this study consists of a comprehensive review of state-of-the-art remote sensing techniques related to water quality assessment. However, to address the objective of this work, i.e. to assess Galamsey in Ghana by means of optical remote sensing, a selected subset of analysis-ready-data (ARD) is evaluated. The usage of ARD is preferred over raw data (from optical satellites without any processing) as decision makers and policy makers usually require an integrated view on the phenomenon under investigation rather than an algorithmic workflow (Leeuw et al., 2010).

An analysis of available data portals and platforms, however, showed a significant lack of such ARD related to inland water quality. Among six analysed platforms (see Table 2), only 3 provided ARD. Out of them, problems were detected regarding the covered time period (e.g. Copernicus Land Monitoring Service), transferability among geographic regions (e.g. NASA EOSDIS) and data accessibility as well as handling (e.g. Copernicus, UNESCO Water Quality Portal). The African Regional Data Cube (see last entry in Table 2) provides multi-year collections of optical Landsat imagery but concurrently no data related to water quality. Due to the absence of desired ARD, we have decided to use Google Earth Engine (https://earthengine.google.com/). Although operated commercially, the platform that offers rich processing facilities free of charge (Gorelick et al., 2017). The use of the platform represents a compromise between the use of the largest possible amount of remote sensing data and the lowest possible complexity in the generation of ARD since the use of the platform functionalities requires only little training. Moreover, the raw data provided at the Earth Engine platform is very similar to those image collections stored in the African Regional Data Cube. Therefore, we assume that results obtained from the Google platform are essentially similar to the ones created with the data cube.

Table 2: Overview of analysed data portals and platforms providing access to remotely sensed data. All links were accessed last on 14th Dec. 2019.

Data Portal/ Platform	**Water Quality Data Available?**	**Remarks**
USGS Earth Explorer (https://earthexplorer.usgs.gov/)	No	Raw data and ARD related to vegetation available but no water quality datasets
Copernicus Land Monitoring Service (https://land.copernicus.eu/)	Yes	Inland water quality data is available, but time-period is restricted to 2019. Complex data handling
NASA EOSDIS (https://worldview.earthdata.nasa.gov/)	Yes	Only regional datasets available with limited spatio-temporal coverage

UNESCO World Water Quality Portal (http://www.worldwaterquality.org/)	Yes	Only pilot studies with limited spatio-temporal coverage. No further analysis facilities.
Google Earth Engine (https://earthengine.google.com/)	No	Raw data and ARD related to water quantity (extent and occurrence) but rich processing facilities to generate water quality data available free of charge
African Regional Data Cube (Digital Earth Africa) (https://www.digitalearthafrica.org/)	No	Raw data and ARD related to water quantity (extent and occurrence); concurrently with limited processing facilities

At the policy level, data from other countries, such as good practices implemented in Argentina (Iribarnegaray & Seghezzo, 2012) and lessons learned from the water governance issues in South Africa (Meissner, 2016), is used. In addition, further research on the available water and mining policies of Ghana, such as the National Water Policy of Ghana and Ghana Minerals and Mining Acts of 2006 and its amendments' in 2015, provides information to understand how far they have come, and which clear steps they have taken to cross to the next phase. Finally, an assessment of governmental decisions and executive orders is conducted to ascertain the level of commitment by policy makers in this regard and to analyse their level of political will to collaborate with other stakeholders such as the private and academic sectors.

Experts Interviews

In order to gain the best possible insight into the topic of remote sensing- based water quality assessment, we identified expert interviews as a valuable tool. We identified two experts who were available for an unstructured interview:

- Karin Schenk, Project Manager at EOMap GmbH in Germany, who has many years of experience in the field of remote sensing and water quality
- Abeiku Arthur, AngloGold Ashanti employee responsible for water quality monitoring, a mining company operating gold mines in Ghana.

The interviews were conducted in May and November 2019 and subsequently evaluated regarding our research questions.

Results

Available Water Quality Indicators and Measures

Here, we propose a list of available water quality indicators extracted from Gholizadeh, Melesse, & Reddi (2016) and Glasgow, Burkholder, Reed, Lewitus, & Kleinman (2004). For each water quality indicator, in addition to a brief description, we include a rating to indicate the extent to which the indicator can be associated with Galamsey (see Table 1) and whether the indicator can be determined by optical remote sensing. The rating scheme for remote sensing is based on Table 1, where a "+" stands for a direct spectral relationship between the indicator and the spectral properties of water and a "-" indicates that there is no such relationship. With "o", the relationship is either less direct, or overlaid by other effects.

Tabulated in Table 3 are nine indicators that are available to assess water quality, but only four of them can be spectrally captured – chlorophyll-a, coloured dissolved organic matter (CDOM) content, turbidity and total suspended solids (TSS). Furthermore, only some of the indicators show a link with complementary indicators that assess mining activities based on discharged wastewater and heavy metal ions, like the use of mercury for instance. These indicators are change in pH and temperature. If those indicators are considered based on their direct association to Galamsey and at the same time can be spectrally traceable, then only turbidity and TSS remain.

Table 3: Available water quality indicators and their relationship to Galamsey and the degree to which the indicators can be traced spectrally by means of optical remote sensing.

Indicator	**Description**	**Galamsey**	**Spectrally traceable**
Chlorophyll-a	This plant pigment indicates algae abundance in water bodies as it is a proxy for phytoplankton. It shows a strong spectral response in the visible portion of the spectrum. Algae blooms can be caused by a series of factors but no clear relationship to mining seems to exist (Brezonik, Menken, & Bauer, 2005).	-	+
Temperature	The surface temperature of water bodies. It controls availability of oxygen and other chemical components that in turn affect biological activities. Contaminants could influence the water temperature, but seasonal effects could superimpose them making the relationship less clear (Torgersen, Faux, McIntosh, Poage, & Norton, 2001).	o	-

Coloured Dissolved Organic Matter (CDOM)	Water-soluble organic substances with yellowish to brownish colour determine water colour often intersecting with chlorophyll-a absorption features. Their occurrence is mainly controlled by natural process (Brezonik, Menken, & Bauer, 2005), therefore they cannot be used as an indicator for mining activities.	-	+
Turbidity	Turbidity is a main descriptor of water quality and relates to organic as well as inorganic particles in the water. It refers optically to water clarity. Increased soil erosion as well as overburden material from mining sites could lead to higher turbidity values (Moore, 1980).	+	+
Total Suspended Solids (TSS)	Particles floating in the water contribute to this indicator that gives a measure for fluvial transportation of mostly an-organic material. Closely related to turbidity and water clarity and therefore spectrally assessable (Oxford, 1976).	+	+
pH	The pH value is an important chemical property of water bodies controlling biological activity and chemical processes. It is controlled mainly by the underlying geology, plant growth but also by chemical wastewater draining e.g. from mining sites. Changes in pH could indicate the presence of mercury used for gold mining. The pH value is not spectrally measurable (Simeonov et al., 2003)	+	-
Dissolved Oxygen	Availability of dissolved oxygen is vital to aquatic ecosystems. Algae blooms could significantly reduce oxygen levels causing the collapse of whole ecosystems. It cannot be assessed spectrally (Simeonov et al., 2003).	-	-
Nutrient Indicators	This term summarizes the occurrence of different chemical species such as phosphorus or nitrogen. Intensive agriculture activity could cause phosphorus levels to raise significantly, thus, favouring the occurrence of algae blooms. Using optical remote sensing, these species cannot be assessed directly (Mattikalli & Richards, 1996)	-	-

Electrical Conductivity	Electrical conductivity varies with the concentration of metal ions in the water column. Increases in conductivity could indicate enhanced metal concentrations e.g. due to mining wastewater. It cannot be assessed spectrally (Simeonov et al., 2003).	+	-

Based on our comprehensive review of available water quality indicators, and followed by a critical analysis of their measures, we have synthesized a useful information that easily see the correlation between water quality, Galamsey and remote sensing (Figure 3).

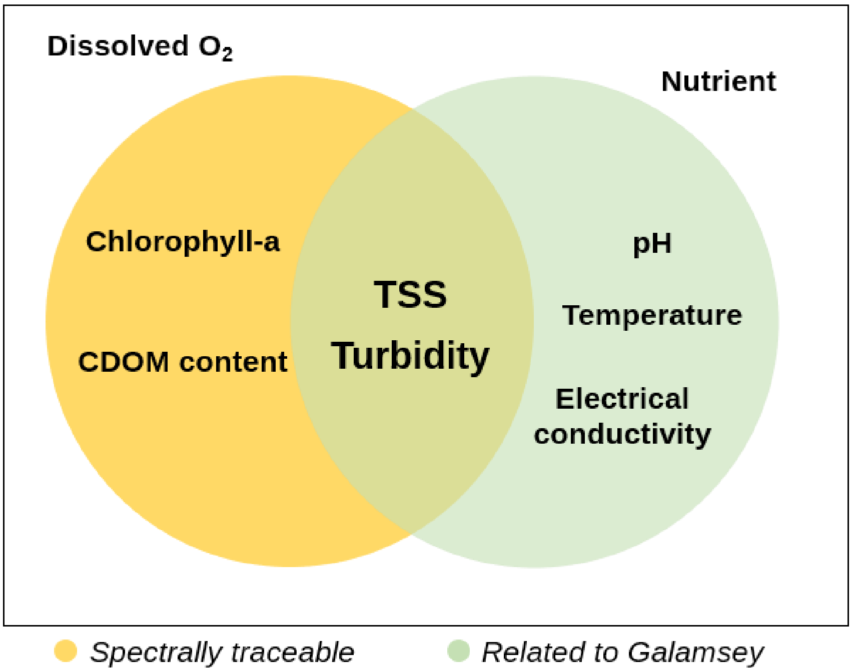

Figure 3: Available water quality indicators with turbidity and total suspended solids (TSS) fulfilling the aspects of being able to be spectrally measured and associated with Galamsey. (Note: CDOM refers to coloured dissolved organic matter).

Space-Borne Remote Sensing of Water Quality

As discussed in the previous section, the use of turbidity and TSS is particularly important in remote sensing of water quality. While changes in both measures may be natural (e.g. due to increased sediment input during rainy season), studies on (illegal) mining with structures similar to Galamsey in the Brazilian Amazon have shown that fluctuations in turbidity correlate significantly with the extent of mining activity (Lobo, Costa, & Novo, 2015).

As denoted previously, turbidity and TSS exhibit a strong relationship with the physical properties of water bodies and their spectral characteristics. Both measures are functions of the sediment type that is expressed by grain size and form (Doxaran, Froidefond, and

Castaing, 2003). Therefore, most approaches to retrieve turbidity and TSS from remotely sensed imagery must be calibrated to meet local conditions that might be highly varied by space and time. This prerequisite is supported by several scientific studies aiming to develop and calibrate statistical models for water quality retrieval at regional scale (e.g. Carpenter and Carpenter, 1983; Dekker, Vos, and Peters, 2001; Potes, Costa, and Salgado, 2012). Algorithms calibrated for estuarine and coastal water bodies lower the transferability to other geographic regions and inland water bodies (reviewed in Dogliotti et al., 2015; Chen, Muller-Karger, and Hu, 2007; Brando and Dekker, 2003). This is a crucial aspect, as developing countries are clearly underrepresented in such remote sensing-based studies and, therefore, virtually no empirically based algorithms for turbidity and TSS retrieval are available for Ghana.

To manage the issue of transferability, numerical and physically based approaches are assumed to provide a higher degree of transferability compared to statistical algorithms and less dependency on in-situ samples that are often not available especially in developing countries and remote areas. Whilst numerical (Pozdnyakov et al., 1998) and physically based models (Odermatt et al. 2008) provide promising opportunities for time- and space-independent water quality retrieval, these algorithms are mostly subject to restricted intellectual property rights and commercial license agreements making the usage more cost-expensive and restrictive.

Despite the challenges of (i) non-available remote sensing-based studies, (ii) non-existent algorithm, and (iii) issue of transferability, we managed to generate a map using multi-year (2013-2019) Landsat-8 satellite observations on Google Earth Engine by applying a regression formula developed by Liu & Wang (2019) for lakes in Vietnam. When we analysed sample data showing turbidity in the western part of Lake Volta, Ghana, we identified visible prospects and caveats of the remotely sensed data. The map in Figure 4 shows the standard deviation of turbidity values over the time-period in relative units. Especially high values can be observed in the westernmost part of the area (Figure 4b). Because it is necessary to distinguish an anthropogenic signal, such as increased sediment input due to gold mining, from natural noise; we are not able to determine whether the variability in the western region is increased due to mining activity, or whether increased sediment input occurred due to natural fluvial input. Also, the spatial detail available from the remotely sensed data only covers larger water bodies due to the necessary water masking. Consequently, smaller ponds and rivers that are important for the supply of the local population especially in rural areas are omitted. Due to the lack of local calibration of the model, we are cautious to make any statement on the interpretation of the results, especially since the natural variability of the turbidity is not known. However, these shortcomings could be overcome if we have access to commercial license algorithms.

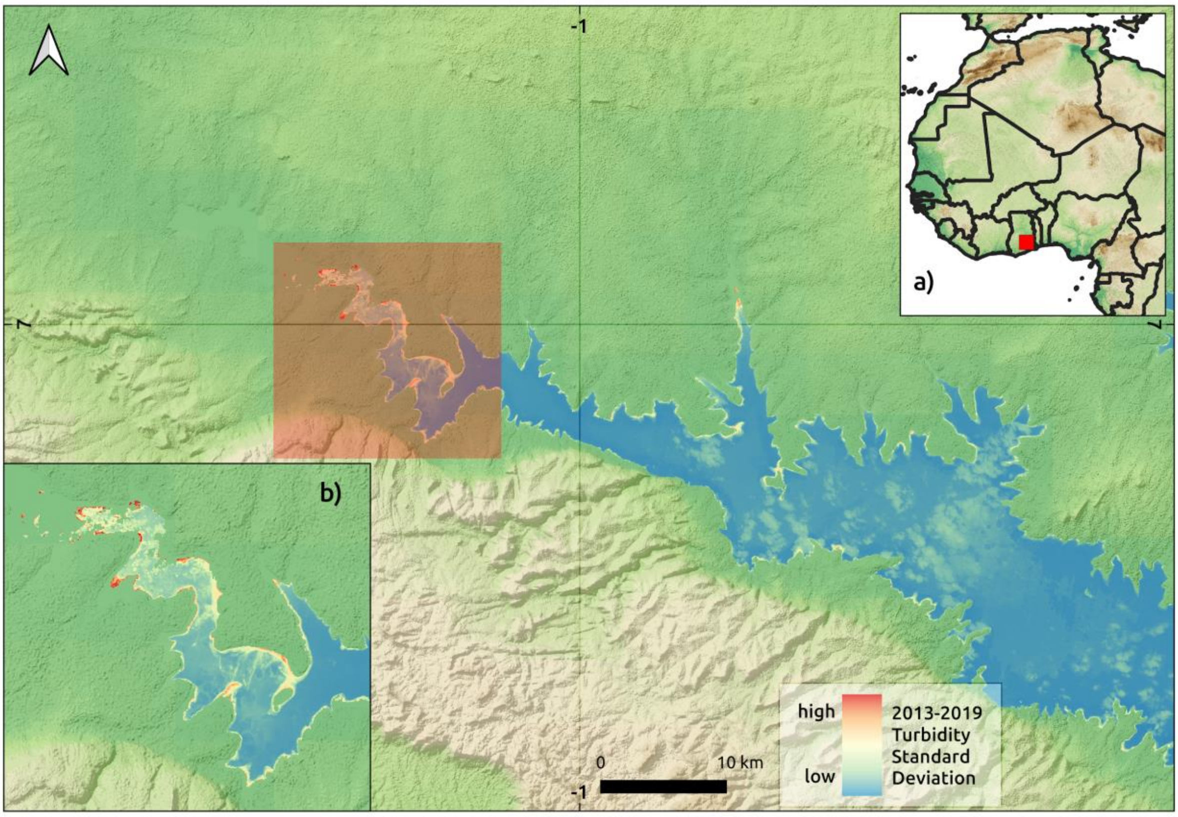

Figure 4: Map showing standard deviation of multi-year turbidity (2013–2019) derived from optical Landsat-8 imagery using Google Earth Engine and a regression approach developed by Liu & Wang (2019) for the western part of Lake Volta, Ghana.

a) Overview of the study area (marked with a red square) in relation to the coast of the Gulf of Guinea located south of Lake Volta.

b) Westernmost part of the lake area where turbidity standard deviation values are high. Limited information can be gathered for the assessment of Galamsey because interpretation of the results is hampered by the absence of calibration and validation data. Nevertheless, this shows that a regional algorithm to retrieve turbidity from remotely sensed data has the potential practical advantage of helping to provide integrated view on the phenomenon.

Identified Policy Requirements

At the rate of environmental deterioration and the level of pollution and damage caused to major freshwater sources in Ghana, special measures ought to be taken in all sectors to help resolve and mitigate the negative results from Galamsey activities. In tackling any further contamination of fresh water sources (surface and underground water source) and tracking the areas of possible contamination and the presence of unauthorized mining activities, remote sensing imagery is considered a key mechanism to help in this fight.

For the above to work effectively, policies and institutions have to be set up to help regulate, protect, enhance, enforce and promote the usage of space technology in helping resolve water management issues as a result of Galamsey and to subsequently help streamline these practices till they are completely eliminated as an environmental and social nightmare for the country. It has to be placed on record that the destructive outcome of Galamsey activities on water sources does not entirely reflect the outcome of formalized ASM in an economy. This is because, once it is well formalized with a good implementation of policies, ASM can help create more jobs at the local level and provide more capital for the economy through taxation.

In addressing the policy gap in the protection of water bodies and curbing Galamsey as well as regulating legally recognized ASM operations, an outline of Ghana's water and mining policies is discussed below. Despite the existence of the Ghana Water Company Limited (GWLC, 2019) in charge of water processing and distribution of processed safe drinking water across the country (mostly in urban regions) since in July 1999, the most recent Ghana Water Policy was introduced in 2007 (GoG, 1999). The policy laid out the key areas of focus in the access of water and its management; it further looked at ways for the improvement of community (rural) water and sanitation. But this policy failed to address possible challenges related to mining activities, protection of water bodies and the solution mechanisms to use in such case.

Additionally, in 1994, the Environmental Protection Agency (EPA) of Ghana was established by the government and among its many mandates, it was tasked "to prescribe standards and guidelines relating to the pollution of air, water, land and any other forms of environmental pollution including the discharge of waste and the control of toxic substances" (GoG, 1994). But the limitation of the agency fell on the powers that it was given by the act which states that "investigate complaints of injury to human beings and animals or damage to land and pollution of water bodies resulting from the use of pesticides." (EPA, 2019). Thus, the agency works mainly in regard to pollution by pesticides and there was no indication of coverage in the mandate to cover investigation in regard to harmful effects from other chemical substances on the environment specifically on water sources and land. It is rather interesting to note that EPA under the same Environmental Protection Agency Act of 1994 Act 490 and the Ghana Environmental Assessment Regulations 1999, LI 1652, "requires that undertakings likely to have significant impacts on the environment must register with the EPA and obtain environmental permits before commencement of construction and operations" (EPA, 2019). And the process of registration and obtaining environmental permits from the EPA includes the screening of operational sites as well as submitted documents confirming Site Plan duly signed by a Licensed Surveyor, Block Plan, Evidence of Neighbourhood Consultation, and a Lease Agreement by a Technical Review Committee. But then again why does Galamsey and ASM activities seems to have unchecked negative environmental impacts on water sources and land? This brings us to look at the mining policies of Ghana that provides the legal basis for mining and ASM to operate.

The mining sector of Ghana was solely controlled by the government from 1965 and 1980 through the nationalisation of minerals resources (Ofori, 2015) but this was reformed and opened for private investment as a result of conditions attached to the implementation of the IMF Structural Adjustment Program in Ghana during the 1980s. In the wake of restructuring and formalization the mining sector including the ASM segment, the then Provisional National Defence Council (PNDC) military government introduced the Mineral and Mining Law 1986, PNDC Law 153 as the main legislation on Ghana's mining sector from 1986 till 2006 (Ofori, 2015); and also introduced the PNDC Law 218, the Small Scale Gold Mining Law in 1989 (PNDC, 1989).

In 2006, under the New Patriotic Party (NPP) new legislation was enacted that dubbed the "Minerals and Mining Act", 703 of 2006 which became "Ghana's Mineral and Mining Act" in which the sector was formally classified into two different mining operations namely large scale and small-scale mining (Ofori, 2015). Four commissions were established under this legislation namely the Minerals Commission (with the main focus on regulating and managing the development of mineral resources of Ghana); Inspectorate Division (focused on enforcing the mining regulations and its amendments which ensures health and safety in mining operations); Forestry Commission (focused on regulating the usage of forest and wild resources, as well as conserving and managing those resource) ; and Water Resources Commission (focused on the management and regulation of water resources and the coordination of any policy related to them) (Ofori, 2015). The 2006 Minerals and Mining Act took the weight of setting out policies that protect the land and water bodies from harmful mining activities that will jeopardize their security thereof – thus covering the loopholes found in the Environmental Protection Agency Act of 1994.

Despite the great length put in place by the government of Ghana in curbing any illegal acts and its correlating effects, we saw the opposite happening whereby Galamsey became a bane to the environmental protection efforts put in place in the wake of climate change. This then called for new legislation that will enforce strict regulations in the ASM sector and thus curb Galamsey operations in the country. In January 2017, as the water and land degradation worsened due to Galamsey and generated huge media and public outrage, the NPP government imposed a ban on ASM activities in the country which lasted almost two years (Oxford Business Group, 2018). During the ban period in the same year, the government established the Inter-Ministerial Committee on Illegal Mining (IMCIM) to help curb the illegal mining activities in the country and the committee released a guidebook in August 2018 titled "Road Map for Lifting of Ban on Artisanal & Small-Scale Mining And The Way Forward". This guidebook paved the way for the ban to be lifted by the government in 2018 (GoG, 2018). The guidebook helps to regulate and formalise the ASM sector properly and help ensure that environmental protection and human rights protections are adhered to by the operators who will be provided a legal permit. This new system also ensures that aspiring ASM operators get clearance from EPA, Water Resources Commission and must other set criteria that are in-line with the Small-Scale Gold Mining Law of 1989.

Despite these efforts being put in place, it was revealed in a recent investigative report that some key workers under this new directive help to curb Galamsey and its accompanying menace by engaging in corrupt practices with some aspiring ASM license applicants to circumvent the legal procedure that ensures checks and balance in the sector (Anas, 2019).

Finally, it is important to assess the countries' and government's readiness to work hand-in-hand with scientists to help track and make use of water portals that have been contaminated or are in the process of being contaminated to help curb the correlating effects that ensue as a result of Galamsey activities.

As of 7th July 2017, a team of three Ghanaian engineering students with the aid of the International Space Station, launched Ghana's first satellite, named GhanaSat-1 into space to undertake coastal mapping of the country for academic and coastal security purposes (MIoG, 2017). This also served as a test mission for the team, because plans are far underway to send the second satellite named GhanaSat-2 into orbit, which soon will be purposed to help in the "Monitoring of Illegal Mining (Galamsey) activities; Detection of Oil Spillage; Monitoring Forest Fires; and Monitoring Deforestation activities" (MIoG, 2017) .

Not long after, the current president of Ghana launched the Ghana Astronomy Radio Observatory at the country's main Earth satellite location (GoG, 2017). This added to help create the atmosphere needed for further partnership and development of Ghana's aspiring space program.

And in recent time, the Government of Ghana entered an intergovernmental partnership with Kenya, Senegal, Sierra Leone, and Tanzania to create the Africa Regional Data Cube (ARDC) (GPSDD, 2019) which is a tool that joins the latest Earth observation data and satellite technology to help address various issues relating to agriculture, food security, deforestation, urbanization, water access, and many more including the effects of illegal mining activities on the topography of member states – an initiative of the Global Partnership for Sustainable Development Data (GPSDD, 2019). But the issue of logistics and the required human resource for this sector becomes another ground for discussion and deliberation.

In all, the above exposé of the past, and current policies put in place to help curb the negative impact of Galamsey and ASM on water bodies and the environment in general brings to light several key policy pitfalls and loopholes. Possible solutions that are feasible and prime are provided and discussed in the next section.

Discussion

Opportunities and Challenges of Water Quality Assessment based on Remote Sensing

A potential water quality product derived from multi-year optical remotely sensed imagery was presented in Figure 4. The interpretation of displayed values in long-term variability of water turbidity regarding illegal mining activity, however, is hampered by the lack of an appropriately calibrated model adapted to local conditions. Therefore, it is not possible to derive causality chains of cause and effect related to the observed patterns. This highlights two major challenges in the use of remote sensing data: Firstly, detailed in-situ measurements must be available in order to adequately interpret remote sensing data. Secondly, a precise understanding of the anthropogenic and natural processes within a hydrological catchment area and their interference is required to assess the dynamics of sediment transport and water quality and thus detect possible illegal mining activities. Both aspects are explained in the following.

1. Availability of in-situ data for calibration and validation

Remote sensing can potentially provide information on individual aspects of water quality in inland waters. However, for the information obtained to be usable, it must achieve the accuracy and reliability of laboratory measurements currently used as a reference in Ghana (Abeiku Arthur, personal communication). Current attempts reported in the scientific literature (see Results) were found to be not yet enough to allow a sound and reliable assessment of the impact of mining on surface water quality. This aspect concerns the transferability of approaches, the reproducibility of results and the possibility of making statements on uncertainties. For example, physically based models are characterized by a high degree of transferability, but most of the models are not freely accessible. Furthermore, the lack of ARDs severely limits the direct usability of remote sensing products for non-experts (see Table 2).

Therefore, calibration and validation activities are necessary to allow the establishment of a local reference database for the development of parameter derivation workflows. The Ghanaian EPA holds such data, but the data are only accessible on request. Furthermore, an evaluation of the different indicators showed that optical remote sensing can only capture a small part of the multi-dimensional phenomenon of water quality (see Table 3 and Figure 3) and of mining activities. Remote sensing should therefore be an element among others in the assessment of water quality. Although the provision of information for larger areas is an advantage of remote sensing, point-based, accurate in-situ measurements are indispensable to calibrate and validate models.

2. Assessing interference effects

While optical remote sensing approaches of water quality assessment in general lack of widely known restrictions such as cloud coverage, they are considered not applicable under optically shallow water conditions (Karin Schenk, personal communication). Interference effects hamper their usage in Ghana in particular: Since mining areas in Ghana are located in regions that are also inhabited by local communities, and large-scale official mining claims and small-scale illegal mining areas overlap, the breakdown of a signal (e.g. increase in water turbidity) into individual polluters is a challenging issue. Favoured by the humid climate and the lack of effective wastewater treatment in Ghana, wastewater from households, illegal mines and large-scale extraction sites is discharged via tributaries of major watercourses and lakes such as Lake Volta (Figure 4). This aspect is therefore also a direct reference to the postulated theoretical framework (see Figure 1) into which this study is embedded.

Thus, a signal cannot be uniquely assigned to a specific causality. This problem also exists for current monitoring initiatives, which are carried out by larger mining companies using in-situ samples (Abeiku Arthur, personal communication). In order to be able to interpret the collected data, the sample stations are positioned in such a way that entries of local households can be deducted. In order to apply similar approaches with remote sensing methods, a high temporal frequency of image acquisitions seems appropriate. In addition, simultaneous observation of water quality parameters and changes in land surface (i.e. changes in vegetation) can lead to a better understanding of causal relationships.

In addition, space-borne remote sensing data can only be used to derive information for larger surface waters. Smaller water bodies such as ponds and small streams cannot be processed reliably due to their spatial extent or geometry. Sensors with high spatial resolution (sub-meter range) can minimize this problem, if watercourses are not covered by vegetation, for example. Thus, not only space-borne but airborne and near range sensing system (e.g. drones) seem worthwhile to consider in future research to improve the capacities to detect and assess the impacts of illegal mining on surface water quality.

Linking Available Remotely Sensed Data Sources to Policy Requirements

During the analysis of the available literature, shortcomings and limitations of remote sensing of water quality have emerged (see previous section). Some of these limitations are due to technical nature or natural conditions (e.g. high cloud cover in tropical regions) and therefore cannot be influenced. Other limiting factors include the availability and conduct of scientific studies, the availability of algorithms, and the dissemination of information. These can therefore be influenced and are therefore part of our recommendations to decision and policy makers (see next section). The fourth step of the analysis, the integration of the identified policy requirements with remote sensing technologies, is dealt with here:

Firstly, the requirement of tracking areas of possible contamination and identifying the presence of unauthorized mining activities is currently partly addressed by state-of-the art remote sensing approaches. In theory, optical remote sensing allows the extraction of signals indicating illegal mining activity through changes in water turbidity and suspended matter content. However, this requires the calibration and validation data often mentioned. On the other hand - and this is particularly important for the situation in Ghana - the interference phenomena already discussed must be considered. For this, the integration of local expert knowledge seems indispensable in order to guarantee a coherent interpretation of the data. In addition, it is important to note that remote sensing alone cannot cover all aspects of Galamsey: The underlying structures not only cause effects on natural ecosystems such as water bodies but are an expression of complex socio-economic and socio-cultural settings. Thus, to address the outlined governmental efforts on curbing mining, remote sensing is one tool among others.

Secondly, the readiness of local authorities and politicians to collaborate with scientists is considered a crucial asset to strengthen the policies and measures put into place to ban illegal mining activities. The approaches identified towards the establishment of a domestic space programme and cooperation with other African states in the Digital Earth Africa project show the political will to establish appropriate infrastructures that are basically open for everyone. There is also the possibility of international exchange in order to share knowledge and form multilateral cooperation. Therefore, we conclude that current efforts fulfil the policy requirement of collaboration among different actors and scientists. Such initiatives could therefore also contribute to a better understanding of interference effects.

Thirdly, we clearly identified pitfalls and loopholes rendering policy attempts in realm of illegal mining often ineffective. Based on our analysis and interviews with practitioners, we cannot give a definite answer to the question whether the usage of remote sensing could lead to significant improvements regarding this aspect. However, there is the potential to improve governance by using transparent and comprehensible workflows. Baack (2015) argues that the increasing availability of data leads to “datafied publics” in which individuals have the possibility to break the monopoly of state authorities on data and make informed decision based solely on their own interpretation. Thus, in addition to the identified top-down approaches, there is the possibility of bottom-up initiatives from local communities. Successful examples of such open data-driven self-empowerment can be found in different countries and socio-economic settings (Filippi, Fusco, & Nanni, 2013; Hagen, 2011; Panek, 2015

Recommendations and Conclusions

Based on the results and the critical analysis of each component, we strongly recommend the establishment of a **Knowledge Database** for managing remote sensing-based water quality retrieval strategies and in-situ measurements. Further, harmonized data structures and interfaces will facilitate dissemination of information in a standardized manner. Such **Knowledge Database** shall consist of different Earth observation-based tools like geospatial analysis, algorithms and workflows as well as in-situ data for calibrating and validating remote sensing-based retrieval models. The database should give detailed information about the accuracy and uncertainty of data and algorithms. On top of that, it should allow the user to evaluate if the data fits the purpose, and report information about spatio-temporal transferability. To ensure that the data can be easily accessed, shared and processed, we also recommend the usage of standardized web-interfaces and harmonized data models.

Examples for these harmonized interform and data model could be one of the following, or a combination of both:

1. **The INSPIRE directive by the European Commission (Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007)**
   INSPIRE establishes a harmonized infrastructure of spatial information in the European Union (see https://inspire.ec.europa.eu/). The proposed Knowledge Database could take data models and harmonisation approaches from INSPIRE and leverage information in an INSPIRE-compliant way.
2. **The SHERLOC directive by The United Nations Office on Drugs and Crime (UNODC) (https://sherloc.unodc.org/cld/v3/sherloc/)**
   SHERLOC facilitates the dissemination of information related to transnational organized crime. By using SHERLOC as an example, the proposed database could foster international collaboration between scientists, shareholders and local authorities. Thus, also non-scientific actors shall be enabled to find the most appropriate data, tools and workflows for their problems and questions.

Regarding the content of the **Knowledge Database**, we recommend the use of the following services and platforms:

- The Calibration-Validation (CalVal) platform established by the Committee on Earth Observation Satellites (CEOS) to allow for calibrating and validating remote sensing-based water quality retrieval strategies (see http://calvalportal.ceos.org/)
- The UNESCO World Water Quality Portal as an example on how to share and access water quality related data from space with different user groups via web-interfaces and portrayal services (see http://www.worldwaterquality.org/)
- Efforts such as Digital Earth Africa (https://www.digitalearthafrica.org/) as an example on how to provide large amounts of earth observation (EO) data via standardized interfaces using the latest data warehousing and cloud technology.

In all, the various benefits and usage of satellite and remote sensing imagery has been discussed at length in this paper concerning water quality and mining. This topic is a classic example of the importance of science and governance working together in achieving a common goal - the science revealed the hidden truth and the options of various possible solutions to the issue of water management which gives a clear guidance for the governance aspect to provide the medium and space for which the solutions and findings derived from the analysis of the issues can be explored and implemented. Water has been the source of life since the formation of the earth and it has been the resource that has helped maintain the existence of living organisms on our planet all these while. As important a commodity that it is, water as a natural resource should not be left unguarded. It should be the priority and concern of all government. A conscious effort has to be made by all stakeholders in pushing for a world where fresh water sources are protected from pollution and harmful human activities that endangers its existence and preservation.

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