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Modeling of Water Availability for Food System Transformation in Upper Offin Sub-basin and Mankran Micro-Watershed of Ghana: Scenarios Analysis

A Research Report

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TERMS AND ACRONYMS

CHIRPS	Climate Hazard Group Infrared Precipitation with Station
CN	Curve Number
DEM	Digital Elevation Model
ECMWF	European Centre for Medium-Range Weather Forecasts
ESA	European Space Agency
ET	Evapotranspiration
FAO	Food and Agricultural Organization
GWQ	Groundwater flow
HA	Hectares
HRU	Hydrologic Response Unit
IWMI	International Water Management Institute
mm	Millimeters
PERC	Percolation
Q	Streamflow
SSF	Sub-Surface Flow
SW	Soil Water
SWAT	Soil and Water Assessment Tool
SYLD	Sediment yield
t/ha	Tons Per Hectare
WYLD	Water yield

SUMMARY

Agriculture remains the primary livelihood in Ghana, marked by a growing emphasis on cocoa production nationwide. Existing research highlights the importance of supplementing rainfed cocoa production with irrigation. Simultaneously, mining has emerged as a key driver of the country's economic growth. However, there is an urgent need to assess the measurable impacts of cocoa production with supplemental irrigation and mining on water resources sustainability and quality. This study aims to investigate how the supplementary irrigation of coca and mining affects the water balance components and water quality, with a focus on sediment yield in Ghana. It builds upon a baseline study in the Upper Offin sub-basin and an upland watershed of the Mankran micro-watershed using the Soil and Water Assessment Tool (SWAT) model. The analysis indicates that applying supplemental irrigation to 15% of the cocoa area from shallow groundwater would not significantly affect basin water yields. However, the impacts of supplemental irrigation on 5% of the cocoa area from shallow groundwater would significantly affect the groundwater flow in the Upper Offin sub-basin. Conversely, expanding supplemental irrigation to 38% of the cocoa area (with landscape slope less than 8%) and encompassing the entire cocoa area in the Mankran micro-watershed significantly influences hydrology. In the Mankran micro-watershed, supplemental irrigation to all cocoa farms increased evapotranspiration, percolation, and sub-surface flow by up to 9%, 28%, and 21.5%, respectively. In contrast, catchment water yield has been decreased by 19% and groundwater flow ceased due to supplemental irrigation. On the other hand, mining in the Upper Offin watershed (covering 5% of the area) and the Mankran micro-watershed (covering 6% of the area) significantly impacted hydrology and sediment yield. Surface runoff, catchment water yield, and sediment yield increased, respectively by 28%, 7%, and 80% for the Upper Offin watershed. Similarly, the Mankran micro-watershed showed a significant increase in surface runoff, water yield, and sediment yield by 34%, 8%, and 147% due to mining. Percolation and groundwater flow significantly decreased in both the Upper Offin and Mankran micro-watershed. The findings indicate that expanding mining poses a challenge to cocoa production from shallow groundwater. Mining areas must identify suitable areas to minimiz adverse effects on irrigated cocoa production and implementation land reclamation on mined areas. Further research is required to refine the representation of mining activities in the SWAT model for more accurate results on the location and spatial coverage of mining impacts. The study underscores the necessity of context-specific management strategies, considering both agricultural and mining activities in water resource management plans for long-term environmental health and socio-economic viability.

1. INTRODUCTION

Population growth and climate change pose an immersing challenge to food security in Africa (Giller 2020; Shankar 2018). In Ghana, agriculture stands as a cornerstone of the national economy, encompassing a diverse range of crops and practices. Cocoa cultivation is a vital cash crop and holds a pivotal role in shaping the agricultural landscapes of the country (Nunoo et al. 2015). As a major contributor to the global cocoa market, Ghana is renowned for its high-quality and flavorful cocoa (Voora et al. 2019). Nevertheless, the region's agriculture relies heavily on rainfed systems, which are grappling with the adverse impacts of climate change and variability (Asante et al. 2021; Asante and Amuakwa-Mensah 2014). These challenges manifest as prolonged droughts, erratic rainfall, and rising temperatures (Adaawen et al. 2019; Fagariba et al. 2018), posing a significant threat to agricultural productivity (Sultan and Gaetani 2016), especially for smallholder farmers (Serdeczny et al. 2017).

Over the years, cocoa cultivation in Ghana has experienced a steady and notable expansion, reshaping landscapes and livelihoods (Green 2017). The economic attraction of cocoa has led to consistent growth in cultivation areas. Responding to the global demand for cocoa, Ghanaian farmers have expanded their cocoa farms, sometimes venturing into previously untapped regions (Merem et al. 2020). The production has traditionally relied predominantly on a rainfed system, with limited but slowly growing adoption of irrigation practices (Asante et al. 2022). Smallholder farmers, often the backbone of this sector, relied on age-old techniques passed down through generations (Antwi-Agyei et al. 2018). The story of cocoa production in Ghana unfolds as a narrative of sustainable agriculture and economic significance (Yaro 2013). However, it is important to recognize the vulnerabilities associated with a sole dependency on rainfall, particularly in the face of dynamic climate change. Yamba et al. (2023) identified a clear expansion of Guinea Savannah agroecology more than half of the forest transition belt in Ghana.

In response to these changes, smallholder farmers in cocoa-producing areas of Ghana have taken the initiative to introduce supplemental irrigation for cocoa production (Koide et al. 2021; Tilahun et al. 2023a). While the rainfed system remains the backbone of cocoa production, the integration of supplemental irrigation is a forward-looking approach to ensure productivity and resilience in the face of climate variability and population growth (Asante et al. 2022). Furthermore, government initiatives and other donor support programs have played a role in promoting the expansion of cocoa farms, encouraging farmers to adopt modern farming practices and technologies (Ingram et al. 2018).

In cocoa-producing areas, a significant challenge arises as gold and cocoa compete for land, resulting in cocoa land being converted to mining (Snapir et al. 2017). Gold mining in Ghana is a complex system broadly divided into two groups: large-scale modern surface and underground mining and small-scale mining (artisanal surface mines), also called galamsey. Gold mining is favored due to its potential for quick profit compared to the seasonally poorly paid cocoa activities, contributing to economic growth in the nation. However, it has raised environmental concerns in the region, impacting the hydrology and water quality (Hirons 2014). A transition from rainfed cocoa production to supplemental irrigation is expected to alter the hydrological landscape. Furthermore, the extensive use of chemicals in the mining process, along with fertilizers and chemicals for cocoa production, is exacerbating environmental concerns. Striking a balance between economic development and environmental preservation from cocoa production and mining is not only a national imperative but also a global necessity.

Conducting modeling studies (when there is no observed data) on the impacts of cocoa production with supplemental irrigation is crucial for ensuring sustainable water use, enhancing productivity, and conserving the environment. Similarly, assessing the impacts of mining in terms of hydrological changes and water quality is of paramount importance. Such impact studies on hydrology and water quality are limited at sub-national and watershed scales. The objective of the study is, therefore, to evaluate the hydrological response and water quality impacts resulting from the expansion of cocoa production with supplemental irrigation and mining activities. The study was conducted in the Upper Offin sub-basin and the Mankran micro-watershed, where cocoa cultivation covers about one-third of the watershed size and mining is actively implemented. The output from this study would provide insights for researchers and decision-makers on the pathways to improve water management and sustainable cocoa productivity on a broader scale.

2. MATERIALS AND METHODS

2.1. Study area description

This study took place in the Upper Offin sub-basin and the Mankran micro-watershed in Ghana (Figure 1). The livelihood of the region depends on agriculture, which engages approximately 70% of the households (Asiedu-Darko 2014). Mining also plays a significant role, contributing 40% to the nation's gross foreign exchange, equivalent to 5.7% of its GDP (Mensah et al. 2015). Based on a 30 m Digital Elevation Model (DEM), the elevation of the Upper Offin sub-basin ranges from 157 m to 777 m with a mean elevation of 274 m above sea level (asl). Whereas, the elevation of the Mankran upland watershed ranges from 186 m to 536 m, with a mean elevation of 284.5 m asl. The topography of the two watersheds depicted that most of the landscapes are above 8% slope for both the Upper Offin and Mankran watersheds.

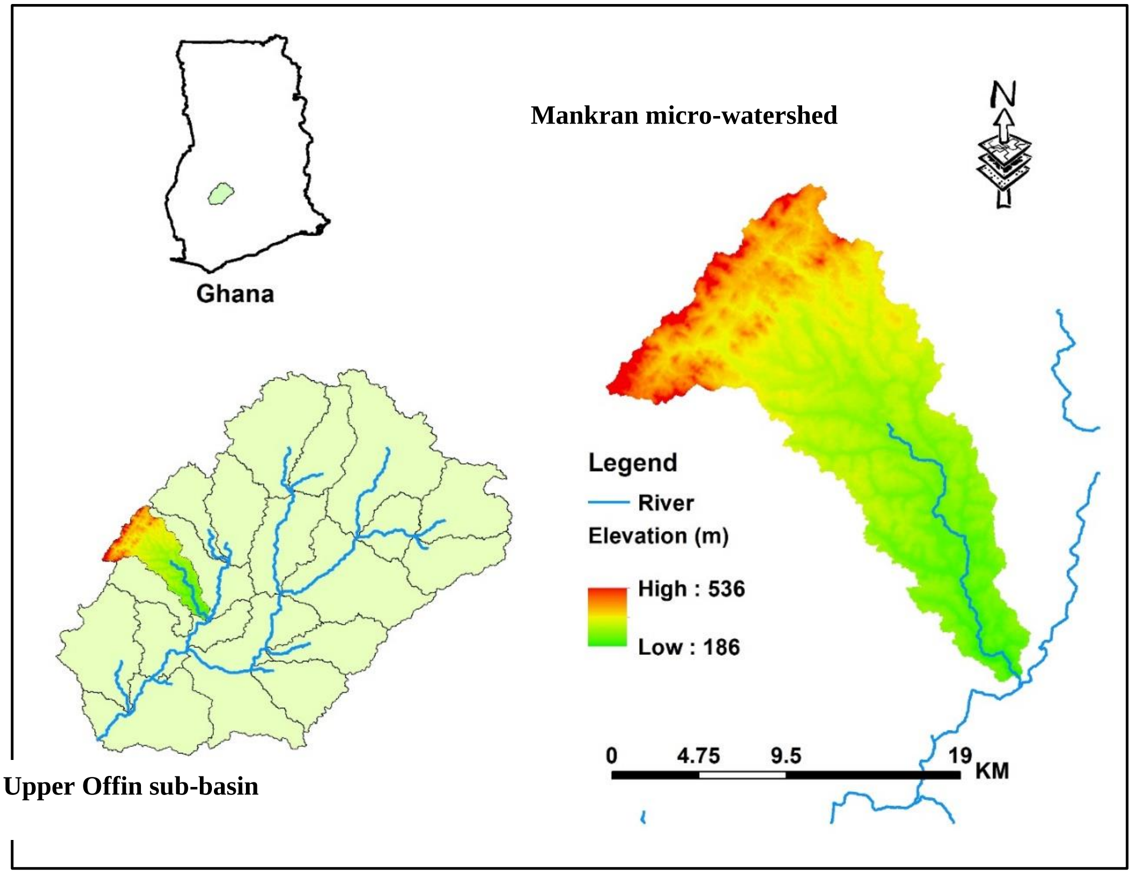


Figure 1. Location of Upper Offin sub-basin and Mankran micro-watershed in Ghana
(Source: Assefa et al. 2023)

The Upper Offin sub-basin spans 3,068.5 km^2, while the Mankran watershed covers an area of 127 km^2. Based on Climate Hazard Group Infrared Precipitation with Station (CHIRPS) rainfall data (Funk et al. 2015), the mean annual rainfall ranges from 1,019 mm to 1,751 mm. Whereas, the maximum and minimum daily temperatures for the watersheds range from 23 ^{O}C to 39 ^{O}C and 13 ^{O}C to 27 ^{O}C, respectively, using temperature data from the European Centre for Medium-Range Weather Forecasts (ECMWF) of Atmospheric Reanalysis for Global Climate (ERA5).

Based on the European Space Agency's (ESA) land cover classification for 2020 (Zanaga et al. 2022), the dominant land use in the Upper Offin sub-basin is forest (66%), followed by shrub (15.8%), and grassland (8.2%). Similarly, the dominant land use for the Mankran watershed is forest (74.8%), followed by shrubs (15%) and grassland (5.6%). According to the Food and

Agricultural Organization (FAO) soil classification (Sanchez et al. 2009), orthic Acrisols are the dominant soils in both watersheds (94% and 99.5% of the Upper Ofin and Mankran watersheds, respectively). Orthic Acrisols are moderately well drained with sandy clay loam texture and are categorized under hydrologic soil group class C.

2.2. Methodology for scenario modeling

This study builds upon prior baseline research focused on hydrological modeling and characterization of the same study areas (Assefa et al. 2023). The Soil and Water Assessment Tool (SWAT) previously calibrated and validated in the baseline study is employed here with additional scenarios (Figure 2). The study includes three supplementary irrigation scenarios covering 5% 10%, and 15% of the cocoa area. In addition, the study assesses the impact of mining, considering 5% of the Upper Offin sub-basin as a mining area (Snapir et al. 2017). The transitions from rainfed cocoa production to supplementary-irrigated cocoa production and mining are separately evaluated for their impacts on the hydrology and stream water quality (using sediment load) of the Upper Offin sub-basin and Mankran micro-watershed.

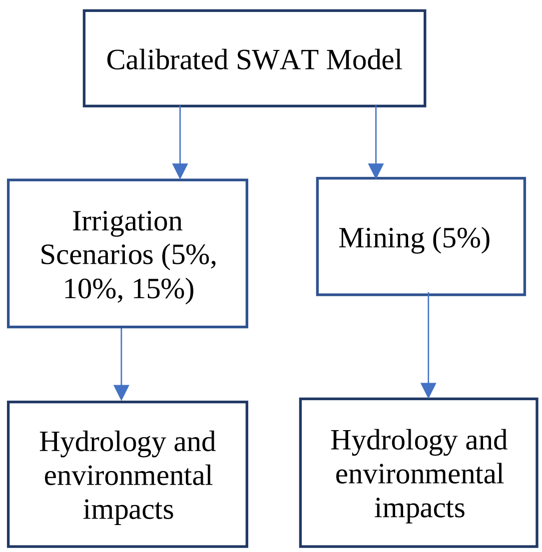


Figure 2. Methodology to evaluate the impacts of cocoa irrigation and mining on the hydrology and environmental impacts of the Upper Offin sub-basin and Mankran micro-watershed using the calibrated SWAT model
Source: Adopted from Assefa et al. (2023).

2.3. Impacts of irrigation on water balance and sediment yield

The cocoa farmland from Abu et al. (2021) with a 10 m resolution was used as input to locate the areas. To configure the SWAT model for supplemental irrigation, the inclusion of cocoa farm management details is crucial. Information on tillage practices, fertilizer and pesticide applications, planting density, and other relevant factors for cocoa cultivation was obtained through surveys conducted with a total of 16 farmers in the cocoa-producing area. This survey, conducted by the International Water Management Institute (IWMI) for other research needs, captured essential data on the type, amount, and timing of agricultural practices.

The average values from the collected data were incorporated into the SWAT management file. For the implementation of supplementary irrigation scenarios, cocoa Hydrologic Response Units (HRUs) with landscape slopes of less than 8% were specifically chosen around the outlet of the Upper Offin sub-basin and in the Mankran micro-watersheds (Figure 3A). Different supplemental irrigation coverages of 5%, 10%, and 15% of the cocoa area were considered for the irrigation scenarios.

In the case of a 5% cocoa area under irrigation, the total irrigated area would encompass approximately 4,800 hectares (ha). Similarly, for 10% and 15% coverage, the irrigated areas would extend to about 9,900 ha and 14,500 ha, respectively. The Mankran micro-watershed (sub-basin) was also designated as a target area, testing both 38% and 100% cocoa cover areas under supplemental irrigation.

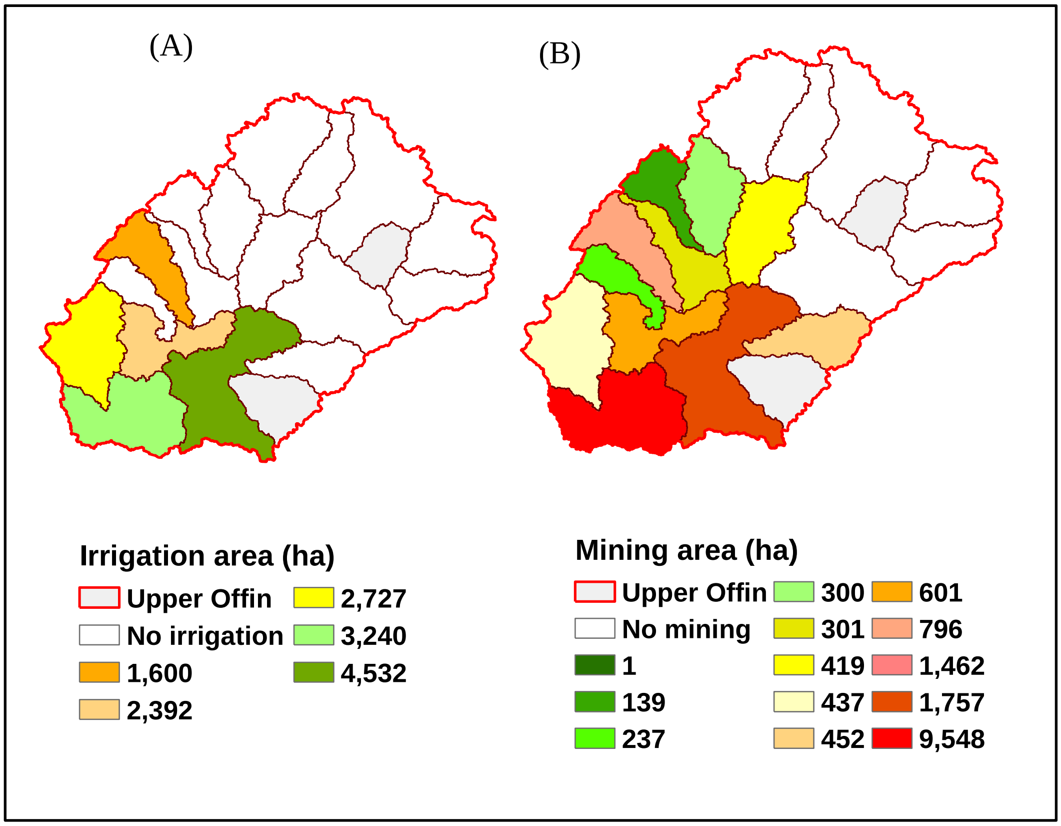


Figure 3. Locations of sub-basin area in Upper Offin. Supplemental irrigation (A) and mining (B) were considered. Supplemental irrigation accounts for 15% of the cocoa area and mining covers 5% of the Upper Offin sub-basin. The coloring only shows the sub-basin of SWAT where the HRU was modified. **(Source: Authors construct)**

Concerning supplemental irrigation amount, the study focused on the dry months of November, December, January, February, and March, assigning irrigation water application amounts for each month as 97 mm, 126 mm, 130 mm, 105 mm, and 68 mm, respectively, sourced from a shallow aquifer (Tilahun et al. 2023b). During the setup of the SWAT model, we implemented a weekly irrigation frequency by dividing the monthly amounts into four, resulting in single water applications ranging from 17 mm in March to 32.5 mm in January with 60% irrigation efficiency based on the Sekyi-Annan et al. (2018) estimates.

Furthermore, farm management practices, including planting, fertilizer applications, and pesticide application, were integrated into the Hydrologic Response Unit (HRU) management. Cocoa planting commenced in the last week of May 2001, with annual harvesting scheduled for the last week of December, beginning in 2006, five years after planting. A new fertilizer entry was established in the SWAT database, featuring a 30% mineral phosphorus fraction, and applied at a rate of 375 kg/ha during mid-April. Similarly, Bifenthrin pesticide was applied at a rate of 0.5 l/ha three times a year, specifically in April, July, and October.

The impacts of cocoa production with supplemental irrigation, along with its associated farm management practices on water balance components and sediment yield were assessed in comparison to the baseline condition. A one-tailed paired 't' test was conducted to evaluate the significance of changes (5% significance level) in hydrological and environmental variables due to supplemental irrigation with the baseline scenarios. This comprehensive evaluation encompassed water balance components such as evapotranspiration, catchment water yield, surface runoff, percolation, groundwater flow, sub-surface flow, and sediment yield.

2.4. Impacts of mining on hydrology and the environment

To incorporate mining into the SWAT model, a series of procedures were implemented. Initially, it was assumed that 5% of the Upper Offin sub-basin is presently designated for mining operations, drawing from the findings of Snapir et al. (2017). Next, Hydrologic Response Units (HRUs) were identified with relatively flat slopes within each sub-basin to represent mining areas, primarily around river outlets (Figure 3B). All HRUs were selected with a 2% landscape slope from each sub-basin, particularly those close to the river, and some HRUs with slopes ranging from 2% to 8% near the outlets of the Upper Offin and Mankran watersheds.

Subsequently, deep tillage (sub-soiler-bedder Hip-rip tillage) was applied monthly to the chosen HRUs, following the frequency of tillage recommended by Kessey and Arko (2013). As the third step, the land uses and covers of the selected HRUs were converted to bare areas. In the fourth step, the Curve Number (CN2) values, calibrated during model calibration, were adjusted for each selected mining HRU, accounting for the mineral extraction site and local soil conditions, as detailed in Gilewski and Węglarz (2018). Mining was assigned to various land covers, such as forest, grassland, shrubland, and cocoa, depending on the landscape slope.

Subsequently, the calibrated and validated SWAT model underwent simulations to evaluate the impacts of mining on water balance components and sediment yield. A one-tailed paired 't' test was conducted to evaluate the significance of changes (5% significance level) in hydrological and environmental variables due to mining activities. Key water balance components under consideration included evapotranspiration, catchment water yield, surface runoff, percolation, groundwater flow, sub-surface flow, and sediment yield.

3. RESULTS AND DISCUSSION

3.1. Impacts of cocoa farm irrigation on water balance and sediment yield

In the baseline study, evapotranspiration accounts for 72% and 74% of the rainfall for the Upper Offin and Mankran watersheds, respectively (Assefa et al. 2023). The result presented in Tabe 1 indicates that, with an expansion in cocoa supplementary irrigation coverage in Upper Offin, there was an increase in evapotranspiration (ET), percolation (PERC), sub-surface flow (SSF), and soil water (SW), whereas groundwater flow (GWQ) and water yield (WYLD) decreased compared to the baseline. The reduction in groundwater flow was statistically significant ($p<0.05$) for supplemental irrigation applied from shallow aquifers to 5% of the cocoa area. Whereas, the reduction in catchment water yield was not significant for supplemental irrigation applied up to 15% of the cocoa area. On the other hand, streamflow (Q) and sediment yield (SYLD) remained constant, regardless of the coverage of supplementary irrigated cocoa areas expanding to 15% of the watershed area.

Table 1. Cocoa irrigation scenarios for Upper Offin sub-basin

Hydrologic variables	Baseline (no irrigation applied)	Irrigation applied (5% of cocoa area)	Irrigation applied (10% of cocoa area)	Irrigation applied (15% of cocoa area)
ET	957.0	961.7	965.5	968.8
PERC	284.6	289.7	294.4	298.5
Q	64.2	64.2	64.2	64.2
GWQ	78.9	74.5	71.1	67.1
WYLD	183.5	181.5	178.5	174.8
SSF	40.4	41.4	41.7	41.9
SW	78.5	78.7	79.0	79.2
SYLD	0.69	0.69	0.69	0.69

Note: ET, PERC, Q, GWQ, WYLD, SSF, SW, and SYLD refer to evapotranspiration, percolation, surface runoff, groundwater flow, water yield, sub-surface flow, soil water, and sediment yield, respectively. All units are in mm except for SYLD, which is in t/ha.

However, notable hydrological changes were observed, as shown in Table 2, particularly at the sub-basin level where irrigation was applied (Figure 3). For this analysis, the Mankran SWAT sub-basin was chosen, considering the same monthly water application amounts. The cocoa plantation covers approximately 33% of the land in the Mankran SWAT sub-basin. The impacts of cocoa farm supplementary irrigation scenarios on water balance components were evaluated for the case where irrigation was limited to cocoa areas with a landscape slope less than 8%, covering about 38% of the cocoa area (Figure 4A), and another where irrigation was applied to all cocoa farms (Figure 4B). These scenarios were compared with the baseline, which involved no irrigation of cocoa farms (Figure 4C).

Table 2. Cocoa irrigation scenarios for the Mankran micro-watershed

Hydrologic variables	Baseline (no irrigation applied)	Irrigation applied (38% of cocoa area)	Irrigation applied (all cocoa area)
ET	986.9	1019.7	1074.0
PERC	255.1	279.2	325.5
Q	59.0	65.6	65.9
GWQ	42.9	29.1	0
WYLD	145.6	133.7	118.9
SSF	43.6	45.5	53.0
SW	81.4	83.3	85.7
SYLD	0.37	0.37	0.37

Note: ET, PERC, Q, GWQ, WYLD, SSF, SW, and SYLD refer to evapotranspiration, percolation, surface runoff, groundwater flow, water yield, sub-surface flow, soil water, and sediment yield, respectively. All units are given in mm except for SYLD, which is given in t/ha.

The findings in Table 2 indicate notable changes in ET, PERC, and SW under irrigation scenarios. Specifically, irrigating cocoa farms with landscape slopes below 8% led to a 3.3%, 9.5%, and 3.4% increase in ET, PERC, and SSF of the watershed, respectively, compared to the baseline (Figure 4A and Figure 4C). Conversely, irrigating the entire cocoa farm resulted in an 8.8%, 27.6%, and 21.5% increase to ET, PERC, and SSF of the watershed, respectively, compared to the baseline (Figure 4B and Figure 4C). It's worth noting that the impact on catchment soil moisture from irrigation was minimal, and no observable changes were identified in sediment yield under the irrigation scenarios (Table 2).

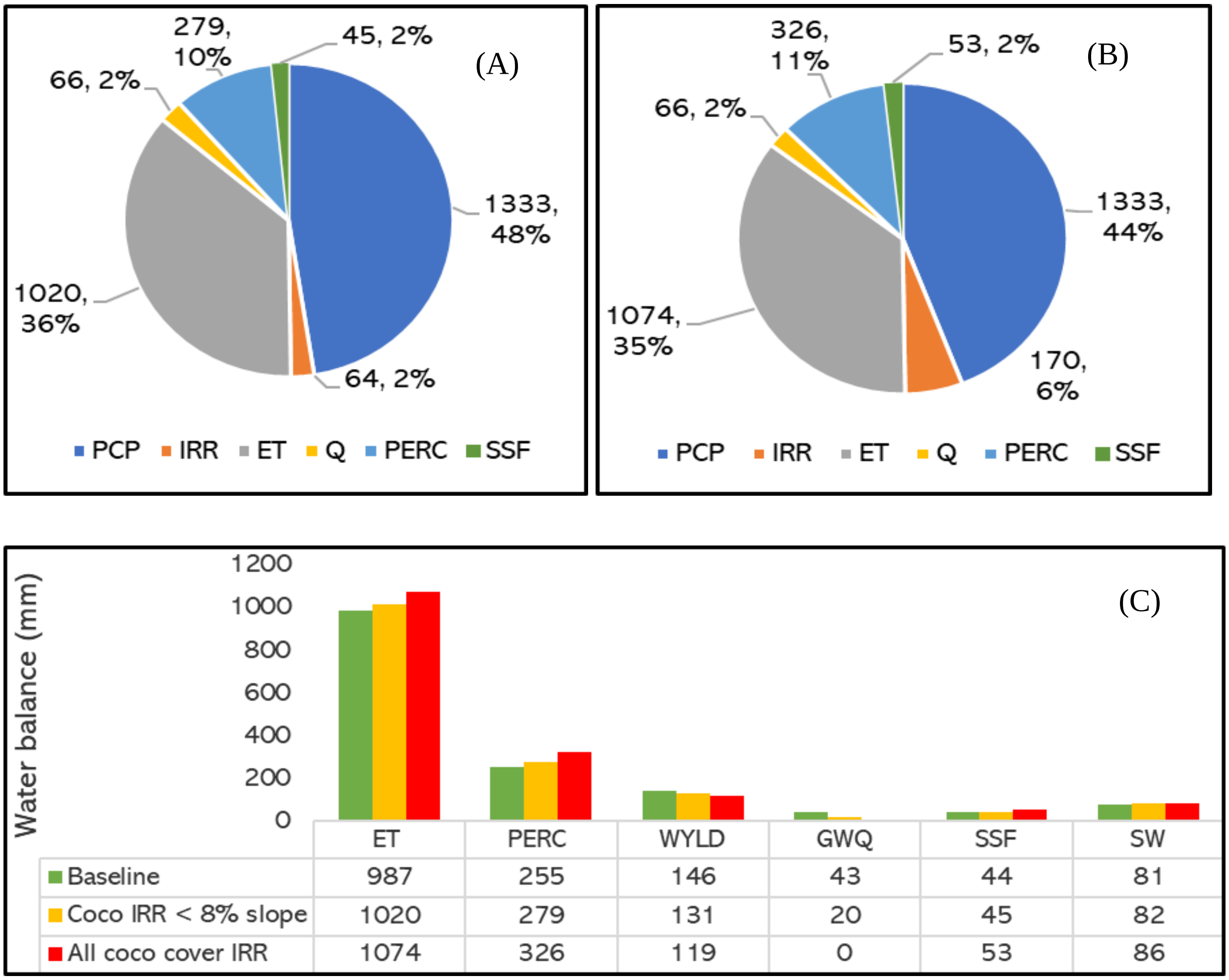


Figure 4. Hydrology of Mankran micro-watershed (A) cocoa irrigation limited to slope less than 8%; (B) irrigation applied to all cocoa land cover; and (C) mean annual water balance components for baseline and irrigation scenarios. PCP, IRR, ET, Q, PERQ, SSF, WYLD, GWQ, and SW refer to precipitation, irrigation, evapotranspiration, surface runoff, percolation, sub-surface flow, water yield, groundwater flow, and soil waters, respectively. **(Source: Authors construct)**

In contrast, irrigating cocoa farms from shallow aquifers diminished catchment groundwater flow significantly, leading to a consequential reduction in water yield. Specifically, cocoa irrigation for landscape slopes below 8% resulted in a 53% decrease in watershed groundwater flow and a 10% reduction in water yield compared to the baseline (Figure 4A and Figure 4C). The reduction in groundwater flow was found statistically significant ($p<0.05$). In the case where the entire cocoa farm was irrigated, watershed groundwater flow decreased significantly from 43 mm to zero, accompanied by a 18.3% decline in water yield (Figure 4B and Figure 4C). The reduction in catchment water yield was also significant ($p<0.05$) in this case. Notably, there were no discernible changes observed catchment soil moisture and sediment yield due to the irrigation practices (Table 2).

The temporal fluctuations in water balance components (ET, PERC, WYLD, and GWQ) were predominantly shaped by the rainfall pattern, identified as the primary driver (Figure 5). Across the period from 2012 to 2018, all water balance components exhibited a decrease corresponding to the declining rainfall. Notably, ET and PERC demonstrated an increase with expanding cocoa irrigation coverage, reflecting a proportional rise in evapotranspiration and percolation. Conversely, water yield and groundwater flow experienced a decrease due to the extraction of water from shallow aquifers for irrigation.

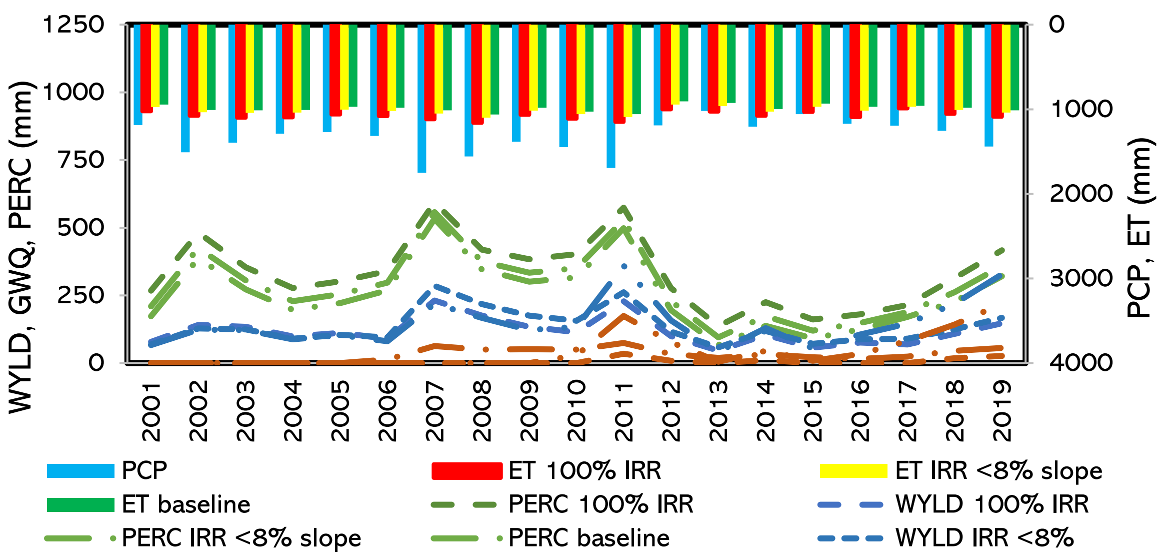


Figure 5. Temporal changes of water balance components in the Mankran sub-basin for baseline and irrigation scenarios
(Source: Authors construct)

3.2. Impacts of mining on water balance components and sediment yield

In the baseline study, sediment yields were found to be 0.69 t/ha per year for the Upper Offin sub-basin and 0.37 t/ha per year for the Mankran micro-watershed (Assefa et al. 2023). The findings from the assessment of mining impacts, as presented in Table 3, indicate notable increases in surface runoff, water yield, and sediment yield within the Upper Offin sub-basin. Mining activities have led to a significant ($p<0.05$) rise of approximately 28%, 7%, and 80% in surface runoff, water yield, and sediment yield, respectively, in comparison to the baseline conditions. Conversely, percolation and groundwater flow experienced significant reductions of approximately 5% each due to mining. Changes in evapotranspiration, soil water, and sub-surface flow, when compared to the baseline, were observed to be minimal.

Table 3. Mining scenarios for the Upper Offin watershed

Hydrologic variables	Baseline (no mining applied)	Mining applied (5% of Upper Offin watershed
ET	957.0	952.6
PERC	284.6	271.2
Q	64.2	81.9
GWQ	78.9	75.2
WYLD	183.5	196.7
SSF	40.4	39.7
SW	78.5	77.9
SYLD	0.69	1.25

Note: ET, PERC, Q, GWQ, WYLD, SSF, SW, and SYLD are evapotranspiration, percolation, surface runoff, groundwater flow, water yield, sub-surface flow, soil water, and sediment yield, respectively. All units are in mm except for SYLD, which is in t/ha.

Similarly, significant hydrological changes were identified, as illustrated in Table 4, when comparing the SWAT sub-basin level (considered Mankran micro-watershed case) to the baseline. Approximately 6% of the Mankran watershed was designated as a mining area based on slope considerations. The outcomes indicate a significant ($p<0.05$) increases in surface runoff, water yield, and sediment yield, with respective increments of 34%, 8%, and 147%. Similarly, mining activities in the Mankran micro-watershed led to an 8% reduction in percolation and an 18% decrease in groundwater flow. Noteworthy, there were no significant alterations observed in evapotranspiration, sub-surface flow, and soil moisture due to mining.

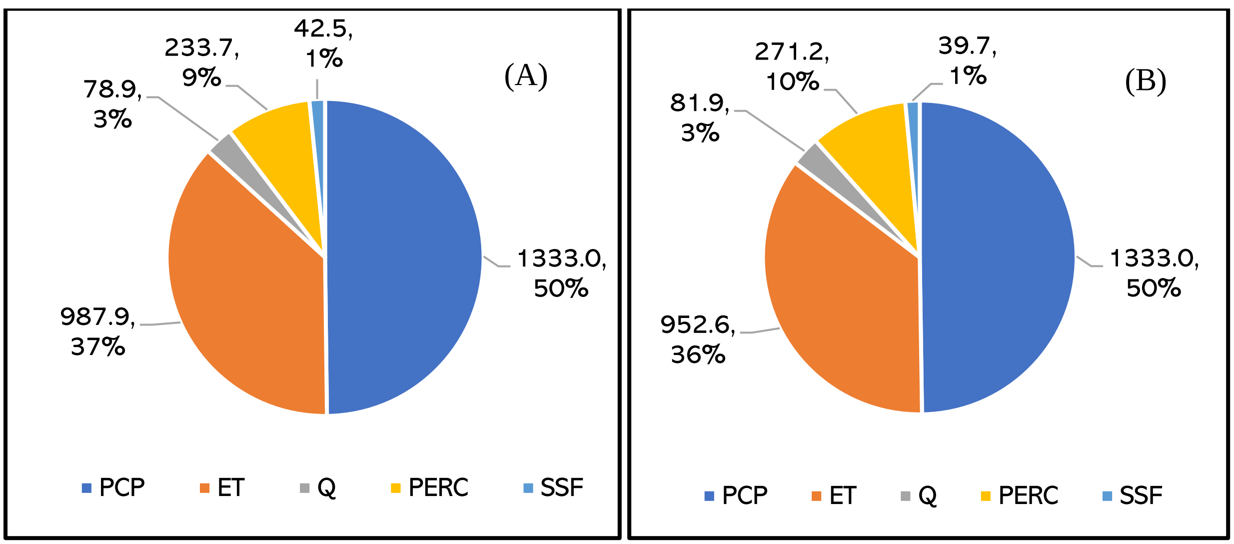
Table 4. Mining scenarios for the Mankran micro-watershed

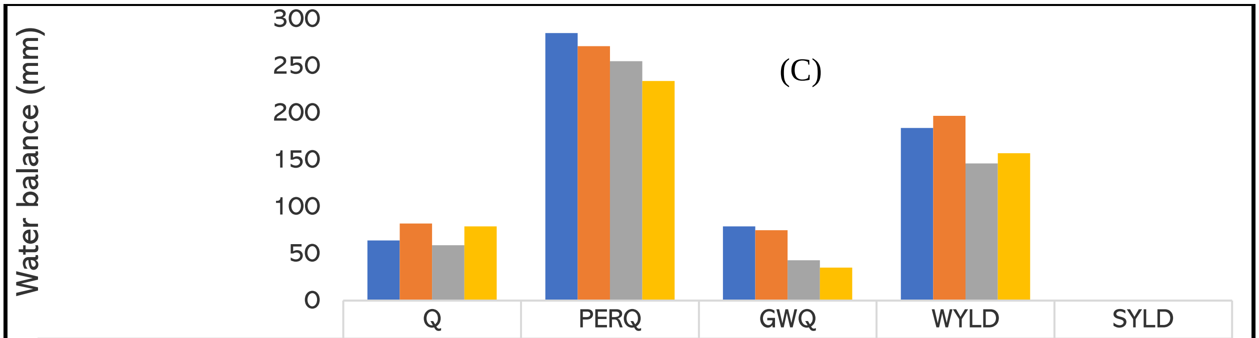
Hydrologic variables	Baseline (no mining applied)	Mining applied (6% of Mankran watershed)
ET	986.9	983.0
PERC	255.1	238.1
Q	59.0	80.0
GWQ	42.9	28.4

Hydrologic variables	Baseline (no mining applied)	Mining applied (6% of Mankran watershed)
WYLD	145.6	151.1
SSF	43.6	42.7
SW	81.4	81.7
SYLD	0.37	0.91

Note: ET, PERC, Q, GWQ, WYLD, SSF, SW, and SYLD are evapotranspiration, percolation, surface runoff, groundwater flow, water yield, sub-surface flow, soil water, and sediment yield, respectively. All units are in mm except for SYLD, which is in t/ha.

The hydrological water balance after the implementation of mining for the Upper Offin watershed and the Mankan micro-watershed are depicted in Figure 6A and Figure 6B, respectively. Changes in hydrological water balance components due to mining for both study areas are illustrated in Figure 6C. A decrease in percolation led to a reduction in groundwater flow and an increase in surface runoff, while catchment water yield exhibited a minimal increase. This was attributed to alterations in catchment characteristics resulting from deep tillage and land cover conversion in the mining area. Similar to the baseline, all hydrological balance components mirrored the rainfall pattern, as shown in Figure 7, depicting the temporal dynamics of the Mankran micro-watershed.





	Q	PERQ	GWQ	WYLD	SYLD
Baseline Upper Offin	64	285	79	184	0.69
Mining Upper Offin(5%)	82	271	75	197	1.25
Baseline Mankran	59	255	43	146	0.37
Mining Mankran(6%)	79	234	35	157	0.91

Figure 6. Hydrological balance components for the Upper Offin watershed (A), the Mankran micro-watershed (B), and changes in some of the water balance components (C) (Source: Authors construct)

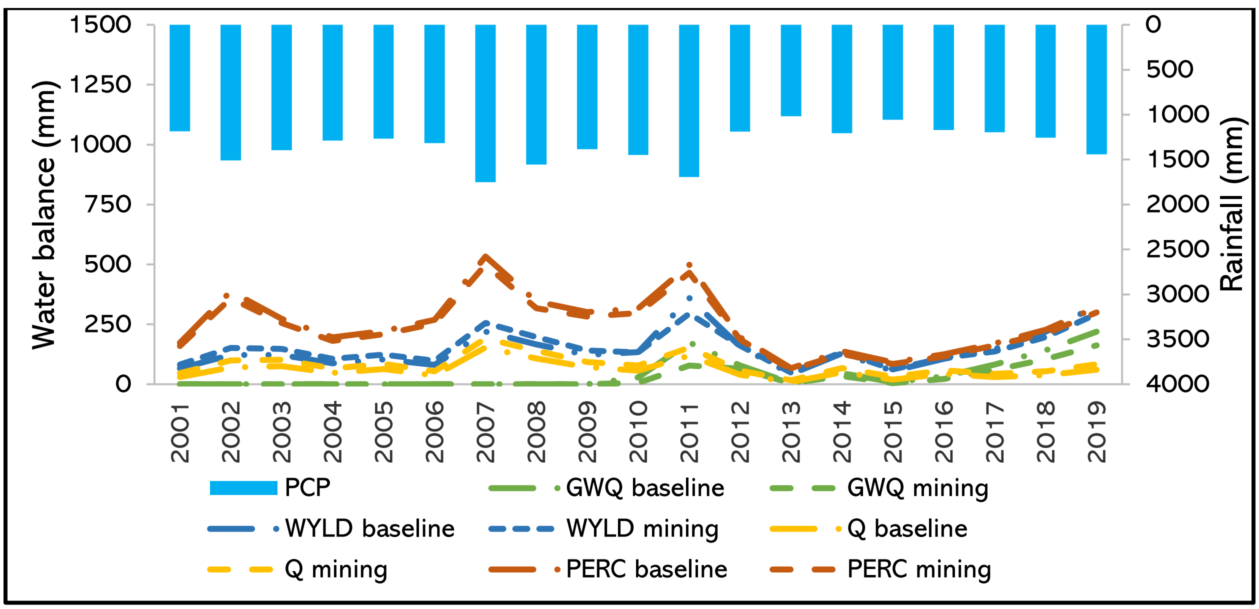


Figure 7. Temporal dynamics of hydrological components for baseline and mining scenario in the Mankran micro-watershed. (Source: Authors construct)

3.3. Implications on the sustainability of cocoa production

The findings indicate that mining activities can have significant adverse effects on water availability for irrigation. Excavation and extraction processes can disrupt the hydrological balance, causing changes in water tables and reducing the overall availability of water for agricultural use. Farmers may face challenges in securing an adequate and reliable water supply for their crops. The expansion of mining would further pose a threat to the sustainability of cocoa production from groundwater. This requires the use of both surface and sub-surface water storage in an integrated manner.

Sustainable integration of irrigated agriculture and mining activities requires a multi-faceted approach that addresses environmental, social, and economic considerations. To achieve this balance, comprehensive water management plans should be developed, incorporating efficient irrigation techniques alongside water recycling and treatment facilities in mining operations. Conversely, land use planning needs to identify suitable areas for mining alongside implementing effective reclamation and rehabilitation to restore soil fertility and hydrological functions in mined areas. Furthermore, continuous research and monitoring efforts can contribute valuable data to adjust practices, fostering a sustainable balance between irrigated cocoa production and mining for the benefit of communities and ecosystems.

4. CONCLUSIONS AND RECOMMENDATIONS

The findings of this study carry significant implications, shedding light on the potential repercussions of supplemental cocoa irrigation and mining on hydrology and the environment within the Upper Offin sub-basin and Mankran micro-watershed. Utilizing a carefully calibrated and validated SWAT model and conducting scenario analyses, significant hydrological impacts were observed in both the Upper Offin sub-basin and Mankran micro-watershed due to the adoption of supplemental irrigation. The impact on groundwater flow due to the adoption of supplemental irrigation was also significant for a 5% cocoa area in the Upper Offin sub-basin. However, the adoption of supplemental irrigation in the Upper Offin sub-basin exhibited minimal impact on catchment water yield for up to 15% of cocoa areas. Similarly, a significant influence on hydrology was observed due to supplemental irrigation for cocoa areas below the 8% slope (38% of cocoa area) and when complete cocoa cover under supplemental irrigation in the Mankran micro-watershed. This shift resulted in a noteworthy increase in evapotranspiration, percolation, and sub-surface flow by approximately 9%, 28%, and 21.5%, respectively. In contrast, catchment water yield declined by 18% and groundwater flow ceased, which would be evident, indicating increased environmental impact compared to the baseline.

The scenario involving mining showed significant hydrological and environmental changes in both the Upper Offin and Mankran micro-watersheds. Surface runoff, catchment water yield, and sediment yield experienced significant increases compared to the baseline, while percolation and groundwater flow decreased significantly because of mining activities in both watersheds. These findings underscore the necessity for further research, specifically focusing on the location and spatial coverage of mining, incorporating a validated representation of mining activities in the SWAT model to provide accurate insights into the impacts of mining.

The findings show that the expansion of mining activities can pose substantial challenges to sustainable cocoa production under supplemental irrigation. Supplemental irrigation needs to integrate both surface and sub-surface storage sources for the sustainability of cocoa production. To achieve the balance between irrigated cocoa production and mining, a comprehensive water and land management plan needs to be developed incorporating efficient irrigation techniques and land reclamation. Establishing a robust monitoring system is also crucial to continuously assess hydrological changes in response to cocoa irrigation and mining activities, enabling real-time adjustments based on observed environmental impacts through adaptive management strategies. Lastly, integrating the study's findings into local and regional policies governing cocoa production, supplemental irrigation, and mining activities is imperative. Such integration can play a pivotal role in informing and shaping guidelines and regulations that promote sustainable practices, ultimately minimizing adverse environmental effects due to livelihood and economic activities of communities.

REFERENCES

Adaawen, S.; Rademacher-Schulz, C.; Schraven, B.; Segadlo, N. 2019. Drought, migration, and conflict in sub-Saharan Africa: what are the links and policy options? Current Directions in Water Scarcity Research 2, 15-31 Available at: https://doi.org/10.1016/B978-0-12-814820-4.00002-X.

Abu, I.O.; Szantoi, Z.; Brink, A.; Robuchon, M.; Thiel, M. 2021. Detecting cocoa plantations in Côte d'Ivoire and Ghana and their implications on protected areas. *Ecological indicators*, 129, p.107863 Available at: https://doi.org/10.1016/j.ecolind.2021.107863.

Antwi-Agyei, P.; Dougill, A.J.; Stringer, L.C.; Codjoe, S.N.A. 2018. Adaptation opportunities and maladaptive outcomes in climate vulnerability hotspots of northern Ghana. *Climate Risk Management* 19, 83-93 Available at: https://doi.org/10.1016/j.crm.2017.11.003.

Asante, F.; Guodaar, L.; Arimiyaw, S. 2021. Climate change and variability awareness and livelihood adaptive strategies among smallholder farmers in semi-arid northern Ghana. Environmental Development 39, 100629 Available at : https://doi.org/10.1016/j.envdev.2021.100629.

Asante, F.A.; Amuakwa-Mensah, F. 2014. Climate change and variability in Ghana: Stocktaking. Climate 3(1), 78-101 Available at: https://doi.org/10.3390/cli3010078.

Asante, P.A.; Rahn, E.; Zuidema, P.A.; Rozendaal, D.M.; van der Baan, M.E.; Läderach, P.; Asare, R.; Cryer, N.C.; Anten, N.P. 2022. The cocoa yield gap in Ghana: A quantification and an analysis of factors that could narrow the gap. *Agricultural Systems* 201, 103473 Available at: https://doi.org/10.1016/j.agsy.2022.103473.

Asiedu-Darko, E. 2014. Farmers' perception on agricultural technologies a case of some improved crop varieties in Ghana. Agriculture, *Forestry and Fisheries* 3(1), 13-16 Available at: doi: 10.11648/j.aff.20140301.13.

Fagariba, C.J.; Song, S; Soule Baoro, S.K.G. 2018. Climate change adaptation strategies and constraints in Northern Ghana: Evidence of farmers in Sissala West District. *Sustainability* 10(5), 1484 Available at: https://doi.org/10.3390/su10051484.

Funk, C.; Peterson, P.; Landsfeld, M.; Pedreros, D.; Verdin, J.; Shukla, S.; Husak, G.; Rowland, J.; Harrison, L.; Hoell, A. 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Scientific data* 2(1), 1-21 Available at: https://doi.org/10.1038/sdata.2015.66.

Gilewski, P.; Węglarz, A. 2018 Impact of land-cover change related to urbanization on surface runoff estimation, p. 03014, *EDP Sciences* Available at: https://doi.org/10.1051/matecconf/201819603014.

Giller, K.E. 2020. The food security conundrum of sub-Saharan Africa. *Global Food Security* 26, 100431 Available at: https://doi.org/10.1016/j.gfs.2020.100431.

Green, E. 2017. From extensive to involutionary growth: a dialectic interpretation of the boom and busts of cocoa production in the Gold Coast. Journal of Agrarian Change 17(3), 518-534 Available at: https://doi.org/10.1111/joac.12153.

Hirons, M.A. 2014. Mining, forests and land-use conflict: the case of Ghana, University of Reading Available at: https://doi.org/ 10.13140/RG.2.2.11497.90726.

Ingram, V.; Van Rijn, F.; Waarts, Y.; Gilhuis, H. 2018. The impacts of cocoa sustainability initiatives in West Africa. *Sustainability* 10(11), 4249 Available at: https://doi.org/10.3390/su10114249.

Kessey, K.D.; Arko, B. 2013. Small scale gold mining and environmental degradation, in Ghana: issues of mining policy implementation and challenges. *Journal of Studies in Social Sciences* 5(1).

Koide, J.; Yokoyama, S.; Hirouchi, S.; Hirose, C.; Oka, N.; Oda, M.; Yanagihara, S. 2021. Exploring climate-resilient and risk-efficient cropping strategies using a new pond irrigation system: an experimental study in northern Ghana. Agricultural Systems 191, 103149 Available at: https://doi.org/10.1016/j.agsy.2021.103149.

Mensah, A.K.; Mahiri, I.O.; Owusu, O.; Mireku, O.D.; Wireko, I.; Kissi, E.A. 2015. Environmental impacts of mining: a study of mining communities in Ghana. *Applied Ecology and Environmental Sciences* 3(3), 81-94 Available at: https://doi.org/10.12691/aees-3-3-3.

Merem, C.; Twumasi, A.; Wesley, J.; Olagbegi, D.; Crisler, M.; Romorno, C.; Alsarari, M.; Isokpehi, P.; Hines, A.; Ochai, S. 2020. Exploring cocoa farm land use in the West African Region. *Int. J. Agric. For* 10(1), 19-39 Available at: https://doi.org/10.5923/j.ijaf.20201001.03.

Nunoo, I.; Darko, B.O.; Owusu, V. 2015. Restoring degraded forest landscape for food security: Evidence from cocoa agroforestry systems, Ghana. *Enhancing food security through forest landscape restoration: Lessons from Burkina Faso, Brazil, Guatemala, Vietnam, Ghana, Ethiopia and Philippines* 122 Available at: http://dx.doi.org/10.2305/IUCN.CH.2015.FR.2.en.

Phelan, L. 2021. Soil and Water Management Practices in Cocoa Production in Ghana and Ecuador Doctoral thesis, De Montfort University Available at: https://dora.dmu.ac.uk/handle/2086/20984.

Sanchez, P.A.; Ahamed, S.; Carré, F.; Hartemink, A.E.; Hempel, J.; Huising, J.; Lagacherie, P.; McBratney, A.B.; McKenzie, N.J.; Mendonça-Santos, M.D.L. 2009. Digital soil map of the world. *Science* 325(5941), 680-681.

Sekyi-Annan, E.; Tischbein, B.; Diekkrüger, B.; Khamzina, A. 2018. Performance evaluation of reservoir-based irrigation schemes in the Upper East region of Ghana. *Agricultural Water Management*, 202, 134-145 Available at: https://doi.org/10.1016/j.agwat.2018.02.023.

Serdeczny, O.; Adams, S.; Baarsch, F.; Coumou, D.; Robinson, A.; Hare, W.; Schaeffer, M.; Perrette, M.; Reinhardt, J. 2017. Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. Regional Environmental Change 17, 1585-1600 Available at: https://doi.org/10.1007/s10113-015-0910-2.

Shankar, S. 2018. Biotechnology for Sustainable Agriculture, pp. 207-234, Elsevier Available at: https://doi.org/10.1016/B978-0-12-812160-3.00007-6.

Snapir, B.; Simms, D.M.; Waine, T.W. 2017. Mapping the expansion of galamsey gold mines in the cocoa growing area of Ghana using optical remote sensing. International journal of applied earth observation and geoinformation 58, 225-233 Available at: https://doi.org/10.1016/j.jag.2017.02.009.

Sultan, B.; Gaetani, M. 2016. Agriculture in West Africa in the twenty-first century: climate change and impacts scenarios, and potential for adaptation. Frontiers in plant science 7, 1262 Available at: https://doi.org/10.3389/fpls.2016.01262.

Assefa, T. T.; Atampugre, G.; Tilahun, S. A.; Cofie. O. 2023. Modeling of Water Availability for Food System Transformation in Upper Offin Sub-basin and Mankran Micro-Watershed of Ghana: A Baseline Study. Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Initiative on West and Central African Food Systems Transformation. 32 pages.

Tilahun, S.A.; Gbodji, K.K.; Minh, T.T.; Mabhaudhi, T.; Cofie, O. 2023a. Peter Oppong's inspiring journey: smallholder farmers like Oppong are reaping the benefits of solar-powered irrigation, a cost-effective and easy-to-implement technology. Colombo, Sri Lanka: International Water Management Institute (IWMI) Available at: https://hdl.handle.net/10568/134558.

Tilahun, S.A.; Amponsah, A.K.; Atampugre, G.; Birhanu., B. Z., D.; M., Darko, S.; Mabhaudhi, T.; Cofie, O. 2023b. Integrated land and water resources assessment for sustainable irrigation development in changing agroforestry landscapes: A case study of Ghana. Catena, Submitted.

Voora, V.; Bermúdez, S.; Larrea, C. 2019. Global market report: Cocoa, JSTOR vailable at: https://www.jstor.org/stable/pdf/resrep22025.pdf.

Yaro, J.A. 2013. The perception of and adaptation to climate variability/change in Ghana by small-scale and commercial farmers. Regional Environmental Change 13, 1259-1272 Available at: https://doi.org/10.1007/s10113-013-0443-5 .

Yamba E.I.; Aryee J.N.A.; Quansah E.; Davies P.; Wemegah C.S.; Osei M.A.; Ahiataku, M.A.; Amekudzi, L.K. 2023. Revisiting the agro-climatic zones of Ghana: A re-classification in conformity with climate change and variability. PLOS Clim 2(1): e0000023. Available at: https://doi.org/10.1371/journal.pclm.0000023

Zanaga, D.; Van De Kerchove, R.; Daems, D.; De Keersmaecker, W.; Brockmann, C.; Kirches, G.; Wevers, J.; Cartus, O.; Santoro, M.; Fritz, S. 2022. ESA WorldCover 10 m 2021 v200 Available at: https://doi.org/10.5281/zenodo.7254221.