Small Reservoirs in Northern Ghana: Monitoring, Physical Processes, and Management

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DOI
10.4233/uuid:81e5e8a8-2bee-4af5-b1bc-c7b210f9cb55

Publication date
2023

Document Version
Final published version

Citation (APA)
Annor, F. O. (2023). *Small Reservoirs in Northern Ghana: Monitoring, Physical Processes, and Management*. [Dissertation (TU Delft), Delft University of Technology].
https://doi.org/10.4233/uuid:81e5e8a8-2bee-4af5-b1bc-c7b210f9cb55

Small Reservoirs in Northern Ghana

Monitoring, Physical Processes, and Management

Frank Ohene Annor

Small Reservoirs in Northern Ghana:
Monitoring, Physical Processes, and Management

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus Prof.dr.ir. T.H.J.J. van der Hagen
chair of the Board for Doctorates
to be defended publicly on
Wednesday 22 November 2023 at 10:00 o'clock

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The work leading to these results has received funding from the European Commission's Horizon 2020 Programme (2018-2022) under grant agreement No. 776691 (TWIGA) and the Horizon Europe Research & Innovation Programme 2021-2027 (grant agreement no. 101086209 – TEMBO Africa). The opinions expressed in the document are of the authors only and in no way reflect the European Commission's opinions. The European Union is not liable for any use that may be made of the information.

Keywords: Small reservoirs, irrigation, rural water supply, water management

Printed by: Proefschrift-aio.nl

ISBN/EAN: 978-94-6366-776-0

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> “The impossible becomes possible
> if only your mind believes it
> Chris Bradford

To my wife, children, and family

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Introduction

Satellites cannot see everything on the ground,
and ground measurements cannot cover everywhere.
A careful combination of the two are needed with models.

1.1 Background of Small Reservoirs

Small reservoirs constitute a substantial part of the manageable water resources in Sub-Saharan Africa [1] especially in West Africa's Volta Basin. They are also commonly found in South America particularly in the savanna region of Brazil where a lot of these are dotted on the landscape. These reservoirs are relied on for irrigation, fishing, livestock watering and other domestic and commercial uses [2]–[4]. They are often sited close to communities therefore making them crucial for resilient food production. They are characterised by their small size (less than 100 Ha in surface area), wide distribution (more than 2000 in the Volta Basin with 160 of them, for example, in the Upper East Region of Ghana alone) and flexibility in their management. Unfortunately, they are ungauged and often neglected in hydrological monitoring even though they could reduce flood peaks.

In recent years, the Government of Ghana, through the "one village one dam" project is constructing additional reservoirs. The management of the existing reservoirs and new ones will therefore become more imperative for optimising the use of the water resources for irrigation, hydropower, and the environment. This will require insights in the monitoring of their storage volumes in data scarce environments [2], [5]. Due to cloud cover it is almost impossible to monitor small reservoirs with only optical images in all seasons. Volume-Elevation curves established for small reservoirs could be used for other ungauged ones in the same region with similar shapes (depending on the shape of their slopes; convex, concave or straight) to estimate their volumes using the surface area estimated through remote sensing only [2], [6]. In estimating the volume of reservoirs, the depth-area-volume relationships is critical if the estimate will be done using remote sensing. This is because it is easy to measure the surface area which can then be related to the storage volume using the depth-area-volume correlation. This limits the requirement for further in situ measurements which are hardly done for small reservoirs due to the cost of instrumentation. However, low-cost instrumentation for small reservoirs using the TAHMO Network is considered for this study. Coupling low-cost in situ observations such as from the TAHMO network with satellite data and models provides much more insights which leads to better management of these small reservoirs. This combination is what this research work explores.

1.2 The Role of Remote Sensing in Ungauged Basins

Ungauged basins lack the required in situ data for accurate monitoring of the water resources in them. This makes it difficult for water management in the basin especially in terms of planning for climate extremes such as drought and floods. Remote Sensing techniques present an interesting opportunity to do this monitoring with readily and freely available satellite data sets from Landsat, Envisat and the Sentinels from sources such as Copernicus [2], [3], [5], [7], [8] among many others. For example, satellite observations together with hydrological modelling have been used to improve estimation of reservoir outflow for ungauged basins even though the initial results could be improved with better temporal sampling of the satellite data used [9].

Knowing the quantity of water available in a sub-basin or reservoir helps smallholder farmers to plan better for their irrigation needs including choice of crops to grow for the season and better soil water management during the dry season. With more than 80% of farms operated by smallholder farmers with a large population of them being female farmers (70%), farming with an unknown quantity of water does not only make farming risky but also unproductive [10]. According to Annor et al. [10], the Small Reservoirs Project (www.smallreservoirs.org) has developed toolkits for estimating the volume of water stored in reservoirs using a combination of bathymetric analyses and remotely sensed surface areas of the reservoirs. Most of the tools were developed for the Volta Basin in West Africa but they are applicable globally.

The Small Reservoirs Project in 2014 developed a Bayesian classifier for improved classification of water bodies for runoff estimation, reservoir water balance assessment and flood mapping for the Volta basin [3]. This tool was developed with the support of the European Space Agency's (ESA) TIGER and Alcantara projects, and the Canadian Space Agency's SOAR Africa project using Radarsat-2 Images. One key recommendation from the research that led to the development of the tool included the combined use of in situ data and new Earth Observation (EO) data such as the Sentinels to monitor inland waterbodies especially those used for irrigation [10]. Through the Spot5-Take5 initiative by ESA, the researchers led by Frank Annor, used a time series of 27 Level-2A products over the Upper East Region of Ghana to show that Sentinel-1 images and Sentinel-2 (simulated with the Spot5 images that were available by then) were great additions to the satellite constellations available for near-real-time water monitoring for operational water management including drought and floods in ungauged basins. Annor et al. and other researchers [2], [3], [5], [8], [10]–[13] showed that establishing satellite-based time series and trends is a pre-requisite for reducing risks associated with farming as well as to enhance the resilience of communities against floods. Understanding the water storage dynamics of reservoirs, for example, can help attenuate flood peaks and safe lives [11]. Small reservoirs can also be used to determine the watershed response in ungauged catchments [14]. With this background, the research aims at understanding how small reservoirs are managed in the Volta basin. Specifically:

1. To provide a timeseries of small reservoir storage using a combination of in situ and remote sensing methods.
2. To assess the water balance of small reservoirs.
3. To compute the evaporation losses of small reservoirs using different methods and approaches.
4. To provide an overview of how small reservoirs in the Volta basin are managed and the implications for resilient community development.
5. To assess the sustainability of the TAHMO station network for water management in low-resource settings, including the monitoring of small reservoirs.

The results presented in this thesis, therefore aim at answering the following research questions to meet the above stated objectives:

1. Can we monitor small reservoirs all year round with only remote sensing data?
2. What is the water balance of small reservoirs?
3. Is evaporation the largest loss of small reservoirs and what accounts for this?
4. How can we measure evaporation losses in a cost-effective way using low-cost sensors and/or remote sensing data?
5. How are small reservoirs managed to increase the resilience of communities?
6. Does TAHMO offer sustainable low-cost solutions for in situ monitoring of small reservoirs?
7. How do small reservoirs upstream affect hydropower downstream in the Volta basin especially in Ghana?

1.3 Outline of thesis

The thesis is organised in five chapters with chapter 1 being the introduction providing a background to the study, the objectives and the research questions that need to be answered to meet the objectives.

Chapter two looks at the management of small reservoirs in Northern Ghana including algorithms used to delineate them and estimate the volumes of these reservoirs using remote sensing (optical and radar imagery), and well-established regional equations on reservoir volume and surface area relations.

Chapter three looks at the possible impact of small reservoirs on hydropower production downstream in the Volta Basin, by simulating a reoptimisation and reoperation of the Akosombo and Kpong dams in Ghana together with the Volta River Authority (VRA). Here, the allocation of water in the Volta basin among multiple and often competing uses including hydropower and small reservoirs is presented.

In Chapter four, how evaporation in small reservoirs can be estimated using various methods including the use of in situ observations, satellite data and a combination of these is investigated, lessons drawn, and recommendations made.

In Chapter five, we conclude on the findings of the research carried out in this study and its importance to science and society in Africa and beyond.

In Appendix 1, we present a decade of work on the Trans-African Hydro-Meteorological Observatory and its contribution to science and society. Here, findings on the sustainability of the TAHMO station network for water management in river basins are discussed.

2

Small Reservoirs in Northern Ghana

> *Action without thought is empty.*
>
> *Thought without action is blind.*
>
> **Kwame Nkrumah**

Parts of this chapter have been published in HydroSpace 2015 by Annor et al., 2015 and in Annor, F. O., van de Giesen, N., Liebe, J., van de Zaag, P., Tilmant, A., & Odai, S. N. (2009). Delineation of small reservoirs using radar imagery in a semi-arid environment: A case study in the upper east region of Ghana. Physics and Chemistry of the Earth, 34(4–5). https://doi.org/10.1016/j.pce.2008.08.005.

2.1 Introduction

Small reservoirs are important for water resources management in the Volta Basin. These reservoirs are relied on for irrigation, fishing, livestock watering and other domestic and commercial uses. They are often sited close to communities, making them crucial for resilient food production. They are characterised by their small size (less than 100 Ha in surface area), wide distribution (more than 160 of them for example in the Upper East Region of Ghana in the Volta Basin alone) and flexibility in their management. Unfortunately, they are ungauged and often neglected in hydrological monitoring. In recent years, the Government of Ghana through the “one village one dam” project is constructing additional reservoirs. Planning and managing existing reservoirs and new ones will therefore become more imperative for optimising the use of the water resources for both irrigation, hydropower, and the environment. This study provides insights in small reservoir planning and management with a focus on the monitoring of storage volumes and evaporative losses in data scarce environments.

The findings from the research show that it is feasible to monitor the volume dynamics of small reservoirs using radar imagery all year round although there could be challenges when the reservoir has reeds at the tail ends. Due to cloud cover it is almost impossible to monitor the small reservoirs with only optical images in all seasons. Volume-elevation curves established for small reservoirs could be used for others in the same region with similar shapes (depending on the shape of their slopes, they can be classified as convex, concave or straight) to estimate the volume of ungauged reservoirs using the surface area estimated through remote sensing. In estimating the volume of reservoirs, the depth-area-volume relationships is critical, especially if the estimate will be done using remote sensing. This is because it is easy to measure the surface area which can then be related to the storage volume using the depth-area-volume correlation, thereby limiting the requirement for further in situ measurements which are hardly done for small reservoirs due to the cost of instrumentation.

2.2 Use of Small Reservoirs in the Volta Basin

Small reservoirs serve multiple purposes in the semi-arid region of West Africa especially Northern Ghana and Southern Burkina Faso (there are over 2000 small reservoirs in these areas alone). The reservoirs were initially constructed for irrigation and/or livestock watering. The reservoirs are currently being used for many purposes, including domestic uses (washing of clothes and vegetables, bathing), construction (brick making), fishing, recreation, and car washing in addition to the original purposes (irrigation and livestock). The reservoirs are located in communities (consisting of about 1-5 villages). However, recent developments have led to small towns close to these villages using 160 litre barrels in "motor kings" as they are popularly called to fetch water for various uses outside the immediate vicinity of these small reservoirs. In a typical day, more than 80 barrels of water could be fetched from a reservoir for use outside the intended targeted beneficiaries.

There is no doubt about the benefits these small reservoirs (lakes) bring to the communities. However, in the past two decades, there have been perceptions that the gains obtained from small reservoirs are offset by negative factors such as evaporation, seepage, and sedimentation alongside the activities of the operators of the "motor kings". Hence during the dry season (November - May) when the water in the reservoirs would be much needed for irrigation and livestock watering, some of them are already dried-up (only the very small ones with depths less than 2m at the end of the dry season). To plan, manage and study the impact of small reservoirs at river basin scale [3] it is important to find a cost-effective way to monitor them. There have been some studies on small reservoirs at basin scale using a combination of remote sensing (radar and optical imagery) and in situ measurements, which lay the foundation for the monitoring of the extent (volume) of the reservoir [2], [4]–[6], [8], [14], [15]. In this chapter we provide a framework for monitoring the dynamics of small reservoir extent using a simple water balance method based on remote sensing and in situ data collected with pressure transducers [16].

2.3 Framework for monitoring small reservoirs extent in the Volta Basin

Optical imagery for monitoring small reservoirs extent in the Volta Basin is well established but limited to cloud-free days [2], [3], [14]. Due to cloud cover, Synthetic Aperture Radar (SAR) data was used in tests for mapping small reservoirs in the Volta Basin [2], [14]. These were, however, fraught with some challenges such as induced Bragg scatter, reeds at the tail ends and low contrast between water and surrounding dry areas [2], [3], [14] making it impossible to automatically map the extent of the reservoirs all-year round. Quasi-manual methods were however successfully applied by [2] with no a-priori optimal polarisation [3].

Following the challenges posed by optical imagery and reeds in the tail ends of SAR imagery, another method (Bayesian Classifier) was developed by [3] to automatically map small reservoirs extent and to study the dynamics. This enabled all-year round monitoring of the extent of small reservoirs automatically. With the bathymetry known or with an established known or with an established Area-Volume correlation, the volume of the reservoirs could then be estimated.

2.3.1 Determining the bathymetry of small reservoirs

In estimating the volume of reservoirs, the depth-area-volume relationships is critical especially if the estimate will be done using remote sensing [3]–[5], [10], [14], [16], [17]. This requires a good knowledge of the bathymetry of several reservoirs to establish regional relationships which can be applied to other (ungauged) reservoirs in the region [2], [3], [17] depending on the shape of their slopes (convex, concave or straight).

Bathymetry is the study of the depth of reservoirs, lakes, and oceans. This can be done simply but painstakingly with a measuring stick, stadia rod, fishfinder, or in a more complex manner with an echosounder (sonar), depending on the depth of the reservoir and the surface area. For this study, a Raymarine Dragonfly GPS E70085 which can detect depths of up to 15 meters, which is much more than the depth of the reservoirs studied, and an inflatable boat mounted with an outboard motor was used for the bathymetry. The Raymarine Voyage Planner and GPS Utility software were used to download and visualise the data collected during the bathymetry. The software allows one to convert the data into other more user-friendly formats such as gpx and csv. It is extremely important to check that a sonar can support multiple tracks with depth before using it for bathymetry on a lake or small reservoir otherwise the data will be less useful.

2.3.2 Preparing a TIN map

Preparing the Triangular Irregular Network (TIN) map is an important step in processing bathymetric data. The raw files come in various formats. They need to be converted into text files with at least three (3) columns of data – the Eastings (X), Northings (Y) and Depth/Elevation (Z). The Depth could be negative with respect to the datum used or the water surface. First, the data collected needs to be pre-processed or “cleaned”. To remove areas outside the reservoir at the water/dry land boundary, many readings are required along the shoreline. The reading from the shoreline can then be merged with the readings from the sonar. This can be done in any spreadsheet software, TrackMaker or any GIS Software, and is required because it is difficult to get the exact outline at the shoreline with a boat. It requires one walking around the reservoir with a handheld GPS. Processing of the data from the handheld GPS is explained in detail by [16].

Figure 2.1: Point file of Lake Binaba created in saga from the XYZ text file

The XYZ file can then been converted into a point shapefile *(Figure 2.1)* and the outline into a polygon shapefile in any GIS software. QGIS and SAGA were used in this study, but any GIS software may work as well with the right plugins. It can also be noted in *Figure 2.1* that more points were taken at the shoreline and tail-end of the reservoir than close to the dam wall.

Although not compulsory, to get a better understanding of the bathymetry of the reservoir, it is advantageous to add a Digital Elevation Model (DEM) as an additional layer of data *(Figure 2.2)*.

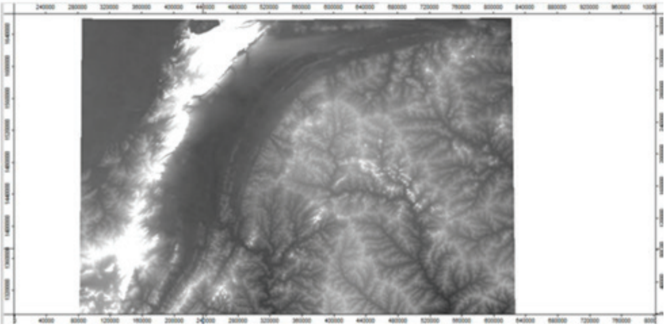

Figure 2.2: SRTM DEM of Lake Binaba in Northern Ghana

The point data set has to be converted into grid *(Figure 2.3)* using triangulation or any other method that works best for the data collected and then converted into a TIN file *(Figure 2.4)*.

Depending on the processing power of the computer for the conversion of the gridded data to TIN file, a higher grid specification of about 10m x 10m, can be used instead of a grid of 1m x1m depending on the resolution of the data being processed.

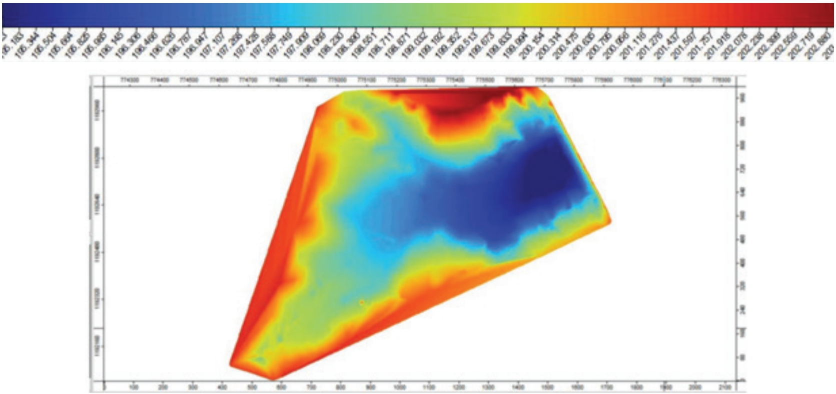

Figure 2.3: Gridded data of Lake Binaba obtained from triangulation of the point data

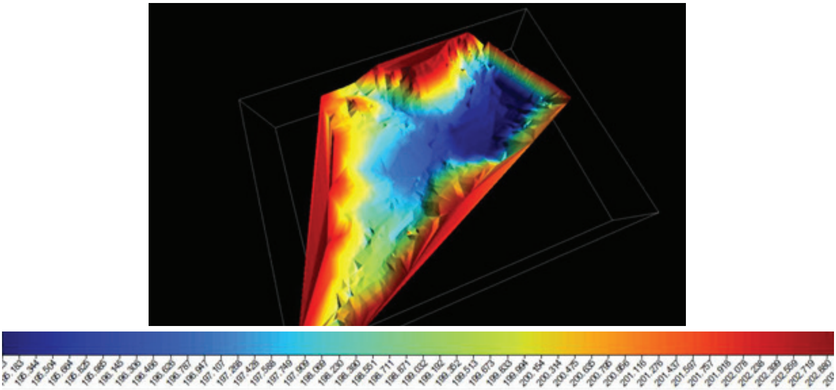

Figure 2.4: TIN of the Gridded data of the Binaba dam

The geometry, which is now prepared, is an important input and can then be used for 3-D modelling as was done by Abbasi et al. [18] to understand the energy budget of the reservoir. It could also be used to develop the volume-elevation curve for the reservoir [16].

2.3.3 Estimating the volume of small reservoirs

According to Liebe et al. [3] there exists a robust regional relation between the volume of a small reservoir and its surface area. In Northern Ghana, this is given by Eq. (2.1).

$$V=0.00857A^{1.4367} \qquad \text{Eq. (2.1)}$$

Where:

V = Volume in m^3

A = Area in m^2

Based on Eq. (2.1), one can explain more than 95% of the observed variation in volume based on measurement of the lake surface area alone. This approach allows for the use of remote sensing to estimate the evolution of storage over time in many reservoirs at basin scale. With the volume of the reservoirs known, better plans can be made for the use of the water in them.

2.3.4 Operational use of satellites for managing small reservoirs in the Volta basin

Climate change is exacerbating pollution, land degradation, lack of ecosystem services and unsustainable use of water and land resources [19]. This puts a lot of stress on the limited quantity of water stored in dams especially in Africa [20]. To meet the Sustainable Development Goal (SDG) 6 by 2030, there is the need for more investments in water infrastructure. This needs to be a top priority not only in the Volta basin but also in other parts of Africa having water scarcity issues. The limited water infrastructure investment coupled with slow uptake of No/Low regret investment projects is gradually inhibiting Africa's economic development [19]. This situation calls for a better planning of new water infrastructure and an efficient management of existing ones. This is easier said than done especially where most reservoirs are not (properly) gauged. As presented in Chapter 1 of this thesis, it is possible to monitor the surface extent of water bodies from space (using satellite imagery only) relying on well-established relationship between their volumes and surface areas (Eq. 2.1 - [2], [3], [17]). The area alone explained over 95% of the variance in the Area-Volume correlation [6], [14], [17] indicating that monitoring stored water in reservoirs by just their surface areas from space was doable and quite accurate. The distribution of small reservoirs and a few medium sized (Tono and Vea) and large reservoirs (Bagre) in Northern Ghana and Southern Burkina Faso is presented in *Figure 2.5*.

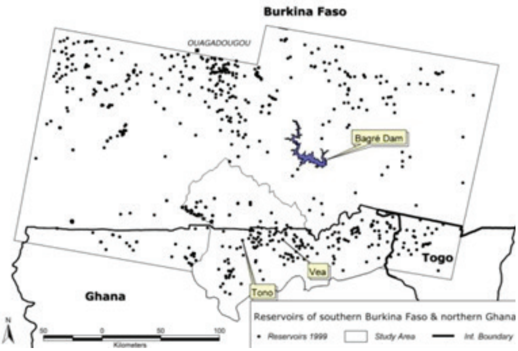

Figure 2.5: Map of reservoirs in Northern Ghana and Southern Burkina Faso in the Volta basin. Source: [19]

Long time series of both optical (Landsat, SPOT, RapidEye, Quickbird) and radar (ASAR, ESR-1/2, Radarsat-2) images and more recently Sentinels (TWIGA Project, 2021) have been used for operational mapping of small reservoirs all showing very promising results [2], [5], [14], [15], [19], [21]. Examples of these, are presented by Annor et al. [2], [3], [10], [19] in *Figure 2.6.*

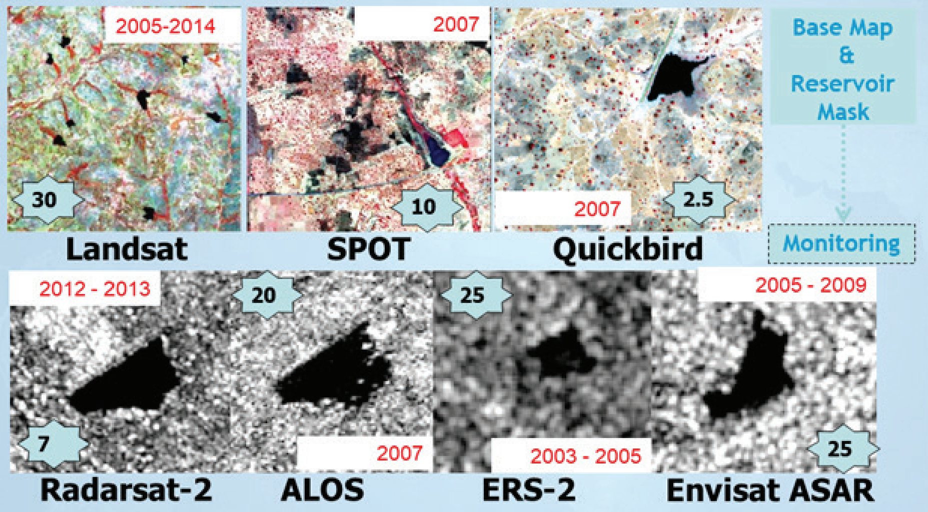

Figure 2.6: Optical and radar imagery used for operational monitoring of small reservoirs. Source: [19]

Methods and algorithms for operational monitoring of open water

Annor et al. [10], [19] provided a methodology for using a combination of in situ data and satellite data (optical and radar) for all-year monitoring of small reservoirs for the Volta basin which can be applied in other basins *(Figure 2.7)*.

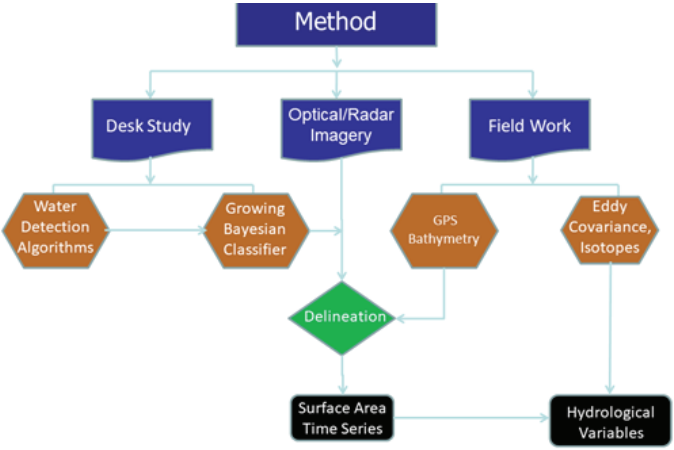

Figure 2.7: Open water delineation processing flowchart. Source: [19]

The method selected is based on the quality of the available data (Table 2.1). A novel approach, the Naïve Bayesian, is a much more innovative method to ensure easy classification under all conditions (reeds with radar or cloud cover with optical images)[2], [3], [10], [19]. The decision rule used by the Naïve Bayesian approach is presented in *Figure 2.8.*

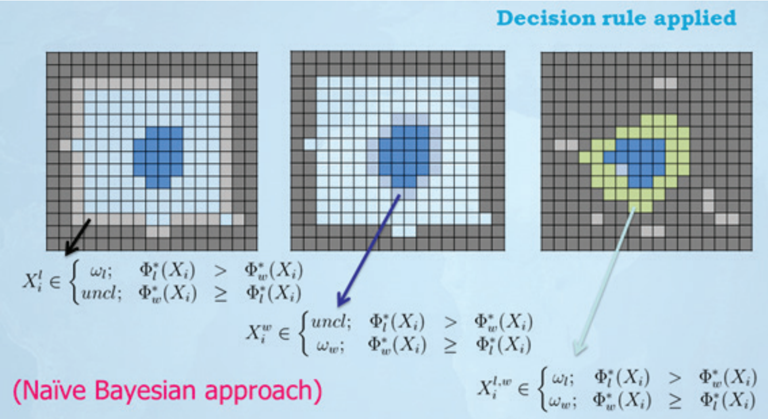

Figure 2.8: Naïve Bayesian Approach for delineating open water using radar and optical imagery. Source: [19]

Table 2.1: Common algorithms for delineating open water with satellites

Algorithm/Classification	**Optical**	**Radar**
Normalised Difference Water Index	√	x
Modified Normalised Difference Water Index	√	x
Normalised Difference Vegetation Index	√	x
Enhanced Vegetation Index	√	x
Threshold classification	√	√
Supervised MLC	√	√
K-means classification	√	√
Manual classification	√	√
Active Contour (Snakes) classification	√	√

Another approach for classification of open water using optical images, referred to as adaptive threshold, is shown in Figure 2.9 [19], [22].

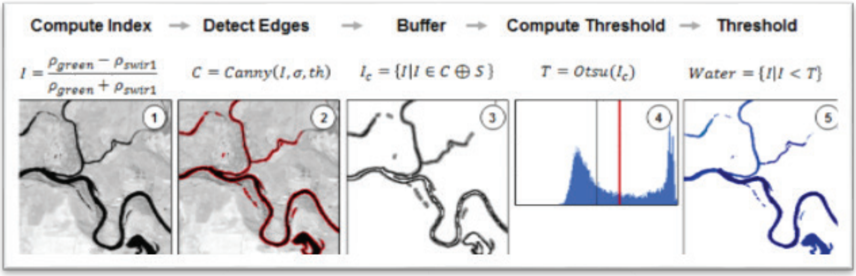

Figure 2.9: Adaptive Threshold approach for delineating open water using optical imagery. Source: [19], [22]

Research has shown that a combination of both optical and radar satellite images yield optimal results especially with clouds affecting optical images in the rainy season, and radar images sometimes requiring more polarization modes to reduce the effect of Bragg scatter *(Figure 2.10)* [2], [3], [19]. Dual and quad - polarizations such as for the Synthetic Aperture Radar (SAR) aboard the ESA Sentinel-1A/B satellites are helpful to yield optimum results.

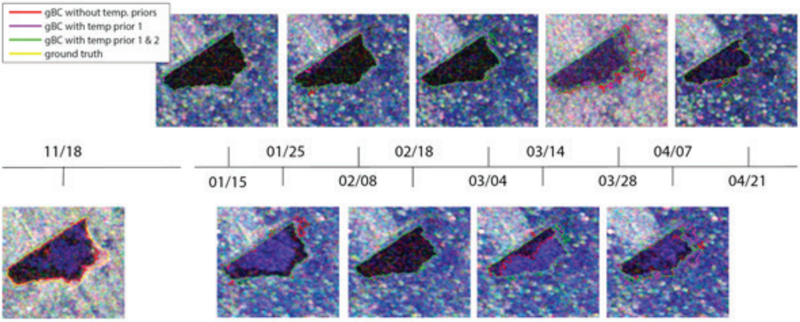

Figure 2.10: Typical problems with Bragg scattering with SAR images. Top row is FQ17W and bottom row FQ4W (steepest incidence angle). Bragg scatter mostly occurs with steeper incidence angle. Source: [19]

The Bayesian algorithm was used for the operational monitoring of small reservoirs in the Upper East Region of Ghana *(Figure 2.11)* in the Volta basin with a combination of optical and radar imagery [3], [10], [16], [19]. This creates more room for seamless integration of in-situ data and satellite data for improved classification of water bodies for flood mapping, runoff estimation and water balance assessment.

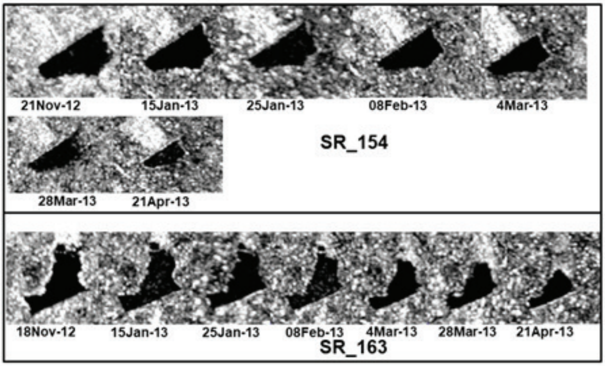

Figure 2.11: Operational monitoring of small reservoirs in the Upper East Region of Ghana at the end of the rainy season (Nov.) until the dry season (May). Source: [19]

The surface area-volume correlation used in Figure 2.11 was first developed in 2002 and re-evaluated after 10 years [2]–[6], [10], [19], [23]. It turned out that the correlation has not been affected much by sedimentation at least for the Volta basin [10], [19], [23]. This is because of low sedimentation rates and the weaning of sand from streams and rivers in the basin. This cannot be said to be true for all basins, which points to the continued need for a dedicated effort of using in situ data combined with new observation systems, such as the Sentinels, to develop and update these correlations. From the results presented in this chapter, we show that the Sentinels from the European Space Agency (ESA) are a great addition to the satellite constellations. These are available for near-real-time water monitoring so can be combined with cost-effective TAHMO ground stations (see Appendix 1) for operational water management. The availability of these data sets (Sentinels and TAHMO data) in the Volta basin will support decision making to alleviate poverty and protect lives and property.

3

Reoptimisation and Reoperation of Akosombo and Kpong Dams in Ghana and the impact of Small Reservoirs upstream in the Volta Basin

Every River has its own people

This chapter has been published as Trade-offs between hydropower production and downstream flow requirements. Dams, development and downstream communities: implications for re-optimising the operations of the Akosombo and Kpong Dams in Ghana. Tema, Ghana: Digibooks Ghana Ltd. pp.228-248. ISBN: 978-9988-2-5046-1. Authors: Frank O. Annor, Maxwell Boateng-Gyimah, Marloes Mul, Philip Padi, Afua Adwubi, Kwame Darkwa and Charles Addo (2017).

Abstract

The project "Reoperating Akosombo and Kpong dams" seeks to restore downstream ecosystems and livelihoods. The Water Evaluation And Planning (WEAP) tool was used to assess four reoperation scenarios on future hydropower production and irrigation expansion in the Lower Volta basin including the impact of increasing or reducing the number of small reservoirs upstream of the basin. The scenarios are

(i) S1: Maintaining current flow regime based on hydropower requirement from Akosombo dam;

(ii) S2: Reinstating natural flow dynamics (up to 2010 spillway levels);

(iii) S3: Maintaining sufficient water for irrigation while reintroducing natural flow regime; and

(iv) S4: Reintroducing pre-dam flows that provide the conditions conducive for aquatic weeds control and clam production.

Throughout the simulation period (2016-2050), the potential average hydropower generated in the reference scenario is 5,256 GWh/annum. However, S1 increased generation by 0.2% whereas S2, S3, and S4 reduced power generation by 45%, 58% and 74%, relative to the reference scenario. Climate change projections will affect potential hydropower production, ranging from -8% for CC scenarios with decreasing water availability to +8% for CC scenarios with increasing water availability. Only Scenario 1 (optimization of hydropower production) satisfies the hydropower criteria of at least 6 GWh/day, whereas the other scenarios fail in this respect. In addition, S1 is the only scenario that managed to supply the FIRM (mean power output) hydropower requirement of 4,415 GWh/annum.

Adding new turbines to Akosombo dam during the wet season to make use of the extra water stored generated 9% increase in hydropower production per turbine added (S3 scenario) during the wet season increasing annual hydropower production by 1-2% only. This by no means offsets the reduction in hydropower and requires a strategic approach to augment hydropower production with other sources of energy.

For irrigation water demand, the present abstraction rate ($10m^3/s$) will not be affected during reoperation. Increasing abstraction rate to $38m^3/s$ to account for the anticipated irrigation expansion and increase in the number of small reservoirs, effective from the year 2020 would mean that the water demand for some few dry years will not be fully met (about 0.1% shortage).

3.1 Introduction

Every river basin has a unique population living in it. As a result, aquatic systems and their floodplains constitute important ecosystems that bring several socio-economic opportunities to riverine communities. One key benefit of the Volta River system, the Akosombo and Kpong hydropower dams which, hitherto, supplied about 95% of Ghana's energy demand. As a necessary 'evil,' the creation of the hydropower dams has altered the natural flow of the Volta River, impacting adversely livelihoods of downstream communities. Therefore, this study aims to investigate the technical and economic feasibility of a technique for re-operating and re-optimising the operations of the Akosombo and Kpong hydropower dams to reintroduce (or improve) downstream livelihoods and ecosystems, while maintaining, and indeed enhancing, power generation and reliability taking into consideration upstream developments such as the construction of additional small reservoirs. There are currently about 2000 small reservoirs in the Volta basin with a total storage of about 232 Mm^3 [1]. The maximum storage capacity of the Akosombo dam is 148 km^3, and over 30 Bm^3 of water flows to the Volta estuary per year on the average downstream of the Akosombo dam [24].

The concept of reoperation and reoptimisation of dams examines changing the flow regime to restore important ecosystem services that were offered by dammed rivers prior to the construction of the dam(s). During the pre-dam conditions, there were seasonal variations in flows (extremely low flows in the dry season and very high flows in the wet season). The low and high seasonal flows favoured the development of some ecosystem services on which the downstream communities depended on various times of the year. These included clams harvesting during the low flows, and flood recession agriculture after the high flows. Notwithstanding these benefits during this pre-dam period, there were water-borne diseases such as river blindness (onchocerciasis), bilharzia and malaria. Post-dam conditions brought about a near steady water level irrespective of the season. This in a way reduced the incidence of diseases such as onchocerciasis. However, due to the steady water level *(as shown in Figure 3.1 and Figure 3.2)*, downstream communities lost some of their livelihoods that depended so much on the seasonal variations such as the clam harvesting. Also, sandbars have built up and weeds infested the water due to low flows (reduced peaks). The sandbar builds up at the estuary due to the low flows thereby limiting the length of sea water intrusion which controls aquatic weeds growth. Reoperation and reoptimisation therefore seeks to operate the dams in such a way that low and high flows are released downstream consistent with pre-dam conditions to restore downstream ecosystem services while ensuring that power generation is increased at the same time. The reoptimisation and reoperation study of the Akosombo and Kpong dams assessed the feasibility of reoperating the two dams to restore the historical favourable flow conditions in the Lower Volta, in order to combat some of the challenges described above. Re-operating dams is an innovative way of addressing these challenges, while noting at the same time that reoperation can potentially increase or reduce the total annual hydropower production. The conventional way of operating a hydropower dam is depicted in *Figure 3.1*; dynamic flows are filling the dam and a steady flow regime is released. Due to the difference in inflow and outflow during the season the water level in the reservoir is fluctuating as well. During the dry season, the water level reduces as less water is flowing in than flowing out. The hydropower production throughout the year is relatively steady as a function of the water level and outflow. The re-operated dam on the other hand *(Figure 3.2)* releases flows that mimic the natural flow regime. In this scenario, as inflow and outflow are almost equal, the water level in the dam is steady. Hydropower production is therefore more efficient (there is more MWh per m^3). However, the hydropower production fluctuates throughout the year, and during the peak flow period, additional investments are required to harness the hydropower. Reduction in hydropower production during the dry season needs to be compensated for by increasing electricity generation capacity in the network.

The concept of dam reoperation has been there for some years [25], and more recent studies assess how it could work to maintain ecological health under climate change [26]. However, there are few examples of the concepts being put into practice and actual benefits of reoperation identified. This study of the Akosombo and Kpong dam reoperation and reoptimisation was therefore carried out to determine the viability of this concept in a river system that is said to belong to an Environmental Class B (slightly modified system [27]) focusing on hydropower production under different scenarios for downstream flow requirements [28] and climate change scenarios, which are described in the next sections.

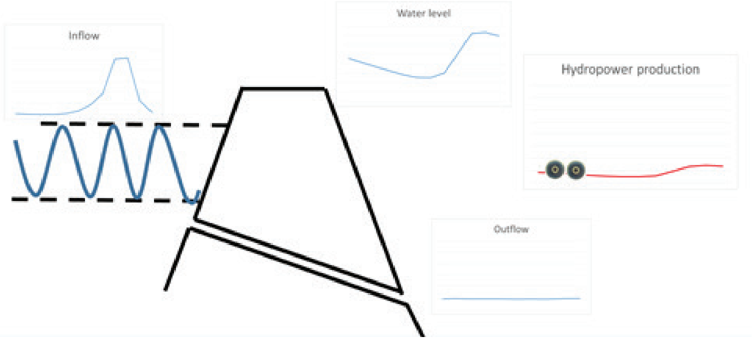

Figure 3.1: Dam operated for hydropower

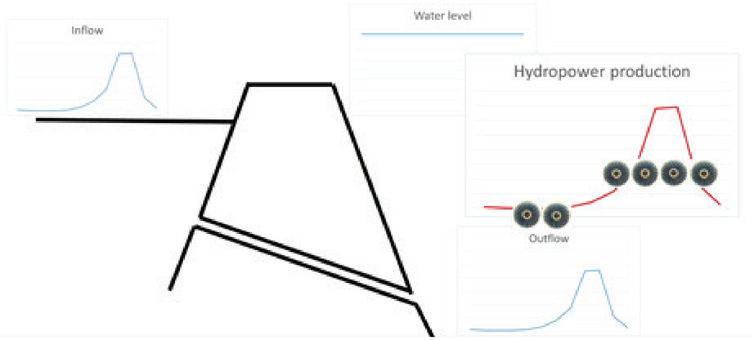

Figure 3.2: Conceptual model of dam reoperation

3.2 Methodology

The study employed desk study, and discussions with downstream communities and dam operators. Firstly, a study was used to define the downstream restoration hydrographs needed [29] as well as the impact of small reservoirs on this [28]. Secondly, a hydrological model (SWAT) was set up by Water Research Institute (WRI) in Ghana [30] to define the changes in flow due to competing water uses upstream and climate change. A water resources planning model was then set up using the Water Evaluation And Planning Tool (WEAP) to develop trade-offs between the competing uses to optimize hydropower production while meeting downstream flow requirements.

3.2.1 Restoration hydrographs for scenario building

Four (4) scenarios were defined for consideration in the water allocation model [29]. Recognising that the dams are permanent structures, the flows through the turbines were presented in four scenarios towards mimicking the pre-dam conditions to guarantee the maximum benefits accrued to the communities [29]. The scenarios are (i) S1: Maintaining current flow regime where streamflow is based on hydropower requirement from the Akosombo dam; (ii) S2: Reinstating natural flow dynamics (up to 2010 spillway levels); (iii) S3: Maintaining sufficient water for irrigation while reintroducing the natural flow regime; and (iv) S4: Reintroducing the pre-dam flow that provides the conditions conducive for weeds control and clam production.

For each of the scenarios, hydropower production is calculated. With the current number of turbines, the total hydropower production would automatically be reduced. Therefore, for S3, alternatives were developed by introducing additional turbines which harvest hydropower during the peak flows, thereby reducing the non-productive flows. The alternatives compose of 1, 2, 3, 4 and 5 additional turbines.

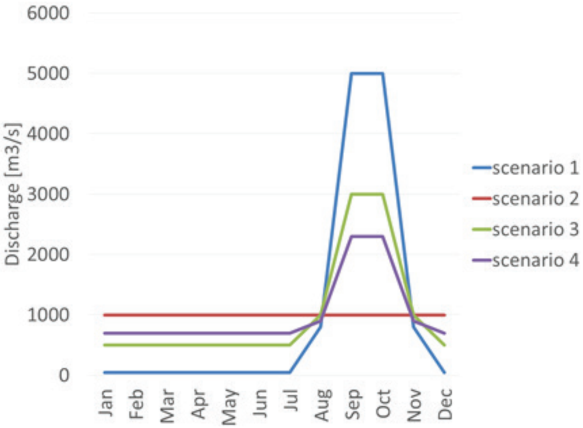

Figure 3.3: Hydrographs for scenarios of reoperation and reoptimisation of Akosombo and Kpong dams

3.2.2 Climate projections for the project area

Climate change projections used in the WEAP modelling are based on the research carried out by the WRI of Ghana [31] and are described in this section. To this end, climate simulations from two emission scenarios out of the six from the Intergovernmental Panel on Climate Change [32] were selected and downscaled for the Volta Basin. These are the A1B and A2 scenarios, the A1B scenario represents "business as usual" and lies between the extremes produced by other scenarios [32]. The A2 scenario represents a more differentiated world with local traditions being held onto which leads to a slow uptake of new technologies and over-reliance on fossil fuel which leads to high emissions [32]. In general, temperatures are expected to increase for both scenarios. Rainfall for each scenario is also expected to increase [31].

3.2.3 Streamflows

The changes in streamflows were assessed by running the climate change scenarios through the Volta SWAT hydrological model. The SWAT model output [31] under the two climate change projections gave about 17% increase in streamflow by 2025 (17.1% and 16.2% under the A1B and A2 scenarios respectively) basin wide. Considering all upstream consumptive demands including small reservoirs, inflows into Akosombo were projected to decrease by 17% [31]. In the WEAP model, both extremes (± 17% change in stream flow) are simulated up to 2050.

3.2.4 Hydropower Capacity and demand

According to MATREX/IESS [33], Ghana's power system has a total installed capacity of about 2,900 MW. The hydropower generation is distributed among the three hydro plants as follows: Akosombo (1020 MW), Kpong (148 MW) and Bui (400 MW), constituting about 54%. Thermal and solar power generation makes up the remaining 46%. The thermal generation is obtained from Aboadze (T3, TICO and TAPCo) and Tema (TT1PP, CENIT, MRP, Sunon Asogli and Siemens) [33].

The peak demand for Ghana for the year 2016 was estimated to be 2,477 MW while available supply is 2,698 MW, giving a surplus of 221 MW. However, the contribution from hydropower seems to be on a downward trend currently, which, calls for more thermal complements with an overall increase in energy production. This is due to a change in the distribution of annual flows as well as an overproduction of hydropower during periods with low supply from alternative sources, causing lowering of the water levels in the dam and an overall reduction in hydropower production per unit of water.

The information obtained above from the previous studies [29], [34] was used to set up the WEAP model described below.

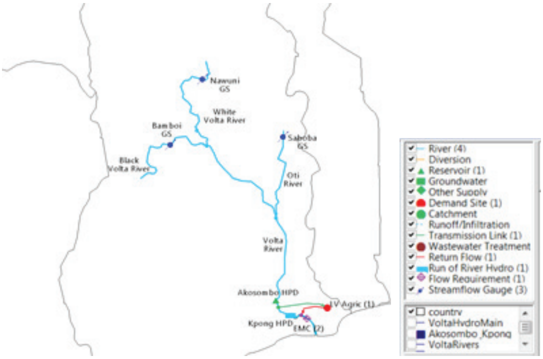

Figure 3.4: Schematic view of the Lower Volta WEAP model for the Akosombo and Kpong Reoperation and Reoptimisation project

3.2.5 WEAP model setup

The Water Evaluation And Planning (WEAP) system was selected for modelling the re-optimisation and re-operation of the Akosombo and Kpong dams. This was due to the fact that it is free software for developing countries and local capacity exists to support the beneficiary to apply it. WEAP is an Integrated

Water Resources Planning tool developed by the Stockholm Environmental Institute (SEI) in 1988 [35]. WEAP is used for simulating water storage (surface and groundwater), water demand, water supply, streamflow (runoff), evaporation and other local water 'losses" (e.g., infiltration), crop water requirements, environmental flow requirements/ecosystem services, reservoir operations, pollution/instream water quality, hydropower generation under scenarios of varying policy, hydrology, climate, land use, technology, and socio-economic factors. It integrates stakeholder processes, water balance assessment, scenario (policy) development and could also be linked with several models and utilities such as QUAL2K, MODFLOW, MODPATH, PEST, Excel, and GAMS (https://weap21.org/).

WEAP was first used in the Volta Basin in 2003 by Andah et al. [36] with several follow-up models developed by the International Union for the Conservation of Nature West and Central Africa Office (IUCN-PACO) in 2008 and together with the Volta Basin Authority (VBA) in 2012, as well as McCartney et al. in the same year [37]. They were used as tools to support Volta Basin Water Resources Planning and decision making (policies on water allocation).

The current model is an update of the first daily operational model developed using WEAP to simulate the reoperation and reoptimisation of the Akosombo and Kpong dams using historic data from 1981 to 2013 and projected to 2050 [38]. Data used consisted of water levels, storage-elevation curves, reservoir upstream and downstream elevations, releases from the dams and hydropower generated. Net inflows are computed using the mass balance approach for each day of operation for the Akosombo dam and Kpong run-of-the river hydropower dam using *Eq 3.1* [38].

$$\text{Net inflow}=(\text{Final Storage}-\text{Initial storage}+\text{release})/\Delta t \qquad \text{Eq. (3.1)}$$

Where

Net inflow is in m^3/s

Final Storage is in m^3

Initial storage is in m^3

Release is in m^3

Δt is time in seconds

The model is set up to run on a daily time step for the Lower Volta sub-basin where the Akosombo and Kpong Dams are located as well as irrigated farms, and provisioning services for the populations. This was developed to capture the "real" operations of the Akosombo and Kpong dams by the Volta River Authority (VRA).

The model focuses on releasing water to meet the four reoperation scenarios downstream of Akosombo and the Kpong hydropower dams to assess the various trade-offs between the different uses (hydropower, environment, and irrigation). *Figure 3.4* presents the schematic view for the model.

3.2.6 Input data

3.2.6.1 Water demands

For the Lower Volta, only Hydropower, Agriculture (Irrigation) and the Environmental Flow Requirements (restoration scenarios) [29] are used. The irrigation water requirement as of 2016 was 10m^3/s which is quite insignificant compared to the reservoir releases from Akosombo and the inflows to the Kpong Dam (approximately 1,000m^3/s) [39]. However, intakes are sensitive to water level fluctuations.

3.2.6.2 Hydropower projections

Figure 3.5 shows the hydropower generation, energy consumption and projections for Ghana. The country relied solely on Akosombo and Kpong dams for her energy needs for nearly 3 decades after construction. Taking into account the growing economy and urbanization, thermal sources were introduced in the early 1990s. The need to increase the thermal component was heightened following the energy crisis in the country in 1997, arising from the low water levels in the Akosombo dam. Recognising the insecurity related to the reliance on the weather and, by extension, the climate in hydropower generation, it was necessary to safeguard and maintain the power generated to sustain economic growth of the country. In the early years of the generation mix, production (supply) exceeded demand (consumption) and hence Ghana could export energy to other West African countries. However, recent low water levels in the Akosombo dam as well as the increasing demand for energy due to population and economic growth has had a lot of negative implications for the energy sector, demanding a shift from relying heavily on hydropower to diversified energy sources (especially thermal energy) which are normally associated with a higher cost of production per KWh relative to the former. The projections for Akosombo after 2016, was prepared with VRA experts on the assumption that the hydropower plant would not generate more than the "FIRM" (4,415 GWh) per year as shown *Figure 3.5.*

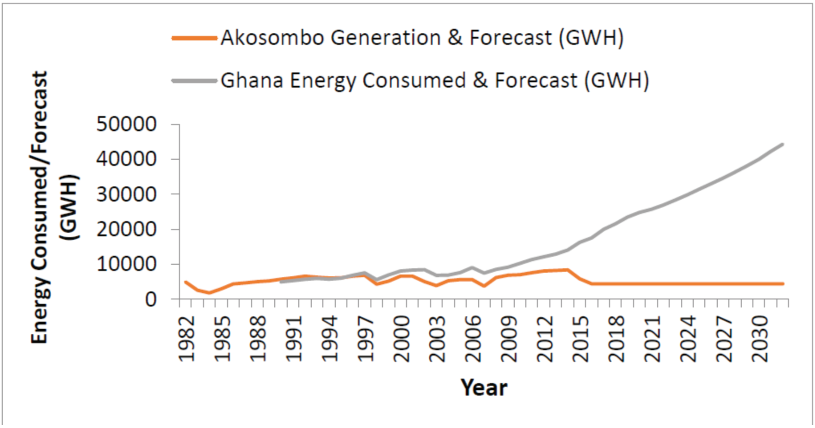

Figure 3.5: Ghana's Energy demand/consumption forecasts

3.2.7 Physical constraints of the Akosombo and Kpong dams

The maximum hydraulic outflow (flows through the spillway + turbines) is 22,297m^3/s. The maximum turbine flow for Akosombo is 1,600m^3/s. There was an increase in the generation efficiency from 90% to 93% after the retrofits in 2006. The top of inactive storage for Akosombo dam is 74,000 Million m^3 (equivalent of a water level of 73 m) out of the total storage of 148,000 Million m^3 (84 m water level).

3.2.8 Model calibration, verification and evaluation criteria

The WEAP model was calibrated with historic inflows and power production and verified with the VRA team. The calibration was done using the observed volume of the reservoir and the hydropower generated. It must be noted that one of the most sensitive parameters in WEAP is the energy demand which was used for the calibration. In reality, the operation of the dams is more dependent on the capacity to generate instead of the demand to be met. After calibration (1981-2000), the modelled and observed volume at Akosombo gave a regression correlation coefficient of 0.987 with a Nash–Sutcliffe model efficiency coefficient of 0.984, while the annual hydropower production (1984-2000) gave a regression correlation coefficient of 0.737 with a Nash–Sutcliffe model efficiency coefficient of 0.664 (See *Figure 3.6*; [40]).

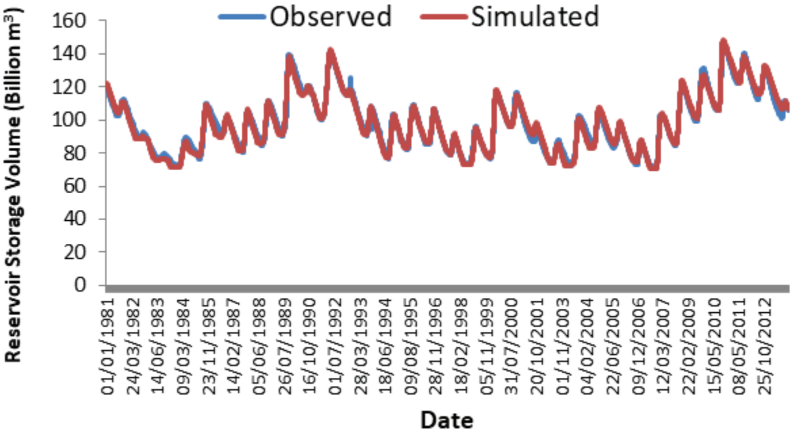

Figure 3.6: Simulated and observed water storage volume at Akosombo (1981-2013

In assessing the feasibility of the scenarios, three (3) main criteria were used.

(i) Annual Hydropower power production has to be close to the current generation or at least has to match the FIRM (4,415 GWh) at Akosombo;

(ii) The minimum daily electric output needed at Akosombo for system stability is 6 GWh hence the percentage of time this demand is not met is considered; and

(iii) the flow scenarios should meet downstream flow requirements and irrigation demand.

3.3 Results and Discussion

Figure 3.7 shows the daily average hydropower production at Akosombo over the simulation period (2016-2050) and depicts that only S1 meets the minimum hydropower criteria at all times.

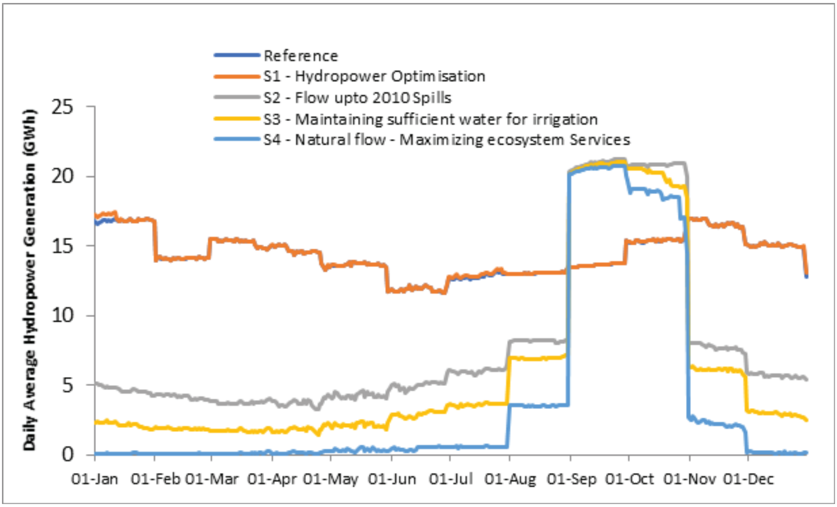

Figure 3.7: Daily Hydropower Generation at Akosombo (2016-2050) for the 4 main scenarios and the reference scenario.

Table 3.1 shows that, on average, S1 generates energy comparable to the current scenario or above the 4,415 GWh “FIRM” at Akosombo. Each of the restoration scenarios (without additional investments) fails to reach the FIRM hydropower production during the dry season. The hydropower production decreases from 45%, 58% and 74% for S2, S3 and S4, respectively. For the daily firm power generation of 6 GWh, *Table 3.2* shows that only the reference and S1, are able to maintain the minimum power generation. The other scenarios fail 7, 8 and 10 months per year for S2, S3 and S4, respectively. For S4 this basically means that, except for the two flood peak months (September and October), the minimum power generation is not reached.

Table 3.1: Hydropower production at Akosombo

	Total (2016-2050)		Maximum (2016-2050)		Minimum (2016-2050)		Average (2016-2050)	
Scenario	GWh	% w.r.t Ref.	GWh	% w.r.t Ref.	GWh	% w.r.t Ref.	GWh	% w.r.t Ref.
Reference	183,970	100.0%	6,241	100.0%	835	100.0%	5,256	100.0%
S1 - Hydropower Optimisation	184,341	100.2%	6,241	100.0%	835	100.0%	5,267	100.2%
S2 - Flow up to 2010 Spills	100,618	54.7%	3,603	57.7%	831	99.6%	2,875	54.7%
S3 - Maintaining sufficient water for irrigation	76,463	41.6%	2,684	43.0%	807	96.7%	2,185	41.6%
S4 - Natural flow - Maximizing ecosystem Services	48,624	26.4%	1,581	25.3%	578	69.3%	1,389	26.4%

Table 3.2: Percentage of time minimum hydropower production is met for the various scenarios

Scenario	% time in a year >= 6 GWh	No. of months
Reference	100%	12
S1 - Hydropower Optimisation	100%	12
S2 - Flow up to 2010 Spills	39%	5
S3 - Maintaining sufficient water for irrigation	33%	4
S4 - Natural flow - Maximizing ecosystem Services	17%	2

The alternatives with adding additional turbines, do not change the minimum power generation, as the turbines will be operated only during high flows. The additional turbines are able to generate additional hydropower during the wet season, increasing the power generation by about 9% per additional turbine *(Figure 3.8)*. However, for the total hydropower production in a year, the added benefits in terms of hydropower generation are less than 1% per additional turbine, as they are only operational during 2 months in the year.

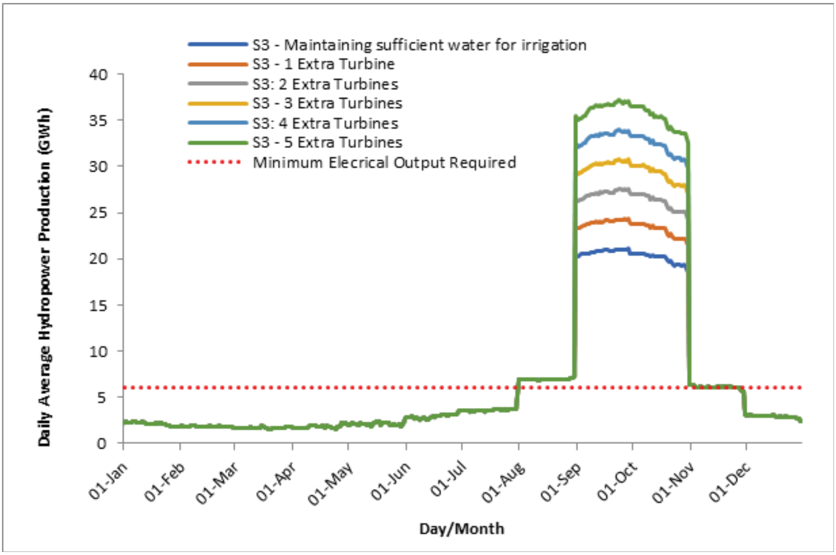

Figure 3.8: Hydropower production (Daily Average from 2016-2050 at Akosombo) for S3 with 1-5 additional turbines

The impact of the climate projections from WRI [31] leading to +/-17% increase in streamflow resulted in either a reduction or increase in hydropower production by 8% (see *Figure 3.9*). For the climate projection with increasing streamflow, the targets for FIRM and minimum hydropower production are more easily met. However, for the climate projection with a reduction in streamflow, more failures of meeting the hydropower production requirements are expected.

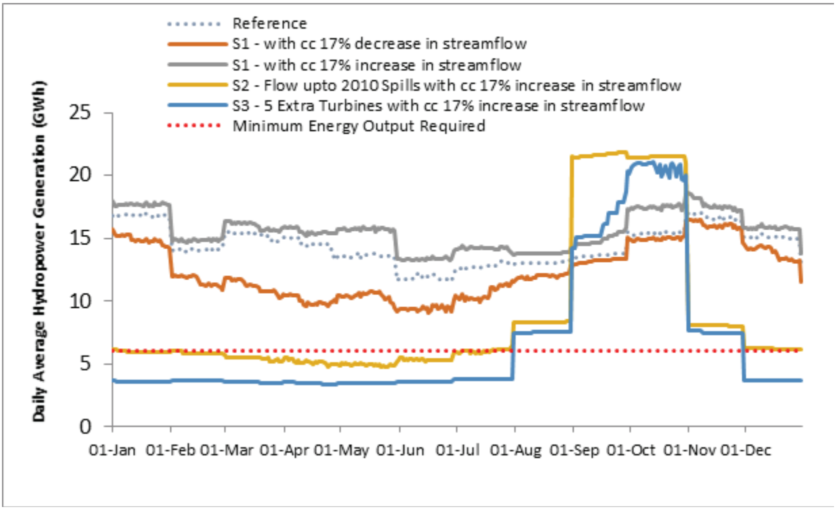

Figure 3.9: Daily Average Hydropower Generation at Akosombo with Climate Change Considerations

Climate change (See *Figure 3.10*) will cause an increase or reduction in hydropower production by 8% on the average per annum.

On an annual basis, *Table 3.3* shows that irrigation water shortages are negligible (less than 0.1% of the total demand) on average (2016-2050) for all scenarios. The irrigation demand as of 2016 was 10m^3/s which increased to 38m^3/s by the end of the simulation period 2020 [14]. Regardless of the increase, it is not expected that the shortages for irrigation in S1, S2 or S3 will become significant. However, for S4, future irrigation requirements will be affected. The downstream flow regime for S1, S2 and S3 (*Figure 3.10*) follow the proposed hydrographs during the peak flows. However, during the low flows, the discharge is slightly lower than the proposed hydrographs. For S4, the peak flows do not manage to reach the target of 5,000 m^3/s for the months of September and October.

Table 3.3: Unmet Annual Irrigation Water Demand in the Lower Volta basin from 2016-2050

Scenario	Maximum		Average	
	Unmet Demand (m^3)	% of Demand	Unmet Demand (m^3)	% of Demand
Reference	668,872	0.06%	80,696	0.01%
S1 - Hydropower Optimisation	668,872	0.06%	79,863	0.01%
S2 - Flow up to 2010 Spills	1,408,417	0.12%	385,584	0.03%
S3 - Maintaining sufficient water for irrigation	1,429,337	0.12%	560,111	0.05%
S4 - Natural flow - Maximizing ecosystem Services	1,960,448	0.16%	906,886	0.08%

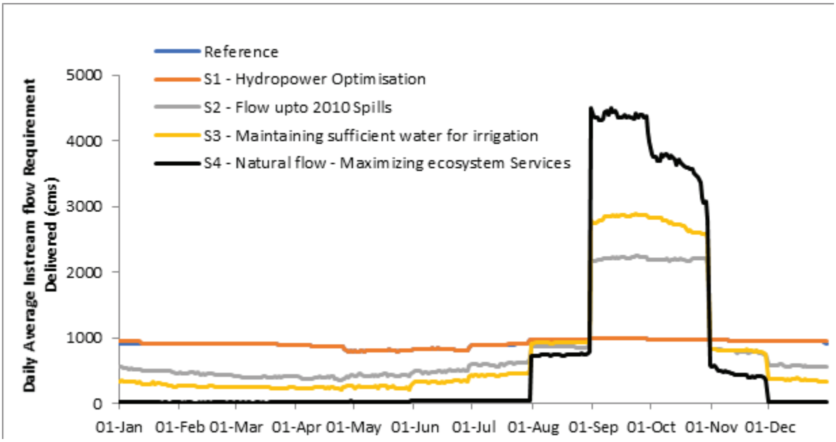

Figure 3.10: Average daily Downstream flow requirements delivered (2016-2050

3.4 Conclusions

Providing restoration flows to the downstream communities of Akosombo and Kpong dams adversely affects the hydropower production. Throughout the simulation period (2016-2050), potential average hydropower generated in the reference scenario was 5,256 GWh/annum. Hydropower optimisation (S1) was 5,267 GWh/annum, S2 generated 2,875 GWh/annum, S3 generated on average 2,185 GWh/annum and S4 1,389 GWh/annum, representing reduction of 45%, 58% and 74% for S2, S3 and S4, respectively. Uncertainty in climate change projections affects potential hydropower production, ranging from -8% for CC scenarios with decreasing water availability to +8% for the CC scenario with increasing water availability. Only Scenario 1 (optimization of hydropower production) satisfies the minimum hydropower criteria of 6 GWh per day, whereas the other scenarios fail in this respect. In addition, S1 is the only scenario that manages to supply the FIRM hydropower requirement of 4,415 GWh/annum.

The results obtained shows that, reoperating the dams will have major negative implications for hydropower production. The value created by adding up to five (5) turbines was a 9% increase per additional turbine in hydropower production (S3 – CC increase), during the wet season. This means adding more turbines cannot compensate for the reduction in hydropower due to reoperation. This calls for a more strategic approach to augment hydropower production with other sources of energy.

For irrigation water demand, the present abstraction rate (10m3/s) is relatively low and will not be affected during re-operation. Increasing the abstraction rate to 38m3/s to account for the anticipated irrigation expansion with additional small reservoirs will result in a few possible dry years. The demand for those years will not be fully met (about 0.1% shortage), especially when the outflow from Akosombo is very low (i.e. 2 turbines are operated). The shortage of irrigation water demand, however, could be said to be negligible for all the plausible reoperation scenarios (S1, S2 and S3 with additional turbines). Quantifying the trade-offs in re-operating the Akosombo and Kpong dams is therefore important especially for environmental flow downstream and hydropower production upstream [41].

4

Evaporation measurements over small reservoirs in Ghana's Upper East Region

Evaporation at night can be higher than during the day.

This chapter has been submitted to the journal of Physics and Chemistry of the Earth as Evaporation measurements over small reservoirs in Ghana's Upper East Region. Authors: Annor, F. O., Abbasi, A., & van de Giesen, N.

4.1 Introduction

In the hydrological cycle, evaporation plays a major role. However, it is difficult and expensive to directly measure evaporation fluxes in the field continuously for an extended period of time [42], such as with the Eddy Covariance Method. Still, evaporation is by far the most crucial factor in explaining water losses from reservoirs [43]. Accurate estimation of evaporation is required for irrigation management and water resources planning. Knowledge of hydrologic fluxes including evaporation is required for monitoring and understanding hydrological and ecological processes [19], [44]–[49].

Due to the complexity of direct measurements, most evaporation estimations are derived from meteorological variables [50]–[52]. Over land surfaces, often the reference (E*ref*) or potential evaporation (E*pot)* instead of the actual evaporation (E*act*) is estimated based on meteorological variables. Reservoir evaporation measurements and studies are more frequently undertaken for large reservoirs than for smaller ones [3], [13].

Evaporation is measured directly using lysimeters or Eddy Co-variance (EC) systems, and indirectly using meteorological parameters with analytical methods (energy balance, water budget and mass transfer) or empirical equations [54], [55]. Since small reservoirs in the Upper East Region are ungauged, the methods used here focus on how the various components of the water and energy balances could be estimated by remote sensing, meteorological variables, and other in-situ measurements.

The general thinking is that small reservoirs in (semi-)arid environments are not efficient because their evaporation losses are relatively large. For planning purposes, one would typically assume that the evaporation is equal to, or larger than Eref such as calculated by the Penman formula. Due to the fact that meteorological data are typically not gathered over water, one would use values measured over land. During the dry season, the air over land tends to be warm and dry, resulting in a very high Eref. Because water is not limiting in a reservoir, it is reasonable to assume that evaporation is at least E*ref*. Studies in Tunisia [56] suggest that Eref may even be exceeded in an oasis as a local circulation is set up between a wet area and the surrounding dry area, thereby increasing advection of additional energy towards the evaporating surface. Interestingly, for the Upper East region of Ghana, it has been shown [14] that E*act* is often less than E*ref*. Typical values for Eref during the dry season are 4mm/day – 10mm/day. However, the Eact values found through two methods were closer to 5mm/day – 6mm/day.

In this chapter, measurements are presented that should:

a) Confirm or refute that *Eact* < *Eref*, and

b) Provide insights into the processes that produce these results.

Specifically, several hypotheses will be tested and discussed:

a. The internal boundary layer over the lake and its spatial and temporal dynamics reduces *Eact*;

b. Asymmetries between day and night long-wave radiation prevent that reduction of evaporation during the day is fully compensated by extra evaporation during the night; and

c. The observed radiative cooling of the top layer of the reservoirs reduces *Eact*.

4.2 Methods

4.2.1 Evaporation Studies

There are many ways to estimate evaporation from water bodies with various levels of difficulties and data requirements. The three most commonly used types of methods are: direct measurements using evaporation pans and Eddy Covariance systems, analytical methods (energy balance, water budget and mass transfer), and empirical equations. In this section, these methods are further elaborated upon, and some are used to compute the evaporation losses from two small reservoirs in the Upper East Region. A more comprehensive overview of evaporation methods and their pros and cons can be found in [52], [57]–[60].

Detailed evaporation studies of small reservoirs are rare. When such studies are undertaken, they are often based on sparse data or data collected remotely [3], [4], [10], [49], [54], [59], [61]. In Africa, there are only a few studies on small reservoirs. Alazard et al. [57] carried out a study on the El Haouareb dam with a capacity of 104 Million m^3 in Tunisia which is much bigger than the small reservoirs (< 5 Million m^3) in the Upper East Region of Ghana being studied here. Prior to that, there was a study by Elsawwaf et al. [58] in Egypt. This shows the need for a better understanding of the evaporation processes of small reservoirs especially the thermal stratification and the advection from surroundings to improve evaporation estimation [61]–[63]. Evaporation from small reservoirs is affected by the fetch, slopes, and roughness lengths, which make them complex and interesting to study [23], [54].

For the mass balance and energy budget methods of estimating evaporation from lakes, it is important that the volume (mass) and temperature (heat) distributions in the lake are known. In estimating the volume of reservoirs, the depth-area-volume relationship (explained in Chapter 2 of this thesis) is critical especially if the balances are based on remote sensing [3], [6], [17], [64]–[66].

Parameters that affect the change in the energy stored in the water and the Bowen Ratio are important for small reservoirs [58]. Evaporation from small reservoirs is not only affected by weather parameters such as global (solar) radiation, relative humidity, air temperature, wind speed, and atmospheric pressure but also by the water temperature, depth, and area (shape) and turbidity (quality of the water) [67]. Evaporation depends also on the vapour pressure gradient and radiant energy supply [60], [68].

The Bowen Ratio Energy Balance (BREB) and Eddy Covariance (or Eddy-Correlation flux) methods require high quality and expensive instrumentation but are deemed to be much more accurate than other evaporation estimation methods over short periods of time [3], [58], [59], [63], [67]. Evaporation processes are complex and may not be fully captured or fully understood with only simplifying physical models since many factors affect it that are not directly measurable. Hence empirical methods for estimating evaporation from reservoirs, although simple and economical, have to be used with care, especially over short time periods [60].

4.2.2 Evaporation measurement using pans

The pan evaporation method is the most common for estimating lake evaporation due to its ease of use or interpretation of the results. The challenge often faced is the selection of the correct pan coefficient [52], [69] as well as its maintenance (adding water to or removing water from the pan, controlling birds, keeping the environment tidy and regular readings by local hosts or operators). The standard pan evaporation is corrected with *Eq. (4.1)* using the correct pan co-efficient to estimate the reservoir/lake evaporation.

$$E_o = K_p E_{pan} \qquad \text{Eq. (4.1)}$$

Where:

E_o=Lake Evaporation (mm)

E_p=Pan Evaporation (mm)

K_p=Pan Evaporation Coefficient

K_p depends on the management and operation of the pan, its location, the period of the year, the type of pan being used [52], [69] and for a more detailed estimate, the average wind speed, fetch, and relative humidity are needed [70]. For evaporation measurement in reservoirs the pan can be floated on the water [71].

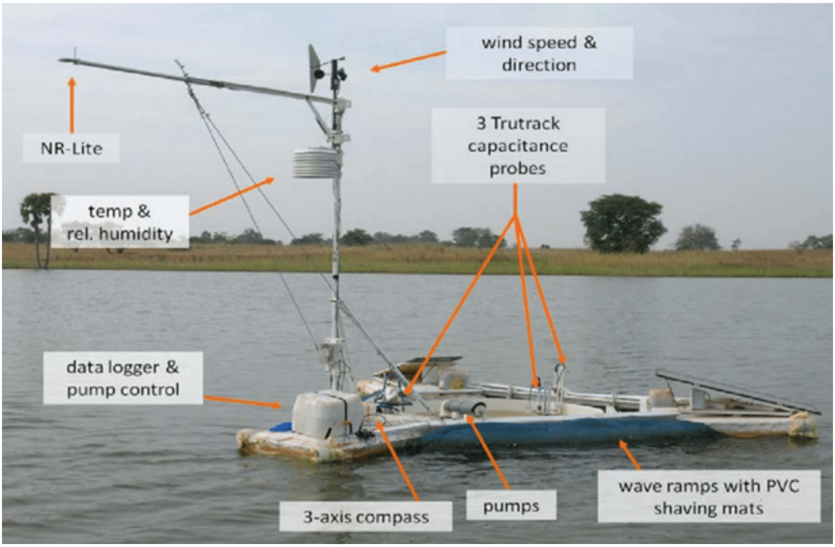

Figure 4.1 Floating Evaporation Pan installed for evaporation experiments in the Upper East Region of Ghana [71]

At the Binaba dam, a Colorado sunken pan *(Figure 4.2)* was installed and used to measure evaporation on a daily basis at 6.00am GMT. A standard automatic weather station that measures the wind speed, wind direction, atmospheric pressure, temperature, relative humidity, rainfall, and global solar radiation at 2m at 15minutes temporal resolution was also installed. The station had a Decagon EM50G logger and Decagon sensors (now referred to as METER/TAHMO

Generation 1 station) consisting of a PYR: solar radiation (W/m^2); Davis Cup Anemometer: wind speed (m/s), wind direction (°); ECRN-100: precipitation (mm); VP-3: Vapour Pressure (kPa) and temperature (°C) [72].

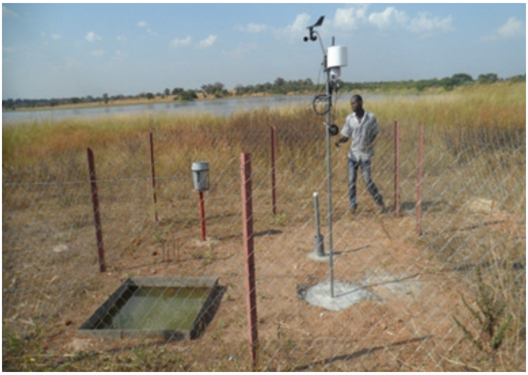

Figure 4.2 Colorado Sunken Evaporation Pan and an Automatic Weather Station set-up for Lake Binaba in the Upper East Region of Ghana

4.2.3 Evaporation Measurement using Eddy Covariance

An Eddy covariance (EC) system measures at high temporal frequencies 3D wind speed and scalar atmospheric variables for which one would like to know the vertical flux in the lower atmospheric boundary layer. In our case, we were interested in the sensible heat flux and the evaporative fluxes. Unfortunately, no fast hydrometer was available, only a 3D wind speed sensor that also measures air temperature was used. This implies that there is a direct measurement of the sensible heat flux. The evaporation can be derived through the measurement of some additional variables using the method presented in Vercauteren et al. [73]. The measurements and derived values for our set-up include 3D wind speed, momentum flux, sensible heat flux, Monin Obukhov length (or other stability parameter), flux footprint (80% of flux), and air temperature. Auxiliary measurements captured air pressure, and relative humidity at different heights.

The EC data logging was done with a DOS-based program (EddylogP - [74]) designed to store serial data from the sonic anemometer. The data was stored at 10 Hz in binary format which could easily be read by Alteddy [74]. The flux measurements were processed using the method proposed by [75] using the Alteddy software version 3.90 [74]. The raw fluxes were accumulated over a period of 30 minutes interval for the analysis.

Two reservoirs, Lake Binaba (10.778927oN, 0.464859oE) and Lake Winkogo (10.713025°N, 0.859063°W), were studied within the framework of a bigger project - the Challenge Program for Water and Food (CPWF-V3) [76] in the Volta basin. Details of the communities are presented in Chapter 1 of this thesis and [4], [23], [54]. Lake Binaba *(Figure 4.3)* has a surface area of about 30ha, a mean depth of 1m and a maximum depth of 4m whereas Lake Winkogo *(Figure 4.4)* had a surface area of 7.5ha, a mean depth of about 0.7m and a maximum depth of 2.5m.

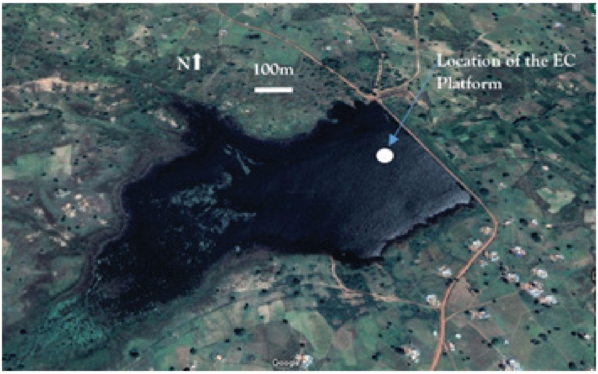

Figure 4.3 Location of the floating EC platform over the Lake Binaba

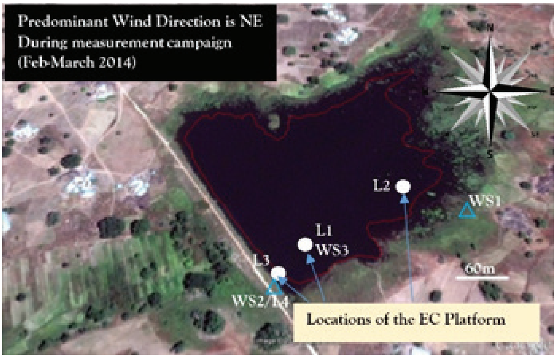

Figure 4.4 Locations of the EC platform (L1, L2, L3 in water – white dots, and L4 on land) and Meteorological Stations (WS1, WS2, WS3 – blue triangles) over the Lake Winkogo

4.2.3.1 Lake Binaba Eddy covariance system set-up

At Binaba, an Eddy covariance (EC) system was set up comprising of a compass, wind vane, cup anemometer, air temperature and relative humidity sensors, and a Gill Windmaster sonic anemometer [77] to measure sonic temperature, sensible heat and 3D windspeed. A Kipp & Zonen CNR1 radiometer [78] was installed, which was made up of a pair of pyranometers and pyrgeometers used only during part of the measurement campaign (October 18 to October 29, 2012) to measure the balance between incoming short-wave and long-wave infrared radiation as well as the surface-reflected short-wave and outgoing long-wave infrared radiation from which the net radiation is computed. The CNR1 includes Resistance Temperature Detectors (RTD) to measure its internal temperature. During the rest of the measurement campaign, when the CNR1 was not used (February 2012, June 2012, November – December 2012), the EC was equipped with a Kipp & Zonen NR Lite 2 Net radiometer [79] to measure the net radiation. The EC measurements were taken at a frequency of 10Hz. The EC was installed on a floating platform. 10-minute averaged temperature measurements in the water were taken using HOBO TidbiTs v2 temperature data loggers [80] at various depths. This temperature measurement is cost-effective, accurate and suitable for continuous monitoring of temperature [81].

A floating platform designed by Gijsbers et al. [82] was used to set up an eddy covariance system on the Binaba dam to measure the energy fluxes *(Figures 4.5 - 4.7)* ensuring that it was able to float, freely turn around its anchor cable and be stable with a large righting moment *(Figure 4.8)*. The platform was constructed with wooden boards, a 3m long PVC tube with a 22 cm diameter sealed at the bottom (water-tight) and filled with lead weights and batteries (at the bottom) to provide a low natural frequency (eigenfrequency). The long tube with the weight at the bottom gives a large righting moment.

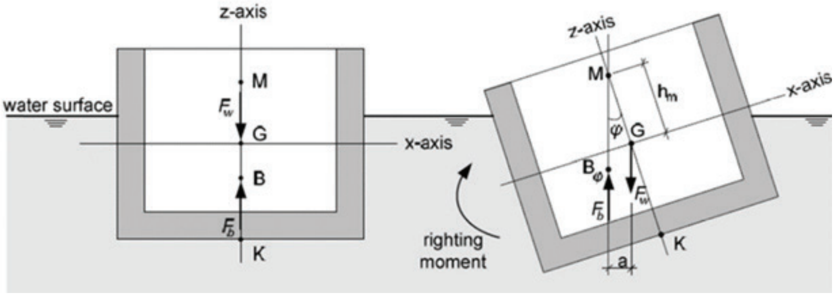

Figure 4.5: The concept of righting moment from Gijsbers et al. G is the centre of gravity, B centre of buoyancy of the floating platform, Fw is the force exerted by the weight, Fb is the buoyancy force, and M is the metacentre. [82]

The movement of the platform was monitored with an accelerometer [82], which confirmed that it was stable with no fluctuations to increase the vertical turbulence fluxes [82]. The top of the floating platform was at first made of an aluminium frame which was used to mount the instruments, then later a wooden frame was added to the aluminium platform to provide enough room for the solar panel, water-tight containers for the palmtop (which runs the EC software from Elbers - [75]), loggers and the mounting of the sensors. The sensors included the combined shielded temperature and relative humidity sensor, sonic anemometer and radiometer. The design of the platform therefore evolved from October 2011 *(Figure 4.6)*, to February 2012 *(Figure 4.7)* and to November 2012 *(Figure 4.8)*. The final platform had a large, inflated tube to provide a large second moment of the water plane. The initial versions started with no tube, empty gallons (commonly known as the "Kuffour gallons" in Ghana) and the last version with the inner tube. The first, second and third setups with improvements of the platforms for the Eddy Covariance system are shown in *Figures 4.6 - 4.8.*

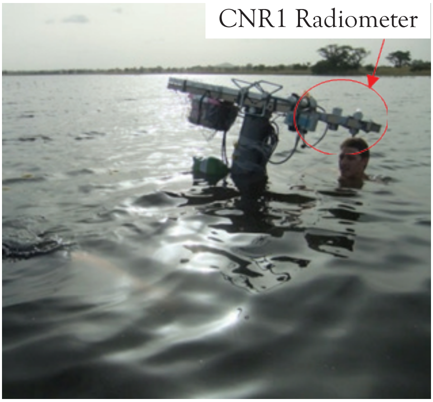

Figure 4.6: EC system on the 1st floating Platform installed in the Lake Binaba with a CNR1 Radiometer floating on a PVC pipe

There were two problems with the first EC system shown in Figure 4.6. These were mainly logger connection problems and stability of the platform. The design therefore had to be modified to make it more stable and to reduce the weight on the platform. This led to the second EC system shown in Figure 4.7.

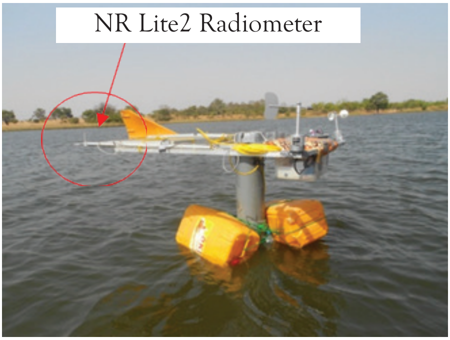

Figure 4.7: EC system on the 2nd floating Platform installed in the Lake Binaba with a NR Lite 2 Radiometer floating on a PVC pipe

The second setup was more stable but also suffered from a logger malfunctioning. This meant the logger had to be rebuilt but this time in a more simple but robust form. This was done and installed on the 3rd Setup (EC system) shown in Figure 4.8. The stability of the setup was further improved with a rubber tube and less weight on the platform itself. The anchoring was done at the bottom of the PVC pipe and allowed for free rotation. The initial results from the third setup were good and lead to the extended campaign for EC measurements in November-December 2012 – the results of which are presented in this Chapter.

Figure 4.8: EC system installed on the 3rd floating platform in the Lake Binaba with NR Lite2 Radiometer floating on a PVC pipe fitted with an inflated rubber tube with a metal and wooden platform with the sonic anemometer at 1.90m above the water surface.

4.2.3.2 Lake Winkogo Eddy covariance system set-up

The EC system with the same sensors as Binaba was set up in Winkogo from 2 February – 8 March 2014 but with the CNR1. The system was mounted on a heavy-duty height-adjustable tripod mast *(Figure 4.9)* because the reservoir was shallow enough at the time of the field work (mid of the dry Season). The EC measurements were made at three different places (at the tail end of the lake (L2), middle of the lake (L1) and closer to the dam wall (L3) as well as on land (on the dam wall – L4) – see Figure 4.4) at four different heights (1.54m, 2.95m, 3.5m and 4.25m from the surface of the lake) at a frequency of 10Hz. This was done in order to study the build-up of the internal boundary layer of the lake.

In addition to the EC system, three meteorological stations were set-up; two on land (the first on land about 100m from the lake and the second one on the dam wall which was also one of the locations for the EC measurements – L3 in *Figure 4.4*, and the third station was attached to the EC system to measure relative humidity and temperature only. The land-based meteorological stations consisted of a Decagon EM50G logger and Decagon sensors consisting of a PYR: solar radiation (W/m^2); Davis Cup Anemometer: wind speed (m/s), wind direction (°); ECRN-100: precipitation (mm); VP-3: Vapour Pressure (kPa) and temperature (°C) [72]. All meteorological stations were set to measure at 15 minutes temporal resolution (averaging).

Figure 4.9: EC system installed on Lake Winkogo on a heavy-duty adjustable tripod platform

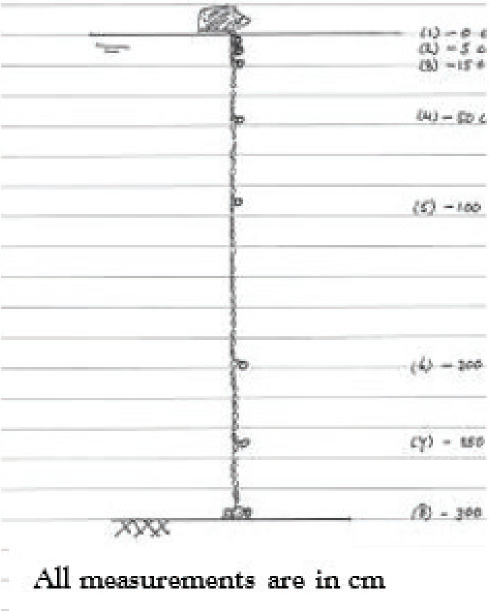

Figure 4.10: A sketch of the buoy with string and TidbiTs in water [4]

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[4] Picture and diagram provided by Dirk Floris van Duijn (2012).

TidbiTs were installed (Figure 4.10) at two locations, Point 1 (10.71301°N, 0.85933°W); Point 2 (10.71315°N, 0.85928°W) on the reservoir to determine the temperature profile in the water. This measurement helps to determine the heat storage in the reservoir.

4.2.4 Evaporation from the Water Balance Method and Remote Sensing

For small reservoirs in the Upper East Region of Ghana, in November (just at the beginning of the dry season) where most reservoirs are at full capacity (see Chapter 2 of the thesis for the computation of the volume of the reservoirs), some components of the water balance could be estimated and left out *(Figure 4.11; Eq. (4.2))*.

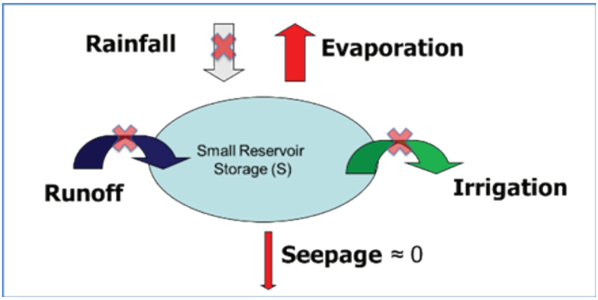

Figure 4.11: Water balance of small reservoirs at the onset of the dry season

$$P+\cancel{Q_{is}}+\cancel{Q_{ig}}=Q_{os}+\cancel{Q_{og}}+E_o+\Delta S/\Delta t \qquad \text{Eq. (4.2)}$$

Where all units are converted into depth of water per day

P = Rainfall (mm/day)

Q_{is} = Surface water inflow (mm/day)

Q_{os} = Surface water outflow (mm/day) for irrigation

Q_{ig} = Groundwater inflow (mm/day)

Q_{og} = Groundwater outflow (mm/day)

E_o = Evaporation (mm/day)

$\Delta S/\Delta t$ = Change in storage over time (mm/day)

Evaporation estimates were made for 34 reservoirs *(Figure 4.11)* using remote sensing and established regional reservoir depth-area-volume relationship (see Chapter 2 of this thesis) using *Eq. (4.3)*. This assumes Q_{ig} and Q_{og} cancel out or are relatively small which may not be the case in all seasons.

$$E_o = \Delta S / \Delta t \qquad \text{Eq. (4.3)}$$

4.2.5 Evaporation according to the Vercauteren Method

Evaporation from the EC measurements was calculated using the Vercauteren et al. [73] method presented as *Eq. (4.4* which relies on the measurement of the sensible heat flux at one measurement height as was done in Binaba. Although at Winkogo measurements were done at different heights to study the effect of fetch on the evaporation rates

$$E = \frac{\Delta}{\gamma} \cdot \frac{H}{L_e} + E_A \qquad \text{Eq. (4.4)}$$

Where Δ is the slope of the saturation vapour pressure curve (kPa/K), ϒ is the psychometric constant (kPa/K), H is the sensible heat flux (W/m2), Le is the latent heat of vaporisation of water (Le = 2.453 x 106 J kg-1), EA is the drying power of Air = f(u)(es*- ea) (mm/s), and E is the rate of evaporation (mm/s).

The wind function used is the same as that of Vercauteren et al. [73] and presented as *Eq. (4.5)*. Where u is the mean wind speed (m/s) adjusted to a height of 2m using a logarithmic wind speed profile [83].

$$f(u) = 1.25 \times 10^{-8}\ u \qquad \text{Eq. (4.5)}$$

Eq. 4.2 and *Eq. (4.5)* are then used to estimate evaporation according to Vercauteren et al. [73]. For Binaba and Winkogo E and EA have been converted into mm/day.

4.2.6 Bowen Ratio Energy Balance Method (BREB)

The ratio between heat and evaporative fluxes from the water surface is the Bowen ratio (β) [84] which can be used to calculate the evaporative flux as

$$\lambda E = \frac{R_n - G}{1 + \beta}$$ Eq. (4.6)

By definition, the Bowen ratio can be estimated by the ratio between the sensible heat and latent heat as shown in Eq. (4.7).

$$\beta = \frac{H}{\lambda E}$$ Eq. (4.7)

Furthermore, if the turbulent transport coefficients of heat and water vapour are assumed to be equal above the water surface, the Bowen ratio can be estimate with Eq. (4.8) [73].

$$\lambda E = \gamma \frac{T_s - T_a}{e_s^* - e_a}$$ Eq. (4.8)

Where

T_s = Water surface temperature (K)

T_a = Air temperature (K)

e_s^* = the saturated water vapour pressure at the water surface temperature (hPa) and e_a is the vapour pressure at the air temperature (hPa)

γ = the psychometric constant (0.67hPa/K)

BREB is considered as the standard method for the estimation of evaporation over lakes, but it has a high input requirement [3], [59], [67], [85], [86].

4.2.7 FAO Penman Method

The FAO-56 Penman-Monteith method was used for computing reference evaporation [83]. This relies on the Penman combination equation of 1948 [50].

In CropWat8.0, which is a windows-based program [87], one can compute reference evaporation on a daily, decade and monthly time step based on the Penman equation [83] by providing time series of minimum and maximum daily temperatures (oC), relative humidity (%), wind speed (m/s) and sunshine hours. CropWat then computes the reference evapotranspiration in mm/day.

4.2.8 Jensen-Haise (1963), Evaporation Estimation Method

This method relies on just air temperature (T_a) and solar radiation (R_s) as input parameters and is given by *Eq. (4.9)*.

$$E = \frac{(0.025T_a+0.08)R_s}{28.6} \qquad \text{Eq. (4.9)}$$

Where Ta is the air temperature (°C), Rs is the (incoming shortwave) solar radiation (W/m^2) and E is the evaporation in mm/day [88]

4.2.9 Energy Balance Method

This method relies on the energy balance equation *(Eq. (4.10)* to estimate evaporation. The energy transfer between the air and water at the surface of the reservoir is analysed using this method [89]

$$\lambda E=R\_n\text{-}H\text{-}G \qquad \text{Eq. (4.10)}$$

Where all units are in W/m^2

λE=Latent heat flux (negative during due formation)

R_n=Net radiation (positive for energy flow to the water surface)

H=Sensible heat (heat gained or lost by air at the water surface and positive when energy flows away from the water surface)

G=Heat storage in the reservoir (positive when heat is stored)

E= Rate of Evaporation from the water surface

λ=Latent heat of vaporisation of water

4.2.10 Modified Turc (1996) Evaporation Estimation Method

This method *Eq. (4.11)* was proposed in 1996 [90]using a modified form of the Turc (1961) equation [56]. It also requires only solar radiation (Rs in MJm^2/day) and maximum daily temperature (T_{max} in °C) for the estimation of evaporation (E in mm/day). K_2 is a dimensionless coefficient 0.0123.

$$E = \frac{K_2(23.89R_s+50)T_{max}}{T_{max}+15} \qquad \text{Eq. (4.11)}$$

4.2.11 Auxiliary measurements for Lake Binaba and Lake Winkogo

In Binaba and Winkogo, aside the EC, evaporation pan and the standard meteorological station measurements; water samples were collected *(Figure 4.12).* Water level measurements were taken with Solinst pressure sensors with an integrated logger and turbidity measurements carried out with a Secchi disk in 10 small reservoirs. In addition to these, a Distributed Temperature Sensor (DTS) set-up was made for measuring the temperature profile for the Lake Binaba *(Figure 4.13)*[5] .

Figure 4.12: Sampling points for water and water level measurement locations in Binaba

Figure 4.13: DTS cable set-up (Left) and DTS installed in the Lake (Right) at Binaba

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[5] This was outside the scope of work. Details can be found in [133]

4.3 Results

4.3.1 Evaporation Measurement using Pans

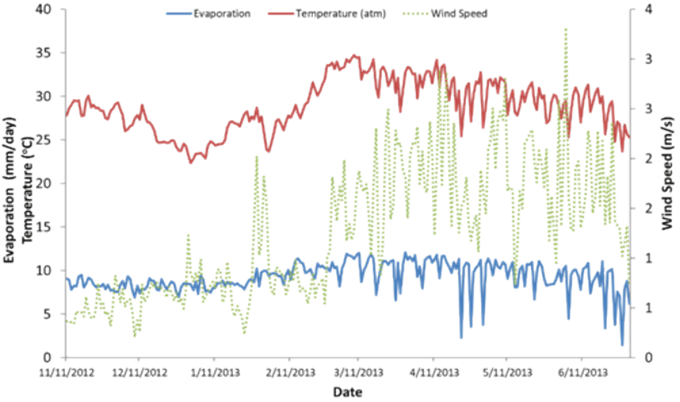


Figure 4.14: Daily Pan Evaporation, Temperature and Wind Speed in Lake Binaba

The reservoir evaporation computed from the standard pan evaporation ranged between 1.4mm to 12mm per day with a daily average of 9mm *(Figure 4.14)* near Lake Binaba. Evaporation is high during sunny dry days and low on cloudy and humid days. This therefore creates low evaporation at night because heat storage in the water is limited due to the low depth of the water in the pan compared to small reservoirs. FAO 56 [83] suggests correcting the pan co-efficient from one pan to the other, and then into lake evaporation. As discussed earlier, the choice of this co-efficient (Kp) could be problematic. FAO 56 [83] recommends the choice of Kp based on the pan type, fetch and climate condition (mean relative humidity and windspeed). For Lake Binaba (see - *Figure 4.2*) a Kp of 0.55 could be used based on the average wind speed (<2m), upwind fetch of the pan (<100m) and average relative humidity of about 40% [70], [83]. This translates the average evaporation at Lake Binaba to about 5mm/day using measurements from the Colorado sunken pan.

4.3.2 Evaporation using remote sensing and water balance method

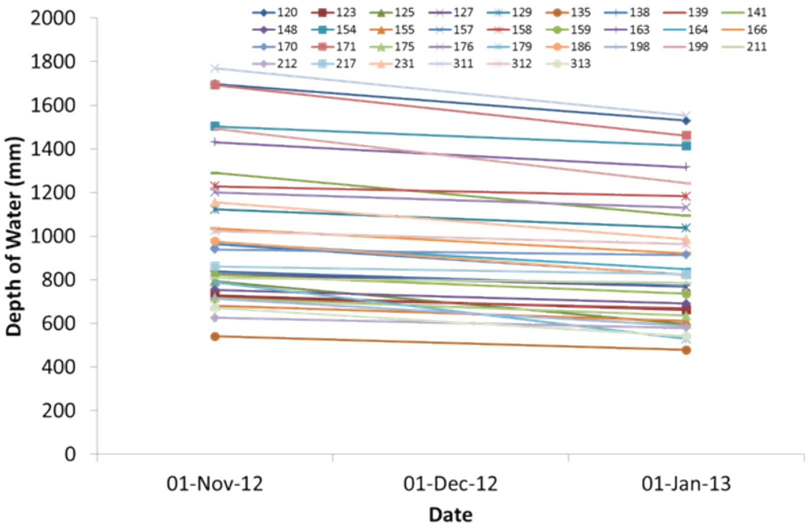


Figure 4.15: Evaporation estimates of 34 small reservoirs in the Upper East Region of Ghana

From *Figure 4.15* (also see Chapter 2 of this thesis), reservoir evaporation was estimated to range between 0.4mm/day to 5mm/day with an average of about 3mm/day. The maximum evaporation was realised from Reservoir No. 179 which is small in surface area and shallow in comparison to others. At the end of the rainy season there is still groundwater-surface water interaction (Q_{ig}>0) leading to a possible underestimation of the evaporation rates in *Figure 4.16*. The variation in downstream water levels in the wells is as a result of water use.

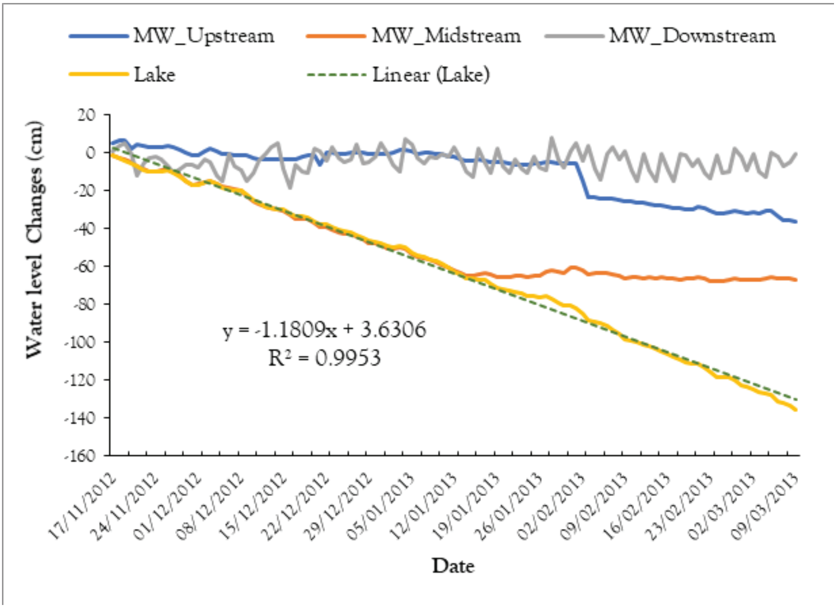


Figure 4.16: Variation of water level in Binaba in monitoring wells (MW) and the reservoir (lake). Note that these measurements are all relative changes in water levels.

The combined remote sensing and water balance method can be used to estimate evaporation losses in small reservoirs but only for certain periods of time in the year. For other periods of the year, water use, and other inflows and outflows cannot be assumed to be negligible or cancel out. This will require accurate measurement of these water balance/budget components to estimate evaporation which is somewhat challenging. For larger units of time, the water budget method could be accurate for the estimation of evaporation. Still, this result shows that net losses are not very high.

In Lake Binaba, the water level measurements were done with a Solinst levellogger [91], and together with the bathymetry (Chapter 2 of this thesis) used to estimate water level changes in 2011 during the filling of the reservoir. The results are presented in *Figure 4.17* and show that from the end of October/beginning of November there is almost no inflow into the lake.

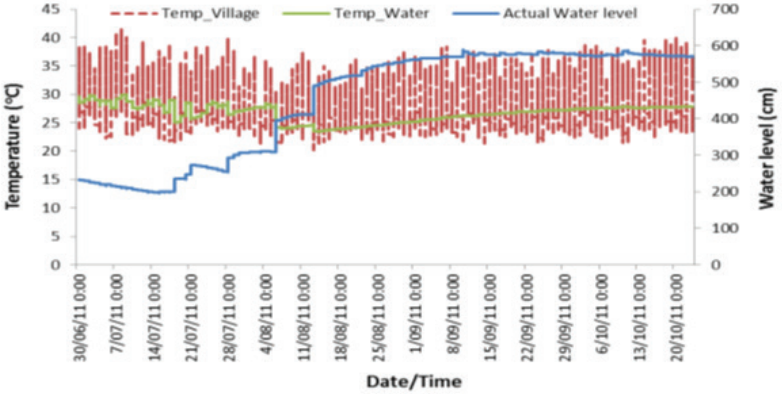


Figure 4.17: Filling of the Lake Binaba from June until December (2011)

4.3.3 EC results for Lake Binaba

The observed sensible heat flux is low (daily average of 1Wm^{-2} during the day and 11Wm^{-2} in the night) in general with more warming of the atmosphere during the night than during the day *(Figure 4.18)*. Day was considered from sunrise (6.00am) to sunset (7.00pm).

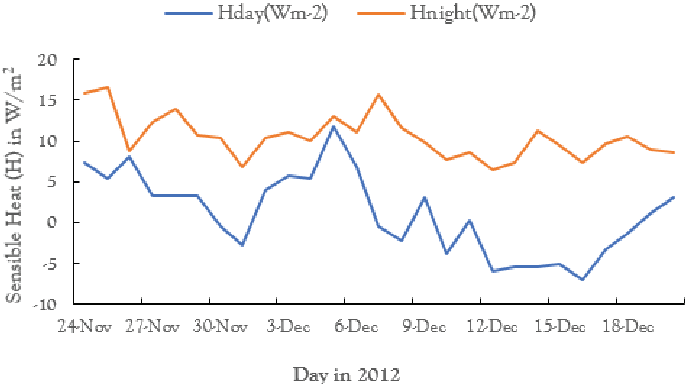


Figure 4.18: Average Daily Sensible Heat Flux measurements in Lake Binaba

Figure 4.18 shows that the atmosphere warms the water in Lake Binaba during the days in the second half of the measurement campaign.

Figure 4.19 shows that using the Vercauteren method [40], most of the evaporation was driven by the drying power of air during the measurement campaign. This is commensurate with *Figure 4.18* as explained above and shows that in the second half of the measurement campaign, the evaporation is only due to the drying power of air (E_A).

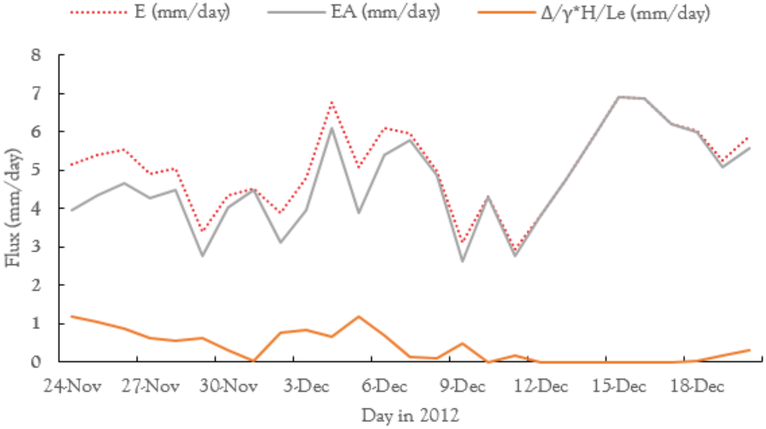


Figure 4.19: Evaporation components according to Eq. (4.2) from Vercauteren for Lake Binaba. Where Δ is the slope of the saturation vapour pressure curve, γ is the psychometric constant, H is the sensible heat flux. Le is the latent heat of vaporisation of water (Le = 2.453 x 106 J kg-1), EA is the drying power of Air = f(u)(es- ea), and E is the rate of evaporation.*

The sensible heat measurements and the corresponding evaporation rates are presented in Figure 4.19. From Figure 4.19 using the Vercauteren et al. method [73], the average daily evaporation for the period (November – December 2012) was estimated to be about 5mm/day with a minimum of 3mm/day and a maximum of 7mm/day.

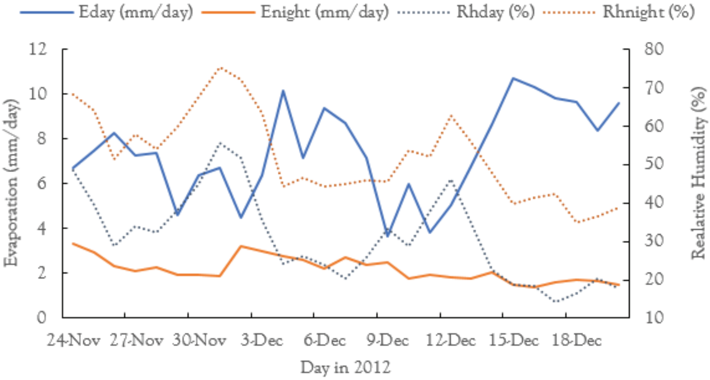


Figure 4.20: Day and night asymmetry of evaporation fluxes for Lake Binaba using the Vercauteren et al. (2009) method

Average, minimum, and maximum evaporation for the period during the day was 7mm/day, 4mm/day, and 11mm/day respectively; and at night, 2mm/day, 1mm/day, and 3mm/day respectively. Using Vercauteren [73], there was more evaporation during the day than at night but the evaporation at night cannot be neglected (see *Figure 4.20*). This result is due to more drying power of air during the day than at night (high relative humidity at night, low air temperatures and low wind speed – *Figure 4.21*).

4.3.3.1 Wind Function and ABL Analysis for Binaba

Figure 4.21 shows the day and night asymmetry of evaporation and wind speed. We can see that evaporation according to Vercauteren et al. [73] at night correlates well with wind at night more than for the same analysis done for daytime. To understand the relationship between the wind function and evaporation, the sensible heat flux normalised with the difference between the air temperature and water surface temperature was plotted (*Figure 4.25*).

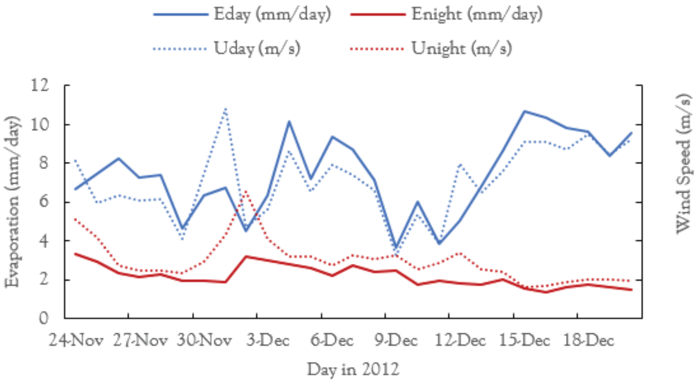


Figure 4.21: Day and night asymmetry of evaporation fluxes with wind speed for the Lake Binaba

In Binaba the wind direction was predominantly from the South-Western direction (*Figure 4.22*).

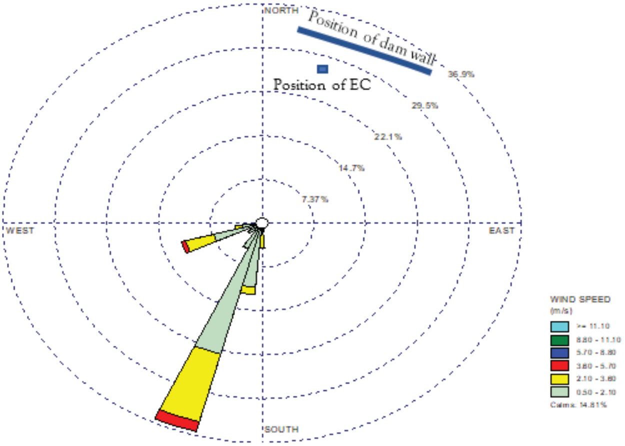


Figure 4.22: Windrose diagram for Binaba from Nov. 24 – Dec. 20, 2012

The ABL conditions observed in Lake Binaba are presented in *Table 4.1*, *Figure 4.23* and *Figure 4.25*.

Table 4.1: ABL analysis For Lake Binaba using definitions from Barthlott et al.[59]

	ABL	Occurrence (% of time)
	Neutral	1%
	Stable	28%
	Unstable	71%
Neutral	Unstable	Stable
L→+/- ∞0 & Z/L=0	L<0 & Z/L<0	L>0 & Z/L>0

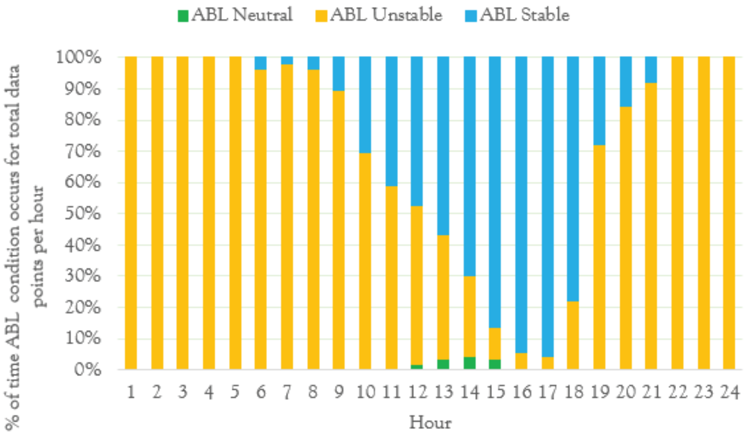


Figure 4.23: ABL condition throughout the day at Lake Binaba

From *Figure 4.23*, it is observed that unstable ABL occurs mostly at night at Lake Binaba when the water surface temperature is warmer than the air temperature. During the day (from 10.00am), the ABL becomes more stable until evening (7.00pm) when the air temperature is warmer than the water surface temperature. The difference between the water surface temperature (T_s) and air temperature (T_a) on Lake Binaba (T_s-T_a in *Figure 4.23*) was on average 4.3 °C with a minimum of 1.5 °C and a maximum of 6.1 °C during the day; and at night, an average of 2.3 °C, a minimum of 0.0 °C and a maximum of 3.7 °C.

Generally, high wind speeds are observed when the ABL is stable (*Figure 4.25*). Unstable ABL conditions (*Table 4.1*) drive evaporation which is similar to what was observed by Abbasi et al. [54]. The positive unstable ABL is buoyancy-driven transport which takes place mostly during the night (*Figure 4.23*).

From *Figure 4.25*, we can conclude that there is no clear wind function. Instead three main clusters can be observed; with the ABL being more stable (negative $H/(T_s$-$T_a))$ during the “clear day” (10.00am – 5.00pm) with varying wind speeds, unstable (positive $H/(T_s$-$T_a))$ during the “dark night” (10.00pm – 4.00am) with low wind speeds and unstable with varying wind speed at night and during the day.

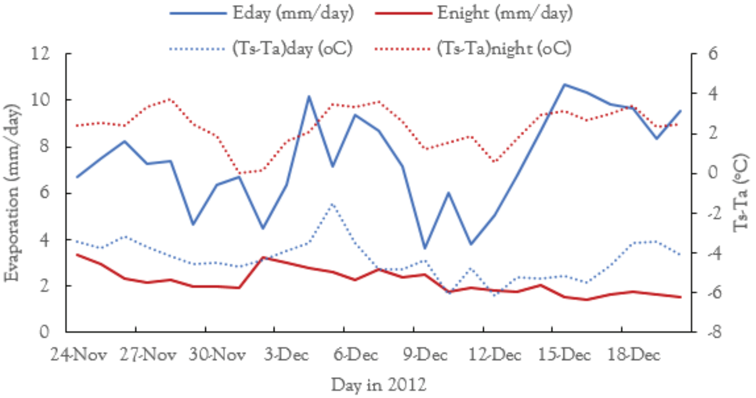


Figure 4.24: Day and night asymmetry of evaporation fluxes with average day and night temperatures for Lake Binaba

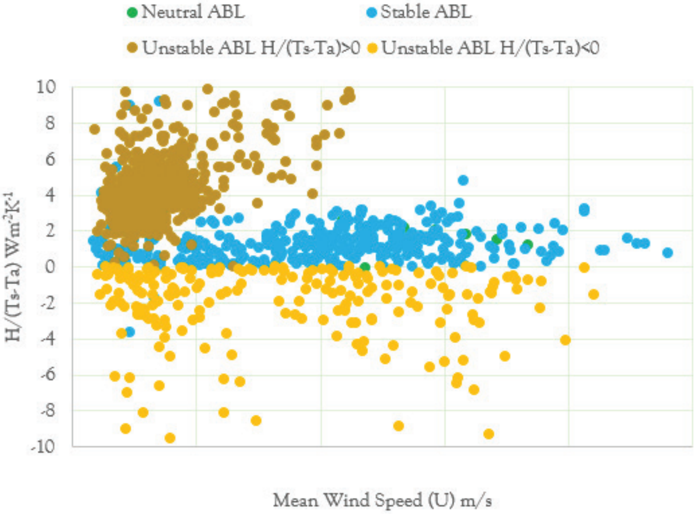


Figure 4.25: ABL and Wind Function Analysis for the Lake Binaba

4.3.4 Evaporation from other methods compared to EC measurements

Generally, the other methods used for estimating evaporation including FAO Penman-Monteith (*Figure 4.26*) over-estimate evaporation from Lake Binaba compared with the Bowen Ratio Energy Balance (BREB) method. The BREB method has an average rate of evaporation which matches with field measurements of water levels assuming groundwater exchanges with the water in the reservoir can be neglected as stated earlier on in this chapter. However, the method requires good measurement of at least the sensible heat flux and the water surface temperature, which could be tricky at times [73]. The evaporation results using the various methods is presented in *Figure 4.26* and the correlation between them presented in *Table 4.2.*

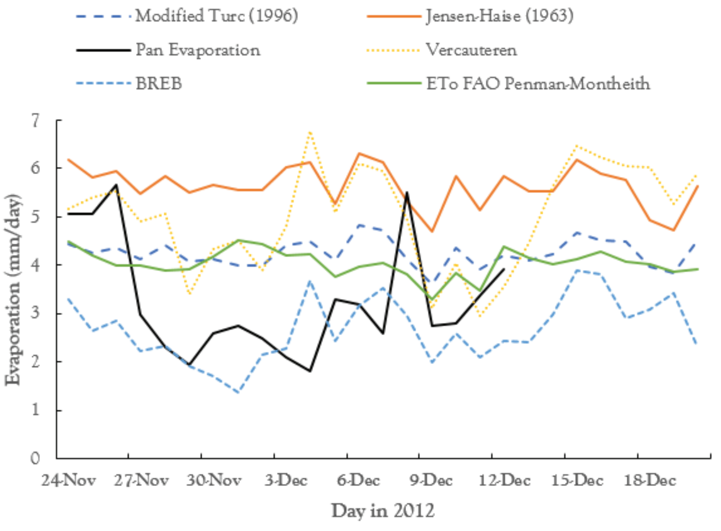


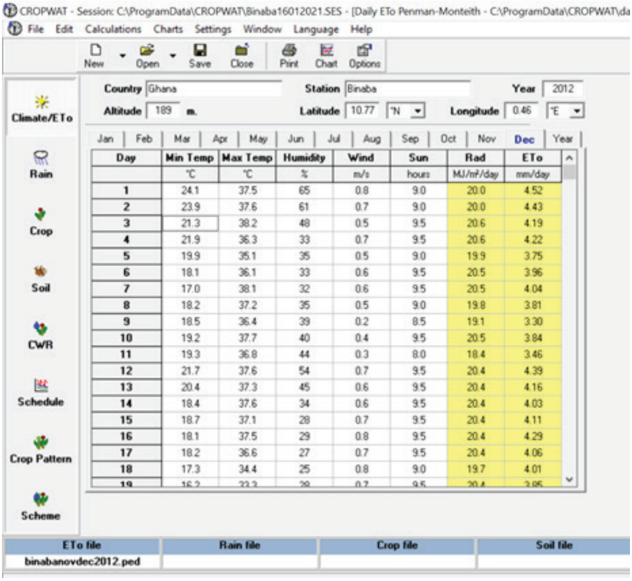
Figure 4.26: BREB evaporation compared to other methods for evaporation estimation for the Lake Binaba

Table 4.2: Correlation between daily evaporation estimates using different methods for Lake Binaba

	Modified Turc (1996)	Jensen-Haise (1963)	Pan Evaportion	Vercauteren	BREB	Eref (FAO-56 Penman)
Modified Turc (1996)	1					
Jensen-Haise (1963)	0.89	1				
Pan Evaporation	0.03	0.04	1			
Vercauteren	0.69	0.45	0.14	1		
BREB	0.56	0.35	0.29	0.75	1	
E_{ref} (FAO-56 Penman)	0.34	0.56	0.05	0.29	0.12	1

Table 4.2 shows that the radiation-based methods (Turc and Jensen) correlate well with each other while the Vercauteren et al. [40] method has a strong correlation with the BREB method. The pan evaporation has a poor correlation with all other methods. The correlation between ETref from FAO-56 Penman-Monteith and the others was weak except for the Jensen Haise method.

The daily average evaporation estimated with the different methods are about 4mm/day for Modified Turc (1996), 6mm/day for Jensen-Haise (1963), 3mm/day for Pan Evaporation, 5.0mm/day for Vercauteren et al. [73], and 3mm/day for the BREB method. The FAO-56 Penman-Monteith method computed using CropWat8.0 (*Figure 4.27*) gave an average evaporation of 4mm/day with a minimum of 3mm/day and a maximum of 5mm/day for the period using the climate data from the station at Lake Binaba. However when the climate data for Navrongo (about 90km away from Binaba) which is one of the closest cities for which data was available for that period from the Ghana Meteorological Agency (GMet) was used, the average evaporation from the FAO-56 Penman-Monteith method resulted in 7mm/day, 5mm/day and 9mm/day as the average, minimum and maximum evaporation respectively. This is higher than the values obtained when the weather data from the Binaba station (which was next to the lake) is used in the CropWat8.0 model [87].



CROPWAT - Session: C:\ProgramData\CROPWAT\Binaba16012021.SES - [Daily ETo Penman-Monteith - C:\ProgramData\CROPWAT\da

Country Ghana

Station Binaba

Year 2012

Altitude 189 m.

Latitude 10.77 °N

Longitude 0.46 °E

Day	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	m/s	hours	MJ/m²/day	mm/day
1	24.1	37.5	65	0.8	9.0	20.0	4.52
2	23.9	37.6	61	0.7	9.0	20.0	4.43
3	21.3	38.2	48	0.5	9.5	20.6	4.19
4	21.9	36.3	33	0.7	9.5	20.6	4.22
5	19.9	35.1	35	0.5	9.0	19.9	3.75
6	18.1	36.1	33	0.6	9.5	20.5	3.96
7	17.0	38.1	32	0.6	9.5	20.5	4.04
8	18.2	37.2	35	0.5	9.0	19.8	3.81
9	18.5	36.4	39	0.2	8.5	19.1	3.30
10	19.2	37.7	40	0.4	9.5	20.5	3.84
11	19.3	36.8	44	0.3	8.0	18.4	3.46
12	21.7	37.6	54	0.7	9.5	20.4	4.39
13	20.4	37.3	45	0.6	9.5	20.4	4.16
14	18.4	37.6	34	0.6	9.5	20.4	4.03
15	18.7	37.1	28	0.7	9.5	20.4	4.11
16	18.1	37.5	29	0.8	9.5	20.4	4.29
17	18.2	36.6	27	0.7	9.5	20.4	4.06
18	17.3	34.4	25	0.8	9.0	19.7	4.01

ETo file	Rain file	Crop file	Soil file
binabanovdec2012.ped			

Figure 4.27: FAO-56 Penman-Monteith Evaporation Computation in CropWat8.0

4.3.5 EC results for Lake Winkogo

4.3.5.1 Wind Function and ABL Analysis for Winkogo

The experiment in Winkogo had as goal to understand better the internal boundary layer and how that impacts surface evaporation. As shown in the previous sections, evaporation from lakes is highly influenced by the drying power of air which makes the surrounding land conditions and wind speed and direction important.

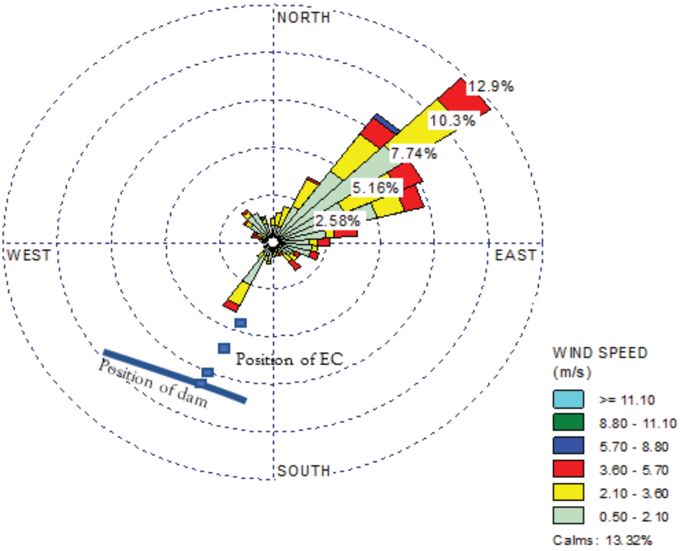


Figure 4.28: Windrose diagram for Winkogo with the tail-end of the lake at the centre of the circle from February 6 - March 8, 2014

Unlike in Binaba where the wind direction was from the South-West (*Figure 4.22*) so the fetch over water was large (distance from the shore to the EC setup), at Winkogo the predominant direction was from North-East (*Figure 4.28*) which was not the largest fetch over water for all EC positions. Air transport was from land to water with a wind speed of less than 2m/s most (50%) of the time.

From *Figure 4.29 to Figure 4.33*, it was difficult to get a clear understanding of the ABL at Winkogo. It was only on a few occasions where structural patterns were observed mostly when the wind direction was from the North (<45°).

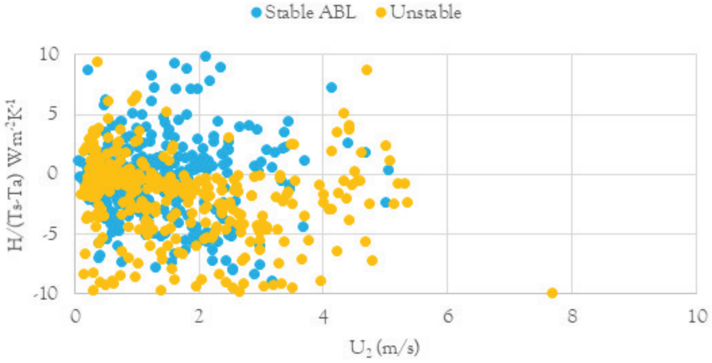


Figure 4.29: Stability plot for stable and unstable ABL of the Lake Winkogo from 6 February – 8 March 2014

The measurement heights and the stability conditions were not clear from *Figure 4.30 to Figure 4.32*.

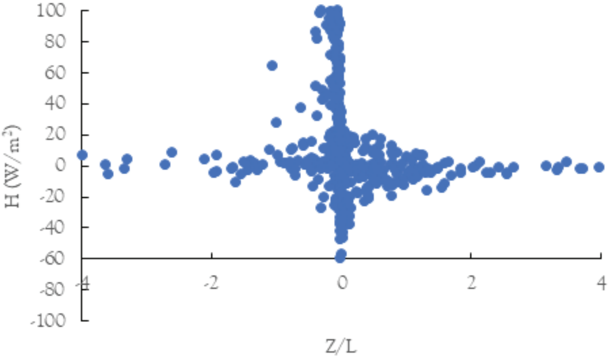


Figure 4.30: Sensible heat flux and stability parameter (Z/L) for Lake Winkogo (day & night)

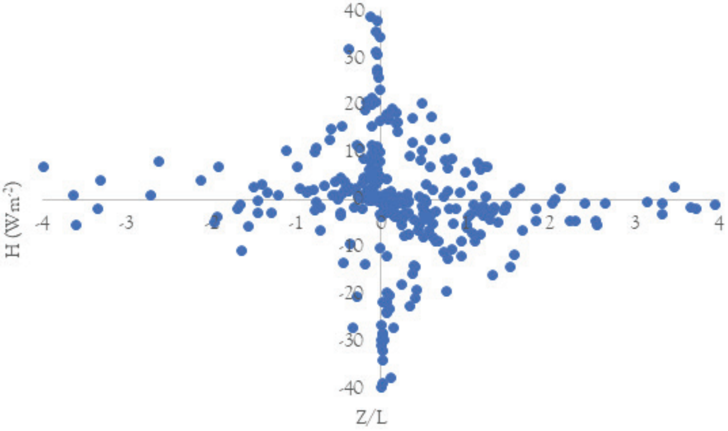


Figure 4.31: Sensible heat flux and stability parameter (Z/L) at night for Lake Winkogo

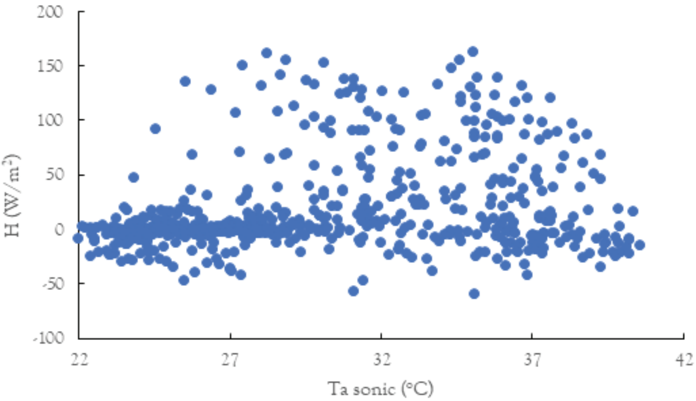


Figure 4.32: Sensible heat flux against temperature for Lake Winkogo at all heights

There was no clear pattern between sensible heat flux and air temperature over the lake (*Figure 4.32*). The diurnal pattern of temperature at the middle of the lake (L1) at various heights is shown in *Figure 4.33*. The temperature at the height of 2.95m and 3.5m is consistent with normal air temperature profile (as one goes higher the cooler it becomes) however the temperature at 1.54m compared with the one at 2.95m is not consistent which could be due to the measurement at 2.95m being outside the air-lake atmospheric boundary layer. This could also possibly explain the patterns observed in *Figure 4.34* - *Figure 4.36*, of the sensible heat flux at different heights.

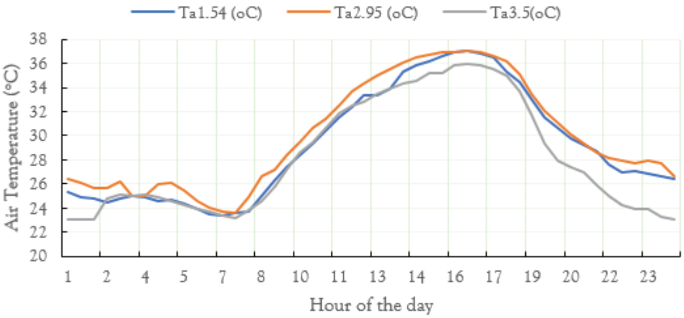


Figure 4.33: Variation of temperature at different heights in the middle of the Lake Winkogo (L1)

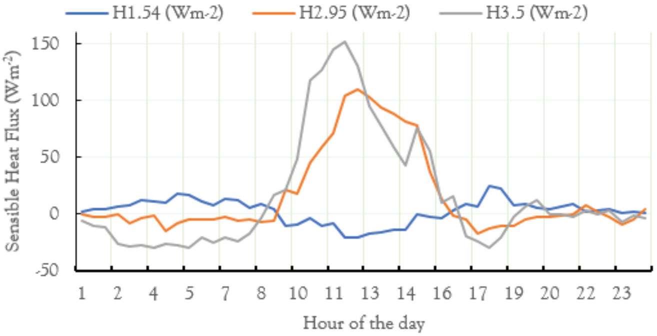


Figure 4.34: Sensible Heat flux measurements at 3 different heights at the Middle of Lake Winkogo (Location L1)

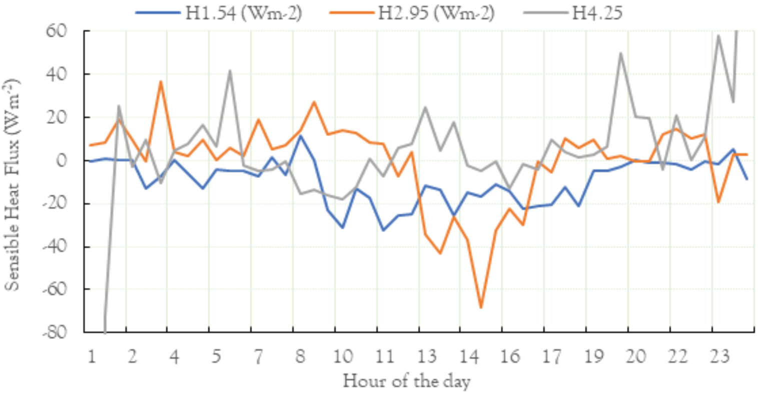


Figure 4.35: Variation of Sensible heat flux at various heights at the tail end of the Lake Winkogo (location L2)

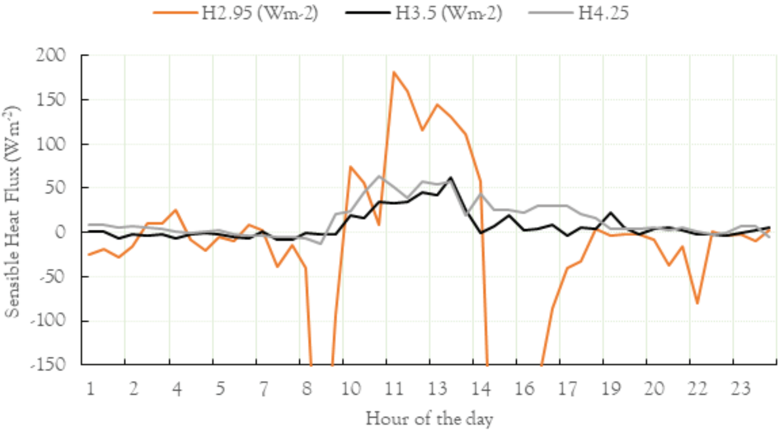


Figure 4.36: Variation of Sensible heat flux at various heights close to the dam wall of Lake Winkogo (location L3)

The theoretical height of the internal boundary layer for Winkogo (*Figure 4.37*) according to Elliot [60], shows that any measurement done above the height of 2 meters at L2 (tail end of the lake) and above 3.5 meters at L1 (Middle of the lake) will be outside the boundary layer. The build-up of the internal boundary layer is not the same as in Binaba$_1$ (as expected), due to the small size of the lake which makes it behave similar to that of land.

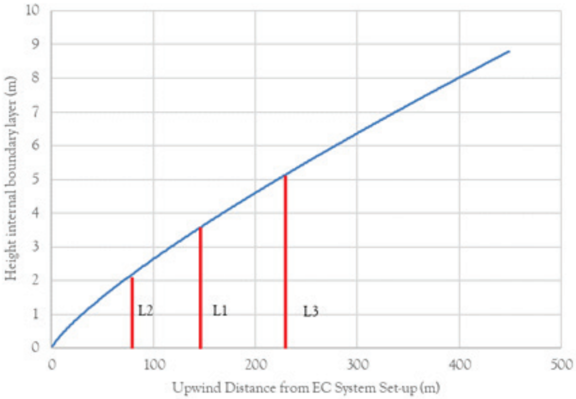


Figure 4.37: Theoretical height of the internal boundary layer for Lake Winkogo

Figure 4.37 corroborates the explanation provided for *Figure 4.33* - *Figure 4.36*. The heights of the internal boundary layer were computed using a roughness length (z_o) of 0.005m for water and roughness length (z_{oo}) of 0.03m for land in *Eq. (4.12)*. Where x is the distance from the shoreline and δ_i is the height of the internal boundary layer in meters.

$$\frac{\delta_i}{z_o} = \left[0.75 + 0.03 \ln\left(\frac{z_{oo}}{z_o}\right)\right] \cdot \left(\frac{x}{z_o}\right)^{0.8} \qquad \textit{Eq 4.12}$$

Table 4.3: ABL conditions over Lake Winkogo (Feb 6 – Mar 8, 2014) at specific locations and heights

Location		**On Land (L4)**	**Close to the dam wall (L3)**	**Middle of the Lake (L1)**	**Tail end of the Lake (L2)**
Height: 1.54					
Time of Day	ABL	Percentage of time			
Day (9.00am - 4.00pm)	Stable			33%	0%
	Unstable			67%	100%
Night (10.00pm - 5.00am)	Stable			88%	35%
	Unstable			12%	65%
Transition (Other hours)	Stable			73%	21%
	Unstable			27%	79%
Height: 2.95					
Day (9.00am - 4.00pm)	Stable	3%	37%	20%	71%
	Unstable	97%	63%	80%	29%
Night (10.00pm - 5.00am)	Stable	76%	67%	66%	30%
	Unstable	24%	33%	34%	70%
Transition (Other hours)	Stable	61%	62%	79%	15%
	Unstable	39%	38%	21%	85%
Height: 3.5					
Day (9.00am - 4.00pm)	Stable		22%	22%	
	Unstable		78%	78%	
Night (10.00pm - 5.00am)	Stable		57%	80%	
	Unstable		43%	20%	

Transition (Other hours)	Stable		56%	61%	
	Unstable		44%	39%	
Height: 4.25					
Day (9.00am - 4.00pm)	Stable		0%		56%
	Unstable		100%		44%
Night (10.00pm - 5.00am)	Stable		25%		32%
	Unstable		75%		68%
Transition (Other hours)	Stable		46%		50%
	Unstable		54%		50%

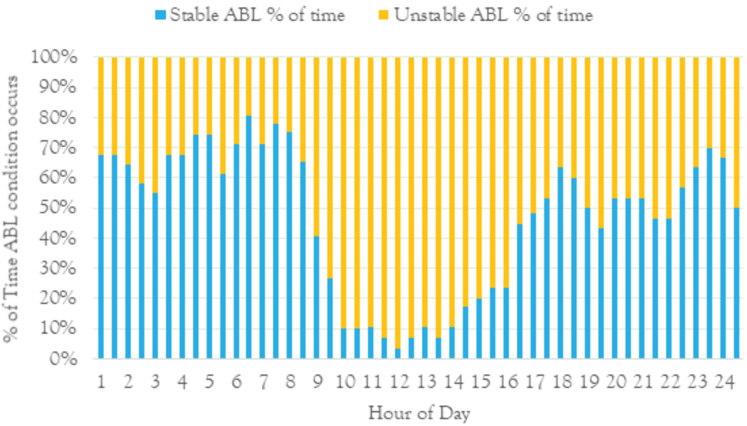


Figure 4.38: ABL condition throughout the day in the Lake Winkogo

From *Figure 4.38*, it is clear that the ABL was unstable most parts of the day and more stable at night$_{1}$ which is different from what was observed at Lake Binaba. This means the average temperature on the water surface (Ts) was higher than that of the air (Ta) above it *(Figure 4.39)*. This dries the air above the water causing more evaporation from the lake during that period according to Vercauteren et al. [73].

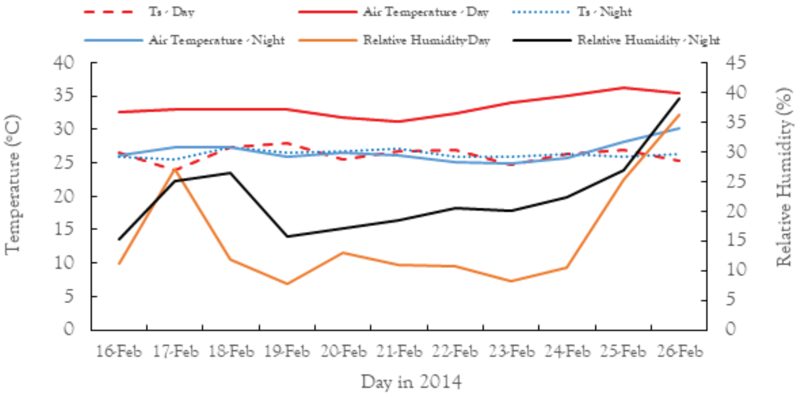


Figure 4.39: Air and water surface temperatures during the day and at night at Winkogo

Table 4.4: ABL state during the day and at night with wind direction between 0o-90o for all heights and locations for Lake Winkogo

Time	**ABL State**	**Count of ABL (30min Interval)**	**% of Time**
Day	Total	401	50%
	Stable	162	40%
	Unstable	239	60%
Night	Total	399	50%
	Stable	317	79%
	Unstable	82	21%

For the predominant wind direction (North-East) which occurred about 56% of the time during the measurement period, the ABL state was more unstable ABL (60%) during the day than at night (21%). Figure 4.40 - Figure 4.42 show that at times the air transport is from land to water, or the measurement was outside the boundary layer especially during the night and when the EC was at the tail end.

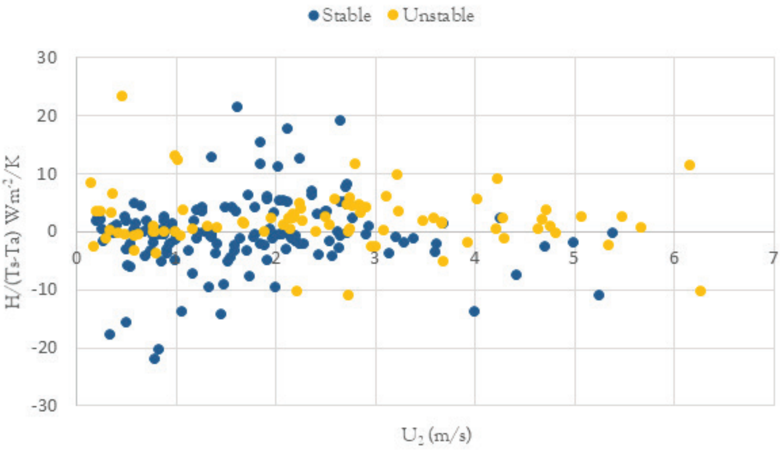


Figure 4.40: Wind Function for Winkogo when the wind direction is from the North

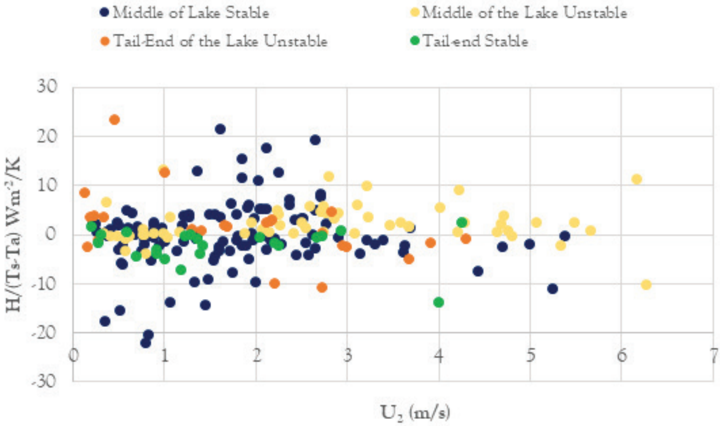


Figure 4.41: Wind Function at Winkogo when the wind direction is from the North at specific locations of the EC but at all heights of measurement

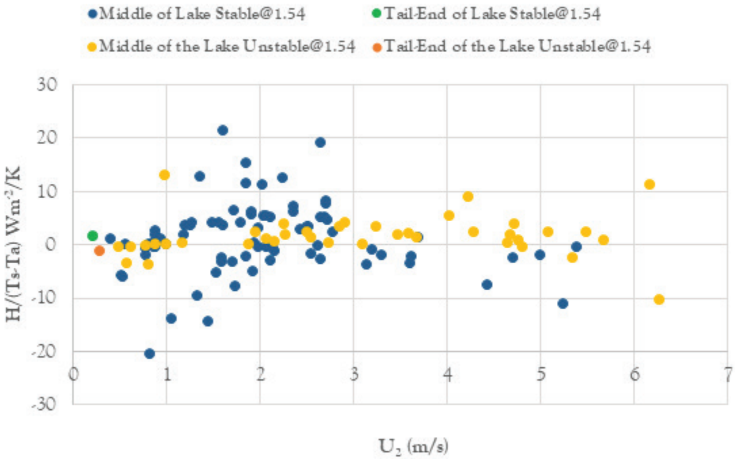


Figure 4.42: Wind Function at Winkogo when the wind direction is from the North at specific location and height of the EC

From *Figure 4.43*, using the (80%) flux footprint (where the atmospheric flux is generated in the upwind direction), L1 (middle of the lake) had the highest with an average of 1780m during the entire measurement period followed by L3 (close to the dam wall) with 847m, L4 (at the dam wall on land) with 830m and L2 (tail end of the lake) with 172m. The footprints during stable ABL and unstable ABL states are provided in *Figure 4.44*.

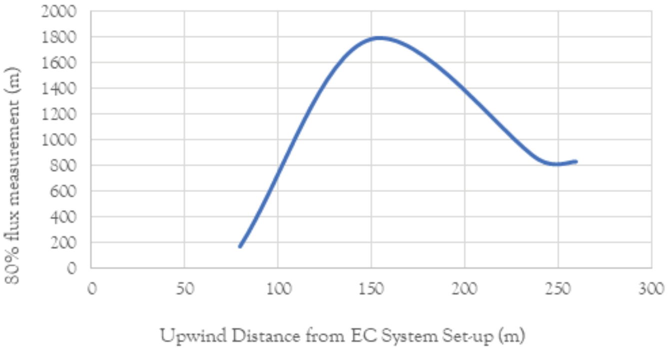


Figure 4.43: The average 80% flux footprint of Lake Winkogo during the measurement campaign

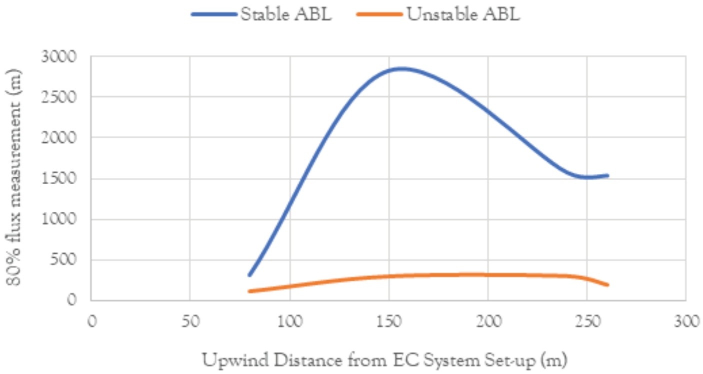


Figure 4.44: The 80% flux footprint of Lake Winkogo during stable and unstable ABL states

Figure 4.44 shows that during stable conditions the footprint of the measurement (contribution of the land surface area) is large up to about 3km so has a wider spread while that during the unstable condition is about 300m.

4.3.6 Radiation Balance Measurements over Lake Winkogo

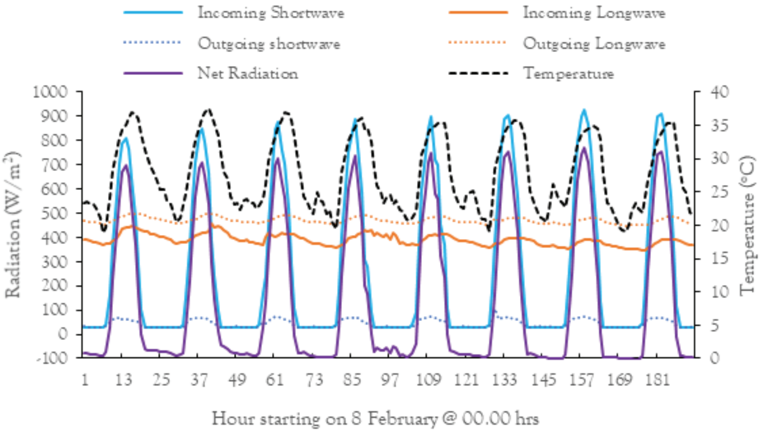


Figure 4.45: Radiation measurements at Winkogo during eight continuous very sunny days

According to Vercauteren et al. [73] and as shown in *Figure 4.19*, if all or most evaporation is due to advection or the drying power of air (EA), then the radiation balance should be zero, which does not seem to be the case in *Figure 4.45*. In Winkogo the drying power of air contributed on the average about 77% of the evaporation according to [73]. The cooling of the lake surface through thermal radiation provides more insight to understand the evaporation processes during the day and at night.

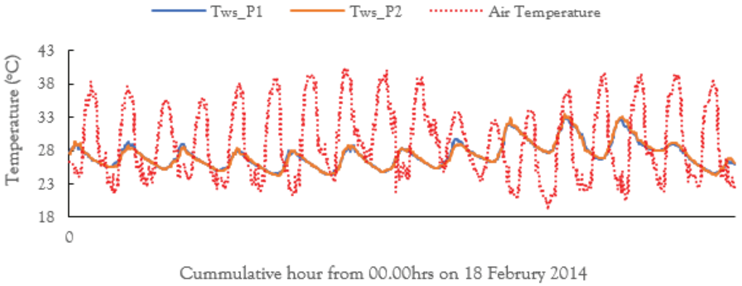


Figure 4.46: Air and water surface temperature variations in Lake Winkogo

Figure 4.46 shows that, there is very little variation in the water surface temperature (Tws) at the two points where the measurements were done which were about 17m apart; P1 (10.71301°N, 0.85933°W) and P2 (10.71315°N, 0.85928°W). Figure 4.46 shows that, the water surface temperature difference at the two points (P1 and P2) was about 0.01°C on the average with a maximum of about 1.2°C at 30minutes temporal resolution. The air temperature varied between 20.0°C and 40.6°C with an average of 29.3°C while the water surface temperature varied between 24.4°C and 33.3°C with an average of 27.4°C at 30 minutes temporal resolution *(Figure 4.47)*.

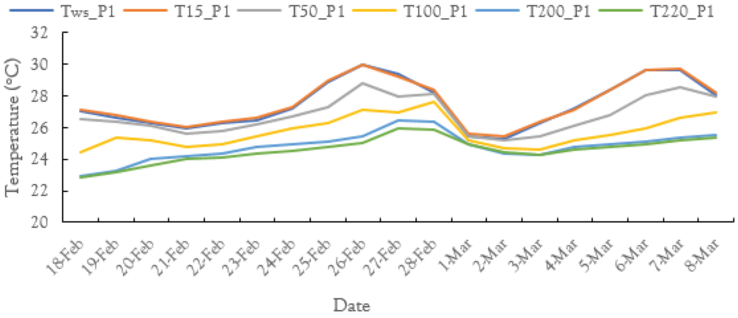


Figure 4.47: Average daily water temperature at various depth (in cm) in Lake Winkogo

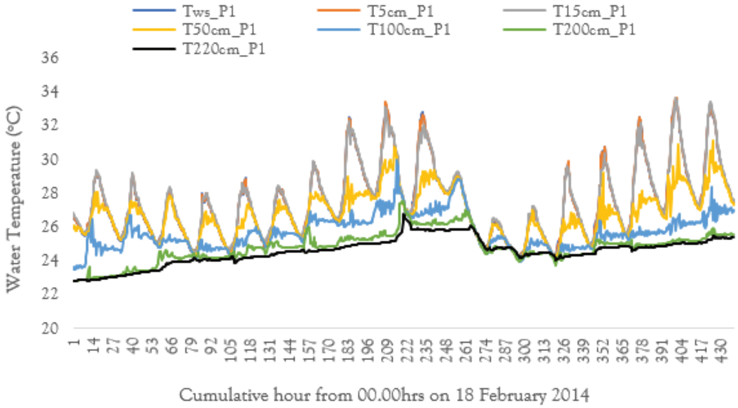


Figure 4.48: Water temperature at various depths in Lake Winkogo

From *Figure 4.47* and *Figure 4.48*, it is clear that there is thermal stratification in Lake Winkogo from the water surface to 15cm, 15-50cm, 50cm-100cm and then at the bottom of the lake (200-220cm). The heat exchange between the air above the water, and the water is occurring mostly within a 15cm layer of the lake from the surface.

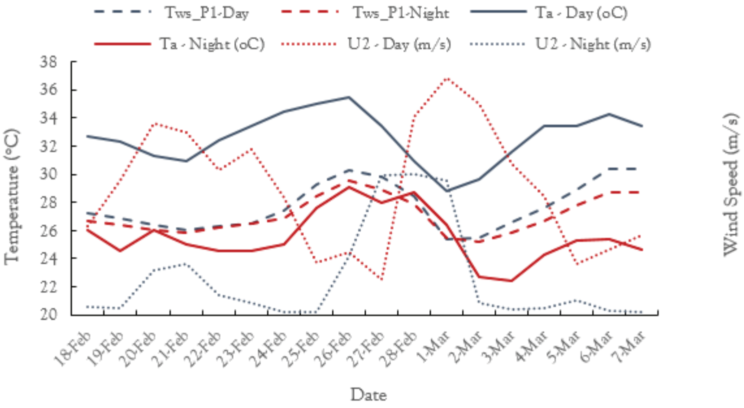


Figure 4.49:Temperature and wind speed at 2m in Lake Winkogo during the day and at night

Table 4.5: Asymmetry of Lake Winkogo temperature and wind speed during the day and at night

	Water Surface Temp. (Day) °C	Water Surface Temp. (Night) °C	Temp. at the bottom of the Lake (Day) °C	Temp. at the bottom of the Lake (Night) °C	Air Temp. (Day) °C	Air Temp. (Night) °C	Wind Speed - Day (m/s)	Wind Speed - Night (m/s)
Mean	27.7	27.1	24.5	24.6	32.6	25.6	1.76	0.51
Min	25.4	25.2	22.8	22.9	28.8	22.4	0.49	0.04
Max	30.4	29.5	25.9	26.0	35.5	29.0	3.28	1.95

From *Figure 4.49* and *Table 4.5*, on average there is very low wind speed (0.04m/s) at night which means the cooling of the lake at the surface from 27.7°C during the day to 27.1°C at night, is mainly through thermal radiation.

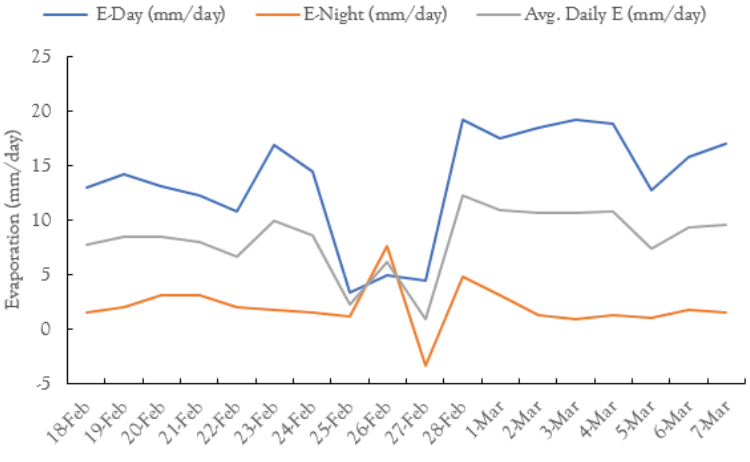


Figure 4.50: Day and night asymmetry in diurnal evaporation in Lake Winkogo according to Vercauteren et al.[73]

Daily evaporation rates in Winkogo during the measurement period according to Vercauteren et al. [73] was 8mm/day on average, with night average of 2mm/day and 14mm/day during the day. On 27th of February *(Figure 4.50)* there was dew due as a result of extremely low air temperatures coupled with relatively high wind speeds at night/early morning.

The average daily evaporation from Lake Winkogo estimated with different methods are 5mm/day for Modified Turc (1996), 7mm/day for Jensen-Haise (1963), 8mm/day for Vercauteren et al. [73], and 4mm/day for the BREB method. The reference evaporation for Lake Winkogo estimated using the FAO-56 Penman-Monteith [94] in CropWat8.0 gave an average evaporation of 6mm/day with a minimum of 5mm/day and a maximum of 7mm/day for the period using the weather data from the station over Lake Winkogo *(Figure 4.51)*.

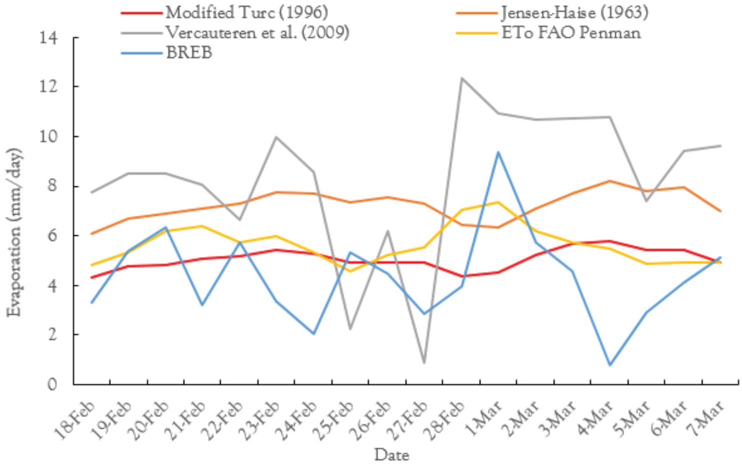


Figure 4.51: Evaporation according to various methods for Lake Winkogo

Table 4.6: Correlation between daily evaporation estimates using different methods for Lake Winkogo

	Modified Turc (1996)	Jensen-Haise (1963)	Vercauteren et al. (2009)	BREB	Eref FAO-56 Penman	Eref FAO-56 Penman (with Bolgatanga data)
Modified Turc (1996)	1					
Jensen-Haise (1963)	0.92	1				
Vercauteren et al. (2009)	0.10	-0.09	1			
BREB	-0.45	-0.54	0.11	1		
Eref FAO-56 Penman	-0.27	-0.38	0.50	0.42	1	
Eref FAO-56 Penman (with Bolgatanga data)	-0.03	-0.10	0.28	-0.12	0.32	1

From *Table 4.6*, there is a very strong correlation coefficient (0.92) between Modified Turc (1996) and Jensen-Haise (1963) similar to what was found for the Lake Binaba *(Table 4.2)*. BREB and Jensen-Haise (1963) and Eref (FAO Penman) and Vercauteren et al. [73] were correlated although not strongly with correlation coefficients of 0.54 and 0.50, respectively.

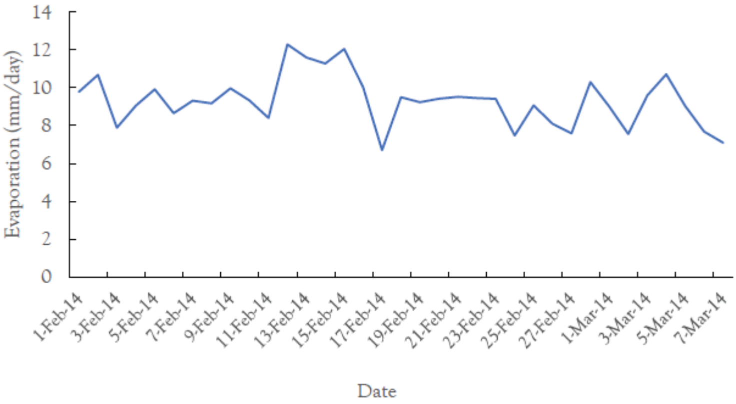


Figure 4.52: Reference evaporation (Eref) according to FAO-56 Penman-Monteith using weather data from Bolgatanga in CropWat8.0

The estimated average reference daily evaporation (E_{ref}) according to FAO-56 Penman-Monteith method *(Figure 4.52)* with Bolgatanga (10.5 km away from Winkogo) weather data was 9mm/day with a minimum of 7mm/day and a maximum of 11mm/day for the same period when the other methods were compared (February 18 - March 7 2014). This is higher than the average value obtained (6mm/day) when the station data from Winkogo was used which calls for some level of instrumentation close to some of these reservoirs (e.g., with cost-effective automatic weather stations such as those from TAHMO [95]). A summary of the evaporation rates using different methods from 18 February to 7 March 2014 (the last field campaign period) for Lake Winkogo is presented in *Table 4.7*.

Table 4.7: Summary of the evaporation rates estimated from various methods used for the Lake Winkogo from 18 February – 7 March 2014

Groups	**No. of Days**	**Total Evaporation (mm)**	**Average Daily Evaporation (mm/day)**	**Variance (mm/day)**
Modified Turc (1996)	18	91.1	5.1	0.2
Jensen-Haise (1963)	18	130.3	7.2	0.3
Vercauteren et al. (2009)	18	149.3	8.3	8.6
BREB	18	78.6	4.4	3.6
Eref FAO-56 Penman	18	101.6	5.6	0.6
Eref FAO-56 Penman (with Bolgatanga data)	18	159.8	8.9	1.1

4.4 Discussion

4.4.1 Evaporation estimation from different Methods

The various methods used for estimating evaporation in this chapter provided different results with some of the values being closer and others wide apart for both Lake Binaba and Lake Winkogo. Comparison of these methods are provided in this section.

4.4.1.1 BREB and Vercauteren et al.

BREB and the EC methods are considered the most accurate by most studies [3], [67], [86], [96], [97] for the instrumentation available within this research work. The Vercauteren et al. [73] method uses measurements of only the sensible heat flux, and standard atmospheric variables of wind speed at one level, relative humidity, and air temperature to estimate lake evaporation through the Bowen ratio.

The average daily evaporation rate according to the BREB method was 3mm/day for Lake Binaba and 4mm/day for Lake Winkogo, whereas the Vercauteren et al. [73] method estimated this to be 5mm/day for Lake Binaba and 8mm/day for Lake Winkogo. The correlation between the two methods was stronger for Binaba with a correlation coefficient of 0.75 but weak for Winkogo with 0.11 as the correlation coefficient.

The strong correlation between the two methods at Binaba could be explained by the fact that both are energy balance based and rely on the Bowen ratio. Both are computed on a half-hourly temporal frequency before being aggregated to daily averages. As such, they are able to capture the differences in evaporation during day and night, which is different from the other methods that are computed on a daily basis.

The Vercauteren et al. [73] method does not directly use the water surface temperature to compute the slope of the saturation vapour pressure curve but uses estimates obtained from equations such as Lowe [98] which was used for the computation with only the air temperature as the input variable. From the results it has been shown that the skin temperature plays a significant role in evaporation, especially during windless nights. This possibly could explain the weak correlation between the two methods at Winkogo which was a very shallow lake compared to Binaba. The performance of methods that rely on the Bowen ratio in advective areas has been questioned due the approximation of the eddy transfer coefficients for water vapour and heat [99].

4.4.1.2 Jensen-Haise (1963) and Modified Turc (1996)

The Jensen-Haise (1963) method, generally leads to an overestimation or underestimation of evaporation depending on the season (dry or wet) due to the higher weight given to air temperature compared to incoming shortwave radiation used in the equation [55], [67]. The modified Turc (1996) is also in the solar radiation-temperature group of evaporation estimation methods [100]. The modified Turc (1996) gives a higher weight to the maximum air temperature in estimating evaporation. Both methods seem to work fairly well when local standard atmospheric data (a station close to or on the lake) is used. The average daily evaporation rate at Lake Binaba according to the Modified Turc (1996) method was 4mm/day and for the Jensen-Haise (1963) method 6mm/day with a strong correlation (coefficient of 0.89) between the two methods. A strong correlation was also obtained at Lake Winkogo between the two methods with a correlation coefficient of 0.92. At Lake Winkogo the average daily evaporation rate was 5mm/day and 7mm/day respectively for the modified Turc (1996) and Jensen-Haise (1963) methods. *Eq. (4.9)* and *Eq. (4.11)* used for the Jensen-Haise and Modified Turc methods respectively, are expected to give highly correlated outcomes because T_{air} and T_{max} are highly correlated.

4.4.1.3 BREB and Radiation-Temperature Group

The correlation between evaporation estimates from the Modified Turc (1996) and BREB was stronger (correlation coefficient of 0.56) than that of the Jansen-Haise (1963) and BREB (correlation coefficient of 0.35) for Lake Binaba. At Lake Winkogo it was the other way round with the Jansen-Haise (193) method and BREB having a higher correlation (coefficient of -0.54) albeit it being negative (overestimation). The correlation between the modified Turc (1996) and BREB was -0.45 for Lake Winkogo. This is logical because the measurement period at Binaba was at the end of the rainy season/beginning of the dry season (November-December) with an average daily temperature of 29oC, a minimum of 26oC and a maximum of 32oC whereas at Winkogo it was at the peak of the dry season (February-March) with extremely high temperatures with a daily average of 29oC, minimum of 25oC and maximum of 34oC. In February and March, temperatures could rise as high as 41oC within the day as shown in Figure 4.48. The Turc (1961) method from which the modified Turc (1996) was developed [89] was used for evaporation estimation over a 10-day period and not daily evaporation rates [101] as has been used in this study.

4.4.1.4 Reference Evaporation for Lake Binaba and Lake Winkogo

The FAO-56 Penman-Monteith method [83] was used as the reference evaporation. This is physically based, so has global application with no or little modification of the input parameters required [102]. The FAO -56 Penman-Monteith method computed using CropWat8.0 [87] gave an average evaporation of 4mm/day. However, when the climate data for Navrongo was used, the daily average evaporation was 7mm/day. For Lake Winkogo, Eref was estimated to be 6mm/day using the weather data installed on the lake and 9mm/day when the data from the GMet Bolgatanga station (10.5 km away from Winkogo) was used. The difference is likely to be the result of the micro-climate set up by the lake. From this study, it has been shown that the flux footprint for the EC at Winkogo was 3km hence using climate/weather data from a station more than 10km away introduces some error. The correlation between the FAO-56 Penman-Monteith method and the others was only strong for Jensen-Haise (1963) method with a correlation coefficient of 0.56 but weak for the others (<0.34) with regards to the Lake Binaba. At Lake Winkogo, the strongest correlation was with Vercauteren et al. method (0.50) followed by BREB (0.42) and Jensen-Haise (1963) method with a correlation coefficient of 0.38.

4.4.1.5 Pan Evaporation

Average daily evaporation for the pan method was 3mm/day for Binaba. This value was similar to what was estimated from BREB (3mm/day), water balance using data from remote sensing (3mm/day) as well as through the actual water level measurements with the water level pressure sensor (about 2.5mm/day). Using the bulk-aerodynamic transfer method and the Monin-Obukhov similarity theory (MOST), Abbasi et al. [54] estimated average daily evaporation in Binaba to be 2.5mm/day. However, there was virtually no correlation between the pan evaporation and other methods. This is not surprising as the pan evaporation is known to have variable performance [83] mainly due to the inability to select the most appropriate pan coefficient. The pan does not behave the same way as small reservoirs due to many factors including different skin temperature, heat storage, wind dynamics, fetch and water quality. In the pan evaporation method, all these factors are integrated in one factor (pan coefficient). It has been recommended that pan evaporation be used over a ten-day period [83] which in effect improves its accuracy.

4.4.1.6 Comparison of the Vercauteren results for Lake Winkogo and Lake Binaba

The Vercauteren et al. [73] method seems practical especially for data scarce areas where sensible heat flux can be accurately measured compared to heat storage. However, some assumptions are not clear at least for the lakes studied. One is the wind function and sensible heat flux correlation. For neither Lake Binaba nor Lake Winkogo there was a clear wind function (or relationship between the wind speed and sensible heat flux). Since we show that the drying power of air, which is the second term in the Vercauteren et al. [73] equation, contributed 94% in Binaba and 73% in Winkogo to the evaporation makes the assumption (e.g., wind function and sensible heat flux correlation) critical. Since there was no clear wind function observed for the sensible heat flux, it could be that this assumption introduces some error in the evaporation estimation (i.e., overestimation of the evaporation rates).

From Lake Winkogo, we see from the radiation balance, that there is a high net radiation which implies that the contribution to evaporation through radiative cooling could be high and not negligible according to the Vercauteren et al. [73] method for Binaba. A substantial portion of the flux footprint is from land instead of water. Fetch effects could possibly account for such differences and lack of clarity of the wind function.

4.4.2 Internal Boundary Layer

From the results, it is clear that for Lake Winkogo, the internal boundary layer is less than 4.5m high. This makes the water surface temperature (skin temperature) a key parameter for evaporation estimation. At Lake Binaba, most of the time the ABL was stable during the day with relatively high wind speeds and unstable at night with low wind speeds, with the unstable ABL condition driving the evaporation at night, which is similar to what was observed by Abbasi et al. [54]. At Lake Winkogo, the ABL was mostly unstable (60% of the time) during the day and stable (79%) at night. The difference between the day/night asymmetries for the two lakes could be a result of the fetch more than the depth since there was stratification in both lakes with only about the first 20cm of the water depth exchanging heat with the air above both lakes. At Winkogo, for the entire period, the ABL conditions were equal (Stable and Unstable were both 50%) in the predominant wind direction over the water. In general, the internal boundary layer over Lake Binaba was more developed than over the much smaller Lake Winkogo.

4.5 Conclusions

Evaporation from Lake Binaba and Lake Winkogo were estimated using various methods including BREB, Pan Evaporation, Vercauteren et al. [73], Jensen-Haise (1963) and the modified Turc (1996) methods. The average daily evaporation rates estimated by the various methods was consistent with what Liebe et al. [14] found using the climate data from the Navrongo station between (1961-1990) and confirms that actual evaporation is less than the reference evaporation when distant climate station data is used instead of local data from the lake surroundings (<3km away from the lake in the case of Binaba and Winkogo). An upwind station does not "see" the lake (is not in the fetch of the station). The FAO-56 Penman-Monteith method [83] in CropWat8.0 works well for small reservoirs so data from a simple cost-effective automatic weather station [95] close to, and downwind from, the lake will help estimate evaporation much more easily and reliably compared to other methods.

According to Vercauteren et al. [73], there is a wind function for evaporation, however this was not clear from this study. Rather what was clear according to the Vercauteren et al. method was that, evaporation at night could not be neglected especially for relatively big lakes such as Binaba.

For smaller lakes, such as Winkogo, evaporation occurs mostly during the day with little evaporation at night due to the ABL conditions. For bigger lakes such as Binaba, a reduction of evaporation during the day is not compensated by extra evaporation at night as a result of radiative cooling of the top layer of the lake and reduced wind speed at night.

From the results, it is also evident that small lakes are complex in terms of their evaporation processes, so each lake is unique and requires localised climate data. Data collected far from the influence of the lake (reservoir) will generally result in overestimation of evaporation. Small reservoirs are thought to lose relatively very much water through evaporation. This is due to the fact that

a) data used are collected far from the lake's influence and

b) evaporation-reducing effect from the internal boundary layer is not taken into account.

This is a reason for using data from a cost-effective weather station such as the one provided by the Trans-African Hydro-Meteorological Observatory (TAHMO) in CropWat (FAO-56 Penman-Monteith) may be more appropriate for estimating evaporation in lakes for data scare regions.

We can conclude, however, that very small lakes, such as Winkogo, evaporate relatively more than the somewhat larger ones such as Binaba. Again, the internal boundary layer plays an important role here. For planning purposes, reservoirs of the size such as Binaba are preferable over reservoirs of the size of Winkogo.

5

Conclusions, Discussions and Recommendations

Everything will soon end.

I Peter 4:7a.

How this study contributes to science and society

Small reservoirs are important for the livelihoods of people in the Upper East Region of Ghana, located in the Volta basin. They are used for many purposes such as fishing, livestock watering, construction, irrigation, recreation, drinking water and other domestic uses [2], [4], [19], [23], [65], [103]–[105]. The reservoirs are sited close to communities to enable them to have access to water all seasons. The Upper East Region has a mono-modal rainfall pattern between April (start) and October (end). The reservoirs are usually full in the beginning of November ([10], [19]).

It has been observed that some of the reservoirs dry up during the dry season especially at the start of the Harmattan season (December - February) when they are most needed. Many reasons have been given for the drying up of the small reservoirs. These include poor lining (construction) of the dam which leads to excessive losses from infiltration and lateral seepage, and through evaporation. Unfortunately, most of the catchments where these reservoirs are sited are ungauged which makes it difficult to monitor them. Methodologies have been developed through this study to monitor these reservoirs in Ghana using remote sensing ([2]–[4], [8], [10], [14], [19], [65], [66], [104], [106]–[110]). These methodologies were used to estimate the reservoir volume and extent (surface area). However, there was still the need to understand the water balance of these reservoirs; their filling and emptying. This required a good understanding of the water balance and energy budget of the reservoirs. This is what this study also addressed.

Aside the usage of water in reservoirs, evaporation is considered to be one of the main components of the water balance or budget of a reservoir [1], [111]. In the hydrological cycle, evaporation plays a key role. It is however not easy, or at least expensive, to directly measure evaporation energy fluxes in the field continuously for a long period of time using the Eddy Covariance Method. Evaporation is, however, an important factor in explaining water losses from reservoirs [58]. Finding a cost-effective way of measuring evaporation flux is therefore key. This study showed that evaporation could be easily measured using the FAO-56 Penman-Monteith method [83] computed using CropWat [87] with data from cost-effective stations like that of TAHMO [95]. The station has to be sited close to them since the internal boundary layer of the lake and its spatial and temporal dynamics reduces actual evaporation (Eact). This means that for stations to monitor lakes (small reservoirs) reliably, they should ideally be as close as possible to the lake and downwind. This corroborates the suggestion by Allen et al. [83] that wind speed should be calibrated for each site and used in the

FAO-56 Penman-Monteith method [21] since micro-climates cannot be easily neglected. From this study (Chapter 4), it has been shown that the flux footprint for the Eddy Covariance system at Winkogo was 3km at maximum. Hence, using weather data from a station more than 10km away is bound to introduce errors. This issue has been the most challenging in evaporation estimation using the FAO-56 Penman-Monteith method as a result of lack of data in most parts of Africa. The FAO-56 Penman-Monteith method has been shown to be reliable, easy to use and accurate when localised data is used. This re-echoes the point to have TAHMO-like stations for monitoring these reservoirs.

This study also showed that small reservoirs can be monitored through remote sensing utilising well-established regional equations of surface area and water volume (Chapters 2 and 4). However, this has a limitation during parts of the year where some components of the water balance (e.g., water use for other activities aside irrigation and infiltration) cannot be neglected.

Since most of the reservoirs in the Upper East Region are ungauged, this thesis explored the use of cost-effective in situ meteorological instrumentation from TAHMO (Appendix 1) and remote sensing to determine the various components of the water balance and energy budget in small reservoirs in low-resource settings. This methodology has been shown in this thesis to work and can be applied to other basins in low-resource settings.

Accurate estimation of evaporation is required for irrigation management and water resources planning including environmental flow requirements [28], [41]. Knowledge of hydrologic fluxes including evaporation is required for monitoring and understanding hydrological and ecological processes [69], [96], [112]–[118] such as for dam operations (chapter 3).

Other main findings from the research are:

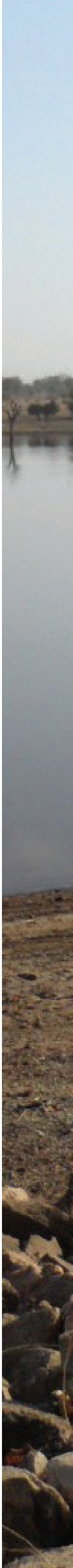
i. Small reservoirs use and direct abstraction of water from streams upstream of the Akosombo dam in Ghana to meet irrigation water demand ($10m^3/s$) is relatively low and will not affect hydropower generation at Akosombo and Kpong. However, increasing irrigation and small reservoir abstraction (or storage) rate to about $38m^3/s$ to account for anticipated irrigation expansion, would mean that the water demand for hydropower for a few years will not be fully met (about 0.1 percent shortage may be experienced).

ii. Even though small reservoirs are widely used in northern Ghana for irrigation, attention to its management is low. If, for example, the Government of Ghana intends to increase the number of small reservoirs through the one village-one-dam project, then it is imperative to instrument these reservoirs to monitor their dynamics using a combination of in situ and satellite data.

iii. The reservoir size of Lake Binaba (30 ha) is better than that of Winkogo (7.5 ha), but both have acceptable evaporation losses which are about 30 – 50% of the reference evaporation.

iv. Average evaporation in small reservoirs in the Volta basin is estimated to be about 5mm/day (i.e. between 3mm/day to 6mm/day) which is much less than what is assumed. This is corroborated by [1], [18], [66].

v. The TAHMO initiative (Appendix 1) which provided the station data used for this study, provides an avenue for Africa to leapfrog and become one the best monitored continents in the world with respect to hydro-meteorology. However, development partners/donors need to support initiatives such as TAHMO so as to help build a much more climate resilient Africa, which will create less problems for the rest of the continents while at the same time being one of the major food baskets of the world in the coming decades. One cannot monitor and plan for what is not measured.



Summary

The importance of small reservoirs for the livelihoods of people in the Upper East Region of Ghana cannot be over-emphasized. They are used for many purposes which include fishing, livestock watering, construction, irrigation, recreation, drinking water, and other domestic uses. The reservoirs were built most often close to communities to support them with dry season water use since the region has a mono-modal rainfall pattern (April – October). The best time to realise the full extent or capacity of small reservoirs is therefore at the beginning of November.

This study was carried out in the Volta basin focusing on the Upper East Region as part of a larger Challenge Program for Water and Food and the EU H2020 TWIGA project. The shallowest (with a maximum depth less than 2m) reservoirs in the northern part of the Volta basin are often dry at the start of the Harmattan season (December - February) when they are most needed. The perception was that this was mainly a result of high rates of evaporation because of high temperatures (going up to 41°C) in that part of the basin in the dry season (Nov – April). Unfortunately, most of the reservoirs are ungauged making their management challenging. Remote Sensing methods have been used to monitor the reservoirs but mainly with regards to their distribution and capacities (surface areas).

In this research, we studied the filling and emptying of the reservoirs with a combination of remote sensing and in situ data, offering better insights into the components of the water balance and energy budget for small reservoirs and thereby the possibility to manage them better. Aside the usage of water in reservoirs, evaporation is considered to be the main component of the water balance of a reservoir. Accurate estimation of evaporation is required for irrigation management and water resources planning. Knowledge of hydrologic fluxes, including evaporation, is required for monitoring, and understanding hydrological and ecological processes. It is however expensive to directly measure evaporation energy fluxes in the field continuously for a long period of time using the Eddy Covariance method. Following this study, a cost effective and reliable way of measuring evaporation flux is proposed using a TAHMO-like meteorological station and the FAO-56 Penman-Monteith method in CropWat.

The main findings from the research are as follows:

- Water abstraction for irrigation, including through small reservoirs of up to $10m^3/s$ from the Volta river, will have minimal impact on hydropower generation at Akosombo and Kpong. However, increasing irrigation and small reservoir abstraction (or storage) rates to about $38m^3/s$ would mean that the water demand for hydropower for some years will not be fully met (about 0.1 percent shortage may be experienced). This means the one-village-one dam project might not create many problems for hydropower generation downstream if they are well-managed (gains not offset by high water losses).

- Evaporation from small reservoirs is not as high as expected. Average actual rate of evaporation is about 5mm/day instead of the reference evaporation of about 10mm/day estimated using meteorological variables from distant (> 3km) weather and climate stations.
- Even though evaporation in small reservoirs is low, the rate of evaporation is higher in shallow and smaller reservoirs. The management of the small reservoirs will therefore require better landuse planning and water allocation to make them fit for the purpose for which they have been constructed for use in the dry season.
- A combination of hydro-meteorological data from TAHMO-like stations and remote sensing offer a better way to monitor and manage the water use in small reservoirs.
- Small reservoirs are good for community water management and not as inefficient as often thought.

Acknowledgements

I am grateful to all who have made this extremely long journey shorter. There is finally light at the end of the tunnel.

First and foremost, I would like to express my sincere thanks to my promotor Prof. Nick van de Giesen and his wife Prof. Martha Larson for keeping faith with me and spurring me on especially when the journey was extremely tough. I could not have done this without your immense support and patience for me. This is also true for Marjan Kreijns, the Director of the Green Village, and the wonderful team at the Impact and Innovation Centre of TU Delft including Lindsey Schwidder, Anna Gralka, Veronique van der Varst, Wian Stienstra and all other colleagues from this centre and Ellen van Andel from TPM – TU Delft. Thank you Dr. Thom Bogaard, Dr. Hessel Winsemius, Prof. Doris van Halem, Betty Rothfusz, Mr. Kees van Beek, Prof. Remko Uijlenhoet, Dr. Rolf Hut, Dr. Olivier Hoes and other colleagues from the department for the immense support offered me during my time at TU Delft.

I am grateful to the European Commission for sponsoring my work through the Horizon 2020 Programme (2018-2022) TWIGA project under grant agreement No. 776691 (TWIGA) and through the TEMBO Africa Horizon Europe Project under grant agreement No. 101086209. I also benefited from the European Space Agency projects Alcantara and TIGER, the Challenge Programme for Water and Food (CPWF) in the Volta Basin and the Re-optimisation and Re-operation of the Kpong and Akosombo Dams Project through their financial support for some of the fieldwork done in this research. I am particularly grateful to the TU Delft Global Initiative especially Roel Kamerling and Claire Hallewas and the rest of the team for your support and friendship.

I am particularly grateful to my current and former colleagues at TU Delft and KNUST especially Dr. Ali Abbasi, who is also a true friend for all the work we did together leading to several publications. Your support was great, and we formed a good team together. I hope we will get the opportunity to continue to work together sometime soon. Thank you Dr. Edo Abraham and David Agoungbome for your support and encouragement. I thank Prof. Samuel Nii Odai, my mentor and Prof. Kwaku Amaning Adjei my “twin brother” for their encouragement and support. Michiel van Haersma Buma, thanks for always being there for me.

Special thanks go to Prof. Eric A. Ofosu, Dr. Marloes Mul, Mr. Maxwell Boateng-Gyimah, and Mr. Ben Y. Ampomah for your mentorship and support during this study. I learnt a lot from you all.

A lot of thanks go to the Mount Zion International Church of the RCCG for being my family in the Netherlands, and for all your prayers, support, and encouragement especially Pastor Hyacinth and Pastor (Mrs.) Helena Nwosu, all the MZIP Council Members, Regional, National and Continental (Europe) Pastors especially Pastor & Pastor (Mrs) Walter, Pastor & Pastor (Mrs) Olowu and Pastor & Pastor (Mrs) Lasisi. I appreciate the support of all Friends of Mount Zion with their words of encouragement and prayers.

Finally, I would like to thank the Ohene Annor, Toko and Omari families and my Trans-African Hydro-Meteorological Observatory (TAHMO) colleagues for standing behind me through thick and thin especially my lovely wife and sons for their immense support, patience, and sacrifice. Thank you Prof. John Selker for your kind words, encouragement, and mentorship.

God bless you all for your contributions in my career. You may not have had an idea about how I appreciated your support however little you may have thought it was.

List of publications

Journal Publications

1. Pinto, R. B., Barendse, T., van Emmerik, T., van der Ploeg, M., Annor, F. O., Duah, K., Udo, J., & Uijlenhoet, R. (2023). Exploring plastic transport dynamics in the Odaw river, Ghana. Frontiers in Environmental Science, 11. https://doi.org/10.3389/fenvs.2023.1125541

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Curriculum Vitae

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1995-1998	Mfantsipim School, Science major Secondary School, Cape-Coast, Ghana
2000-2004	B.Sc. in Civil Engineering (Honours) Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana
2005-2007	M.Sc. Water Management (Water Resources Management with Distinction) UNESCO-IHE Institute for Water Education, Delft, The Netherlands
2007-Present	Lecturer, Civil Engineering Department, College of Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana
2015-Present	CEO Trans-African Hydro-Meteorological Observatory (TAHMO), Nairobi, Kenya
2012-2023	PhD candidate at Delft University of Technology Department of Water Management Delft University of Technology, Delft, The Netherlands
2023-Present	Researcher at Delft University of Technology Department of Water Management Delft University of Technology, Delft, The Netherlands

Appendix 1

Trans-African Hydro-Meteorological Observatory (TAHMO) Stations

Every lake is unique and may require
its own localised wind function and climate data.

Parts of this Appendix is under preparation to Front. Earth Sci, as "A decade of the Trans-African Hydro-Meteorological Observatory". Authors: Annor, F. O., van de Giesen, N & Selker, J.S

A1.1 Introduction

TAHMO's goal is to develop a dense network of hydro-meteorological stations in Sub-Saharan Africa - one every 30 km. TAHMO's aim is not to replace National Meteorological and Hydrological Services (NMHS) or compete with them. Rather, TAHMO works with the NMHS to improve the density of their network and to support them in sustainable climate services delivery.

TAHMO has installed and operates over 650 hydro-meteorological stations in Africa and currently has the largest network of surface stations in Africa. By applying innovative sensors and Information and Communication Technology (ICT), TAHMO stations are both cost-effective and robust [95]. TAHMO integrates ground-based data, satellite imagery and weather forecasting models to produce reliable weather and water information (early warning systems, reservoir operations & management, and index-based insurance, with partners) to farmers, governments and the public through dashboards and mobile platforms (SMS, Apps and voice messaging in local dialects and international languages like English and French). To ensure sustainable operations of the stations, various business models have been developed around the data and information generated from these stations, in collaboration with various SMEs, NHMSs, institutions and sectors in the countries where the stations have been installed. TAHMO works in 23 Sub-Saharan African countries including Kenya, Uganda, Rwanda, Tanzania, Ethiopia, Zambia, Zimbabwe, Lesotho, Madagascar, Malawi, Mozambique, Mali, DRC Congo, Chad, Nigeria, Ghana, Burkina Faso, Togo, Benin, Cameroon, Côte d'Ivoire, Senegal, and South Africa as of 2022.

TAHMO is by far the largest provider of science grade data in Africa with the support of the National Meteorological and Hydrological Services (NMHS), and the Regional Climate Centres (RCCs) in Niger, Kenya, and South Africa. TAHMO's aim is to install 20,000 automatic hydro-meteorological stations across Africa. The main assets of TAHMO are its innovative and robust weather and hydrological stations, data collection methods, dashboards, models, its educational (School2School) and training programs to strengthen NHMSs and start-up companies across Africa. In addition, its business case development in relation to climatic services to sustain the station network is unmatched.

TAHMO provides actionable information to support climate resilient development in Africa and the world as a whole. In this Appendix, the TAHMO initiative, and how it has evolved over the past decade to support the global scientific community, is presented.

A1.2 TAHMO organisation

A1.2.1 Legal Status and Management

TAHMO is a Kenya-based not-for-profit social enterprise, which aims at enhancing climate observation in Africa mostly driven by research needs. Due to strict requirements from the Kenya government, funding agencies, and the Kenya NGO board, TAHMO submits its annual accounts to the board with an annual turnover of about 500,000 Euros. The foundation is run by a board of directors (4 members) with vast amount of experience (co-directors with more than 30 years of work experience in Africa) and a Ghanaian CEO with more than 18 years' work experience. TAHMO is registered in Nairobi, Kenya, with subsidiaries in Uganda and Ghana.

Research and development are at the heart of TAHMO since the two (2) co-directors and co-founders; Prof. Nick van de Giesen from Delft University of Technology (TU Delft) in the Netherlands, and Prof. John Selker from Oregon State University (OSU) in the USA, are in academia together with the CEO of TAHMO, Frank Annor. TAHMO has Francophone and Anglophone staff, so is able to work in many countries in Africa. TAHMO has a well organised administration in Kenya where all accounting and bookkeeping is done. The organogram of TAHMO is presented as *Figure A.1*.

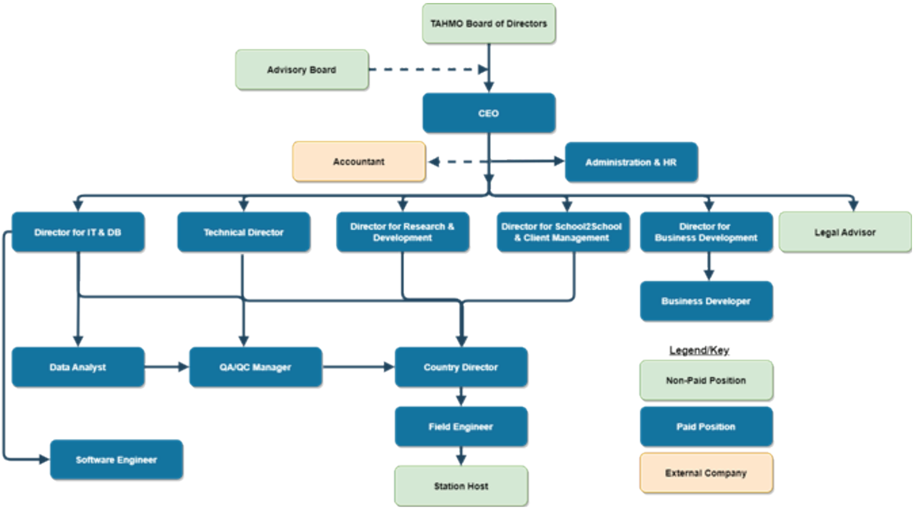

Figure A.1: TAHMO Organogram

A1.2.2 Staff

TAHMO has 23 core staff and many volunteers who support its operations. These are mainly (90%) Africans with PhD, MSc and BSc in civil engineering, electrical engineering, agriculture engineering, environmental engineering, meteorology, water management and computer science. This team has the technical expertise on how to work in various parts of the world - Africa, Asia, Europe, and the USA.

Due to the flexible work environment, peer-to-peer learning, and opportunity to grow, TAHMO staff turnover has been extremely low. Only 2 members of staff changed jobs in the past five years due to personal reasons but are still associated with TAHMO and volunteer their time to support field and administrative work.

A1.2.3 Funding

TAHMO started in Kenya in 2014 with funding from USAID and in Ghana in the same year through the support of the Dutch NWO. These projects helped TAHMO to install about 50 stations in total from 2014 until 2015. From 2016 to 2019, the Weather Company, owned by IBM, supported TAHMO to install 300 stations across 17 countries in Africa at an undisclosed amount. Over the past 5 years, commercial companies, and research projects such as those funded by the European Commission H2020 programme (GroundTruth2.0, Oasis Insurance, TWIGA), the World Bank, the Dutch NWO and IITA have supported TAHMO to increase the network to about 650 stations. TAHMO is therefore largely donor-funded (about 80% of the revenue generated) with some services provided to generate additional income. This is elaborated upon in section A1.5.

A1.2.4 TAHMO station network

The TAHMO station map is shown in *Figure A.2* and its distribution over the years provided in *Figure A.3*. Although TAHMO officially started in 2014, there had been a few tests stations installed as far back as 2012. Kenya and Ghana have the largest numbers of stations with over 100 stations in each of these countries. This is not surprising as TAHMO started in these countries with exceptionally good support through Memoranda of Understanding (MoU) with the Kenya Meteorological Department (KMD) and the Ghana Meteorological Agency (GMet) where TAHMO's offices are still situated in these two countries. In total, over 650 stations had been installed by TAHMO by 2022 in Africa alone with a few stations in Europe and USA *(Figure A.4)*.

Figure A.2: Map of TAHMO Stations installed by the 1st quarter of 2022

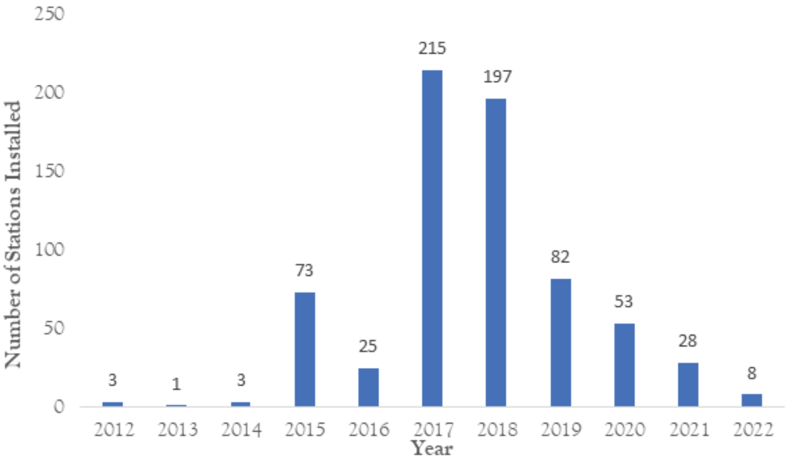

Figure A.3: Number of Stations installed by TAHMO over the past 10 years (as at 1st quarter of 2022)

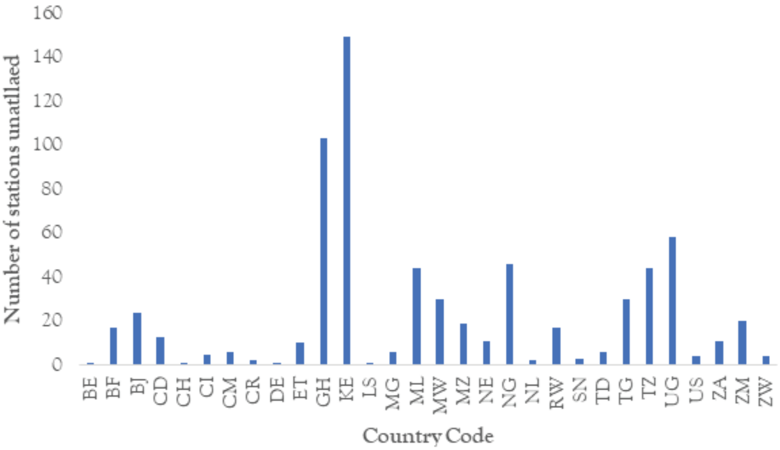

Figure A.4: TAHMO Stations installed per country as at 1st quarter of 2022

TAHMO has a long-standing relationship with the Meter Group (formerly known as Decagon Devices) founded in 1983 by Dr. Gaylon Campbell and located in Pullman, WA, United States. Meter has been instrumental in the success of TAHMO. Together with TAHMO, Meter developed the Generation 1, Generation 2, and the Generation 3 (current model) stations *(Figure A.5)*. The current TAHMO station has no moving parts and is "plug and play", hence makes it easy to install and maintain.

Generation 1 **Generation 2** **Generation 3 (ATMOS 41)**

Figure A.5: Generations of TAHMO Stations installed in Africa as of 2022

All TAHMO stations currently operational in Africa, are Generation 3 *(Figure A.5)*. From 2017, the TAHMO network grew faster with the support of IBM. In this year, TAHMO installed over 200 Generation 3 stations in Sub-Saharan Africa *(Figure A.2, Figure A.3 and Figure A.6)*. The Generation 3 stations brought about an important innovation that enabled over-the-air update of firmware on the stations. From 2017 until 2018, TAHMO had installed over 400 Generation 3 stations in fourteen countries in Sub-Saharan Africa largely supported by IBM. In 2019, an additional 80+ new stations were installed (with some of the countries shown in *Figure A.7*) and some old stations replaced, largely with the support of IBM and the European Commission through Horizon 2020 projects (GroundTruth2.0, Oasis Insurance and TWIGA) thereby adding to the gains in 2018. This took the station network to almost 600 and made TAHMO the largest supplier of African Weather data in the World for research.

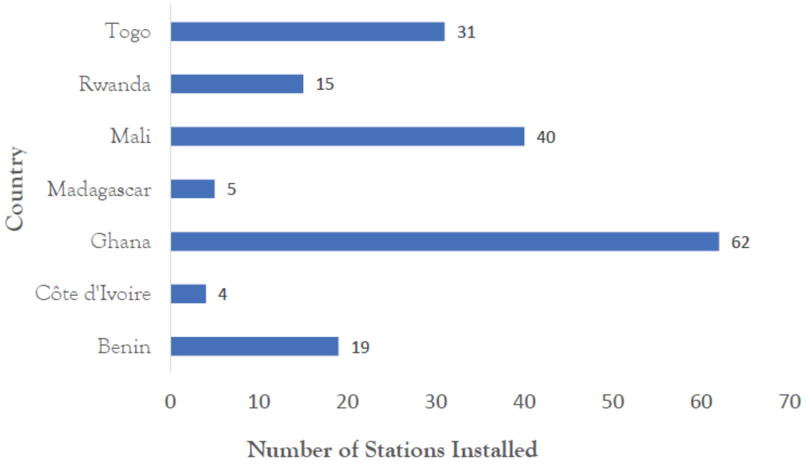

Figure A.6: TAHMO Stations installed largely with the support of IBM from 2017- 2018

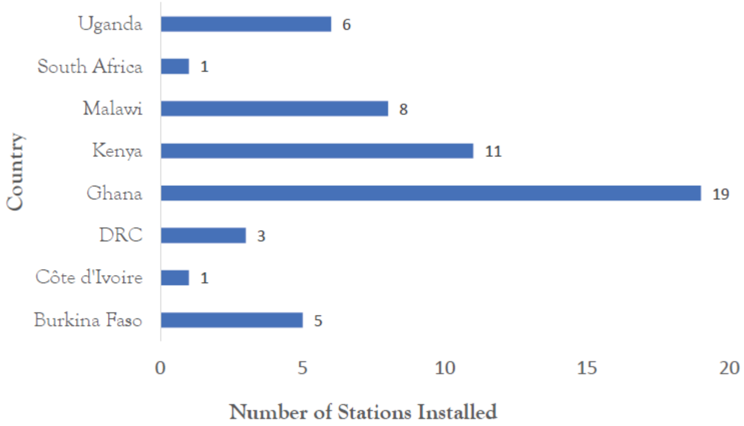

Figure A.7: TAHMO Stations installed in 2019

A1.3 TAHMO station specifications and calibration

TAHMO stations are specifically designed to provide rainfall, temperature, wind speed, wind direction, relative humidity, solar radiation, electrical conductivity of rain, barometric pressure, lightning strikes (within 40km - strength and count) and other critical data, such as water level, using robust sensors with real-time mobile phone uplink. The station has an integrated GPS receiver and an accelerometer to check movements and alignment. TAHMO also installs standalone hydrological equipment for water level, velocity, and discharge measurements.

Although TAHMO has worked with the Meter stations and prefers this as low-cost and robust solutions suitable for Africa, it has also installed and maintained other stations from other manufacturers including Campbell Scientific Instruments, ADCON, Vaisala, SEBA, Sommer and worked with other manufacturers such as MicroStep-MIS. In principle, TAHMO is able to install any station depending on the requirements from the National Meteorological and Hydrological Services (NMHS) in accordance with World Meteorological Organisation (WMO) requirements [2]. In this section, the specifications for the TAHMO Generation 3 stations will be provided since that is what is largely used by TAHMO.

The TAHMO Generation 3 (ATMOS41) station manufactured by the Meter Group is solar powered, recharging six (6) AA batteries *(Figure A.5)* which are readily available in most African countries, has 6-month back-up battery; GSM, GPS, 3-axis accelerometer (12-bit), compass (+/-1 deg), reporting hourly, with 5 min readings, 5 ports for external sensors (SDI-12). It measures twelve (12) parameters. Additional sensors such as soil moisture can be added to the station as and when required. The station can be used with other SDI-12 compatible loggers, or the ZL-6 logger manufactured by Meter. The specifications for the standard weather parameters are provided below.

A1.3.1 Anemometer (2-D ultra-sonic no minimum wind speed, no moving parts)

Wind speed range: 0 to 60 m/s (wind gust 30 m/s)

Wind speed resolution: 0.01 m/s or 5% of wind speed, whichever is larger

Wind speed accuracy: 0.30 m/s or < 3%, whichever is larger

Wind direction range: 0 to 359 degrees

Wind direction resolution: 1 degree

Wind direction accuracy: ±3 degrees

Operating temperature range: -40 to 50 °C

Maximum sampling speed: 1 Hz

Output: average speed, gust speed, direction, vector

A1.3.2 Temperature/Relative Humidity

Humidity resolution = 0.1% RH

Humidity accuracy = 1.8%

kPa humidity range 0-100%

Vapor pressure resolution = 0.01

Vapor pressure range = 0-47 kPa

Rh temperature range = -40°C to 80°C

Temperature resolution = 0.1°C

Temperature accuracy = 0.35 °C

A1.3.3 Rain gauge (custom drip-counting with electrical conductivity)

Rainfall resolution = 0.014 mm

Rainfall accuracy = 2 %

Electrical conductivity resolution = 0.01 dS/m

Electrical conductivity accuracy = 0.001 dS/m

Operating environment = 0°C to 60°C not for snowfall measurement)

The electrical conductivity measurement has not been included in the current ATMOS41 sensors from 2023. There are still considerations to reintroduce this and to add it to the isotope water sampler developed by the OPEnS Lab [3] at Oregon State University for TAHMO.

A1.3.4 Solar radiation (Apogee)

Spectral range = 380 - 1120 nm

Accuracy = ± 5%

Resolution/field of view = Hemispherical, 180°

Measurement range = 0 to 1,750 Wm-2

Operating environment = -40°C to +60°C

A1.3.5 Barometric Pressure

Range = 1 - 120 kPa

Resolution = 0.01 kPa

Accuracy = 0.05 kPa at 25oC

Operating temperature: -40 to +85°C

A1.3.6 Lightning detector

Type = AS3935 Franklin Lightning Sensor

Range = 40 km

A1.4 TAHMO Quality Control and Quality Assurance Procedures

TAHMO's quality control and quality assurance procedures are based on the Oklahoma system [121]. Automated and manual procedures carried out by TAHMO include range, sensor, climate, temporal, step (dips and spikes), delta (stuck at value), sigma (change in variance) tests as well as the use of like instruments (redundant sensors), spatial interpolation and external in situ data and satellite data. These are explained in detailed by Hagenaars [122]. Quality assessment and quality control procedures were sharpened and to a large extent automated in 2018 following the Oklahoma Mesonet approach [121], [123]. A new ticketing system was set up to streamline maintenance issues [123]. Quality assessment and quality control procedures were further enhanced with full automation in additional to manual quality control procedures which were already in place. A new ticketing system (SensorDx) was rolled out to support station maintenance. The enhanced TAHMO quality control and quality assurance system *(Figure A.8)* was proposed in 2018 [123] and implemented in 2019. The quality assurance procedures of TAHMO include station siting, routine maintenance of sensors and loggers, calibration and the efficient quality control system described above. Setting up a functional metadata system was critical for the quality control and assurance of the data collected.

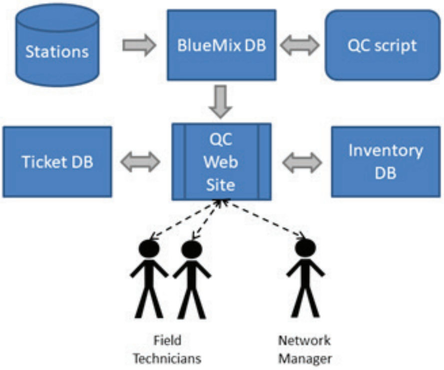

Figure A.8: TAHMO Quality Control System proposed in 2018 and developed in 2019 [123]

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[9] https://tahmoissuetracker.mybluemix.net/#/login

A1.5 TAHMO Business Models and sustainability plan

In order to sustain the operations of TAHMO, it has been looking into several business models (Figure A.9) including station installations, product development and service delivery, all classified as services.

The core business of TAHMO includes station installation, maintenance, data integration, climate modelling and portal or dashboard development. This leads to the development of enhanced hydro-meteorological services such as flood early warnings, agriculture insurance, agriculture and irrigation advisory services, and reservoir management. TAHMO focuses its services in these 3 main sectors (disaster management, agriculture, and reservoir operations), but has also tested a couple more services and business models in the mining sector, construction, energy, commodity trading, and research. Through the EU funded H2020 TWIGA project thirteen (13) additional services [124] were developed and tested by TAHMO and its partners. TAHMO is able to integrate local weather station data, limited area model output, and precipitation satellite and radar data in their processing chains.

In 2017, TAHMO was supported by the Rockefeller Foundation to develop, test, and get endorsement of other business models from key stakeholders in the weather, water and climate sector including the WMO through a Public-Private-Partnership (PPP) for Weather and Climate Services for Africa [125]. This was called the Bellagio conference and was attended by nineteen (19) influential stakeholders in the hydro-meteorological sector from the donor community, WMO, National Meteorological and Hydrological Services (NMHS), Academia, International NGOs and private consultants and businesses [125]. At the conference, the main focus of the discussions and group works was on the demonstration of how various PPPs could work for climate services for Africa. One of the main takeaways for the conference was the fact that "Partners should provide added value and should have a transparent and sustainable funding and revenue sharing mechanism"[125]. At the Bellagio conference TAHMO presented most of its business models that it had developed since 2014 in Accra *(Figure A.9)*.

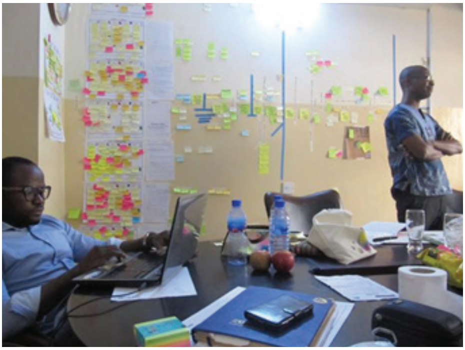

Figure A.9: TAHMO business model workshop in Accra, Ghana (2014)

TAHMO's fundamental policy is to adhere to WMO Resolution 40 [126] to deliver all of its data free of charge to the station's host countries, governments and to researchers developing scientific publications. To ensure sustainable operations of the weather stations, TAHMO requires commercial and non-scientific users to pay a fee to access their unique data set (full-continent in real time with 5-minute resolution with 12 parameters) via an API or the TAHMO data portal (https://portal.tahmo.org/login). The cost of data to commercial users is affordable because each station is supported by a number of clients, whereas traditional stations depend on a single owner.

TAHMO has established Memoranda of Understanding (MoUs) with National Meteorological and Hydrological Services, or other relevant government agency, in each country, to ensure its activities are fully supporting governing authorities, legitimate and supports the plans of these institutions. MoUs are currently in place or being reviewed with Kenya, Uganda, Rwanda, Tanzania, Ethiopia, Zambia, Malawi, South Africa, Mali, DRC Congo, N, Ghana, Nigeria, Burkina Faso, Cote d'Ivoire, Togo, Benin, and Cameroon, with additional countries in process.

A1.5.1 Insurance

TAHMO's data are used by insurance providers for premium computation and offers. Together with the National Meteorological Agencies, TAHMO can provide monitoring services as neutral referees for pay-outs. TAHMO also offers reanalyses as a service to insurance companies, for example providing local rain data, combined with satellite data, to determine whether pay-out for claims should be made (e.g., at the true onset of the rainy season for germination insurance [127]). This ensures that farmers face less risk in cultivating more acreage of land, thereby increasing the food production from Africa. Latin America and Africa will have to feed almost 60% of the world in the coming decades since they have the right climate, land, water, and labour [128]–[130].

A1.5.2 Early Warning System (EWS)

Many major capital cities in Africa (e.g., Accra, Lagos, Dar es Salaam and Nairobi) are regularly flooded during the wet season and struggle to meet year-round water requirements of their citizens. The floods are caused by extreme rainfall events and lack of proper waste management and drainage systems. TAHMO is working with national governments and international donors to provide cost-effective instrumentation and data to support early warning systems thereby making their cities much more resilient to flood events. These include hydrometeorological sensors and modelling provided by TAHMO, and information dissemination including WhatsApp messaging, voice messaging and SMS provided by TAHMO and its partners such as Farmerline limited, based in Ghana. These applications are aimed at urban centres and capital cities in Africa which are experiencing extreme weather conditions.

At present, no predictions are produced directly by TAHMO as a service. TAHMO works with teams that have expertise in forecasting such as IBM, Meteoblue, and ECMWF who utilise the data TAHMO. Similarly, TAHMO works with other flood modelling teams to translate the data to flood predictions (e.g., in Dar es Salam TAHMO worked with Deltares and others [131]. In Dar es Salaam, TAHMO developed both the backend and front-end of the dashboard and coupled this with the hydrological/hydraulic model from Deltares and the FloodTags AI for online (social) media [131].

It is not TAHMO's goal to run parallel weather forecast models to existing ones. It seeks to improve weather forecasts from National Meteorological Agencies and partners that intend to support them do the same such as IBM and Tomorrow.io so they are never in competition with the NHMS.

A1.5.3 Reservoir Operations

Through the TWIGA [124] and TEMBO Africa [127] projects, TAHMO seeks to improve water management information services, starting with reservoir management. This is critical for the optimum management of water resources for energy and food production and flood reduction [127]. It includes operational advice for multi-purpose reservoirs as well as optimal energy production for a mix of hydro-, solar-, and wind-power [127]. This requires streamflow forecasts, radiation forecasts, water balance models, erosion and sediment estimation, and dam wall monitoring [127].

A1.6 Dissemination of TAHMO data and information

TAHMO currently provides weather-related information to users at various levels mainly through APIs, the TAHMO portal (https://portal.tahmo.org/login) and through third parties guided by its data policy [132]. TAHMO works with partner teams with expertise in outreach and communication and relies on existing local nationally mandated institutions for easy uptake. E.g., in Tanzania TAHMO worked with the Disaster Management Department, the Dar es Salaam Multi-Agency Emergency Response Team (DarMAERT), the Ministry of Water and Irrigation (MoWI) and the Tanzania Red Cross Society, who all had their own communication channels from the community level to national level. In Kenya this is done through the Ministry of Water and Irrigation and the Kenya Meteorological Department (KMD) who also have their own communication channels. The Flood Early Warning System set up by TWIGA and TEMBO Africa projects, use the KMD Weather WhatsApp group for dissemination of the warnings. In Uganda, TAHMO works with the Uganda National Meteorological Authority (UNMA), CHAI – a local company which has multiple communication channels with farmers and fishermen at the community level in the cattle corridor, as well as with Airtel Uganda which has a large share of the Ugandan telecommunication market . TAHMO does not reinvent the wheel but builds on existing local structures to enhance sustainability of its services.

A1.7 Results, discussions, and conclusions

TAHMO has over 650 operational stations in twenty-three (23) countries in Sub-Saharan Africa. These stations are cost-effective and require low maintenance. At operational costs of US$50/station per month, the entire TAHMO network

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[10] https://www.climatelinks.org/blog/meteorological-early-warning-system-build-resilience-climate-induced-shocks

could be sustained including the costs of its staff remuneration and cloud solutions. This means TAHMO requires just about half a million dollars per year to sustain the already installed (650) stations.

The largest user base for the data collected by TAHMO are researchers from universities and research institutions. About 200 unique research institutions currently use the TAHMO data globally. In total over 600 institutes, government agencies and private companies use the TAHMO data via the portal or API. There are over 1000 users with configured access to the TAHMO data Portal and another 1000 without full access (e.g., portal demonstration, station map view) (https://portal.tahmo.org/login). From 2019 to mid-2022, there had been close to 10,000 data exports (Figure A.10) with each data export being fourteen (14) stations with six(6) variables on average. There are 900,000 TAHMO API calls per day including internal usage by TAHMO's quality control system and portal. The TAHMO website (www.tahmo.org) is another source of data since it provides graphs of weather data from all stations. The web page visits for the graphs were 28,000 for 2021.

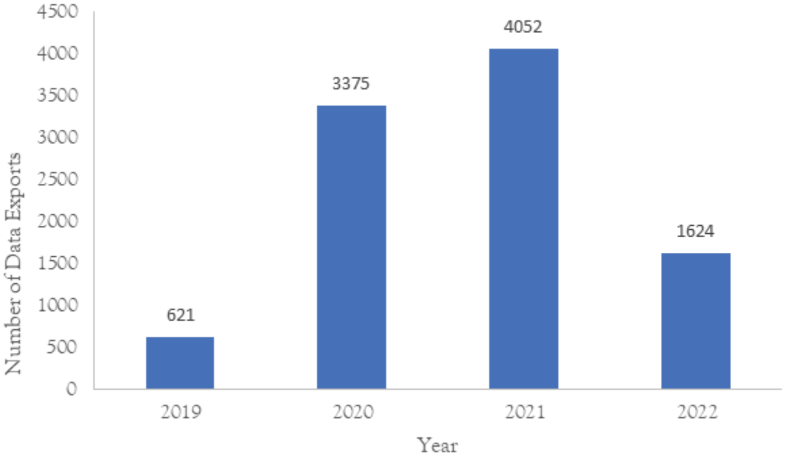

Figure A.10: TAHMO data export as of June 2022

It is evident from this chapter, that the TAHMO initiative has made African data readily available for research across the globe. This helps improve our understanding of climate change and offers opportunities for climate resilient development especially for the agricultural and disaster management sectors. Despite the many gains made by TAHMO over the past decade, sustainable business models for climate services take an extremely long time to develop, since water, weather and climate services are considered mostly as public goods. Additional value is always needed to make these economic goods financially sustainable while still maintaining the public service. There is quite an enormous amount of funding in the weather and climate space but, unfortunately, they are not always well targeted or utilised for initiatives such as TAHMO.

With this in mind, it will take TAHMO quite some time to be self-sufficient through its services. For now, donor and project funding remain a big part of TAHMO for the support of its operations.

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