Using simple mobile technologies to scale up digital collection & processing of climate observation for adaptation actions in Malawi

UNEP CTCN Project: 2022000048

Preliminary Analysis on the Use of Simple Mobile Phones

May 2024

ADAPTATION FUND

UN environment programme

CTCN UN Climate Technology Centre & Network

Table of Content

1. Executive Summary

Climate change poses significant risks to low-income countries, with severe impacts on agriculture, water resources, infrastructure, economic growth and overall livelihoods. In Malawi, the National Commission for Science and Technology (NCST), along with the Department of Water Resources (DWR) and the Department of Climate Change and Meteorological Services (DCCMS), is exploring the use of mobile phone technologies to improve the collection and processing of water, weather and climate data with support from the United Nations Environment Programme and the Climate Technology Center and Network (UNEP CTCN).

This report is part of the project's diagnosis and pre-feasibility phase. It encompasses the preliminary analysis on the use of mobile phones by Gauge Readers and Observers working for DWR and DCCMS (GR&Os) to scale up digital collection and processing of water and weather observation data for adaptation actions in Malawi. The analysis goes further to include cloud computing and data processing technologies that enable effective management and application of the new data resource.

The key findings of the analysis are:

- Mobile and internet penetration in Africa, including Malawi, has rapidly and significantly increased, underpinning the significant feasibility of leveraging mobile and cloud computing technologies for scaled digitisation of observation data.
- Initial prototyping and the project's pre-feasibility assessments demonstrate that mobile technologies, such as free SMS and WhatsApp, are effective.
- There are data quality issues with the digitisation of manual observations using mobile phones, such as consistent formatting and credibility. A bespoke and secure system of technologies and tools are needed as part of data processing of the new approach (e.g., data cleaning, annotation and validation etc.).
- Software dashboards should be tailored to user needs with user-friendly features and visualisations that meet operational requirements of DCCMS and DWR. But that does not duplicate already existing dashboards and that are cost-effective in the long-run.
- A robust data access control system is necessary to ensure data integrity, security and compliance with government protocols. Role-Based Access Control (RBAC) should be used to define specific permissions based on job functions, preventing unauthorised modifications and ensuring users have access to relevant data.
- Successful implementation depends on integrating new data with existing data management systems of DWR and DCCMS, such as HYDSTRA and Climsoft - as well as forecasting and modelling applications for generating ultimate and valuable insights.
- Cloud computing services (AWS, Microsoft Azure, Google Cloud) provide the necessary infrastructure, although local server integration is key for security and data ownership.
- Successful adoption relies on improvements in the micro and macro-environment: from refurbishment of simple monitoring equipment, recurrent training and financial compensation to GR&Os and provision of personal protection equipment, as well as engagement with local communities and international donors.

2. Introduction

Project

In the project "Using simple mobile technologies to scale up digital collection & processing of climate observation for adaptation actions in Malawi", supported by UNEP CTCN, this report constitutes the preliminary analysis on the use of mobile phone technologies.

This report is Activity 3.3 of the project's Output 3, diagnosis and pre-feasibility, aimed at uncovering comprehensive knowledge and guidance shaping subsequent prototyping, technology development and financial sustainability assessment.

The deliverables in Output 3 are:

- Deliverable 3.1.a Diagnosis of hydromet information & systems (MW & Region)
- Deliverable 3.1.b List: equipment recommendations, barriers & opportunities
- Deliverable 3.1.c List: previous similar/complementing initiatives in Malawi
- Deliverable 3.1.d IT characteristics of DCCMS & DWR data management systems
- Deliverable 3.2.a Workshop minutes & materials
- Deliverable 3.2.b Report: client needs summary (ToR & system architecture)
- Deliverable 3.2.c Matrix: comparing available versus requested data & system
- Deliverable 3.3 Report: preliminary analysis on the use of simple mobile phones
- Deliverable 3.4 Report on challenges, barriers, risks, opportunities & strengths
- Deliverable 3.5.a Draft system architecture with user manual (summary report)
- Deliverable 3.5.b Matrix: explaining needs reached or not reachable

Scope

The objective of the analysis is to identify optimal mobile phone and cloud computing technologies for collecting, transmitting, validating and applying water and weather data in Malawi that enhances climate adaptation and disaster risk management.

The analysis scope is to evaluate technology options that deliver an integrated process. From the point where a GR/O collects a manual observation data point, uses her/his phone to transmit the observation to an online database, where a back-end quality check ensures consistent data format, codes the data in the database.

Data accessibility should be enhanced through Application Programming Interface (API) for the Government of Malawi's hydro-meteorological data management systems and/or modelling softwares/tools, and be accessible at a front-end and user-friendly data dashboard online where data management and use is controlled by account and user-profiles.

Data should be available for the use in impact modelling and development climate futures for adaptation and disaster risk management.

Methodology

The analysis was done in four steps:

- First, the analysis delves into the wider technology context: i.e., the evolution of mobile technologies in Africa, learnings from similar initiatives, and learnings from DWR and DCCMS's earlier prototyping with Water in Sight 2021-2023 (Vinnova, Swedish Agency for Innovation).
- Second, technology options are identified and evaluated against the needs identified in Activity 3.2 (clients needs summary).
- Third, exploring strategic questions on the enabling environment for a new technology approach are scrutinised.
- Last, findings and recommendations emanating from the analysis are summarised.

3. Context

Evolution of mobile technologies and services in Africa

Mobile and internet penetration and trends

Mobile connectivity has transformed Africa. By 2022, approximately 489 million people were mobile subscribers (43% of the region's population), reaching an estimated 700 million (50%) by 2030 (Figure 1; GSMA, 2023). With SIM-card connections, connectivity is even higher at 980 million in 2022 and where penetration rate is estimated to reach 99% of Africa's population by 2030 (Ibid.). The adoption of 4G technology is accelerating as well. 5G is gaining momentum, particularly in urban areas. The projected subscriptions of smartphones will also rise, from 51% to 88% between 2022 to 2030 (Ibid.).

In Malawi, mobile connectivity and penetration have seen similar significant growth. According to the World Bank, mobile phone penetration reached 60% of the population in 2022, up from 43.7% in just two years (World Bank, 2024) (Figure 2). This indicates substantial progress in mobile access, although the country still ranks relatively low globally in this metric.

Internet connectivity via mobiles is growing rapidly too. In 2022, 25% of Africa's population were connected (12% in 2015) (GSMA, 2023). The connectivity improvements are largely driven by expansions in 3G and 4G networks and the demand for internet based services. Internet usage in Malawi has also been on the rise with 5.86 million (27.7%) users in 2023 - reflecting the broader adoption of digital technologies in the broader population (DataReportal – Global Digital Insights, 2024).

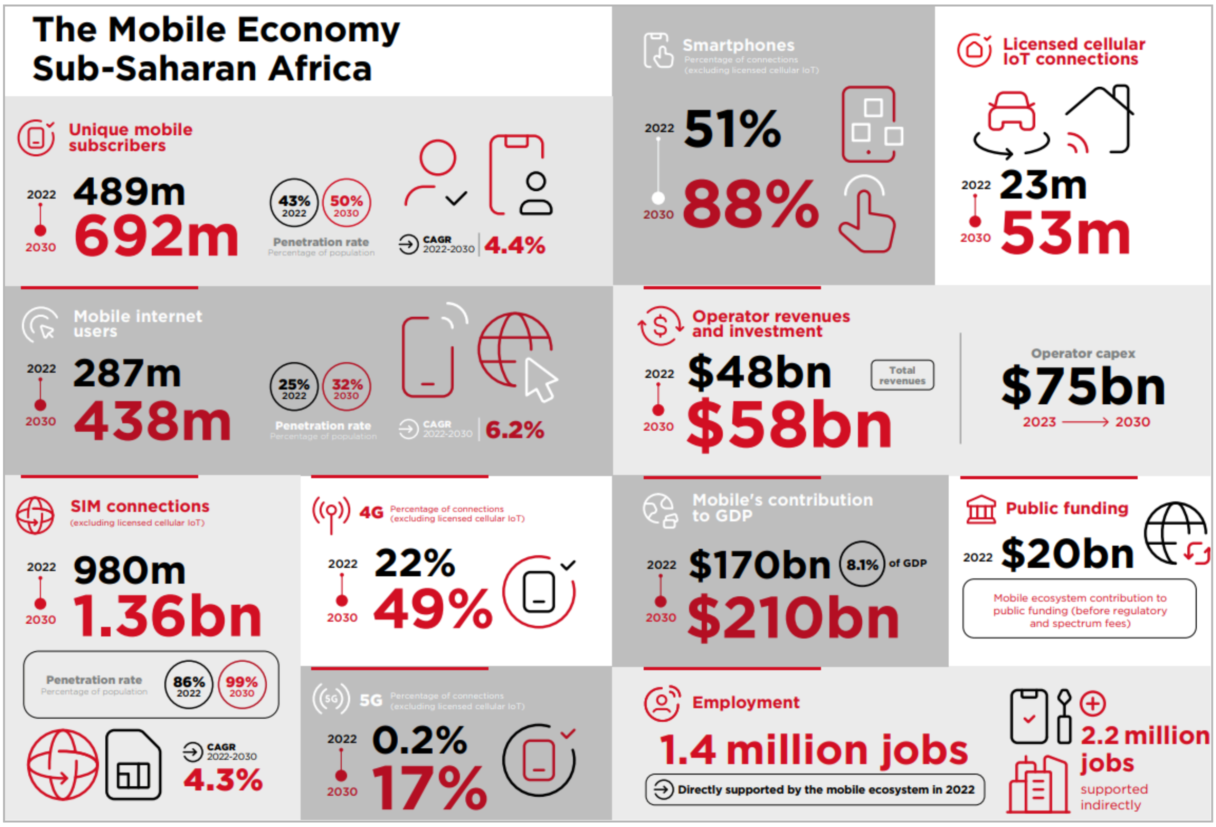

Figure 1. Mobile economy of sub-Saharan Africa (GSMA, 2023).

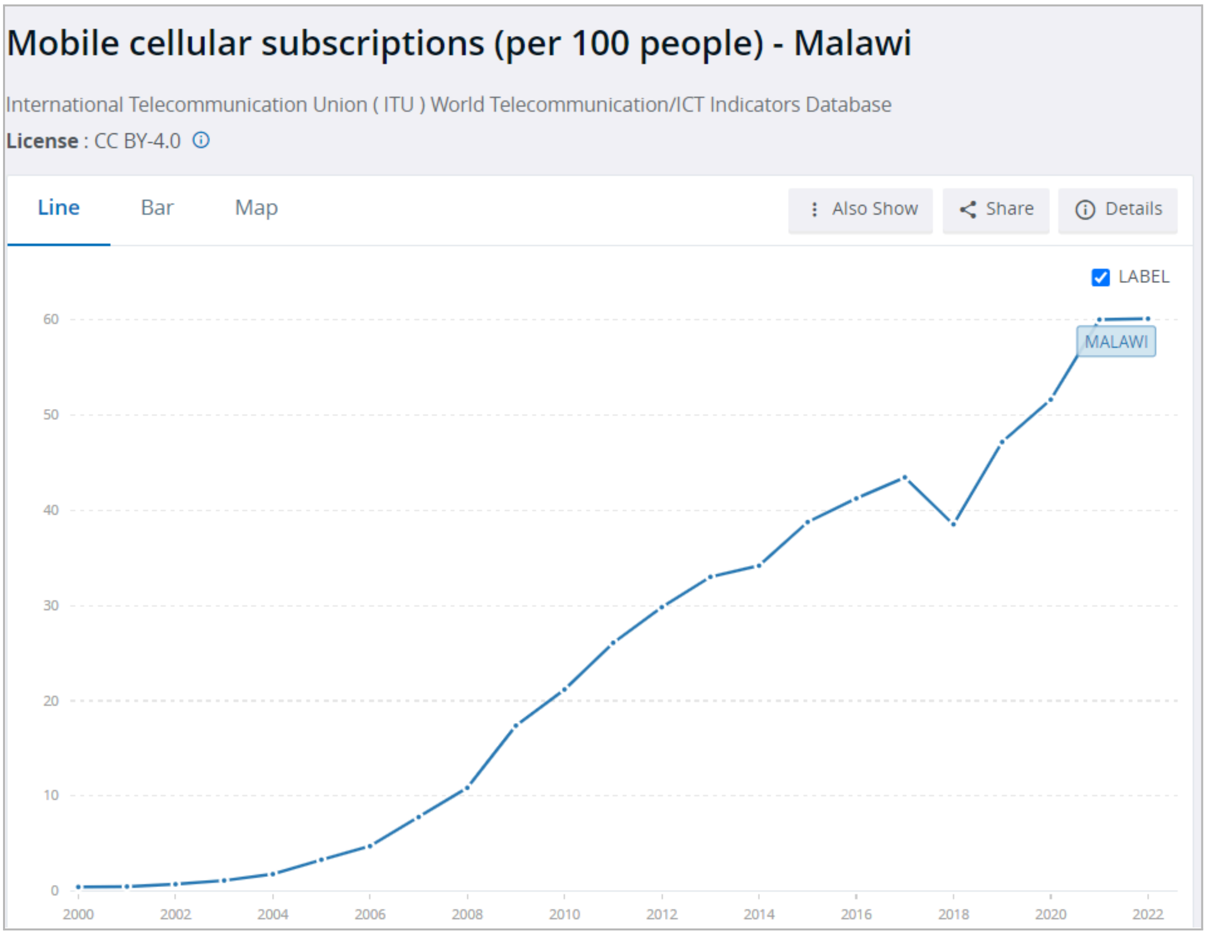

Figure 2. Mobile cellular subscriptions (per 100 people) in Malawi (World Bank, 2024).

Impact of mobile connectivity and communication on sectors and economy

The mobile communication sector in Africa has shown remarkable progress compared to others. Its rapid growth and ability to enhance accessibility and inclusion highlight its transformative impact. Success is largely driven by untapped market demand, concerted improvements in the regulatory environments, and investments and innovations into mobile devices and networks. The mobile sector is also a major economic driver contributing 8.1% to Africa's GDP ($170 billion) in 2022 (GSMA, 2022). This evolution has contributed and enabled a diversity of new innovative digital tools across sectors and points to the ecosystem potential of the project.

Financial services.

Mobile technology has revolutionised financial services in response to the demand of banking services. Leading examples include mobile money platforms such as M-Pesa, MTM Mobile Money, Orange Money, and Opay. Mobile financial services are estimated to grow 10% yearly and could reach $230 billion in revenues 2025 (McKinsey, 2022). As a result, mobile banking has contributed to boosting financial inclusion of Africa's population, from 23% in 2012 to 48% in 2022 (World Economic Forum, 2023).

In Malawi, there are two main mobile banking providers. Airtel Money offered by Airtel Malawi, allowing users to send and receive money, pay bills, purchase airtime, and access other financial services. TNM Mpamba, provided by Telekom Networks Malawi (TNM) offers similar services.

Agricultural services.

Mobile platforms are evolving to provide farmers, especially small-holder farmers, with access to market information, weather forecasts, agricultural advice, insurance and credit to enhance productivity, income and resilience. Digital Climate Advisory Services (DCAS) are emerging as a segmented technology to reach small-scale farmers at scale. Examples include Hello Tractor, allowing farmers to rent tractors on demand (Nigeria, Kenya, and Tanzania), DigiFarm providing access to low-cost seeds, fertilisers, loans and insurance strengthening agricultural value chains (Kenya), and Ignitia (West Africa) providing hyper-local weather forecasts and alerts by SMS for farmers living in tropical climates, tailored to the specific needs of the farmer with advice on planting, irrigation, and harvesting.

Health care.

Mobile health, or mHealth, are improving health care delivery in Africa. Interventions range from SMS reminders for medication adherence, to appointments, health education, remote consultations, contact tracing, among others. Applications are improving access to services, particularly in remote areas. Examples include disease surveillance through mobile data tracking (e.g., the Ebola outbreak in West Africa), SMS-based information to healthcare workers with mHero in Liberia, Hello Doctor in South Africa offering consultations via phones, or M-Tiba in Kenya offering a health wallet to fund individual care.

Water services.

Leading improvements in water services from mobile technologies are evident in the water utility space. Companies and initiatives such as CityTaps (Nigeria) uses smart water metres with prepaid wallets, and Wonderkid (Kenya) who enhance customer care and billing services, demonstrating how water access is strengthened, scaled and improved. The integration of mobile money with water utility services has made a particularly positive impact.

Disparities in mobile access and use

Disparities in mobile internet coverage and usage persist as well despite progress. Africa still has the widest gaps in connectivity globally. Rural and urban areas differ where rural inhabitants are 49% less likely to use mobile internet. In addition, affordability remains a barrier with entry-level devices costing 95% of the monthly income of the poorest 20% of the population.

There are gendered disparities in mobile access in Africa. Women are 8% less likely to own a mobile phone compared to men, and 36% less likely to use mobile internet (GSMA, 2024). Affordability is the barrier (24% of women's monthly income compared to 13% of men's in low and middle income countries) (GSMA, 2024). Other barriers include lower literacy rates, fewer digital skills and cultural norms. According to GSMA, closing the mobile gender gap could add $230 billion to the mobile industry over eight years (Ibid.).

Similar technology initiatives boosting hydro-meteorological services

Initiatives using mobile phone technologies in hydro-meteorological services were previously analysed in the project (Deliverable 3.1 Diagnosis of Hydromet Information Systems). Examples such as TRIM, mWater and Smartphones4Water, showcase that digital solutions are viable. And global initiatives, such as the Google Flood Hub, reflect the even greater capabilities of mobile and ai computing potentials to serve and protect the public.

Learnings from similar technology approaches reveal the following:

- Technologies, however simple, are best integrated as part of a maintainable service and operation, and not as a stand alone use of an isolated piece of technology. For example, asking individuals to use standard WhatsApp or SMS without integrating them into digital database management systems. Disconnected mobile communication still ends up requiring manual management, tracking and transfer of data.
- Operational sustainability is core to sustainability:
    - Align mobile technologies to existing standards applied by the WMO and government operating protocols.
    - Leverage additional technologies, such as mobile payments for paying Gauge Readers and 2-way communication for sustained engagement.
    - Build on strong institutions, such as schools where students oversee weather observation equipment and use data as part of their education.
    - Integrate manual observation data with other data sources such as sensors to collectively strengthen government and stakeholders' hydrological and meteorological analysis.
    - Engage, remunerate and incentivise GR&Os for sustained data collection.

- Smartphone apps offer great versatility and capabilities compared to simpler methods such as SMS and USSD (Unstructured Supplementary Service Data). Especially with GPS location tracking and camera capabilities for image interpretation.
- Apps rely on user training, interface flexibility, mobile data cost recovery, smartphone affordability, smartphone literacy, among others.
- Significant financial investments may still be required in infrastructure and equipment (e.g., complex flood and early warning sensors and software).

Learnings from MVP in Water in Sight projects

Water in Sight piloting, Phase 1

With a US$30,000 grant, Water in Sight prepared its first pilot with DWR and DCCMS (Phase 1), exploring why manual observations of river levels and rainfall were not easily digitised and using mobile phones. The goal was to gain deep insights on design and technical barriers through mock-ups and unrefined prototypes.

The prototype had to work on any type of phone and on all networks. It had to be geographically scalable, and observations needed to be submitted per government and WMO protocol for average 24 hrs rainfall and river levels.

The following technologies were tested:

- A UK phone number (Twilio) for GR&Os to transfer observation, through:
    - Recording audio from the phone.
    - Following instructions from a pre-recorded message, to enter data using the phone's keyboard.
    - Programmable SMS where Observer could send data in an SMS.
- Online database with Amazon Web Services with raw data and audio from Twilio.
- Tableau to visualise data, show diagrams, and make raw data downloadable in .csv.
- Airtel Money Disbursement for monthly compensations to GR&Os.

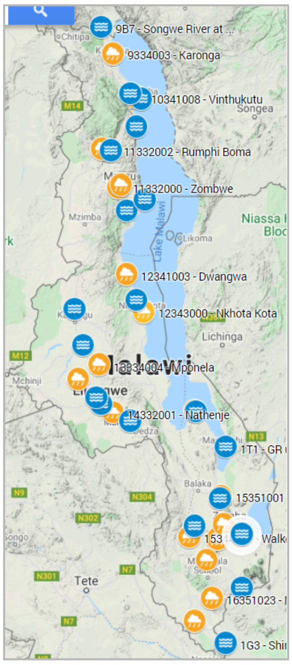

Figure 3. Map of Phase 1 prototyping at 38 stations
(blue icons = river level monitoring stations, orange icons = rainfall monitoring stations)

Three prototypes were designed. At designated times, GR&Os used the UK-number to:

1. Make a phone call, hear instructions in Chichewa, and enter observation data with the phone's keyboard. The voice repeated, and the GR&O confirmed if it was correct by pressing #1 or #2 for new data entry.

2. Make a phone call, hear instructions in Chichewa to record audio from the location to test if machine learning could verify the geolocation.

3. Send the observation data in an SMS.

All designs were tested at 12 river and rainfall monitoring stations in Malawi's southern region. Among the learnings and failures, the team quickly learnt that SMS was the most user-friendly, robust, and reliable method for data digitisation and transmission.

The SMS-prototype was scaled to an additional 26 monitoring stations (figure 3). Between November 2021 and February 2022, 2,500 viable observation data of rainfall and river levels were captured during Malawi's rainy season. Submissions stopped as grant funding ended.

Key learnings included:

- Chichewa is not spoken broadly in northern Malawi. The solution had to be language as well as literacy agnostic.

- Speakers and microphones on phones were often damaged meaning they added little value.

- A UK phone number is not favourable as it appeared observation data left Malawi's territory and was not secure.

- Airtime had to be sent at the start of the month to each GR&Os. This was costly and inefficient, as airtime had to be "saved" for the full month.

- Programmable SMS could be used at scale, but is best used in marketing when reaching large customer or user groups.

Water in Sight piloting, Phase 2

In June 2022, additional Vinnova funding enabled further development in Phase 2 (US$100,000). A Minimum Viable Prototype (MVP) was built. Better and more cost-effective and secure technologies were used, including:

- Africa is Talking (mobile aggregator, Kenya) with zero-rated, shared short code SMS services ('2-way-SMS'). GR&Os send observations in SMS at no cost to her or him. The SMS is sent from anywhere where there is 2G coverage. Water in Sight tops up a wallet with Africa is Talking, from which SMS and maintenance costs are drawn down.

- WhatsApp for Business using a SIM-card phone number, aggregates messages from GR&Os and is designed as individual conversation flows between the GR&O and administrator. The administrator's interface with the channels is via a simple web app.

- Google Big Query database connects SMS and WhatsApp, offering a serverless data warehouse and SQL querying with built-in machine learning. An algorithm was built to clean observation data from errors.

- A simple web app (www.waterinsight.se/data-center, React App Beta, figure 8-11) visualises and posts data in downloadable format. Data Center provides a Chat App for easy communication with GR&Os and a Station inventory with station metadata.
- Malawi's Airtel Money and Mpamba were used for bulk disbursements of monthly compensations to GR&Os, February to August 2023 (figure 5).

The MVP design was based on:

- GR&Os were trained with laminated instructions and illustrations on-site with instructions on timing and format of daily observation. A terms of reference was signed clarifying commitments of GR&Os, DCCMS and DWR, and Water in Sight.
- Observers used the shared short code phone number provided by Africa is Talking (#3067) to send a free SMS with their observation data.

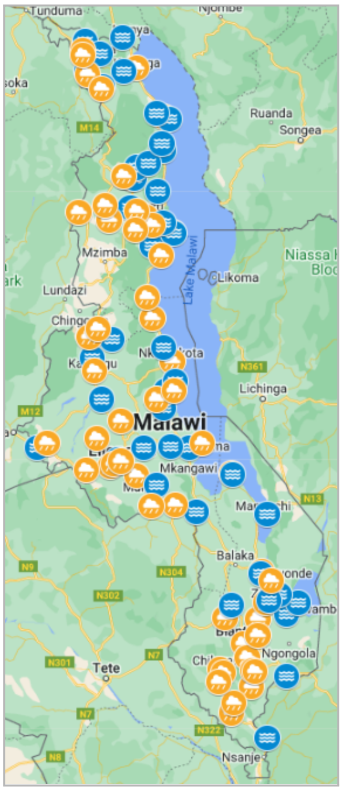

Figure 4. Map of Phase 2 prototyping at 73 stations

- WhatsApp for Business was deployed in Mozambique, where meteorologists send geolocation along with meteorological parameters.
- Data is available real-time in the Chat App and as a cleaned downloadable data.
- DWR and DCCMS staff logged into the Data Center, weekly on average, to interact with the observation data and download it for integrating into ClimSoft and HYDSTRA.

By February 2023, in-field training was scaled to a total of 73 river level and rainfall stations with participation of DWR and DCCMS central and district staff (figure 4). The MVP proved reliable and scalable, and uncovered a roadmap for technical readiness taking into consideration:

- Enhance credibility of manual observations, e.g. via geolocation data, comparison with satellite and sensor observation, using hydrological modelling etc.
    - Credibility is central to DWR and DCCMS for their use of the data in forecasting as well as for their public release of data as official (as is the case with sensor data).
- Bring more automation and integration of observation data, such as APIs.
- Consider additional capacity and technology constraints in the processing of data, for example in the production of daily forecasts, early warnings among others.

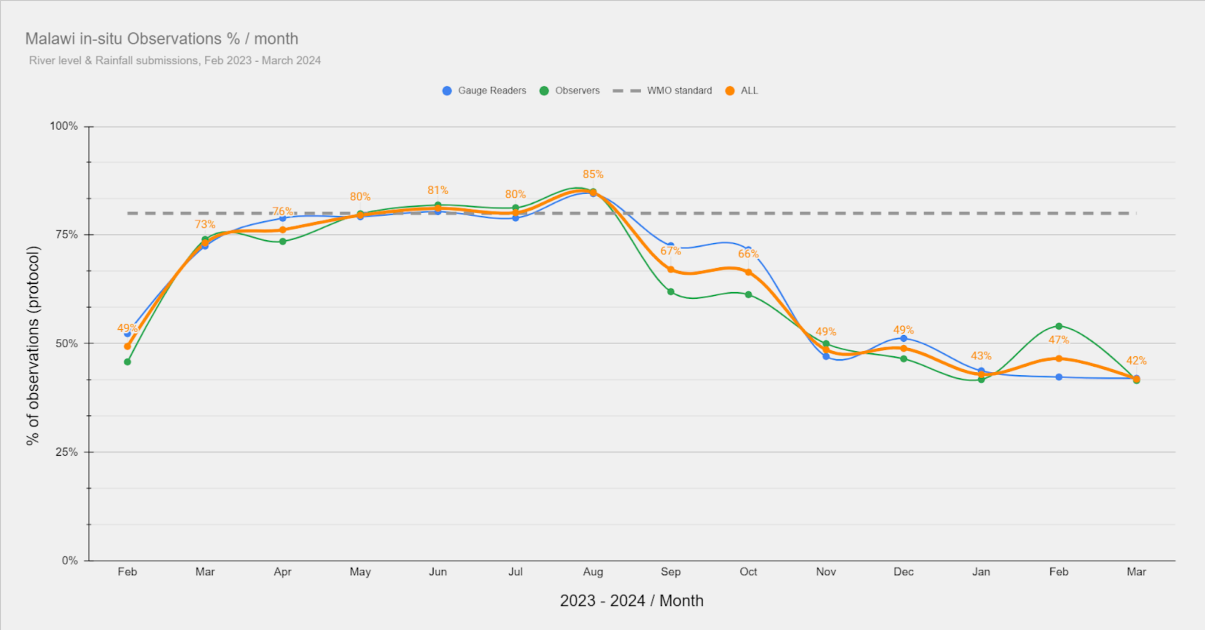

Figure 5. Level of observation data submission during and after Phase 2 (Feb 2023 - Mar 2024, where project engagement agreement with data collected and monthly mobile financial remuneration ends August 2023).

4. Technology Options Overview

The analysis of technology options is structured by their corresponding functional steps, and outlines their requirements, corresponding options, and key findings.

Findings answer to the central question: does the technology option meet requirements to deliver a reliable, scalable, sustainable and valuable solution for hydro-meteorological services?

Mobile phone and communication technologies for data collection

Requirements

The preceding needs assessment found that the mobile communication options should meet the following main requirements:

- Function on any type of mobile phone device, from a basic phone to a smartphone.
- Function on all networks, 2G to 4/5G.
- Be low cost.
- Be secure and reliable.
- Enable near-real and real time data submission and communication.
- Allow for simple numerical formats and code for the water and weather parameters (e.g., TX for maximum temperature).
- Adhere to observation protocols (i.e., timing and frequency of recording, data format, codes for extreme events or disaggregated parameters).

- Work for any languages spoken (numerical only even) and work for those with low or no literacy skills.
- Build several communication channels for different devices and user flexibility.
- Be easy to train, learn and use, and build on existing skills.
- Match GR&Os phone number and geolocation to monitoring station.
- Enable "open" non-scripted communication between user and administrator.

Device options

Mobile phones are widely available, even in remote areas, making them an ideal tool for widespread data collection and communication. Table 1 compares device capabilities.

When surveying GR&Os, 88% of Observers at manual rainfall stations use some form of smartphone. Of DWR's Gauge Readers, smartphone use is significantly less at 25%. This is partly explained by the stronger socio-economic status of Observers (commonly employed). Whereas Gauge Readers are citizens where the majority are small scale farmers.

When evaluating mobile devices for scaled, reliable and sustained collection of water and weather observation, there are three main findings:

- The communication method needs to work on all types of phones.
- Compared to simple phones, smartphones offer greater capabilities in the data collection and transmission process. For example, geolocation sharing at stations and cameras for site investigation or within-app image analysis etc. Benefits must, however, be balanced against:
    - The cost of a smartphone is four to 15 times more than a simple phone.
    - Users may need training in how to use a smartphone.
    - A user interface adjustable to multiple languages and observation protocols.
    - Tailored training to follow a protocol with greater number of user-steps.
    - Internet access and costs for transferring data.

Table 1. Mobile devices options

Device	Technology	Features	Benefits	Challenges	Pricing
Simple/Basic Phones	GSM	Simple interface/screen, physical keypad, limited features (calls and SMS)	Long battery life, durable, easy to use	Limited functionality, no internet access	Low US$ 25 -30
Feature Phones	GSM	Basic internet, simple apps, physical/soft keypad, sometimes camera	Affordable, basic internet access, longer battery life	Limited app support, basic internet capabilities	Low to Moderate US$ 55 - 60
Smartphones	GSM, 4G/5G, Wi-Fi, Bluetooth	Touchscreen, advanced OS, app ecosystem, camera	Advanced features, high-speed internet, app ecosystem, geolocation	Higher cost, shorter battery life, requires data plans	Moderate to High US$ 100 - 550

*GSM = Global System for Mobile Communications

Communication options

A person can communicate or transmit an observation data point in several ways using her or his phone. Yet, it is easy to underestimate contextual user requirements and one can oversimplify the range of abilities that users have.

Therefore, different communication options needed to be analysed against criteria as well as their financial and operational implications. In table 2, a range of communication options for both simple and smartphones, are assessed in detail.

Providers of these mobile communication technology options are either the mobile network operators (MNOs) or mobile aggregator services. Because in-country regulatory approvals are complex and technological establishment processes are lengthy, mobile aggregator providers have emerged globally and regionally.

A mobile aggregator provider is an intermediary between an organisation and the MNOs. They facilitate sending and receiving SMS, images, voice messages, and many of the other mobile communication methods in table 2. The aggregator offers a single interface through which a buyer can connect to multiple MNOs operating in a country. The technical integration between the communication technology and the buyer's database is through API and web-hooks.

Globally, the main mobile aggregator providers include Twilio, Nexmo and Infobip. Within Africa, dominant providers are Africa's Talking, Synq and Africa Development Connect.

When communication options are evaluated for how they help deliver a reliable, scalable, sustainable and valuable solution for hydro-meteorological services, the following findings emerge:

- SMS emerges as the most robust, user-friendly, cost-effective and universally applicable method of communication using any type of phone, any type of mobile network, any type of language, and any level of skills.
- The cost of SMS should be paid by the administrator/buyer, not the user - preferably as a reversely billed expense or rapidly compensated using mobile payment services.
- 2-way SMS enables open and flexible communication compared to other options, such as USSD. 2-way communication is useful for sustained insights and engagement (e.g., communication on extreme weather events).
- Among methods on smartphones, WhatsApp emerges as the most user-friendly, cost-effective and broadly applicable method with additional value of shared geolocation and camera functions.
- Mobile aggregator service providers operate across multiple African countries, allowing for technology transferability and rapid deployment in Malawi, especially Africa's Talking.
- Mobile communication technologies cannot be used in a void. Coded, coupled and continuously updated information on GR&Os (gender, age, risk exposure to crocodiles, floods etc), and the monitoring station and equipment (site and observation equipment status etc.), should be captured and connected to the observation data point.

Table 2. Mobile communication technology options

Method	Short Description	Technology	Format	User Friendliness	Capabilities	Constraints	Costs	Prerequisites	Scalability	Other Considerations
Works on all types of phones										
SMS SMS (2-way) SMS (Bulk 1-way)	Short text messages sent over cellular networks	GSM/cellular network Shared/ Dedicated Short Code (2-way) SMS Gateway	Text based (up to 160 characters)	High	Limited to text (160 characters)	Character limit, no multimedia	Low SMS cost can be reversely billed Requires setup and maintenance cost	Mobile phone with SMS capability	High	Reliable in areas with poor internet connectivity
Programmable SMS	Automated SMS messages sent and received via software platforms	GSM/cellular network with API integration	Automated text message (up to 160 characters)	High	Automation of SMS campaigns, integration with databases	Character limit, costs can escalate with high volume	Moderate Cannot be reversely billed Requires setup and maintenance cost	Access to an SMS gateway API	High	Useful for automated alerts and notifications
Unstructured Supplementary Service Data (USSD)	Interactive text-based communication over cellular networks	Real-time communication protocol GSM cellular network communicating with service provider's computers	Text based, simple menus and commands Section based (messages are not stored)	Moderate	Menus for data collection and interaction	Limited session time, no multimedia	Low Can be reversely billed Requires setup and maintenance cost	Mobile phone with USSD capability	High	Suitable for interactive services, not ideal for complex data
Voice Calls	Direct voice communication between users	GSM/cellular network	Voice	High	Verbal data collection, can handle complex interactions	Requires voice call capabilities, not suitable for automated data	Moderate Cannot be reversely billed Requires setup and maintenance cost	Basic mobile phone with calling capability	Moderate	Effective for qualitative data collection, requires human operators
Interactive Voice Response (IVR)	IVR systems interacting with users via pre-recorded messages	GSM/cellular network with IVR system	Automated voice prompts and user responses via keypad	Moderate	Automated voice interactions, data entry via keypad	Can be complex to set up, limited by user familiarity with IVR systems	High (setup and maintenance) Cannot be reversely billed	Access to an IVR service provider	High	Good for automated surveys, language can be an issue

Method	Short Description	Technology	Format	User Friendliness	Capabilities	Constraints	Costs	Prerequisites	Scalability	Other Considerations
Works on Smartphones										
Smartphone Apps - Social Communication/WhatsApp	Mobile applications designed for broad communication	Mobile operating systems (iOS, Android), Internet	Graphical user interface with multimedia support	High	Multimedia, GPS, complex forms, offline data collection	Requires smartphones, app development costs	Low (communication builds on existing platform) Cannot be reversely billed	Smartphones with internet access	High	Versatile and powerful, but dependent on smartphone penetration and data plans
Smartphone Apps - Data Collection	Mobile applications designed for data collection	Mobile operating systems (iOS, Android), Internet	Graphical user interface with multimedia support	Low/Medium	Multimedia, GPS, complex forms, offline data collection	Requires smartphones, app development costs	High (development maintenance) Cannot be reversely billed	Smartphones with internet access	High	Versatile and powerful, but dependent on smartphone and data plans
Social Media - Facebook - Twitter	Data collection via platforms like Facebook, Twitter, etc	Internet (Web and Mobile Applications)	Multimedia posts, comments, and messages	Medium	Broad reach, multimedia, interactive	Privacy concerns, requires internet access	Low to Moderate Cannot be reversely billed	Smartphones or computers with internet access	High	Useful for reaching diverse audiences, data privacy and authenticity concerns
Online Surveys	Web-based surveys accessed through browsers or apps	Internet (Web-based survey platforms)	Structured forms with various question types	Low	Customizable forms, multimedia support	Requires internet access, potential low response rates	Low to Moderate Cannot be reversely billed	Internet-enabled device	High	Effective for structured data collection, less effective in low internet areas
Chatbots	Automated conversational agents operating via apps or web interfaces	Internet (Web and Mobile Applications)	Text-based conversation with AI/automated responses	Low	Interactive, can handle complex queries, 24/7 availability	Requires development and maintenance, user familiarity varies	High (development and maintenance) Cannot be reversely billed	Internet-enabled device	High	Good for automated, real-time data collection, language support is key
Email	Data collection through email communication	Internet (SMTP protocol)	Text-based messages with attachments	Low	Detailed data collection, attachment support	Requires email access, not real-time	Low Cannot be reversely billed	Email account and internet access	High	Effective for detailed and document-based collection, response times can be slow

Computing technologies for observation data management

With computing technologies, the data point from the communication method (e.g., SMS, WhatsApp) is transferred to an online database storage, processed and connected to multi-computing environments and software (figure 6).

Cloud computing has evolved from a nascent concept in the early 2000s to a fundamental part of modern IT infrastructure. Benefits include on-demand access to computing over the internet (e.g., platform as a service - PaaS, software as a service - SaaS, etc.). Savings are possible with lower IT costs, scaled operations, and faster innovation.

The major providers are AWS, Microsoft Azure, and Google Cloud Platform, offering a wide range of services - from data storage and processing to advanced analytics and AI.

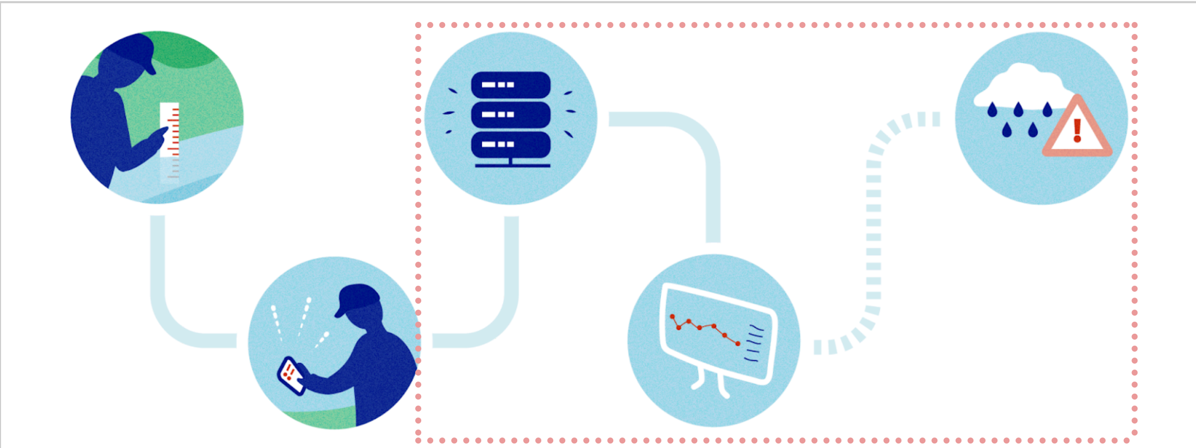

Figure 6. Application of cloud computing within observation data transmission and application process

Requirements

The needs assessment found that computing technologies should meet the following requirements:

- Provide robust database design and management for large volumes of data.
- Access control based on user profiles and management preferences of the Government.
- Handle multiple data formats from various sources.
- Provide built-in or built-on unique algorithms that clean the data from human errors, formatting inconsistencies, outliers and repetitions, etc.
- Allow for built-in and built-on analytics to improve data quality, such as matching geolocation shared by GR&Os to station location or comparison with data from sensors, thereby improving the data's credibility, trust and ultimate value.
- Allow for replication of data to local servers of DWR and DCCMS (as requested and possible), respecting the request for centralised databases that the government has in place and a back up in the case of disruptions to internet connectivity.

- Integration with diverse data sources, including manual and automated sensor data, to uncover comprehensive access and analysis of collective observation data.
- API integration.
- Be cost-effective and scalable.

Cloud computing options

Because cloud computing needs to be robust and sustainable, global providers are preferred: Amazon Web Services (AWS), Microsoft's Azure, and Google Cloud.

AWS database services offer a range of services, such as Amazon Relational Database Service (RDS), DynamoDB, Redshift, Aurora, DocumentDB, and more. Solutions are diverse and technologically mature, corresponding to various needs, such as SQL, NoSQL, and in-memory databases. Compared to Azure and Google Cloud, AWS caters to the greatest variety of database needs. Their services are highly scalable (e.g., Aurora and DynamoDB), and integrate with other AWS services, such as SageMaker for machine learning.

Azure database services include Azure SQL Database, Cosmos DB, Azure Database for PostgreSQL, Azure Database for MySQL, and several more. Their strengths lie in hybrid cloud solutions that integrate well with on-premises servers and systems, as well as integration with other Microsoft products like Office 365. Azure has extensive global data centre coverage which is advantageous for latency-sensitive applications. They have proven high consistency in performance, suited to clients with strict regulatory requirements, such as government agencies.

Google Cloud database services include Cloud SQL, Cloud Spanner, BigQuery, Firestore, Cloud Bigtable, etc. Google Cloud excels in big data and analytics with BigQuery, a powerful serverless data warehouse solution, as well as machine learning integrations with Ai and machine learning tools.

When cloud computing options are evaluated on how they help deliver a reliable, scalable, sustainable and valuable solution for hydro-meteorological services, thes findings emerge:

- Computing providers meet requirements, are comparable in cost and deliver security and database management, transmission and integration functions.
- All providers enable access control systems, allowing the government to manage data use, validation, sharing, and publications.
- All options allow for API.
- Minor differentiators among the three providers are:
    - AWS and Azure are more established in Africa compared to Google Cloud although this appears to be a general assumption from technology journalists.
    - The Government of Malawi has expressed preference for computing that is integrated with local servers, for security, backups and data ownership purposes.
    - Bespoke algorithms and analytical functions need to be built, whereby all providers have a number of existing and emerging tools. Their respective

effectiveness and suitability for water and weather observations in Malawi, however, are unknown and untested.

- From earlier prototyping, Google BigQuery demonstrated capabilities but Microsoft Azure's services and solutions is a better option for a scaled solution, moulded to government preferences and existing use of Microsoft's products.
- Local servers at DCCMS, DWR and the Government of Malawi need to be functional, have access to the internet and be administered to allow API integration.

Technologies for observation data processing

Data processing involves the manipulation and transformation of raw data into a usable format. It is an essential pipeline step of water and weather observation data management. Processing ensures data quality, consistency, format adherence and ultimately the readiness for analysis and reporting. The success of forecasting, modelling and more advanced analytics such as machine learning and ai, relies heavily on the quality of data processing. Data processing can cover a variety of tasks to ensure data quality and data annotation: data cleaning, integration, transformation, enrichment, and validation.

Requirements

The needs assessment found that data processing should meet the following requirements:

- Raw manual observation data needs to be checked for quality issues, transcribed in near real time and coded as "reported data".
- Reported data needs to be checked and calibrated for accuracy.
- Reported data needs to be in a format that meets observation data standards.

Data quality

Data quality can be defined by six dimensions. Accuracy, completeness, consistency, validity, integrity, and uniqueness (figure 7).

Two sets of data quality issues emerged with manual water and weather observation collected in Malawi and Mozambique in earlier prototyping. First, duplicates affecting uniqueness (5.7%), errors and outliers affecting data validity (1.5%), format inconsistencies but with correct values (2%) and incompleteness when observations were not submitted i.e. 'missing' (20% on average during piloting contract period with mobile payments). Examples are presented in table 3.

Observation data also needed review and/or validation to be considered accurate. Accuracy can be undermined by human error, monitoring equipment failure or fraudulent observation data. As part of the government hydro-meteorological mandate, for DWR and DCCMS, the review of manual observations is a distinctive step in data processing, with dedicated staff allocated for the task and routine standards. For DCCMS, for example, the staff responsible for this step has, however, retired and there are limited staff resources to replace the function.

However, a review is equally important and necessary before the government agency releases or annotates the observation data as official. It is important to note that the agencies report similar data quality concerns with observation data from automated sensors.

Table 3. Data formats transcribed directly and cleaned in earlier prototyping

Country	Region	Basin	District	station_name	tation_id	reader	date	time	raw_data	reported_data	Type	Comment
Data format transcribed directly												
MZ	Centro	Zambezi	Massangena (Gaza)	Massangena	GZ008048	Jose Nhatumbo	2024-03-12	07:00	TM 22.4	22.400	Tmin	
MZ	Sul	Save	Tsangano (Tete)	Tsangano	TT003091	Júlio Manica	2024-03-07	18:02	Tx 23.0	23.000	Tmax	
MW	Southern	Shire	Thyolo	Bvumbwe Research Center	15353056	Ellita Kanjoka	2023-02-13	06:38	27.9	27.9	Rainfall	
MW	Northern	North Rukuru	Karonga	North Rukuru River @ Mwankenja	8A5	Ackim Mwankenja	2023-08-17	10:02	0.68	0.680	River Level	
MW	Central	Bua	Mchinji	Bua River @ Mchinji	5E6	Ned Kamanga	2023-03-04	08:11	FLOOD1 2.56	2.560	River Level	FLOOD1*
Data format cleaned and transcribed directly												
MZ	Centro	Pungwe	Barue (Manica)	Catandica	MN005017	Queti Simao Maburendza	2023-05-08	13:08	Catandica Tmx:27.9	27.900	Tmax	
MZ	Centro	Zambezi	Cahora-Bassa (Tete)	Chitima	TT003070	Bergito Estima	2023-06-08	13:04	T.x : 34.4	34.400	Tmax	
MZ	Centro	Zambezi	Tsangano (Tete)	Tsangano	TT003091	Francisco Saimone	2024-05-27	13:03	Tx 17·8	17.800	Tmax	
MZ	Centro	Zambezi	Milange (Zambezia)	Milange	ZB004006	Rodrigues Madeia	2024-02-11	15:00	Tx=31.5	31.500	Tmax	
MW	Central	Nkhula	Nkhotakota	Nkhula @ Galeta	15B16	Polina Dzoole	2023-03-07	17:37	.55	0.550	River Level	
MW	Southern	Thondwe	Zomba	Thondwe in Zomba	2B22	Rose Kalulu	2024-03-15	10:30	0,476	0.476	River Level	
MW	Southern	Shire	Thyolo	Bvumbwe Research Center	15353056	Ellita Kanjoka	2023-02-23	08:36	TR	0T	Rainfall	

*Data collectors were trained to test sending codes of subjective perception of changing flood conditions.

The data quality issues with manual observations from the MVP were not overly complex or large. Bespoke algorithms were built to flag repetitions and errors (and stop them from being transcribed as reported data), inconsistent formats were corrected and the cleaned data was transcribed as reported data. WMO standards recommend an ideal submission performance level of 80% (i.e., performance where submissions are not submitted 20% of the time) meaning that GR&Os performed on target. Also following WMO recommendation, missing values are annotated as "-999" or "M". And for validation, Water in Sight's flood hydrologist and satellite observation expert reviewed the reported data as hydrologically consistent. The team found that manual observation data, regardless if digitised through phones or written in log books, can be assessed for accuracy using a multipronged approach: calibration and triangulation against sensor data and satellite observations; sharing gps-location from phones; and statistical analysis.

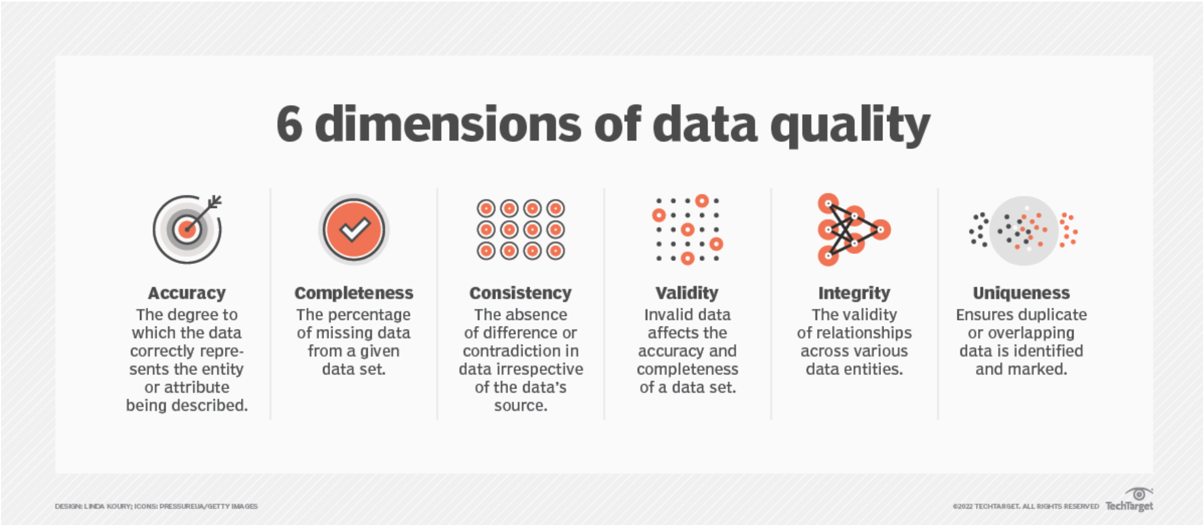

Figure 7. Data quality takes several factors into account (TechTarget, 2022).

The technology options for improving data quality can, as with most data processing, be sourced by purchasing and using tools on the market or by building bespoke back-end data processing tools with unique algorithms - or a combination of both.

Off-the-shelf tools are offered by the cloud computing providers, and integrate with their other services. It is essential to understand the data, to label (annotate) the data, identify baselines, establish the criteria for data quality, and set curation and improvement targets of data, and the way data is deployed.

Data processing tools available on the market vary. They include: cleaning tools using simple interfaces, drag-and-drop features and ability to change data formats; integration platforms or ETL tools (extract, transform, load) that automate data extraction processes from various sources, transforming them into required formats and loading them to target systems; data profiling tools to assess and ensure data quality and integrity; and using programming languages (e.g., Python) for data manipulation and analysis.

When data processing options for data quality are evaluated in how they help deliver a reliable, scalable, sustainable and valuable solution for hydro-meteorological services, the following findings emerge:

- Data quality issues with manual observations follow a pattern, regardless of the GR&O's skills, location or the parameter monitored.

- Technology options and approaches need to reflect the unique patterns of needs within the collection of manual observations specifically.
- Whether off-the-shelf tools are applicable at scale and meet WMO standards for manual observation data quality, remains untested.
- Earlier prototyping finds that building bespoke algorithms was an optimal method reflecting the needs discovered.

Data annotation

Data annotation is a foundational process of labelling or tagging data to make it recognisable and understandable for modelling and machine learning algorithms. Machine learning (and ai) make more accurate predictions or categorisations on annotated data, meaning that correct annotations are essential for subsequent prediction effectiveness and accuracy.

In brief, there are different annotation categories approaches to manual observation data. Text annotations involve labelling by entity recognition (names, dates, locations, product names within text, etc.). Image annotation involves bounding boxes (delineating objects in an image to label them). Segmentation is dividing an image into segments and labelling each, and land annotation involves identifying specific points of interest in an image (e.g., water level against a gauge plate). Data annotation methods can range from manual, with greater high accuracy and based on contextual understanding, to semi-automated that combine human intervention and tools and automated annotation that use algorithms to label data based on predefined rules.

The optimal method and value of annotation for the project is not known. This is due the ongoing selection of geographical areas where testing in Output 4 will take place. When sites are selected, it will clear which insights the data should bring.

When data processing options for data annotation are evaluated in how they help deliver a reliable, scalable, sustainable and valuable solution for hydro-meteorological services, the following findings emerge:

- Data annotation methods need to be tested, starting with samples and trying tools that are cost-effective, easy to maintain or automated within existing ICT infrastructures. Small scale testing prevents mistakes (e.g., irreversible inconsistencies, inefficiencies when scaling).
- Data annotation tools should leverage industry experience in hydro-meteorology and WMO guidance.
- The value of data annotation needs to be assessed strategically. For example, to what extent does it improve accuracy of downstream hydrological modelling and forecasting? Does application softwares or models require data annotation in the first place? Or, what are the financial and operational efficiencies that the government can benefit from?

Interface technologies for data access, visualisation and application

Requirements

The needs assessment found that interface technologies should meet the following requirements:

- Data formats should match HYDSTRA and Climsoft formats.
- Data in .csv formats (manually pulled from dashboard, and/or via API).
- Access managed with user profiles.
- User-friendly interfaces for intuitive interaction with data (e.g., filtering, selection by parameter, geographic scale, time frames etc.).
- Analytical features designed and developed to meet operational needs, avoiding duplication of existing softwares (e.g., HYDSTRA functions).
- Visualisation based on basic hydro-meteorological interpretation (e.g., presentation of rainfall in monthly or seasonal averages, inter-annual comparison etc.).

Data access

Data access management and controls is important for several reasons:

- Preventing unauthorised modifications, strengthening data integrity.
- Preventing loss of data or data breaches.
- Mitigating security risks and tracking data usage and accountability through access logs, where for example, errors can be traced back.
- Streamlining data workflows, ensuring users have access to data they need without overwhelming them with irrelevant information - improving operational efficiency.
- Enabling a multi-user and well-coordinated environment for systematic work processes where various stakeholders are involved in the use and analysis of water and weather observation data - such as different government agencies and researchers.

The Role-Based Access Control (RBAC) method offers clear steps in setting up the data management structure. First, data sources are catalogued based on sensitivity and criticality (e.g., data for flood warnings). Roles, responsibilities and permissions are then identified for staff who interact with the data based on their job function. Roles and permissions are organised by job function, not individuals. A simplified RBAC guideline helps clarify permissions and expectations against the roles. For DWR and DCCMS, such roles need to be refined based on existing organisational structures, functions and levels of permissions.

Typical RBAC roles include:

- Administration
    - Database administrator responsible for creating and managing user accounts and has full access for backup, recovering and maintenance.

  - System administrator manages the IT infrastructure, servers and has broad access to system-level operations and configurations.
- Development
  - Application developers and data engineers accessing schemas, modifying testing and development environments, and managing data pipelines and ETL processes.
- Operational
  - Analysts who have read access for analytical tasks and reporting and may have restricted access to parts of databases. This can include roles such as water resources engineers, hydrologists, meteorologists, forecasters etc.
- End-users
  - Communication staff responsible for reporting to internal and external stakeholders, with read-only access to relevant subset of data or analysis.
  - External parties who need specific data based on approved access.

Implementing a data access management system can be done by building it into the cloud computing databases (e.g., Microsoft SQL Server, Oracle Database, or PostgreSQL support fine-grained access controls, encryption, and audit trails). Designing user friendly interfaces helps administrators implement and allocate different access levels.

When data access options are evaluated on how they help deliver a reliable, scalable, sustainable and valuable solution for hydro-meteorological services, the following findings emerge:

- Data access levels need to be pragmatic and easy to implement and maintain.
- Technological solutions should be rolled out in phases, starting with critical ones.
- Training helps staff understand their roles, permissions, and importance of data security.
- Overprotecting water and weather observation data is a risk, restricting its ultimate use and value, and limiting staff's ability to provide feedback and ideas for improvements.

Data features and visualisation

HYDSTRA, Climsoft and modelling software have dashboard interfaces with features and visualisations, providing a range of functions for DWR and DCCMS staff. Because the UNEP CTCN project focuses on manual observation data, as a distinctive data source, it will be important not to develop features that already exist. Nor to develop superfluous ones or specialised ones requiring multiple data sources (e.g., weather forecasting models for aircrafts).

For a scaled solution, visualisation of manual water and weather observation data has to deliver insights and features that are user friendly and meet the needs of the users. In essence, by applying a user experience and user interaction design process (UX/UI).

UX refers to the entire interaction and the overall experience a user has with the data and the dashboard product, including how the person feels about the interaction. UI refers to the screens, buttons, toggles, icons, and other visual elements that the user interacts with when using a data dashboard, a website or app.

In the previous prototyping, a desktop dashboard was developed based on a UX/UI process and informed by a jobs-to-be-done methodology (i.e., to understand underlying needs and desired outcomes that drive user behaviour when they use a product to accomplish a specific task).

With available financial resources, the following features and visualisation were identified and selected for back and front-end development, as shown in figures 8-11:

- Data centre: reported data can be filtered based on water or weather parameters, dates and geographies; reported data is downloadable in .csv or database formats; and filtered data is visualised in a simple graph per station also shown on a map.

- Chat app: communication log with GR&Os where administrators can communicate freely with the GR&Os (who receive messages as SMS or WhatsApp); and where GR&Os are linked to monitoring stations, and their user profiles are administered.

- Station inventory: monitoring stations and their meta-data are administered and where stations are visualised on maps.

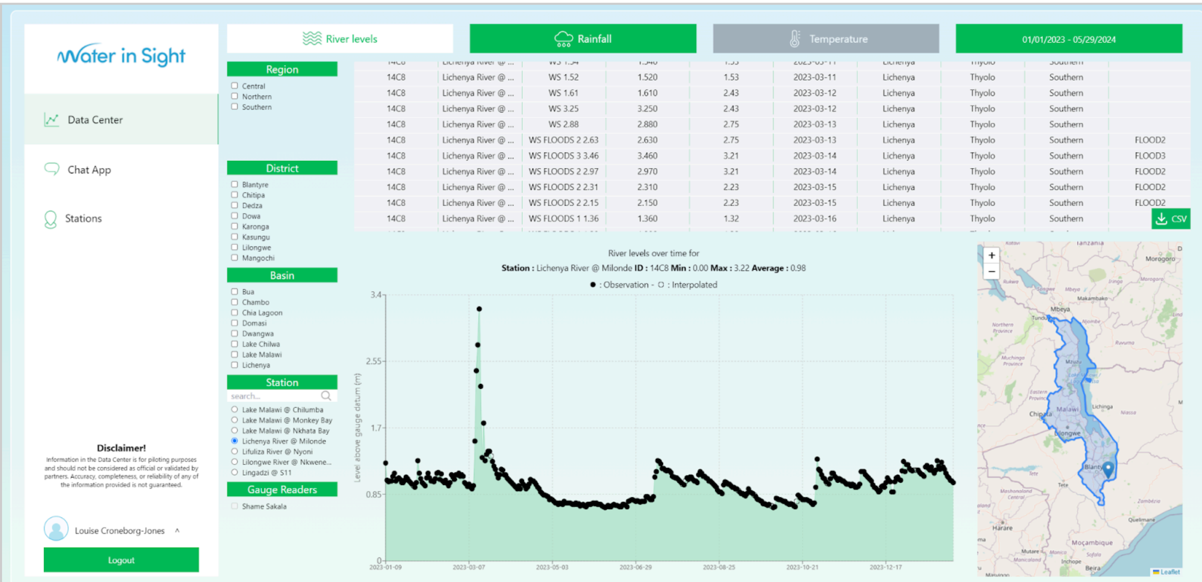

Figure 8. MVP Data Center dashboard, river level observations at Lichenya River, Malawi.

Figure 9. MVP Data Center dashboard, max and minimum temperature at Matchedje station, Mozambique.

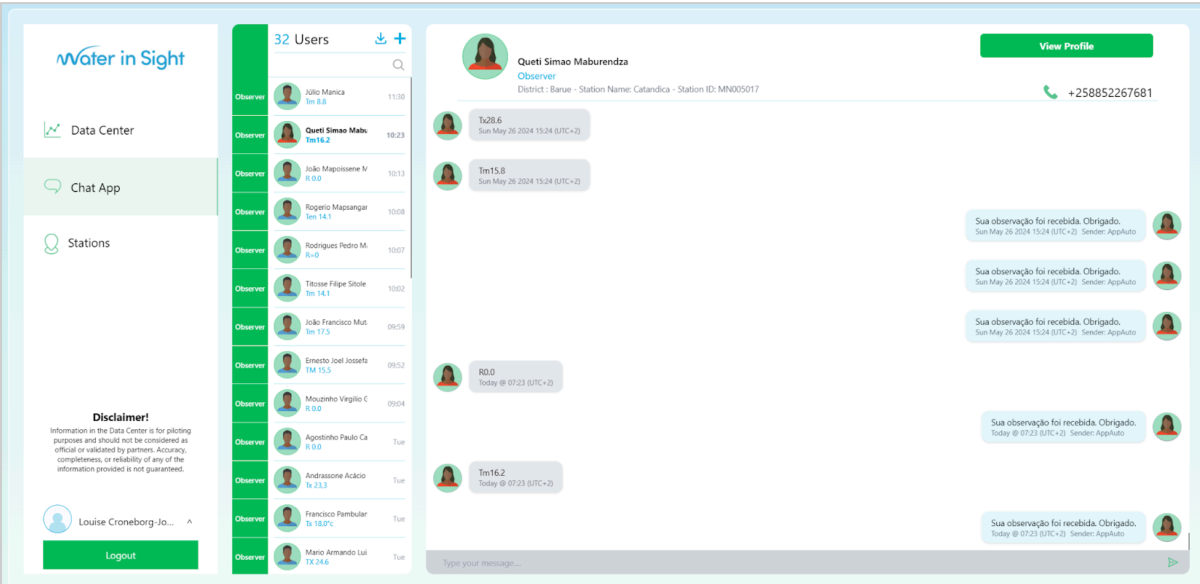

Figure 10. MVP Chat app dashboard, 2-way communication with Catandica synoptic station, Mozambique.

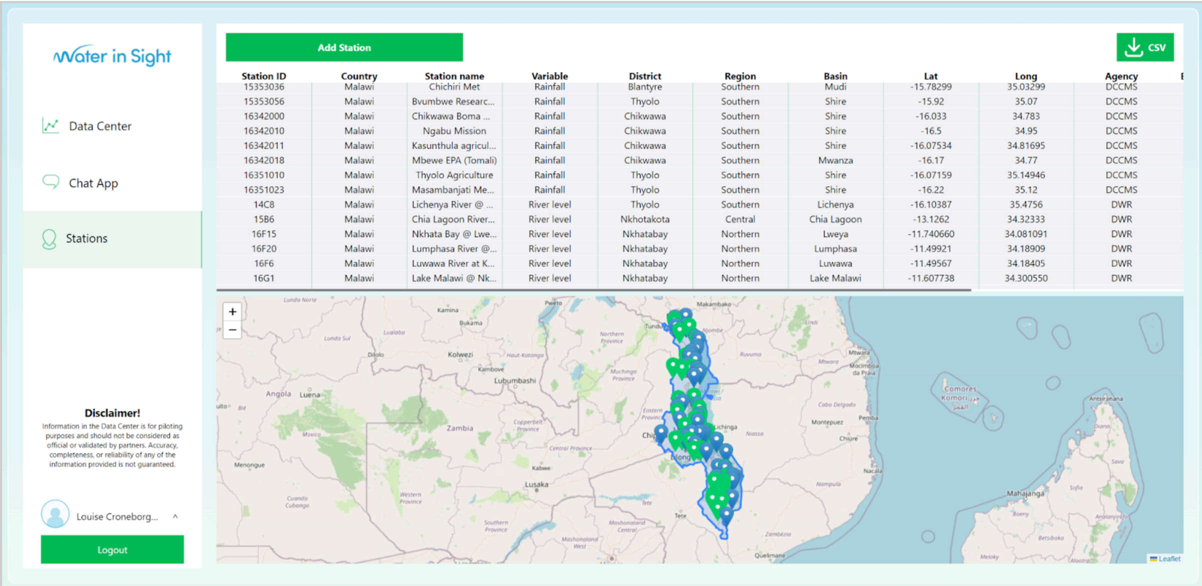

Figure 11. MVP Stations inventory dashboard, Malawi.

The diagnosis and pre-feasibility under the project validated these features, but identified both improvements and additional ones (table 4). These are concurrently studied and drafted in Activity 3.5, i.e., the design of the architecture of the system. These designs will be validated and workshoped with DWR and DCCMS and iteratively produced in Output 4.

Table 4. Future dashboard visualisations and features

	Feature and visualisation	
Analytics	• Hydrological analysis • Meteorological analysis • Different geographic and time scales, compared • Basic statistical analysis (e.g., averages, max/min) • Validation analysis	Examples: • Hydrographs (variation in discharge or stage over time) • Flow duration curves (% of time flow is likely to equal or exceed value) • Rainfall-Runoff relationships (watershed response) • Flood frequency curves (flood probabilities) • Stage-discharge relationships/Rating curves (level/cross section) • Cumulative precipitation graphs • Evaporation graphs • Reservoir storage graphs (volumes) • Spatial distribution graphs • Drought indices graphs (standardised precipitation index)
Formats/Filters	• Flag reported data for potential anomalies • By Gauge Reader and Observers • Report production functions	
Administration	• Administration of user profiles and access control • Feedback and complaints functions • Contact functions	
Automation	• Automate data transfer functions • Automate transcription to HYDSTRA and Climsoft	
Linkages	• Connect and visualise historical data in Climsoft and HYDSTRA • Integrate data from automated sensors • Map additional stations in inventory • Expand station profile functions	
Gauge Readers & Observers	• Bulk chat functions • Emergency alerts • Performance analytics • Photographic storage • Expand user profile functions	
Devices	• Designed for both smartphones, tablets and desktop	

When data visualisation and feature options are evaluated on how they help deliver a reliable, scalable, sustainable and valuable solution for hydro-meteorological services, the following findings emerge:

- Design and development of visualisations and features should be done after careful selection on prioritised user needs and their ultimate application of the observation data.
- Existing software dashboards need to be considered as well as the scope and timeframe of the project.
- Scope-creep based on long wishlists typically overrun on budget and time, with questionable or diluted value as a result.
- Prioritisation of visualisations and features should align with the most critical water, weather and adaptation challenges of the testing site areas, communities, catchments and districts (Output 4) where new dashboard functions add value.
- Visualisations and features shall be versatile for a range of users with respect to language, level of technical hydrological and meteorological skills, impairments, and geographic locations (e.g., at district offices, synoptic stations etc.).

Data application

Broadly, data application in the context of the UNEP CTCN project refers to two things. First, the processing and flow of data from one data system to another. Or, processing of data across distributed computing environments. Second, data for applications in analytical and decision-making softwares and processes.

This brief analysis will focus on the latter, application for impact modelling, developing climate futures for purposes of adaptation and disaster risk management.

In the context of DCCMS's forecasting operations, there is possible data application in:

- Automated transfer into Climsoft.
- Synergieweb and BARON workstations which form the basis of DCCMS's forecasting system and can be tailored to produce alerts.
- In-situ manual weather observations for validation potential in:
    - Weather charts that DCCMS acquires from the South Africa Weather Services used to identify potential weather hazards in short-range forecasts.
    - Charts generated from DCCMS's local Numerical Weather Prediction (NWP) analysis from ECMWF charts.
    - New numerical forecasting model projects at DCCMS.

For DWR's hydrological modelling operations, there is possible data application in:

- Data application/transfer into HYDSTRA.

- Data application/transfer/replicability with future National Water Resources Information Management System (under procurement by the National Water Resources Authority).
- Case and project specific manual hydrological model depending on internal or external stakeholder client.
- Validation of automated surface water sensor observations accessible through SEBA Hydrometrie's HydroCenter and Siap.
- The new iteration of the Operational Decision Support System for Flood and Drought Monitoring in Malawi (under procurement).

When data application options are evaluated on how they help deliver a reliable, scalable, sustainable and valuable solution for hydro-meteorological services in Malawi, the following findings emerge:

- DWR and DCCMS should prioritise how best manual observation data is applied into routine operations, modelling and forecasting softwares, as well as tested into impact modelling and climate futures for adaptation and disaster risk management.
- The selection of testing sites will be informed by criteria such as level of climate risks and adaptation priorities. Once selected, the specific application (modelling/forecasting) can be identified and evaluated in terms of the data application potential.
- Data application is not simply a strategic management issue, but also an operational function to be backed with robust technical systems, softwares and maintenance.

5. Evaluation of Technology Options

Strategic questions

Technological reductionism

It is not uncommon in innovation projects to oversimplify whether technology options are deemed viable, suitable or not. For example, one can assume that most mobile communication options, especially smartphone technologies, should function well in a country such as Malawi. Or that digitisation of manual water and weather observations taken by humans, technically appears to be a very simple undertaking.

Such assumptions underestimate the complexity of diverse contexts, abilities of users and the need to embed a technology within a robust system of data management. This type of technological reductionism is conceptualised as 'technological solutionism' (Saestra and Selinger, 2023). This is a belief that every problem can be solved through technology alone, often neglecting the human, social, and cultural factors that affect the effectiveness of solutions. Oversimplification neglects the many nuances of real-world application of technologies, the operational and financial reality of agencies such as DWR and DCCMS, as well as the individual user's needs, skills and context.

Building new innovations within the climate tech sectors, are rarely immune to technological solutionism. That is why the agile, iterative and small scale testing process is important for gathering insights on the user-solution fit of technology options (i.e., investigate, build, test, fix, deploy, test again and repeat). At times, however, a technology option already on the market appears perfectly suitable. But when deployed, it is not fit for the user or context. For example, recent piloting in Malawi with Gauge Readers deployed an open and cost-free survey app to digitise river level observations. But it lacked suitable user-interfaces and data coding. Despite being cheap and developed, the app did not prove useful or scalable leaving swathes of unannotated observation data.

Time is of the essence

Along with neighbouring countries, Malawi experienced low precipitation during its rainy season 2023 - 2024 with the impact of El Niño. Emergency relief is issued to hamper widespread food insecurity and the risk of famine and undernourishment. Equally, climate change is altering the magnitude and frequency of cyclones and floods. In response, the international community is raising financial commitments to address underlying capabilities in hydro-meteorology. For example, the Early Warnings for All initiative is calling for $ 1.18 billion to close the water and weather observation gaps by 2027.

Mobile and cloud computing technologies can significantly boost the hydro-meteorological sector whilst adaptation and disaster risk management is urgently needed. Yet, in reality, there are few market and entrepreneurial growth opportunities to drive innovations when it comes to business-to-government solutions (B2G). There is little investor and risk capital going into climate information services. Only $470 million was invested in water startups in 2021 globally (mostly in the utility and water supply segment) compared to $27 billion invested in climate tech startups in the first half of 2022 alone (Financial Times, 2024). Although there are few estimates of venture capital in startups for climate services and water, in Africa specifically, these are likely much lower.

Reflecting on this wider innovation ecosystem reality, in the context of mobile and computing technology options, is important because it means that the selection of technology options has to be triaged against cost effectiveness and pragmatism for a viable business model.

Open source and open access?

Discussions on technology options for digitisation often raise questions on open source softwares and open access to data. There are strong policy commitments for open access to observation data and that such data is a public, global good. Questions raised include: Open source softwares must be best, or? How should observation data be shared by DWR and DCCMS, and with which other stakeholders? Should observation data be available at international levels and for all?

With open source software, there are benefits and challenges. Numerou benefits in fact. Cost savings as they are typically free to use, and flexibility to modify the source code to fit specific needs. A high degree of customisation, combined with ability to inspect and fix vulnerabilities, often results in more secure software. Strong community support contributes to continuous improvement, rapid innovation, and quick releases of new features and updates. Open source software also reduces risks associated with vendor lock-in.

But there are challenges. 'Community' support and documentation are not as reliable or comprehensive as proprietary software. Integration with existing systems require additional customisation, and the user interface might not be as customisable, posing a barrier for non-technical users. There are security risks, as vulnerabilities might be overlooked, and attackers can exploit the transparency of the code. The quality of open source projects can vary, with some suffering from inconsistent development and lack of updates. Funding and sustainability may stall development, as projects often rely on donations and voluntary contributions. Legal and licensing issues can also be complex, and leveraging the full potential of open source software requires significant technical expertise by the user.

Open access to official and quality controlled water and weather observation data offers significant advantages. It promotes transparency and allows researchers, policymakers, and the public to make informed decisions. Data openness can enhance scientific research, leading to better climate models, weather forecasts, and disaster preparedness. Open data fosters international collaborations to tackle climate change more effectively.

Challenges include security and privacy concerns, as sensitive information could be misused or lead to vulnerabilities in critical infrastructure. Ensuring data quality and consistency can be difficult when multiple and unverifiable sources contribute to the dataset. There might also be financial implications, as maintaining and distributing high-quality data requires resources that could strain budgets. Furthermore, open access may lead to data overload, where users are overwhelmed by the volume of available information, making it harder to extract meaningful insights.

Operational management and financial consideration

Mandates and maintenance

Government mandates for water and weather observations in Malawi predicate the scalability and impact of digitising manual water and weather observations. For example, how shall a data management system integrate with Malawi's recent efforts and plans to develop a National Water Information Management System? Such integration requires careful attention to data security and streamlining that aligns with agency preferences. The technology options can, correspondingly, connect and move data across different computing systems. In addition, technology options in this analysis should consider regular maintenance, including system updates and user training.

Financial reality

Implementing technologies for manual observation of water and weather in Malawi involves initial setup and recurring costs. Initial costs include purchasing mobile phones (along with personal protection equipment to GR&Os and rehabilitation of manual monitoring equipment), setting up cloud databases, and integrating these technologies with existing systems.

Recurring costs encompass the regular maintenance of mobile devices and databases, expenses for SMS and data use for WhatsApp, as well as workshops and training sessions for data collectors and administrators.

Financial sustainability is explored in the project's Output 5, determining the long term operational and scaling potential of using mobile and cloud technologies for adaptation and disaster risk management.

6. Technology Findings and Recommendations

Table 5 below summarises the derived findings and recommendations.

Table 5. Summarised findings and recommendation

Category	Findings	Recommendations
Mobile phone & communication technologies	*Device options*	
	Communication methods must work on all phone types.	Offer multiple communication options. Balance the benefits of smartphones against cost and training needs. Design user-friendly and very easy methods for data submission.
	Communication options	
	SMS is user-friendly, cost-effective, and works on any phone. WhatsApp is best for smartphones with added geolocation sharing.	Administrator should cover SMS and data costs. 2-way communication offers flexibility. Leverage mobile aggregator services for rapid deployment.
Computing Technologies	AWS, Azure, and Google Cloud all meet requirements, with slight differences. Local server integration is preferred for data security and ownership.	Use Microsoft Azure to align with data capabilities, and integration with local servers. Develop bespoke algorithms for data quality and analysis.
Observation Data Processing	*Data quality*	
	Manual observation data has quality issues like duplicates and errors. Cleaning and validation are necessary for accuracy.	Build bespoke algorithms for data cleaning and validation, informed by sensor and satellites observations. Follow WMO standards for submission performance and data annotation.
	Data annotation	
	Annotation needs testing for large-scale use. Various methods and technologies are available, but suitability needs assessment.	Conduct small-scale testing to find the best annotation approaches and tools. Use natural language processing as appropriate.
Interface technologies	*Data access*	
	Role-Based Access Control (RBAC) ensures data security and integrity. User profiles must define access levels and permissions.	Implement RBAC with clear roles and permissions. Provide training on data security practices. Regularly review and update access controls.
	Data Visualisation and Features	
	Dashboards must be user-friendly, meet operational needs, and integrate with existing systems. Features should be versatile for various user types.	Prioritise essential features and visualisations. Avoid duplication with existing software. Ensure dashboards are customisable and compatible with existing software. Use UX/UI design processes.
	Data Application	
	Manual observation data needs to be integrated into routine operations, modelling, and forecasting. Selection of application methods should be informed by DWR and DCCMS needs.	DWR and DCCMS need to identify and prioritise data application needs. Ensure robust technical systems and maintenance for operational efficiency.

7. Implementing Technology Options

In the project's Activity 3.1, the systems in place (equipment, software) at DCCMS and DWR in which the new technology shall merge, were mapped. The mapping identified barriers, challenges, as well as opportunities and strengths of these systems. The needs assessment (Activity 3.2) and workshops with the project's Working Group have involved further investigation into the systems of the two agencies.

This section presents the internal and external contextual analysis of DWR and DCCMS. Specifically in terms of the agencies' capacity to adopt the proposed technology options. Two analytical tools were used, a SWOT analysis (Strength, Weaknesses, Opportunities and Threats) and a PESTEL analysis (Political, Economic, Social, Technical, and Legal).

In addition, barriers and risks of technology adoption are deliberated. Contingencies and mitigation of these will inform the prototype development and the financial sustainability outputs of the UNEP CTCN project (Output 3 and 4).

Strengths, weaknesses, opportunities and threats

SWOT

Using SWOT identified distinctive factors that enable or impair the capacity of DWR and DCCMS in adopting the technology options (figure 12).

Analysis of strengths, i.e. the attributes within DWR and DCCMS and which are within their control, demonstrated the value of managerial and technical staff support and engagement. Their existing data procedures, as well as cross-agency cooperation, also generates an operational foundation with which the new technology approach can integrate.

With weaknesses, there are capacity gaps in using manual observation data in bespoke analysis (e.g., 10 day weather bulletin, hydrographs etc.). Equally, not trusting the accuracy of the observation data, or the perception that observations were not collected by the agencies themselves, can result in reluctance towards the technology.

Among opportunities, the enabling technology environment in Malawi boosts DWR and DCCMS's as custodians of hydro-meteorology in Malawi. Communities and GR&Os rapidly welcome the technology, as both users and beneficiaries, strengthening DWR and DCCMS's confidence in the approach. International donors also express support and interest, although willingness to include technology in financing and projects is weak (need proof of impact and value, and perceive new technology as risky compared to conventional sensors).

There are three main threats to technology adoption. One, a persistent lack of operating budget and locked-in financing for DWR and DCCMS. Staff retention and replacing retired staff is hard, as is the ability to cover costs for operations let alone make new investments. The 2013 Water Law shifts the hydrological monitoring mandate to the National Water Resources Authority. In a period of transition, the ability to adopt new technologies is undermined. Lastly, the benefits of climate information services depend on participation and input from external stakeholders, such as for early flood warnings. Ultimate impact from the new technology is thus outside agency control. This weakens the rationale for investing, institutional incentives and agency ownership.

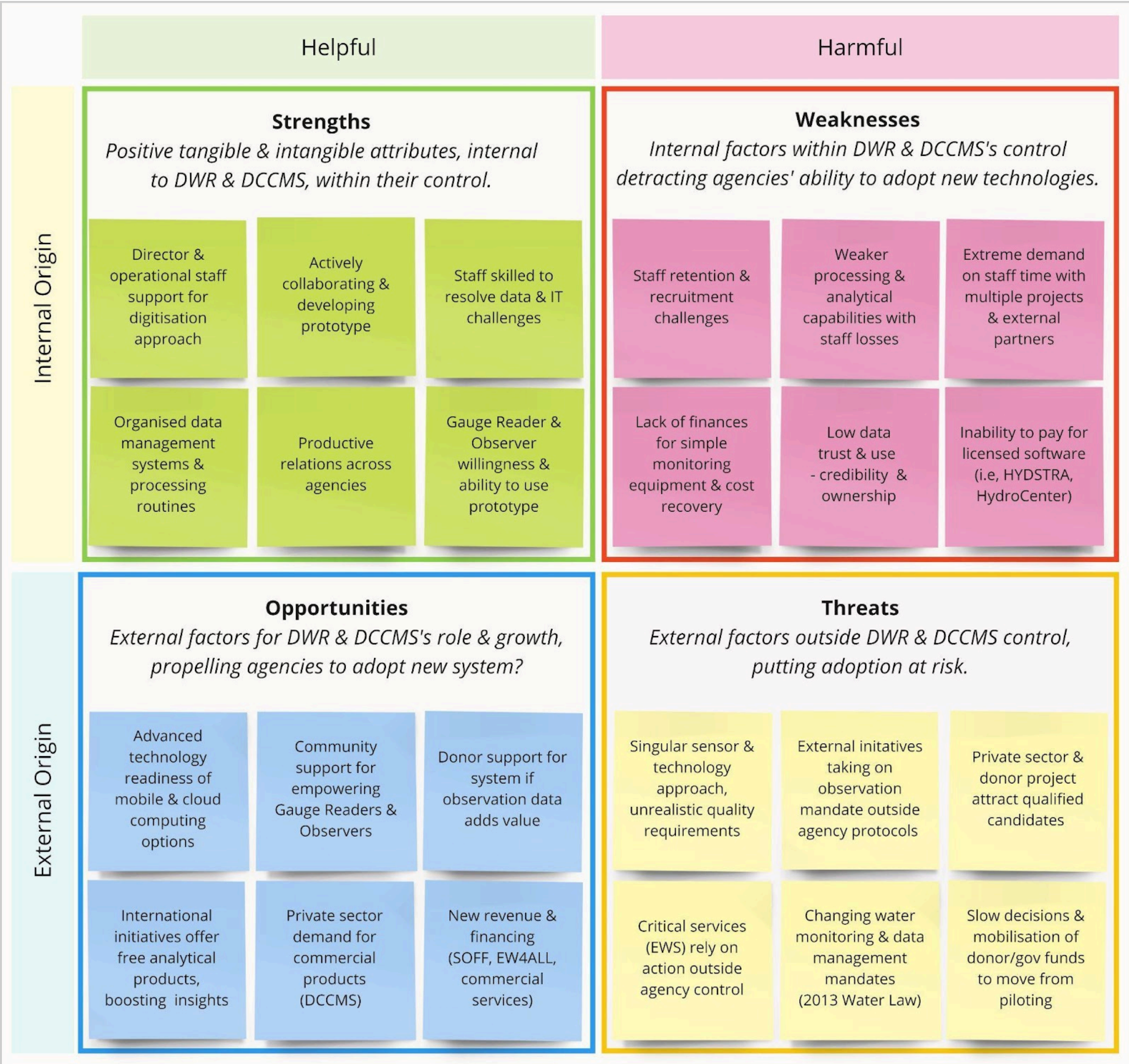

Figure 12. SWOT assessment of implementing mobile and computing technology options

PESTLE

To further explore the external macro-environment that could impact DWR and DCCMS's capacity to adopt the technology, the PESTEL methodology was applied (Political, Economic, Social, Technological, Environmental, and Legal) (Table 6). PESTEL is effective for identifying risks and delineating barriers against opportunities.

Table 6. PESTEL evaluation of implementing mobile and computing technology options

	Political	Economic	Social	Technological	Environmental	Legal
Macro-environment	The GoM has policies in place supporting observation technologies for adaptation & DRM.. Government agencies are committed to enhancing climate information services (NCST, DCCMS, DWR, NWRA, MoA, DoDMA). Partnerships with several international donors (World Bank, UNEP, UNDP, USAid,). Need for political stability and direction to maintain and expand observation initiatives. GoM and donor support for mobile payment and budget allocation needed for Gauge Readers, replacing outstanding cash obligations.	Mobile tech offers the foundation for technology adoption and economic growth. Commercial opportunities for agencies are growing with rising climate risk mitigation need (e.g., 12% growth of parametric insurance) PPP financing model potential. Cost-effectiveness of utilising existing mobile infrastructure to reduce the need for new installations. New technology options come at 10% of conventional Income generation for Gauge Readers with mobile payments (cash 4 work)	Gender disparity: Women are 8% less likely to own a mobile phone and 36% less likely to use mobile internet; feminisation of agriculture contributes to in gendered exposure to climate risks. Affordability: Mobile devices cost 95% of the monthly income of the poorest 20% of the population in Africa. Solution should be free for the user. GR&O motivation growth with technology training and continued support. Community support with feedback loop. Significant exposure to disasters and depletion of natural resources.	Rapid adoption of mobile phones and 4G/5G networks (51% smartphone penetration in 2022 (88% by 2030). Use of cloud computing services (AWS, Azure, Google Cloud) for data management. Emerging technology initiatives in the sector. Emerging opportunities with data streamlining and Ai. Use of data cleaning tools and bespoke algorithms to ensure data quality. Comprehensive and integrated technology approach to avoid technology reductionism.	Increasing climate risks, such as extreme floods and droughts, highlight the need for reliable climate data. Integration of mobile technology with other data sources (e.g., automated weather stations, satellites). Environmental sustainability through application and decision making resulting from improved water and weather data collection (e.g., hydropower production, bridge design, asset protection). Minimal environmental footprint of technology and monitoring equipment.	Compliance with WMO standards and national data management protocols. Data privacy and security concerns regarding data transmission and storage. National regulations for ICT infrastructure and mobile network operations.
Risks	Policy environment risk: **Low** Policy reform risk: **High**	Marco-economic risk: **Low** Donor/tax finance risk: **High**	Social acceptance risk: **Low** Commitment risk: **Low**	Technology risks: **Low** Misconception risks: **Medium**	Environmental risk: **Low** Risks to benefit: **High**	Industry standards risks: **Low** Data and MNO risks: **Low**

Barriers and risks

Barriers

Barriers are those that constitute obstacles for DWR and DCCMS to adopt the technology options uncovered in the UNEP CTCN project. They are partly identified in the SWOT and PESTEL analysis. They are distinctive, however, as they constitute obstacles that are hard to overcome and require targeted and managerial interventions.

A significant barrier is the lack of government budget for DWR and DCCMS's operations and maintenance, as discussed in Section 5. The government also lacks procurement procedures to purchase digital services with recurring payments - the typical payment model for software (e.g., Microsoft 365, Zoom etc.). Also connected to financing for new technologies, is the limited and lengthy donor funded procurements for scaled applications. For example, according to GSMA (2023) few of the innovation startups they support target government or local authorities, as they encounter difficulties in generating revenue. This highlights the necessity for evidence-based business models that effectively engage both public and private institutions.

Staff capacity constitutes another barrier as both DWR and DCCMS are operating with as much as a 30% staff deficit. Several job functions stand vacant as staff have retired and the agencies lack budgets to recruit new personnel, or find it hard to compete for qualified technical candidates. Staff shortage affects entire organisations and the data management and analytical processes. To overcome such barriers, the future technology system for digitisation of manual observation should capture opportunities for further automation of functions, benefiting staff with time saved and greater enjoyment from the job function.

Lastly, the lack of capacity and tools to use and transfer observation data into application, impact modelling and forecasting is a barrier to the ultimate value and benefit of the technology. Automated and safe integration of observation data into data management systems can be an effective tool to overcome the barrier.

Risks

The PESTEL analysis identified potential risks. The likely occurrence and mitigating options for medium and high risks are elaborated in table 7.

Table 7. High and medium risks to DWR and DCCMS adoption of technology

	Political	**Economic**	**Technological**	**Environmental**
Risks	Policy reform risk: **High**	Donor/tax funds risk: **High**	Misconception risks: **Medium**	Risks to benefit: **High**
Likelihood & Impact	**High** NWRA is taking on hydrological monitoring and data management mandate	**High** Large donor funding projects without allocations in pipeline Inflation, currency devaluation	**Medium** Assumed low innovation value, lack of support Challenge in grasping comparative advantages	**High** If observation data is not transferred or used in application, then potential environmental benefits are missed
Mitigation	Ongoing cooperative process Technology development process	Government request for specific technology support Donor and sector engagement	Active government and donor engagement demonstrating innovation value	API from observation database into DMS and application software, and testing within project

8. Conclusion & Next Steps

The preliminary analysis confirms that simple mobile phone technologies can significantly enhance water, weather and climate data collection and processing in Malawi. The initial prototyping phase demonstrated the potential of these technologies. But it is in the pre-feasibility and diagnosis assessment that a roadmap for technology options becomes clear.

However, challenges remain and there are risks. Such as mobilising financial support for large scale and long-term adoption, preventing the risk of the value of financial death that commonly eliminates transition from piloting to product - however successful they were. More importantly, there is a risk that large swathes of observation data is collected, but not used. This points to the importance of leveraging technologies that integrate the solution into applications, forecasting and hydrological modelling - not only in terms of their software or data management systems, but also with DWR and DCCMS's operations and especially the critical applications, such as flood harvard mapping and early warnings.

Next Steps:

- Architecture designs and schematics are drafted based on the preliminary recommended technology options as part of Output 3 and will be deliberated with DWR and DCCMS involvement prior to back and front end development and UX/UI design.
- The project proceeds with the next task, Output 4, where sites for testing are selected, local communities are engaged, GR&Os are training, the technology is deployed and the iterative back and front end technology development process is underway.
- Workshops are in the pipeline for training DWR and DCCMS staff, as well as external stakeholders within government, enhancing skills and supporting more effective use of the technology options.
- Discussions on data ownership, security and access control standards are initiated and will be translated into the back and front-end development per government preference.
- Data integration into applications and softwares will be explored further in parallel to in-field testing.
- As testing gets underway, and if outcomes are successful, advocacy is needed for supportive policies and funding from international donors to strengthen DWR and DCCMS's ability to adopt the technology long term.

References

DataReportal. (2024). Digital 2024: Malawi. Retrieved from https://datareportal.com/reports/digital-2024-malawi

Financial Times. (2023). Climate investors see growing opportunities in water tech. Retrieved from https://www.ft.com/content/516f9896-05bb-4721-a9e2-4065d902d462

GSMA. (2024). The Mobile Gender Gap Report 2024. Retrieved from https://www.gsma.com/r/wp-content/uploads/2024/05/The-Mobile-Gender-Gap-Report-2024.pdf?utm_source=website&utm_medium=button&utm_campaign=gender-gap-2024

GSMA. (2023). The Mobile Economy Sub-Saharan Africa 2023. Retrieved from https://www.gsma.com/mobileeconomy/sub-saharan-africa/

GSMA. (n.d.). Connectivity for Good: Mobile Economy Sub-Saharan Africa. Retrieved from https://www.gsma.com/solutions-and-impact/connectivity-for-good/mobile-economy/sub-saharan-africa/

GSMA. (n.d.). Despite Improvements, Sub-Saharan Africa Has the Widest Usage and Coverage Gaps Worldwide. Retrieved from https://www.gsma.com/solutions-and-impact/connectivity-for-good/mobile-for-development/blog/despite-improvements-sub-saharan-africa-has-the-widest-usage-and-coverage-gaps-worldwide/

McKinsey & Company. (n.d.). Fintech in Africa: The End of the Beginning. Retrieved from https://www.mckinsey.com/industries/financial-services/our-insights/fintech-in-africa-the-end-of-the-beginning

Saestra and Selinger (2024). The Siren Song of Technological Remedies for Social Problems: Defining, Demarcating, and Evaluating Techno-Fixes and Techno-Solutionism. Retrieved from https://www.researchgate.net/publication/374424060_The_Siren_Song_of_Technological_Remedies_for_Social_Problems_Defining_Demarcating_and_Evaluating_Techno-Fixes_and_Techno-Solutionism

TechTarget. (n.d.). 6 Dimensions of Data Quality: Boost Data Performance. Retrieved from https://www.techtarget.com/searchdatamanagement/tip/6-dimensions-of-data-quality-boost-data-performance

World Bank. (n.d.). Digital Development Overview. Retrieved from https://www.worldbank.org/en/topic/digitaldevelopment/overview#1

World Bank. (2022). Mobile cellular subscriptions (per 100 people) in Malawi. Retrieved from https://data.worldbank.org/indicator/IT.CEL.SETS.P2?contextual=default&end=2022&locations=MW&start=2000&view=chart

World Economic Forum. (2023). Africa Digital Mobile Banking and Financial Inclusion. Retrieved from https://www.weforum.org/agenda/2023/11/africa-digital-mobile-banking-financial-inclusion/