



Literature Review: Early warning services and their value in southern Africa

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LITERATURE REVIEW

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Literature review of Early Warning Services and their value in southern Africa

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Abstract

This brief literature review aims to gather comprehensive information on the evaluation of the effectiveness of existing and proposed weather and climate services, with special attention to the realised and potential socioeconomic benefits and associated supply and use costs. In order to benefit from a larger literature base, evaluations from many different countries have been considered, even though our prime interest is southern Africa, notably Zambia, Mozambique and South Africa.

Early Warning Services¹ (EWS) play a critical role in disaster risk reduction, enabling timely responses to climate-related hazards in southern Africa. Southern Africa is highly vulnerable to extreme weather events, including droughts, floods, and tropical cyclones, exacerbated by climate change. Effective EWS can mitigate the socioeconomic impacts of these hazards by improving preparedness, reducing loss of life, and safeguarding livelihoods. In this paper, we review the previous literature on the development, implementation, and potential economic value of EWS in the region. The review examines key components of a fully functional EWS, including nowcasting, risk assessment, communication strategies, and response mechanisms. We dive into the concept of value chain analysis (VCA) and assess the EWS as one coherent 'warning chain' where all steps and actors in the chain are equally important for the best outcome. Furthermore, this paper evaluates existing studies on the cost-benefit analysis of EWS, highlighting their economic justification through reduced disaster-related losses and improved resilience. The findings underscore the need for enhanced investment, policy support, and regional cooperation to optimise the effectiveness of EWS in southern Africa. The paper concludes by discussing its limitations in accounting for non-monetised benefits like well-being and environmental impacts, emphasising the importance of complementary public weather services, and acknowledging that even when considering the limitations of economic evaluation, the potential benefits of EWS are often underestimated.

¹. The term early warning systems is also used. In the context of a benefit assessment however, key is the effectiveness of the **output** of the early warning system, which is the early warning *service*.

1 Introduction

Weather and climate services (hereafter WCS) are vital for informing and preparing communities for weather-related operational conditions and (extreme) events at different time scales, ranging from intra-day information ('nowcasts') via (multiple) day-ahead forecasts to (sub-)seasonal forecasts. Accurate and adequately communicated forecasts and climate predictions enable citizens, businesses, and public institutions to make informed decisions, such as farmers planning planting and harvesting schedules, fishermen timing their ventures, transport operators anticipating detours and delays, and urban planners designing infrastructure to withstand harmful weather conditions. Respectively, early warning systems (EWS) are crucial for disaster risk reduction, saving lives and reducing economic losses during extreme weather events like tropical cyclones, extremely intense or extremely protracted precipitation events, and thunderstorms.

Even to this day, some developing countries still have deficient weather and climate services and often lack effective early warning systems (UNDRR & WMO 2024). This increases the risk of fatalities and damages from weather hazards in already vulnerable countries and communities. Between 1970 and 2021, Africa accounted for 35 % of weather, climate, and water-related fatalities, and yet only 40 % of the African population has access to EWS (WMO, 2024a). This huge gap is being tackled by the *Early Warnings for All* (EW4ALL) initiative, which aims to ensure that everyone on Earth is protected from hazardous weather, water, or climate events through life-saving EWS by the end of 2027. The initiative is built on four pillars to deliver effective and inclusive multi-hazard EWS, and it's co-led by the World Meteorological Organisation (WMO), the United Nations Office for Disaster Risk Reduction (UNDRR), the International Telecommunication Union (ITU) and the International Federation of Red Cross and Red Crescent Societies (IFRC) and other partners. EWS not only aim to avoid casualties, physical damage and disruptions, but once established and widely used, they fundamentally contribute to increased reliability of public and private operations, which in turn supports economic growth and stability.

Africa bears an exceptionally heavy burden from climate change and disproportionately high costs for essential climate adaptation. On average, African countries are losing 2–5 % of Gross Domestic Product (GDP), and many are diverting up to 9 % of their budgets responding to climate extremes. In sub-Saharan Africa, the cost of adaptation is estimated to range from US\$ 30–50 billion annually over the next decade, or 2-3 % of the region's GDP (WMO, 2024a). The increasing frequency of extreme weather events necessitates enhanced early warning systems and disaster risk reduction strategies. Building robust early warning systems can provide timely information to communities, allowing them to take preventive actions. Additionally, investing in disaster risk reduction infrastructure and emergency response plans can mitigate the impacts of extreme weather events, protect vulnerable populations and improve socioeconomic resilience.

Even though modern weather services, in general, entail the collaboration of different actors, especially modern early warning systems, are operated within a complex network of actors and diverse end-users with different needs and capabilities (Ebert et al, 2024). As early warning services are a public good, they are meant to serve the entire society, and thus it is particularly important to ensure their effectiveness for vulnerable groups, such as poor households, women, elderly and disabled people, weather-sensitive livelihoods, and communities with limited resilience. These are also the target groups of the (pilot) EWS developed and tested in the WISER EWSA project. Improved, user context-aware weather forecasts and associated warnings are cost-effective on a per capita basis when compared to the significant benefits derived from their effective use. These benefits, however, do not manifest automatically, as weather and climate services (hereafter WCS) are often merit goods. Beyond ensuring verified accuracy, these services require innovations in delivery methods and content presentation, as well as comprehensive awareness and advocacy campaigns to facilitate their adoption and effective utilisation.

This paper focuses on the value potential of early warning systems in Zambia, Mozambique and South Africa, the partnering countries in the WISER EWSA project. The report is structured in three main sections. The first one, “Geographic Focus”, outlines and introduces the climatic environment and socioeconomic variables affecting the working environment in southern Africa, including details for the countries concerned. Geographic and socioeconomic understanding provides a useful background of the context area. The next section “The Value of Early Warning Systems” introduces a basic economic concept of value chain analysis (VCA) to understand and evaluate the value generation process of EWS as well as shows the main variables impacting the value. A review of the literature on the economic value of EWS is presented in Chapter 4. Discussion and concluding remarks are given in the last section.

2 Geographic Focus – Southern Africa

Southern Africa is characterised by a diverse range of climatic conditions influenced by various geographic and atmospheric factors. Seasonal patterns in southern Africa are mainly resulting from the change between the wet and dry seasons. The wet season typically occurs from November to March, driven by the Inter-Tropical Convergence Zone (ITCZ) shifting southward, bringing rainfall to the northern and central regions. The wet season is crucial for agriculture and water resources. The dry season extends from April to October and is characterised by cooler and drier conditions, particularly in the interior regions. This season sees reduced humidity and minimal rainfall, leading to increased evaporation rates. Large variations in precipitation and prolonged droughts pose significant challenges for water resource management, energy production and agriculture. Since African agriculture is already marked by low productivity, low levels of investment, and high levels of weather and climate-related risk (Sonwa et al., 2016), and over 70 % of smallholder farmers (depending on the region) rely on rain-fed agriculture for their livelihoods, future climatic variations make southern Africa particularly susceptible to weather-related crises such as famine and extreme poverty. In 2024, southern Africa experienced the worst mid-summer drought in over 100 years and the lowest mid-summer rainfall in 40 years, with serious consequences for the population's well-being. In total, 20.9 million people, mainly in Malawi, Mozambique, Zambia, Zimbabwe and Madagascar, were predicted to suffer from acute food insecurity. (OCHA, 2024).

Although the utility and profitability of WCS have been widely recognised, and they have become a daily source of information among public and private sector users in developed countries, there are still significant gaps regarding the realisation of fully fledged WCS in most developing countries. However, the importance of weather and climate services for southern Africa cannot be overstated. Extreme weather events put hundreds of thousands of people at risk each year and as a result of vulnerability and lack of adaptive capacity developing countries are already more affected by weather and climate-related disasters (Padli et al., 2018). With climate change expected to increase the frequency and intensity of such events, the role of operational early warning services (EWS) becomes even more crucial. For example, heavy rainfall events are projected to increase in frequency and magnitude in the future with additional global warming levels (Pinto et al., 2022), hence, timely preparedness and proactive disaster management become even more crucial. Next to significant limitations of resources to develop national EWSs, countries also lack awareness among end-users and shortfalls in end-user orientation and trust in authorities and services provided. In the EWSA project, all these aspects receive attention, inter alia through a strong emphasis on co-development and co-testing approaches.

Understanding the landscape of existing WCS in partnering countries is essential for identifying gaps and opportunities for the development and implementation of EWS and nowcasting. At the moment, communities, especially in Zambia and Mozambique, are reliant on traditional weather forecasts generated by computer models, looking one to several days ahead at fairly coarse spatial resolutions. Yet in tropical regions, the behaviour of weather patterns is always uncertain once they start to develop. Thus, one of the EWSA project's objectives will be to build capacity for nowcasting – i.e. short-term forecasting whereby real-time satellite images over Africa are used to predict weather conditions over the next six hours. Nowcasting offers a way to complement traditional day-ahead weather forecasts by using (near) real-time observations to project how the weather will probably develop over the next few hours. For many storm types and extreme downpours in southern Africa meaningful accuracy regarding likely location, timing and severity is – so far – only possible at time scales of 2 to 3 hours, say 6 to 8 hours at maximum. Table 1 shows the maturity for National Hydro and Weather Services (NHMS) in Zambia, Mozambique and South Africa based on the metric developed for World Bank (2021) study. It should be noted that the maturity level of NHMS has advanced to some extent since 2020/2021.

Our experiences from communities involved have also shown that forecasts are barely being used at all, which underlines the need not only to develop predictions but also the dissemination, reach and accessibility. Whereas day-ahead forecasts may provide generic indications of possible occurrence of storms in a larger region, nowcasts – when received and understood – can provide spatially and temporally more pertinent information and can thereby improve the salience and hence the usefulness of early warnings.

Table 1: Maturity scores for NHMSs in Zambia, Mozambique and South Africa (World Bank, 2021)

Maturity score	National Meteorological Services			National Hydrological Services		
	Questions answered (%)	Score	Level	Questions answered (%)	Score	Level
Zambia	91%	50%	Essential	72%	43%	Essential
Mozambique	50%	32%	Basic	60%	53%	Essential
South Africa	99%	92%	Advanced	91%	75%	Full

2.1 Zambia

Zambia’s climate is highly variable and over the last few decades, it has experienced a series of climatic extremes, e.g. droughts, seasonal floods and flash floods, extreme temperatures and dry spells, many of these with increased frequency, intensity and magnitude due to climate change. Their impacts on the country are evident in climate-induced changes to physical and biological systems which is increasingly putting pressure on vulnerable sectors of the country, in particular agriculture and energy. Zambia is experiencing structural distress marked by high levels of severe food poverty, chronic poverty and impoverishment. Poverty trends are strongly linked to environmental sustainability issues, such as deteriorating fish stocks, soil fertility, drought and floods, and disaster risk (Shepherd et al., 2022).

In the 2022/23 rainy season, Zambia experienced the most severe flooding in 50 years due to heavy rainfall and thunderstorms. The floodings resulted in major casualties and damages, e.g. just in Lusaka Province a total of more than 373,500 people were affected (ECHO, 2023). A year later, the 2023/24 rainy season’s drought led to massive crop failure and damage, affecting food security and livelihoods of 6.6 million people in 84 out of 116 districts (World Bank, 2024). Since agriculture is the main income source for most Zambians, and about 90 % of cultivation depends on rain-fed agriculture, farmers - and the whole society - are highly vulnerable to climate-related hazards (Beyer et al., 2015). The diminished water supply also constrained hydroelectricity generation, the dominant power source in Zambia, which resulted in up to a 1000 megawatts annual deficit in 2024, disrupting businesses, especially small and medium enterprises (World Bank, 2024). Rainfall variability, i.e. both drought and disruptive rainfall, remains a key structural risk to Zambia’s sustainable growth, affecting agriculture and energy sectors as well as small business owners (Gannon et al., 2018; Adu-Ababi et al., 2024).

On top of the drought induced national electricity deficit, the recent contraction in the mining sector, starting in 2021, has triggered a deterioration in the external sector balances and softened fiscal revenues, leading to large currency depreciation, high inflation, and a sharp increase in the cost of living (World Bank, 2024). The government’s significantly constrained capacity to finance public institutions such as Zambia’s Meteorological Department (ZMD), has affected significantly ZMD’s ability to offer and develop WCS. For example, the public budget restrictions limit ZMD’s ability to practice nowcasting and forecasting around the clock. At the moment forecasting is running every day for 9 hours (from 8.00–17.00) and in the Airport for 7 hours (from 6.00–13.00 with weather observers working 24/7), where forecasts are typically issued twice per day: at lunchtime for the afternoon and evening, and in the evening for the night and next day. In addition, the tools to visualize weather events on maps would need a rapid update.

The lack of (nowcasting based) early warnings for hazardous weather puts society at significant risk, especially vulnerable groups and communities in Zambia. In this respect it is important to realise that about 64 % of the population lives under the international poverty rate (\$2.15 per day) and this rises to 81 % when the lower middle-income poverty rate (\$3.65 per day) is applied (WDI, 2024). The prevalence of poverty among those depending on agriculture is the highest – over 78 % (University of Zambia, 2021). The high dependence on rain-fed production and weather in general contributes to farmers' uncertainty about investments in the future and the failure to strategically position the sector according to its comparative advantages. As a result, especially smallholder farmers face challenges of low production and productivity due to the high risk associated with additional investments. As a positive note, a fairly recent study on productivity improvement in Zambia's agriculture (Mwalupaso et al., 2019), assessed that the use of weather information via mobile phones does increase productivity in terms of yield per ha for a selection of smallholders. Yet, the degree of attribution to mobile weather services merits further econometric research. Furthermore, upscaling the productivity effect to all or at least most crop farming requires a broader approach, including awareness raising, education, network access, etc.

A recent report by UNU-WIDER (Adu-Ababio, 2024) studied the impact of climate shocks on firm performance and tax revenue in a low-income country context, using firm-level data from Zambia. They find that extreme weather events, such as excessive rainfall and high temperatures, significantly reduce firms' sales (-4 %), input purchases (-6 %), and sales tax collection (-4 %), particularly in sectors such as manufacturing, retail, accommodation, and construction. Firms respond by reducing employment and wages, reflecting a decline in production. Their findings highlight the need to consider the combined effects of climate shocks on both formal sector productivity and government revenue in developing countries, where taxation on services and goods (e.g. VAT) represents a larger share of government budgets.

2.2 Mozambique

Mozambique faces significant weather-related hazards, including cyclones, tropical storms, droughts, and extreme temperatures. As cyclones predominantly impact the eastern coastal regions of southern Africa, Mozambique – with a long Indian Ocean coastline of 2,500 km – is particularly vulnerable to their destructive impacts. Cyclones and tropical storms bring substantial rainfall and strong winds, leading to severe flooding and widespread damage to infrastructure and communities. The destructive potential of cyclones and tropical storms can result in significant economic losses and displacement of populations. Mozambique also lies at the end of numerous transnational river basins and flooding in its deltas is a perennial threat to both farmers and infrastructure, especially when coupled with cyclonic storm surges.

Multiple cyclones and tropical storms were experienced in Mozambique during the 2023/2024 rainy and cyclonic season. Exceptionally long-lived, powerful, and deadly tropical cyclone Freddy was experienced between February and March 2023. Freddy was the longest-lasting tropical cyclone ever recorded worldwide (more than five weeks) and produced the most accumulated cyclone energy (a metric used to measure the total energy generated by tropical cyclones) of any individual cyclone on record globally (NASA, 2023). Additionally, it is the third-deadliest tropical cyclone recorded in the Southern Hemisphere. In total the 2023/2024 rainy and cyclonic season affected over 130 000 people (~27 000 families), with 135 deaths and almost 200 wounded (OCHA, 2024; other sources such as EM-DAT and INGD may have reported somewhat different figures). Damages to public infrastructures included 468 schools, 155 power poles, 89 health centres and over 700 km of roads. Furthermore, over 30 000 ha of agricultural land were damaged, of which 6,133 ha were completely lost. (OCHA, 2024; other sources such as EM-DAT and INGD may have reported somewhat different figures) It is evident that the socio-economic impacts of these kinds of dreadful weather events are profound, and have a wide-ranging impact on a country's economy, businesses, infrastructure and the well-being of its citizens.

Since agriculture is the most important economic sector in Mozambique, and prime livelihood for a vast majority of the population, adaptation and resilience to severe weather events are vital for the country's economy as a whole. Most of the country's population reside in rural areas and rely on rain-fed agriculture making them extremely vulnerable to weather. According to WDI (2024) 74.5 % of the population is living under the international poverty rate (\$2.15 per day) and 88.6 % under the lower middle-income poverty rate (\$3.65 per day). This puts a high pressure on governmental actions towards sustainability goals and initiatives, including better weather information for the vulnerable communities. Disasters further impoverish the poor and entrap them in the poverty cycle, with vulnerable households more likely to fall back into poverty following external shocks. Indebtedness, depletion of assets, and use of negative coping strategies affecting health and education, are common among highly vulnerable populations (Jha and Stanton-Geddes, 2013). This makes it particularly important that adaptation to climate change takes account of vulnerable groups.

The mandate for water and weather observation and forecasting in Mozambique is delegated to several agencies across two government ministries. The Ministry of Transport² delegates responsibility to the National Institute for Meteorology (Instituto Nacional de Meteorologica, INAM) to monitor and forecast weather and climate and to produce and disseminate climatological data, analyses, and services, as well as weather forecasts and forecasting services. The Ministry of Public Works and Housing, the National Directorate of Water (Direcção Nacional de Águas, DNA), and the five Regional Water Authorities (Administrações Regionais de Águas, ARAs) are responsible for matters relating to hydrology including policy development and management, strategies and investment mobilization for the water supply and sanitation in rural and urban areas, management of water works planning, measuring and forecasting discharge volumes of inland water systems, issuing flood warnings based on these forecasts, and sharing agreements issues for water resources in transboundary basins (based on interview with ARA Sul, 11/2024). At the beginning of the EWSA project, INAM is doing forecasting every day for 8 hours (from 9 am to 5 pm) and at the Airport for 24 hours. The extension of 24/7 nowcasting and EWS aimed at vulnerable urban populations implies extra resources and cost, for which coverage has yet to be found. Given the high risk of disastrous weather events and the need to improve the forecasting of these climatic events, INAM has developed its weather and climate services in recent years in the context of various development cooperation projects. Obviously, better forecasting and nowcasting, enabling better EWS, can lead to huge cost savings and saved lives. Even when the associated investments are largely covered by foreign financing sources, the additional operational and maintenance cost of improved nowcasting and EWS are hard to reconcile with public budget constraints.

2.3 South Africa

South Africa, located at the southern tip of the African continent, is a nation characterized by diverse climates and a multifaceted socioeconomic landscape. The country's climate varies significantly across its regions, influenced by its topography and oceanic proximity. The northwestern part of South Africa experiences an arid climate, while the eastern regions receive more rainfall, supporting subtropical conditions. Climate change poses substantial challenges, including increased temperatures and altered precipitation patterns, leading to more frequent extreme weather events. Projections indicate a temperature rise of 2–3°C by mid-century and 3–4°C by the end of the century under intermediate scenarios (Carbon Brief, 2018). These climatic shifts are expected to impact the general weather conditions, water resources, agriculture, biodiversity and the frequency of extreme weather events.

In April 2022, a fatal weather event hit South Africa when heavy rainfall caused severe flooding and landslides which caused the death of 448 people, displaced over 40 000 people and completely destroyed over 12 000

² This represents the situation since January 2025, following a split of the Ministry of Transport and Communication into two ministries.

houses in the south-east part of South Africa around the city of Durban. It also severely damaged infrastructures: roads, health centres, and schools (ECHO, 2022). Damages caused by the floods included not only major financial losses to the city and its residents (over \$1.4 billion US), but also brought intense emotional and physical trauma to its survivors (US EPA, 2024). According to Pinto et al. (2022), the event concerned has a return time of about 20 years in today's climate in the ERA5 observational data set. An event of this magnitude would have been rarer in a 1.2°C cooler world (i.e. without post-industrial climate change), with a return time of about 40 years. They conclude that the probability of an event such as the rainfall that resulted in this disaster has approximately doubled due to human-induced climate change.

More recently, in October 2024, four northern-eastern provinces (Mpumalanga, Eastern Cape, Free State and Limpopo) experienced severe thunderstorms with intense winds leaving a total of 7 757 homes (involving almost 39 000 people) severely or partially damaged across all affected provinces. In the aftermath of the event, more than 6 200 households and 39 schools were also damaged, and four fatalities were reported. Not even a month later, several districts of Limpopo province experienced heavy rain and hailstorms, causing floods and severe weather-related incidents that resulted in casualties and major damages. And again, two weeks later heavy rainfall and strong winds affected Gauteng and Mpumalanga provinces, resulting in casualties and damage. These frequent and sometimes destructive weather events underline the importance of early warnings and information chains as well as the importance of society's preparedness and resilience.

South Africa boasts the second-largest economy in Africa, with a gross domestic product (GDP) of approximately \$350 billion as of 2024. The economy is diverse, encompassing mining, manufacturing, agriculture, and services sectors. In the fourth quarter of 2024, the economy experienced modest growth, with a seasonally adjusted GDP increase of 0.6 %, driven primarily by a 17.2 % expansion in the agricultural sector. (Reuters, 2025). However, challenges persist, including high unemployment rates, income inequality, and infrastructural deficits. The nation is also undergoing an energy transition, aiming to reduce its reliance on coal and incorporate renewable energy sources, a shift supported by international climate agreements. Another difference to the other EWSA partnering countries is that South Africa is more urbanized, with over two-thirds of the population (over 60 million population by 2023) currently residing in urban areas, a rate expected to increase to 72 % and 80 % by 2030 and 2050, respectively (World Bank, 2024).

Also regarding forecasting and nowcasting, South Africa differs from Zambia and Mozambique as the South African Weather Services (SAWS) has a better observation network and better data processing and modelling capabilities. Thanks to these capabilities SAWS is an important actor in the SADC region regarding the preparation and generation of warnings for various types of weather hazards to the countries in the region, and serves as the WMO Regional Specialist Monitoring Centre, with responsibility for regional leadership and training. SAWS also implements the SADC Regional Meteorological Development Project for the Severe Weather Warning System (SWWS). Since SAWS is already running nowcasting based EWS, the extension of the EWS portfolio in EWSA aims at vulnerable urban populations. The demand for extra resources is therefore relatively smaller as compared to Zambia and Mozambique. However, it is crucial to further develop the EWS in terms of its scope of diverse communication channels to convincingly reach vulnerable communities and this will require extra resources.

After the devastating weather disaster in April 2022, a study by Pinto et al. (2022) indicated that the South African Weather Service and eThekweni municipality issued early warnings, but the warnings had limited reach and the people who did receive them may not have known how to respond to these. Assessments also show that the floods disproportionately affected marginalised communities, with particular devastation in informal settlements. Thus, the magnitude of this disaster on these groups has been exacerbated by pre-existing structural vulnerability in the region (Pinto et al., 2022). This highlights the importance of understanding South Africa's sociodemographic dynamics to ensure the effective implementation of early warning services and promote equitable and fair sustainable development in the region.

3 The Value Generation of Early Warning Systems

There is an expanding collection of literature on the valuation of weather, climate and hydrological (information) services. From various overview studies (e.g. WMO 2015; Rogers and Tsirkunov 2013) it becomes clear that, generally, these services generate socioeconomic benefits which exceed the cost of delivering them many times, for example, 5 to 10 times. Similarly, the literature on the value of early warning services (EWS) has been growing in volume over the past few decades, while most of the publications have shown the explicit value to society. As Baudoin et al. (2016) argued, communication through EWS provides the opportunity to reduce disaster risk by enhancing (short-term) preparedness which contributes to strengthening livelihood resilience at the local level. They also suggest that designing and developing EWS should be a more community-centric approach to meet the needs of the vulnerable communities. Understanding the full value-generation process of EWS is essential for assessing and developing them. To comprehensively analyse the different value-adding steps in EWS, a proper value chain analysis (VCA) is often mandatory or at least useful.

The very basic idea of a value chain is to show how the production of a good or service is organised with special attention to the combined use of resources in subsequent production stages and the (incremental) value of output at each stage. In other words, value chain describes how - in a stepwise process - resources are combined to refine or enhance constituent components into products, or in EWS's case to turn data into information and information into services and warnings. The term was first used by Porter (1985, 2008) and the concept of value chain analysis has since become popular in supporting different types of socioeconomic and managerial evaluations of weather and climate services (WCSs) (Anderson et al., 2015; Cortekar et al., 2020; Lazo & Mills, 2021) as well as EWS (Ebert et al., 2024). Value chains may be displayed for an entire organisation, such as the National Hydro-Meteorological Service (NHMS), or focus on a particular bundle of closely related WCSs. The Figure below (Fig 1) shows a generalised example of a value chain for a WCS, visualising the value-adding steps of how 'raw data' is transformed into service and subsequently into actual outcomes, i.e. responses to information, which create benefits.

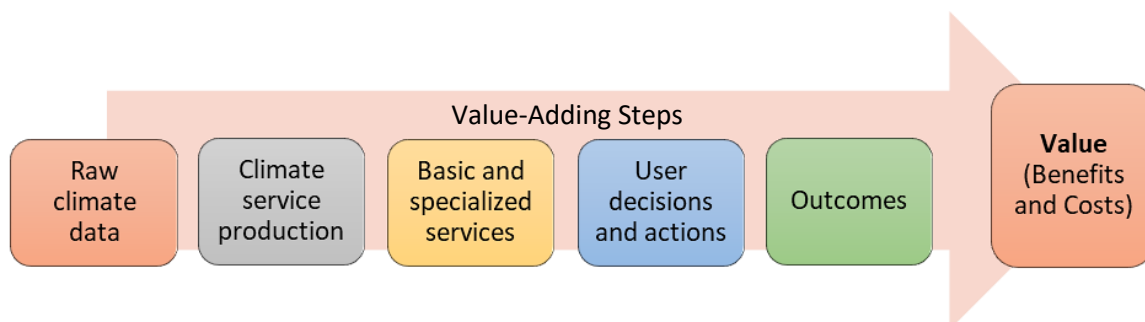


Figure 1: General overview of the WCS value chain (following WMO, 2015)

Identifying a value chain for the purpose of economic evaluation (e.g. cost-benefit analysis) is based on the experience and logic that such (e)valuations first require a proper definition phase. Moreover, VCA can help to identify the gaps and leaks where value is lost during the process. This is derived from the basic principle that met/hydro services do not generate economic and social value *unless* users benefit from the decisions based on the information provided. High accuracy and proper timeliness of warnings can only boost benefits if intended users can access and understand the information and act upon it. If minimum requirement levels of accuracy of WCS are reached in the upstream part of the WCS value chain, the effectiveness of the downstream part of the WCS value chain (reaching, informing, and activating users) becomes crucial for realizing a large part of the benefit potential of avoided cost. Thus, the net value of early warning services,

and WCS in general, is highly dependent on how well the value is transferred and preserved into the next stage – all the way to the actions of the end-user.

The above-described communication sensitivity highlights that EWS must be people-centred, meaning that the messages reach the intended recipients on time and in an understandable format. UNISDR (2006) defines EWS as “a set of capacities needed to generate and disseminate timely and meaningful warning information of the possible extreme events or disasters (e.g. floods, drought, fire, earthquake and tsunamis) that threaten people’s lives”. The *Early Warnings for All* (EW4ALL) initiative distinguishes four essential pillars for end to end, people-centred Multi-Hazard Early Warning Systems (MHEWS):

- Pillar 1: Disaster risk knowledge
- Pillar 2: Detection, observation, monitoring, analysis, and forecasting
- Pillar 3: Warning dissemination and communication
- Pillar 4: Preparedness and response capabilities

Similarly, the UNDRR (2017) lists four elements of efficient people-centred early warning systems as (i) disaster risk knowledge based on the systematic collection of data and disaster risk assessments; (ii) detection, monitoring, analysis, and forecasting of the hazards and possible consequences; (iii) dissemination and communication, by an official source of authoritative, timely, accurate and actionable warnings and associated information on likelihood and impact; and (iv) preparedness at all levels to respond to the warnings received. Kelman and Glantz (2014) also emphasize that each EWS needs to be viewed as a social process which involves technical components embedded in their social context – by keeping people and communities at the centre of an EWS, it can contribute to daily life and livelihoods supporting wider disaster risk reduction and sustainable development endeavours, rather than being a separate system waiting to be triggered only when a hazard appears.

Looking from a VCA perspective, an early warning system can be described as an “information value chain” in which a sequence of actors (organisations, communities and individuals) produces and shares information that helps people take actions to protect themselves against loss caused by hazardous events. More broadly, the value chain concept is a useful framework for characterising the processes, inputs, contributions, contexts, and relationships of actors who, together, produce and deliver critical information to support decisions that lead to beneficial outcomes. (Ebert et al., 2024.) The ‘warning value chain’ as used in the economic analysis of the EWSA project is shown in Figure 2. With the considerations presented above, the EWSA project will focus equally on both sides of the warning value chain: codeveloping the forecast accuracy and quality (‘upstream part’) as well as delivering understandable information that reaches end-users, raising awareness on how to act during the warning (‘downstream side’) and acknowledging barriers that limit people's ability to take proactive measures – as well as decreasing them (e.g. providing weather information in sound format to blind people).

1	2	3	4	5	6	7	8
Observation	QA basic data repository	Forecasts & Nowcasts	Hazard warning(s)	Impact warning(s)	Supporting preparedness	Response & Rescue	Recovery

Figure 2: The warning value chain as used in the WISER EWSA project

Upstream in the warning value chain are the observations, quality-assured data repositories and the generation of forecasts and nowcasts (steps 1-3). Usually, the prime responsibility for these steps resides with the NHMSs, however other actors, such as satellite organisations and hydrological agencies, can be important data contributors. The mid-stream (steps 4-5) of the EWS typically includes modifying and disseminating the warnings – often the weather information or warnings may need modifications, such as

translation to a local language, addition of clear instructions and/or impacts of the weather, for better understandability and accessibility. This can be done, for example in collaboration with the NHMS, the Disaster Risk Management or other actors such as a federation for people with disabilities as well as end users from EWSA's pilot communities. At the downstream end of the warning value chain are the steps for preparedness, rescue and recovery (steps 6-8). In the case of EWS, preparedness relates to short-time preparedness before the weather event. Because of the immediate actions needed, the information flow must be as smooth as possible. Response and rescue are important parts of the chain to limit the casualties and damages from the disaster, and they also provide feedback to develop the system further. The last step, "recovery" includes the implementation of actions to recover from disaster and help people affected.

Characterising the value chain for early warning system options helps the partners to carry out a fair comparison between a service that they may wish to emulate and what is possible in their unique environment. Differences in observing systems, the organisation of the nodes and actors in the warning value chain, and the regulatory environment (among other things), may necessitate major adjustments to the system. (Ebert et al., 2024.) In addition, met/hydro services of similar quality provided in two countries can vary significantly in terms of their benefits depending on the relative nature of weather- and climate-related risks, the number and types of users and their capacity to take actions to avoid harm or increase economic output (Anderson et al., 2015). Because the warning value chain and benefit potential can look very different for neighbouring countries, generic average results of the socioeconomic benefits of WCS and EWS in developed countries cannot be directly transferred to WISER EWSA's specific target groups in selected countries. In the EWSA project the target groups are:

1. vulnerable and disabled people, with limited financial and other resources, in (peri)urban areas
2. population in rural areas, largely dependent on agriculture and fishing

These target groups have less assets per capita than the average in the concerned economies. They usually also have less than average money-earning capacity. All in all, this means that it may be more challenging to create an early warning service which generates sufficient benefits that clearly exceed its costs. In practice, this means that the EWS should reach large numbers of people in these target groups and also really help these people to better and duly respond to weather hazards. This presents the short-term view on benefit generation. In the medium to long term, a systematic reduction in damage, income and health risks may be expected to improve their money-earning capacity and asset accumulation. In other words, better preparedness and resilience can eventually increase people's willingness to invest in their businesses and increase their income level in the long term.

With the above considerations in mind, we review the literature with special attention to the sensitivity of benefits regarding:

- 3.1) scale of uptake of the service
- 3.2) responsiveness and response effectiveness (among target groups)
- 3.3) longer-term and indirect effects

The overall net benefits or benefit-cost ratios are reported more thoroughly in Chapter 4.

3.1 Uptake and accessibility of the service

As outlined above, uptake and accessibility of the information are crucial to the eventual utility of the service - if people cannot access or receive the information the overall benefit will be non-existent. Estimates of the number of people who access and use WCS in Africa lack representation, by only covering a small number of communities in less than half of the African countries, whereas some areas have received relatively more attention. Furthermore, the results are highly variable with access estimates ranging from ~2 % to 86 %,

depending on the service and population. (Vaughan et al., 2019.) Given the unambiguous impact of weather on agriculture, and the fact that agriculture is the main source of income in many African countries (especially for vulnerable people), a great deal of research has explored the relationship between weather, climate, and African agriculture (e.g. Calzadilla, Zhu, Rehman, Tol, & Ringler, 2013; Knox, Daccache, & Wheeler, 2012; Ziervogel et al., 2014). Thus, the examples presented will mainly focus on the agricultural sector.

In southern Africa (Malawi, Mozambique, Namibia and Zimbabwe) estimates of the number of farmers receiving weather information range from 27 % to 86 %, with an indication that radio is the primary source by which farmers access weather and climate information (O'Brien et al., 2000; Patt et al., 2005; Mudombi & Nhamo 2014; Lazo 2015; Coulibaly et al., 2015; Mulwa et al., 2017). Ouédraogo et al., (2021) found that 80 % of farmers in Senegal used weather and climate information services to make decisions on sowing dates, crop variety selection, and fertiliser application. The socioeconomic factors and triggers that significantly influenced the uptake of WCS were age, education, training, farmer's organisation membership, and radio ownership. Similarly, Oyekale (2017) found that among farmers, the likelihood of accessing and using climate forecasts increased significantly with primary, secondary and tertiary education. Mushore (2013) also highlighted that current problems with the uptake of climate forecasts could be solved by educating the users and involving stakeholders in the dissemination of the forecasts to bridge the existing knowledge gap. In accordance with these findings the WISER project is highlighting the importance of stakeholder and user engagement as well as co-development with local communities.

Furthermore, the credibility of the forecast, built on the accuracy of past forecasts and the forecast communicators' reputation, can also restrict uptake (Patt, 2000; Patt and Gwata, 2002). The credibility of forecasts and forecasting institutions is a relevant factor, especially in a non-Western context. Nkiaka et al. (2020) studied forecast quality in West Africa and their findings indicate that even though quality has improved in recent years, challenges for uptake of weather information remain and are related to user understanding, clarity about forecast uncertainty, the insufficient spatial and temporal resolution of forecasts leading to limited trust in forecasts. For example, two studies of the use of forecasts by pastoralists in Kenya and Ethiopia (Luseno et al., 2003; Lybbert et al., 2007) found that confidence in the forecasts determined whether forecasts were used or not. Sen et al. (2021) studied farmers' barriers to the access and use of climate information in Vietnam and the results show that the main barriers were: 1) farmers' lack of trust in formal climate-related services; 2) farmers' lack of perceived risk from climate change; and 3) difficulties in balancing climate adaptation and economic benefits of new interventions. This highlights the importance of building trust with the actors in the information chain and co-development with different stakeholders.

In addition, a decision-maker's relationship with assets such as land or livestock may have a significant impact on how they use and value climate services. Boone et al. (2004) found that in South Africa, municipal livestock managers were less likely to act on drought forecasts than commercial livestock managers because of different goals and values. Similarly, Letson et al. (2001) found that in Argentina, farmers renting land held climate forecasts in higher regard than landowners, probably because owners have less flexibility to act on this information. Results showed that the expected value of the information is three to five times higher for renters than for owners. These cases illustrate the importance of context in determining the use and value of climate information. Initiatives that enhance farmers' literacy, access to radio and ability to observe accurate changes in weather would further enhance their adaptation through climatic forecasts (Oyekale, 2017). Extensive evidence from the study by Vaughan et al. (2019) indicates that Africans' access to WCS varies mostly based on region, livelihood strategy, demographic characteristics, and information type.

The warning also reaching the targeted people is obviously essential in the uptake of the service and in preventing casualties and damages. In OECD countries hazardous weather warnings are usually disseminated through a multitude of channels, where for example smartphone penetration and mobile network coverage are high. Recent studies present a clear digital transition in developed countries in receiving weather

information; Krocak et al. (2024) report that 74.3 % of respondents use cell phone weather apps for routine forecasts, while Vaughn et al. (2023) note that over 75 % rely on weather apps for general forecasts and that 80 % receive severe weather notifications via mobile devices. Despite the high communication access figures the share of people effectively reached by a warning may be lower than 70 %, as was for example shown in a survey during the EWSA project (Vincent et al., 2024). For the target countries in EWSA, this share is appreciably lower, especially in the initial phase of developing EWS without the use of SMS messages and radio. People living in the city are more likely to own a smartphone but in rural areas the representation is still very low. However, the growing number of people accessing smartphones (e.g through a community member) can increase the reach in future which is why developing internet-based communication channels for a larger reach is useful.

3.2 Responsiveness and response effectiveness

A relevant indicator of the usefulness and effectiveness of the EWS is the person's ability to react and respond to the warnings. This includes the ability to take actions that prevent harm to human health as well as damage to property. For example, a study of farmers and pastoralists in Africa (Ingram et al., 2002) found that forecasts had greater value for crop farmers, as they could not move their operations. Pastoralists, on the other hand, were partly sheltered from climate variation by the ability to move their herds and therefore placed a lower value on climate information. Meza et al., (2008) also highlighted that the value of climate information highly depends on the sensitivity of the decision-maker to climate variability.

Sutter and Ericson (2010) studied the benefits of spatially more precise tornado warnings in the USA. Tornado warnings are comparable to nowcasting/EWS under evaluation regarding the short lead time and the uncertainty of what areas are really hit. Despite the significant risks that tornados entail the response rate is only 50 % on average, varying between 30 % and 90 %. Yet, some of the non-response may have to do with people having indications of being outside the tornado trail. The response rate could be increased with more personalised weather alerts. As Mileti and Peek (2000) point out, when a severe weather threat becomes personalised to an individual, they feel it could affect them personally and thus, they are more likely to take protective action. Personalisation is a high strength of the weather app as a medium (Vaughn et al., 2023.), and with increasing use of weather apps for receiving weather information, personalisation of the forecast and severe weather alerts could be one way to increase responsiveness.

Perrels et al. (2012), citing various studies, report response rates for traffic-oriented warnings in Finland of about 40 % average (among those who notice the warning). As not everybody is reached by the warnings (62 %), while responses are not always optimal (80 %), and some other components are neither perfect, an estimated 14 % of the theoretical benefit potential is realised on average, which amounts nonetheless to annual benefits which exceed about 12 times the attributed annual costs. Earlier WISER's HIGHWAY project (Roberts et al., 2022) found that the activities undertaken to increase the use of weather information, including sensitisation at selected landing sites, including the use of community intermediaries, weather flags and weather noticeboards (secondary local communication) has led to greater use of the information. The focus groups at these landing sites indicated that 75 % of those who receive weather information use it to inform their decision-making.

People's responses or non-responses to weather warnings can be analysed using, for example, the Theory of Planned Behaviour (Ajzen 1991; Ajzen 1985), which explains an individual's behaviour in terms of the following three factors: (1) attitudes, (2) subjective norms, and (3) perceived behavioural control. In addition, risk perception can be seen as an important factor affecting people's decision-making (Steynor & Lorena, 2022).

1. **Attitudes** refer to an individual's evaluations of behaviour, which are shaped by their beliefs, values, past experiences, and perceptions of the outcomes of performing the behaviour. For instance, can I trust the warning based on my past experiences (were the forecast uncertainties clearly communicated), and what tangible benefits will I gain by responding to it?
2. **Subjective norms** refer to an individual's perceptions of the social norms and expectations surrounding a particular behaviour, which are influenced by the approval or disapproval of important people in their lives. For instance, what do others, especially those close to me in this community, do when a warning is issued?
3. **Perceived behavioural control** refers to an individual's perception of their ability to perform a specific behaviour, including having the necessary resources, skills, and opportunities. For instance, do I have enough resources (wealth, knowledge, skills) to evacuate and take preventive measures? If there are barriers to preventing damage (e.g. flooding due to poor drainage), people may be unmotivated to take preventive actions.

Klößner (2013) proposes a comprehensive model of determinants of individual environmentally relevant behaviour based on a combination of the most common theories in environmental psychology. The study found that intentions to act, perceived behavioural control and habits were identified as direct predictors of behaviour (Fig 3). Intentions are predicted by attitudes, personal and social norms, and perceived behavioural control. Personal norms are predicted by social norms, perceived behavioural control, awareness of consequences, ascription of responsibility, an ecological world view and self-transcendence values. Respectively self-enhancement values have a negative impact on personal norms. Based on the model, interventions to change behaviour need not only to include attitude campaigns, but also a focus on de-habituating behaviour, strengthening social support and increasing self-efficacy by providing concrete information about how to act. Value-based interventions have only an indirect effect. (Klößner, 2013). This indicates that the key implications directly affecting a person's responsiveness and actions are intentions, habits and perceived behavioural control. Yet, we like to add that permanent 'de-habituation' seems an unlikely condition, rather it turns into 're-habituation' (Lopes & Healy, 2021; Rankin et al., 2009).

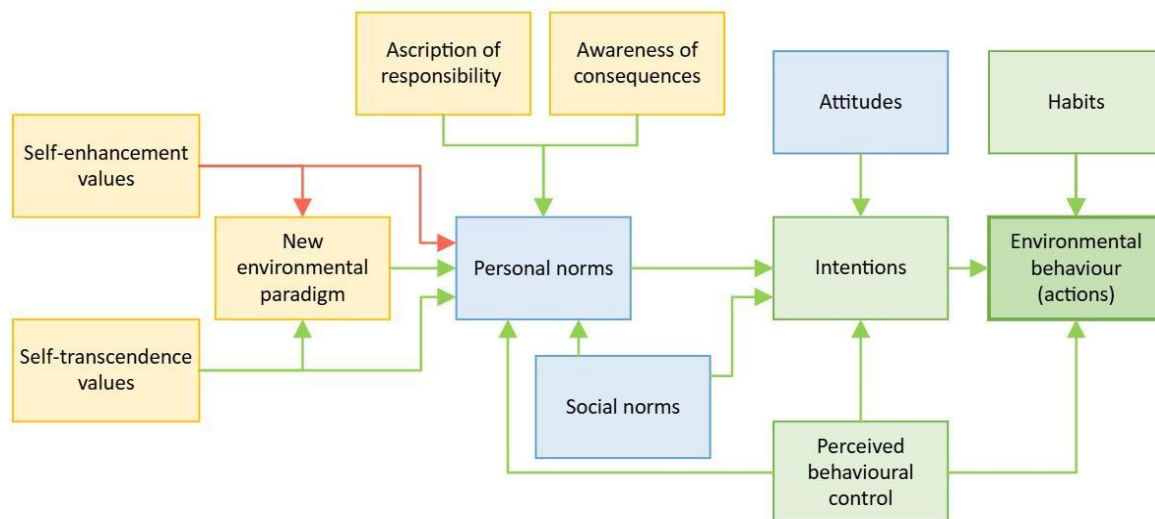


Figure 3: Factors affecting environmental behaviour (following Klößner, 2013)

Assessing different implications that affect the decision-making of reacting or not reacting to weather warnings helps to understand how responsiveness could be increased. Regarding the responsiveness to weather warnings, this highlights the importance of education and campaigns to change social and personal norms, habits and attitudes. Hence participatory engagement of *groups* of envisaged users, as pursued in WISER EWSA, can affect response behaviour directly and through peers. Perceived personal control can be

improved by sharing examples of success stories of people who have taken preventive actions and can evidence avoided damage. In addition, infrastructural conditions can put people at higher risk of being affected by weather. For example, lack of drainage and waste management can lead to roads easily flooding after even slight rain which can demotivate people to react to warnings. Improving the drainage system will most likely lower the risk of flooding after rain, increasing peoples’ perceived ability to affect their situation and the effects of rain. Regarding the weather warnings and taking precautions, it’s also relevant to point out that the colour of the warning can substantially affect people’s responsiveness. Yellow warnings, representing less severe and/or less certain threats, tend to incite less attention or action, especially in areas where yellow warnings are common and occur almost on a weekly basis.

Understanding the disaster preparedness of firm owners and firms is also vital when mitigating socioeconomic losses in Sub-Saharan Africa as micro-enterprises (0–9 employees) employ about 90 % of the working population in low- and middle-income countries (ILO, 2019). Small firms are often the only source of income for local communities and, therefore, the recovery of micro-enterprises after disasters matters for community recovery. It should be realised that a vast majority of the rural population are smallholders, of which only a part of the harvest is sold and the rest is used for their own consumption. This means relatively little savings due to limited participation in the market economy, whereas crop failure may easily entail structural food shortage. Similarly, micro-enterprises are particularly exposed to disasters, but often poorly prepared to cope with and recover from them. Berkel and Tarp (2024) highlight three main socio-psychological characteristics of entrepreneurs associated with their firms’ disaster preparedness: knowledge about climate change (in particularly knowledge about the causes of climate change); descriptive norms (i.e. the extent to which a firm owner thinks that other firm owners are acting to reduce disaster risk); and egoistic values (i.e. pursuing self-serving activities). Effective integration of weather and climate information into societal, as well as business’s, decision-making processes can build resilience to climate shocks across Africa (Nkiaka et al., 2019).

In contrast to studies by Van Der Linden (2015) and Brosch (2021), Berkel and Tarp (2024) note that the association between effect and disaster preparedness is statistically insignificant. This is a relevant finding since the academic literature strongly focuses on the effects and emotions related to climate change and disasters. Affect might be an essential factor in Western contexts, but according to the study among highly vulnerable populations in a low-income setting, affect seems to be less relevant. In practice, this means that instead of just providing information about possible disaster preparedness measures, adaptation actions (awareness campaigns etc.) should try to influence firm owners’ knowledge about climate change, their descriptive norms, or egoistic values, for example, by sharing information about similar firms’ disaster preparedness success stories. In the long term, policymakers should make sure that individuals receive solid education about the causes and effects of climate change. (Berkel and Tarp, 2024.)

3.3 Longer-term and indirect effects

Improved weather forecasts and warnings not only reduce the number of avoided damages or casualties but also have dynamic effects on the economy, such as economic growth, predictability of economic activity, consumption and people's ability to work. One way to assess the overall impacts of EWS is the Triple Dividend of Resilience (TDR) framework (Tanner et al., 2016) which offers a systematic approach for evaluating the benefits of climate resilience investments, such as early warning services. TDR divides the benefits into three categories or “dividends” as illustrated in Figure 4.

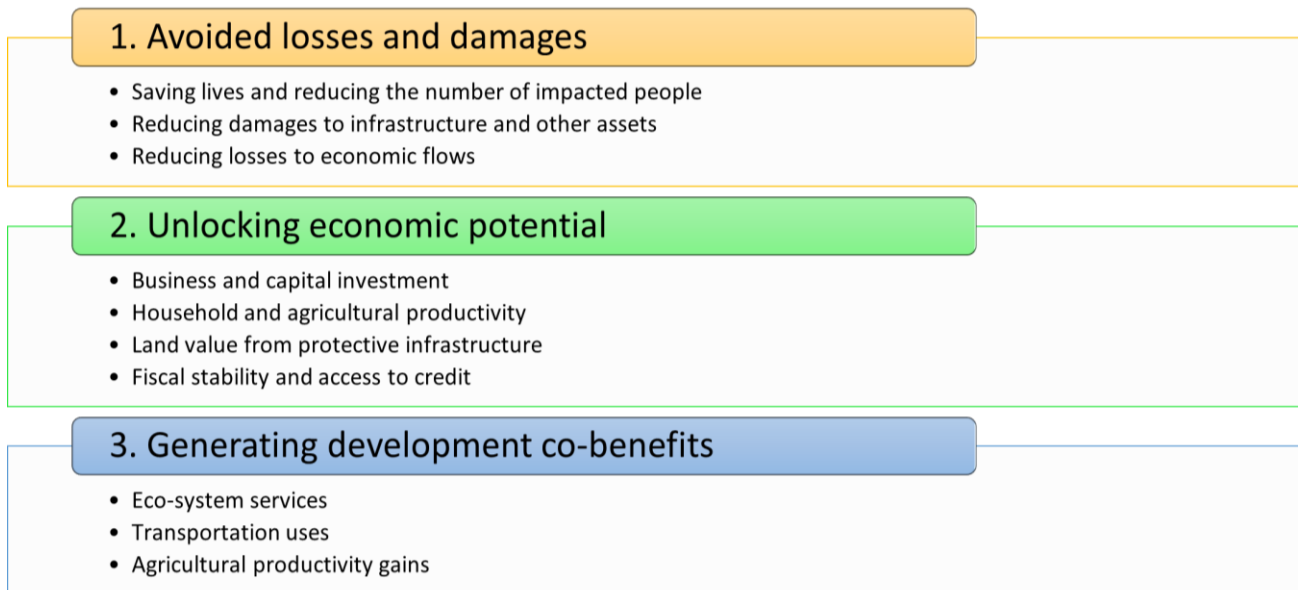


Figure 4: Triple dividend framework (following Tanner et al., 2016)

While saving lives and reducing losses is the first aim of the EWS, for long-term resilience and sustainable development the second and third dividends are also vital. Especially, in natural disaster-prone countries, risks of extreme weather events and disasters create an ongoing risk factor. Consequently, risk-averse households and firms avoid long-term investments (in assets or entrepreneurship) meaning development opportunities are lost. By offering better forecasting of natural hazards and their likely impacts, EWS and other climate services can contribute to development gains as the experienced improved resilience encourages people to invest, more than before, in productive assets, entrepreneurship and innovation. (Apergi et al., 2020.) This economic development effect represents the *second dividend's* benefit of the model for weather preparedness. The improved resilience to weather hazards improves factor productivity, which in turn incites more investments, which on average further improves wealth creation. Moreover, these first and second order induced effects in selected sectors, such as smallholders, can have further positive spillover effects in the broader economy, e.g. for transport and trade.

The third dividend encompasses the economic, social and environmental co-benefits. On a direct level, successful EWS requires inclusive community and user engagement, which can enhance the involvement of women and marginalised groups which ultimately, promotes social cohesion. In addition, the demonstrated benefits of EWS and other climate services in informing investment decisions in the last section stretch across to disaster risk mitigation investment planning and the optimisation of infrastructure investments. For instance, early warnings can signal the need for timely maintenance or upgrades, reducing the likelihood of costly failures during extreme weather events. Additionally, the data and guidance from EWS and other climate services can inform actions and investments to protect and manage the environment, including valuing and optimising ecosystem services. These processes deliver the *third dividend* while also contributing to the realisation of the first two dividends.

Both the second and the third dividend - the 'side effects' of EWS and risk mitigation - offer advantages even when climate disasters don't occur. This means that benefits accrue regardless of whether the anticipated climate risk materialises, resulting in high adaptation benefit-cost ratios (BCRs), even when the value of potentially avoided losses is not factored in (Heubaum et al., 2022). Better awareness of and evidence for the full range of benefits demonstrates higher climate resilience investment returns and the generation of more information useful in decision-making across sectors. There are immediate and significant economic benefits

to households, the private sector and, more broadly, at the macroeconomic level, which makes a stronger economic case for supporting adaptation through EWS and other climate services. In a very generalised sense, the implementation of a new loss-avoiding technique (e.g. a nationwide adoption of nowcasting) reduces the expected average annual cost, in other words, *the risk*. In turn, this allows entrepreneurs to take slightly more risks and thereby achieve higher productivity, either by improving quality and/or quantity. Hence weather and climate services, and in a broader sense (timely) adaptation to climate change, not only directly save costs but also induce extra economic activity (World Bank, 2010). Yet, the size of that induced effect is difficult to assess, and it may build up quite slowly.

Using this TDR framework as a base for an economic analysis can be problematic due to the risk of double counting. Double counting in economic analysis leads to an overestimation of benefits by including the same impact multiple times under different categories. In the TDR framework, this is a concern because benefits are interconnected and they fall under both the second and third dividends. For example, investment in resilience measures and the resulting increase in agricultural productivity are included separately, even though the productivity gains are a direct outcome of the investment. The remedy is to use either output-based measures *or* input-based measures. Similarly, only changes in flows, such as revenues and costs, should be included and not changes in stocks (e.g. reduced value of real estate). To ensure accurate economic assessments, analysts must carefully attribute benefits and use methodologies such as cost-benefit analysis or counterfactual scenarios to prevent inflating the estimated economic gains.

As an example of studies concerning long-term benefits, an earlier WISER study (2020) explored the benefits derived from investments in EWS in Tanzania. The study focused on coastal fishing communities which account for 35 % of rural employment. The study found that the human casualties and deaths due to extreme weather have decreased along the coast and that fishermen's and seaweed farmers' ability to plan their economic activities improved, with some experiencing a rise in income. Theoretically, this means that lower levels of disaster risk should also encourage people to make investments. However, lower levels of risk from better preparedness do not appear to have encouraged higher levels of saving and investment because of other limiting factors – fishermen are poor with little capacity to save and have no access to microfinancing. However, it was perceived that improving EWS increased community engagement and improved local governance, which corresponds to the third dividend.

Looking more specifically at the three pilot countries the study by Adu-Ababio et al. (2024) shows for Zambia that extreme weather events not only – mostly temporarily – reduce output of small and medium sized companies but also reduce tax revenues. The latter effect in turn translates into less public investment, and hence less growth. On the other hand, Bibri (2019) discusses the economic growth effects of (open) data-driven service expansion in (smart) cities. This is to some extent also relevant for weather services, but for Zambia and Mozambique smart city like spin-offs have probably only some relevance for the capitals. All in all, we may conclude that induced macro-economic effects are likely to occur, but it would require a very significant research effort to come up with a credible estimate of the effect in the pilot countries.

4 Overall Economic Value of EWS in Southern Africa

Investments in meteorological and early warning services enable substantial benefits, notably with regard to reduced damages from droughts, floods, and various types of storms. According to the World Bank (2021) investments in strengthening meteorological, hydrological and associated early warning services tend to generate US\$7 to US\$12 for every US\$1 invested, meaning a cost-benefit ratio of 1:7 to 1:12. The same report estimated the net present value of EWS in southern Africa at about 2.4 billion US\$ for a 25-year period (employing a 7 % discount rate). However, this seems an underestimation considering, for example the reduced damage from tropical cyclones in the past five years in the area. The Global Commission on Adaptation (GCA) also assessed the economic value of enhancing EWS, concluding on a cost-benefit ratio of 1:9. The GCA also reports that providing just 24 hours' notice of an impending storm or heatwave can reduce potential damage by 30 %, and a US\$ 800 million investment in such systems in developing countries could prevent annual losses of US\$ 3 billion–US\$ 16 billion (GCA, 2019).

At a regional level, Rodrigues et al. (2016) modelled economy-wide impacts of national seasonal forecast systems in Kenya, Malawi, Mozambique, Tanzania, and Zambia. The study estimated that *perfect information adopted by all farmers* would generate regional GDP gains averaging \$113 million USD per year (\$3 USD per hectare) relative to a baseline situation without forecasts. The estimated benefits in that study are higher for poorer households as they are more likely to be engaged in farming. Similarly, in the HIGHWAY project, an initiative for a regional early warning system for the Lake Victoria Basin in Uganda, significantly improved weather data utilisation and lake navigation forecasts. The enhanced trust in forecasts through collaborative production and communication fostered safer travel and better livelihood protection across the region, evidenced by an estimated 30 % reduction in drowning fatalities on the lake and, when combined with the reduction in other weather-related losses, generates estimated socioeconomic benefits of \$44 million per year. (Roberts et al., 2022).

Another recent example of the substantial benefit potential of early warning services is the comparison of the damages of two similar cyclones in Mozambique occurring in 2019 and 2023. In March 2019, *Cyclone Idai* landed in central Mozambique leading to catastrophic flooding and widespread devastation. Over 600 lives were lost, and the economic toll was staggering, with damages estimated at US\$ 3 billion. Schools, roads, bridges, energy assets and water treatment facilities were decimated, underscoring the devastating impact of natural hazards. (Mozambique Humanitarian Response Plan, 2019). After *Cyclone Idai*, the Government of Mozambique (supported by the UN and the World Bank's Disaster Risk Management and Resilience Program) began producing meteorological warnings, and disseminating them through community radio stations and trained brigades, guiding communities at risk to safety ahead of extreme weather. Fast forward to 2023, *Cyclone Freddy* shook central Mozambique not once, but twice, with very high wind speeds. Compared to *Idai*, the devastation was remarkably reduced thanks to the new EWS. Communities were prepared and had been relocated ahead of the event to safe areas with sufficient supplies of food and water resulting in much lower casualties and damages; 198 lives were lost, and economic damages were estimated at US\$ 500 million (83 % reduction compared to the *Cyclone Idai*) (WMO, 2024b). This substantial decrease in both human and economic losses highlights the effectiveness of the EWS. While the immediate benefits are impressive, they only scratch the surface of the long-term advantages that EWS and climate services can provide.

Another study by Lazo et al. (2015) assessed the willingness to pay (WTP) both for current (i.e. 2015) weather service levels and for improved levels in Mozambique. At the aggregate national level, the 2015 value of weather services for citizens was estimated at 37 million US\$. The estimate for *the incremental value*, based on a weighted average of improvement levels, varies between 5 million US\$ and 66 million US\$, counting over a 15-year period while applying a 3 % discount rate (Lazo presents results for a 50-year period, but in this case, a 15-year period is used).

Other studies have also researched farmers willingness to pay (see Amegnaglo et al., 2017; Zongo et al., 2016; Ouedraogo et al., 2015; Rao et al., 2015; Makaudze, 2014) for weather & climate services information or services in the future, and thus the benefit farmers would expect to receive from the use of such services. Estimates of farmer’s willingness to pay over one year for improved seasonal forecasts in various African countries (Burkina Faso, Benin, Kenya and Zimbabwe) ranged from US\$1.19 to US\$15.36 (adjusted to 2017 USD rates), for i(Vaughan et al., 2019). In Zimbabwe, a neighbouring country to Zambia and Mozambique, farmers stated their willingness to pay US\$ 5.69 annually (Makaudze, 2014). For comparison the order of magnitude of monthly income in rural areas of Zambia, Zimbabwe and Mozambique in recent years is US\$ 80 to US\$ 200.

A World Bank (2018) study on improvements in weather and hydrological forecasting and warning services for Lao People’s Democratic Republic in 2018 provides indications of the expected benefits of improved early warnings, weather forecasts and seasonal forecasts. Using a benefit transfer method utilising a Vietnamese study, while accounting for Lao’s income levels, results in expected benefits for the Lao household population between about 3.7 and 6.2 million US\$ per year. There are approximately 900 000 households in Lao. Just correcting for population size would mean that for Zambia the benefits have to be multiplied by approx. 4 (~14 – 24 million \$), for Mozambique by approx. 7 (~26 – 43 million \$), and for South Africa by approx. 19 (~70 – 118 million \$). Income corrections would further raise these outcomes, but limitations in uptake and response would reduce them (the results for Lao implicitly assume 100 % coverage of the population).

Using a benefit transfer method to estimate values associated with weather services in developing countries, Hallegatte (2012) estimated the potential benefits of providing early warning systems in developing countries based on a study of benefits for similar services in Europe. Taking into account differences in population, increasing risk due to climate change, as well as increased exposure to weather due to the state of infrastructure, Hallegatte (2012) estimated that upgrading early warning capacity in all developing countries would result in between \$300 million and \$2 billion per year of avoided asset losses due to natural disasters. In addition, EWS would save an average of 23 000 lives per year (valued between \$700 million and \$3.5 billion per year using the Copenhagen Consensus guidelines) and would add between \$3 and \$30 billion per year in additional economic benefits.

Hallegatte, Bangalore & Jouanjean (2016) also assessed benefits for various economic sectors regarding avoided losses. A significant part of these avoided losses is attributable to improvements in other components of the NHMS service portfolio. However, to some extent, these benefits are also attributable to early warning services. The partial contribution of that service component is however not specified. The overall benefit of avoided losses for economic sectors was estimated at about 22 million US\$ per year. Assuming a cautious 10 % contribution of early warnings to these avoided losses would mean another 2.2 million US\$ annual benefits attributable to the EWS. (Hallegatte, Bangalore & Jouanjean, 2016). Further sectoral studies in the pilot countries would require significant research effort and credible data. The best example of this kind of sectoral study in Africa is a study by Hansen et al. (2009) which estimated economic benefits of US\$17.7 – US\$41.9 per hectare for farmers in Southern Kenya with the use of global circulation model-based seasonal precipitation forecasts for maize planting and fertiliser management.

Research on the benefits of early warnings still has gaps, and more knowledge could contribute to a more effective implementation of EWS in national and sectoral use. It’s evident that EWS reduces losses in the event of a disaster. However, investments in disaster preparedness can also contribute to economic growth and stability by changing investment strategies and perhaps even increasing the value of investments that come from the increased resilience – and these benefits occur even before a disaster strikes. Providing evidence of both short and long-term benefits to policymakers and investors can help align short and long-term objectives, thereby improving the acceptability and feasibility of disaster preparedness investments.

5 Discussion

The overall picture is that extensions and improvements of weather services in Sub-Saharan Africa produce very significant benefits, which may be expected to surpass the costs of provision many times. Since this prospect seems to apply by and large globally one may even wonder to what extent ex-ante economic assessments of new or improved services are actually useful. Instead, the analytical underpinning of the investment could be reoriented towards *ensuring good quality* of the services throughout the value chain. In turn, this suggests that value chain based *ex-post* evaluations could be more useful alongside occasional focused ex-ante evaluations.

In the preceding chapters, the review focused on socioeconomic valuation of effects, with a fairly strong emphasis on monetised indicators. It should be realised that modern social cost-benefit analysis tends to value effects in terms of eventual *welfare effects*, including physical and mental health as well as environmental effects represented by changes in ecosystem services. Furthermore, in the case of evaluation of public investments, it may be desired to also use non-monetary indicators, such as changes in healthy life years and homelessness. In other words, the eventual judgement of the societal benefits of a public investment can be based on a broader scope set of indicators. The scope has to be decided by the decision makers commissioning the evaluation. More discussion on monetised and non-monetised indicators in relation to early warning systems can be found in Ebert et al. (2024).

As the preceding chapters focused on presenting an overview of the order of magnitude of benefits uncertainties were not so much discussed. It goes without saying that the effectiveness of nowcasting and warning varies from event to event. Therefore, performance indicators typically refer to annual averages. As far as benefit estimates are based on evidenced avoided losses for a series of occurred events, one should realise that sometimes a few events may dominate the results, and may thereby deviate from a long-term (unknown) average. Furthermore, natural hazard-related damage statistics tend to focus on large scale evident direct damage, such as flooded homes, ripped-off roofs, etc. Increases in traffic accidents and localised harvest losses will often only partly be captured by such statistics. Similarly, a part of the health effects of natural hazards may well remain uncaptured by hazard damage statistics. There are also attribution challenges with respect to valuating warning services. Changes in avoided damage may also be attributable to improved preparedness and reduced (physical) vulnerability, alongside improvement in warning services and emergency management. All in all, the impression prevails that benefit potential assessments tend to underestimate rather than overestimate the net potential.

One way to account for these uncertainties regarding potential and achievable benefits is the use of rather high benefit-cost ratios (BCR), i.e. demanding BCRs of 5 or higher. Another reason for applying high(er) BCRs is the strong competition across different public investment needs, such as for health care, education, sanitation, and transport infrastructure. Another aspect, which is scarcely discussed in the literature on valuation of weather services, is the complementarity with other – often public – facilities, such as flood risk and stormwater management, as well as the de-facto access to and confidence in communication channels. Highly accurate short-term forecasts, nowcasts and warnings are to no avail, if these complementary facilities are weak.

Climate change accelerating various types of adverse weather underscores the importance of preparedness and predictability in daily life. It may also mean that weather hazards that were hitherto regarded as less relevant in a certain area may demonstrate a growing damage potential. This also underscores the relation between short-term preparedness, at which EWS aims in the first place, and long-term preparedness, which should also account for the effects of climate change. However, the lessons we learn from responses to early warnings and the apparent effectiveness of short-term preparedness are important inputs for developing long-term preparedness. Without long-term resources and capacity development for the operations and

maintenance of EWS and other climate services, the potential benefits of EWS will not be delivered, resulting in wasted investment. Thus, enhancing climate policies and incorporating climate adaptation into national development strategies are crucial for building long-term resilience.

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