A framework for comparing permanent and forecast-based flood risk-reduction strategies

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A framework for comparing permanent and forecast-based flood risk-reduction strategies

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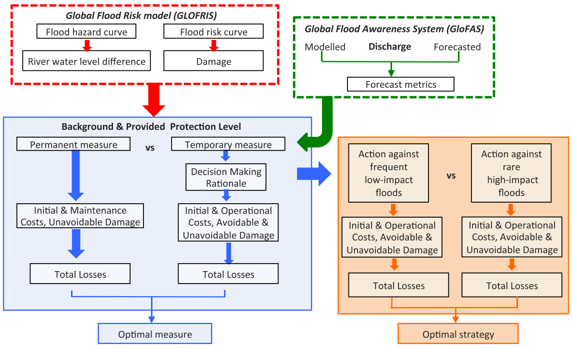
HIGHLIGHTS

- Advances in flood forecasting have enhanced the role of temporary risk reduction measures.
- Forecast-based measures against floods can be used to as an alternative to permanent measures.
- A mixture of permanent and temporary measures can be the most cost-effective flood risk strategy.
- Action against low-impact floods can be worthier than action against high-impact floods.
- Forecast skill plays a major role in the determination of optimal flood risk strategies.

GRAPHICAL ABSTRACT



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ABSTRACT

Flood risk can be reduced at various stages of the disaster management cycle. Traditionally, permanent infrastructure is used for flood prevention, while residual risk is managed with emergency measures that are triggered by forecasts. Advances in flood forecasting hold promise for a more prominent role to forecast-based measures. In this study, we present a methodology that compares permanent with forecast-based flood-prevention measures. On the basis of this methodology, we demonstrate how operational decision-makers can select between acting against frequent low-impact, and rare high-impact events. Through a hypothetical example, we describe a number of decision scenarios using flood risk indicators for Chikwawa, Malawi, and modelled and forecasted discharge data from 1997 to 2018. The results indicate that the choice between permanent and temporary measures is affected by the cost of measures, climatological flood risk, and forecast ability to produce accurate flood warnings. Temporary measures are likely to be more cost-effective than permanent measures when the probability of flooding is low. Furthermore, a combination of the two types of measures can be the most cost-effective solution, particularly when the forecast is more skillful in capturing low-frequency events. Finally, we show that action against frequent low-impact events could more cost-effective than action against rare high-impact ones. We conclude that forecast-based measures could be used as an alternative to some of the permanent measures rather than being used only to cover the residual risk, and thus, should be taken into consideration when identifying the optimal flood risk strategy.

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1. Introduction

Humanity is exposed to various types of hazards that cause thousands of deaths and significant economic damage every year (UNISDR and CRED, 2017). Changes in climate and in environmental, socio-economic and cultural factors further increase flood risk (Milly et al., 2002; Jongman et al., 2012), which is a function of the severity and the occurrence probability of floods, the exposed assets and people, and their intrinsic vulnerability or coping capacity (Kron, 2005; Klijn et al., 2015; Vogt et al., 2018). This increase requires continuous adaptation and effective flood risk management strategies.

Flood risk-reduction actions can be taken at any point in the disaster management process. Traditionally, flood prevention is one of the most common ways. This usually involves permanent solutions, such as structural engineering works (e.g. dikes) and nature-based measures (e.g. restoration of rivers to their natural courses) that provide protection against flooding up to a predefined level. This protection level depends largely on the socio-economic conditions of the country but also to come extent on the risk management policies in place. Countries with the financial capacity and political will to invest in large-scale infrastructure may define their flood risk standards based on a cost-benefit analysis, where the costs of flood protection (e.g. dike construction or reinforcement) and the expected damage are minimized (van Dantzig, 1956; Van Dantzig and Kriens, 1960; Kind, 2012). This is the case in the Netherlands, for example. Other countries do not explicitly take potential socio-economic damage into consideration, and consequently the adopted safety levels are based on the risk policy employed in combination with the economic situation of the country (Angignard et al., 2014; Kampen, 2017). For instance, the United States has kept its flood protection standards unchanged to meet 100-year return levels since the 1960s, despite arguments for revising these standards (NAKC, 2004; Holmes and Dinicola, 2010). Low-income countries with limited resources, such as Malawi, employ little or no long-term flood risk-reduction strategy (Scussolini et al., 2016). For these countries the selection and implementation of effective risk-reduction strategies is particularly challenging, but still no less important (Petry, 2002; Tariq, 2011).

Even when long-term risk-reduction measures are in place, a residual flood risk remains. This risk can be managed with the use of Early Warning Early Action Systems (EWEAS), which translate flood forecasts into flood risk-reduction actions. The contribution of EWEAS to building societal resilience has been widely acknowledged (Golnaraghi, 2012) and they have become an important element of flood risk management (Kellett and Caravani, 2013). The forecast-based measures of the EWEAS can temporarily reduce flood probability and impact (Mens et al., 2008; Rogers and Tsirkunov, 2011; Verkade and Werner, 2011). Examples include the use of flood walls or sandbags to augment dike height (active measures reducing flood probability) (Prenger-Berninghoff et al., 2014), and the reallocation of goods, humanitarian response and evacuation (passive measures reducing flood impact) (Holub and Hübl, 2008). Each category includes actions that can be triggered by forecasts at one or at successive stages; For example, sandbags may be prepared and people may be trained to place them quickly and effectively when it is forecasted that precipitation will be above 'normal' in the upcoming season and then people may be mobilized to position the sandbags when a flood is forecasted to happen in a few days (Bazo et al., 2018; Bischiniotis et al., 2019a). In both cases, the EWEAS are called for as long as their benefits are higher than their operating costs (Rogers and Tsirkunov, 2011; Carsell et al., 2004). Nevertheless, operational decision-makers are often requested to choose for which type of event forecast-based action will be triggered due to the limited financial resources. For instance, the Early Action Protocols of the Forecast-based financing project by the Red Cross (Coughlan De Perez et al., 2015), mandate to trigger humanitarian action when the forecast issues a warning for a flood of a predefined probability of occurrence, disregarding floods of lower probabilities of occurrence.

However, steady improvements in the skill of hydro-meteorological forecasting during recent decades have resulted in longer time spans (Bauer et al., 2015) for implementing forecast-based risk-reduction measures. This in combination with the continuous updates in temporary flood protection measures can enhance the role of EWEAS, which in turn may be available not only to cover residual risk, but also as an alternative to permanent measures. On the one hand, permanent measures have the advantage of providing continuous protection against floods up to a given return level, but this usually comes with a large investment of money and an infrastructure that must be maintained at all times, also when no flood risk is imminent. Conversely, forecast-based measures are generally less expensive and do not require a permanent infrastructure, instead relying largely on the quality of the forecasts that trigger their installation. A systematic exploration of the trade-offs between permanent and forecast-based protection is necessary in order to optimize risk reduction. It may indeed be possible that small adjustments in this trade-off lead to different conclusions on the optimal combination of permanent and forecast-based measures. In addition, the focus of EWEAS on protecting primarily against extreme, high-impact floods may overlook the possible benefits of a system that triggers temporary measures against flood events with smaller impact but higher frequency.

In this paper, we present a methodology that compares permanent and temporary flood-prevention measures in terms of total financial losses, taking into account forecast quality, climatological flood risk and the cost of measures. To evaluate how these two types of measures would have performed, we use time series of forecasted and modelled discharges from 1997 to 2018. Our case study addresses Chikwawa, Malawi, a flood-prone, insufficiently protected district that has so far relied primarily on post-disaster relief, but is currently trying to shift towards permanent and temporary flood risk mitigation strategies such as dike construction (World bank, 2018) and the operation of EWEAS (Osborne et al., 2008; Šakić Trogrlić et al., 2017).

The following section presents the conceptual design and data used for this study, and the results are presented in Section 3. Section 4 discusses the findings and limitations of the study, including suggestions for further research. Section 5 provides a brief conclusion.

2. Data and study design

We use a fictitious example to retroactively describe a number of decision scenarios with regard to permanent and temporary measures. In its conceptual foundations, this example aims to provide new insights that will contribute to an expansion of the existing theories rather than a generalisation of findings.

The starting point is 1997, when a decision had to be made on how to manage flood risk in an area over the coming decades. The existing infrastructure protected against floods of an x-year return period. Permanent protection infrastructure and temporary measures triggered by forecasts could improve the protection level to a y-year return period (x and y are defined in Section 2.6). With the knowledge of the forecasts and hindsight that we now have, we can evaluate which choice, temporary or permanent measures, would have led to lower total financial losses, and analyse why this is the case. On this basis, we can also examine a scenario where only temporary measures were available, comparing a strategy of taking action against frequent, low-impact events (return periods from x to y_1) or against rare, high-impact events (return periods from y_1 to y) in terms of total financial losses.

The methodological framework used in this investigation is illustrated in Fig. 1. We use flood risk indicators from the Global Flood Risk (GLOFRIS) model (Winsemius et al., 2016) for a case study area in Chikwawa. We use modelled discharge, considered as a pseudo-observation, and forecasted discharge time series for a historical period (1997–2018) from the GloFAS model (Alfieri et al., 2013) to evaluate

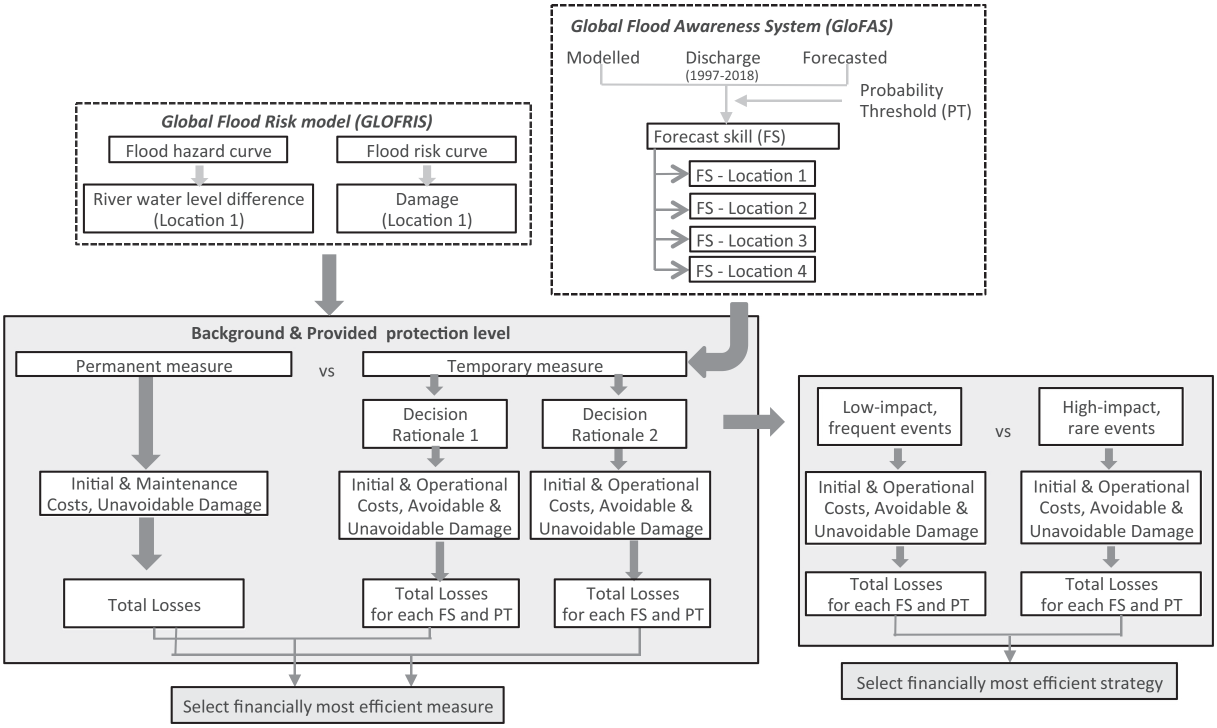

Fig. 1. Overview of the methodology applied in this paper.

forecast skill in predicting flood events at I) a river point located in the case study area and II) at three river points of rivers outside the case study area, aiming to evaluate the adaptability of the decision system to different hydrological conditions and forecasts. The temporary measure is triggered when the forecast provides a flood signal with a predefined probability threshold. Our analysis includes two probability thresholds and two decision-making rationales, which make use of different forecast information to trigger action. Using different background (existing) and provided protection levels, we compare the total losses when applying permanent and temporary measures for each decision rationale. Finally, we compare the total losses when temporary action is taken against I) frequent low-impact and II) rare high-impact events.

2.1. Case study area

Malawi is a low-income country that faces recurrent flood events, which constitute approximately 75% of the country's total average annual loss from disasters. Chikwawa district is located at the Lower Shire Valley (see Fig. 2, left side) and has a sub-tropical climate with strong seasonality and an annual mean rainfall between 800 and 1200 mm,[1], most of which (95%) occurs in the wet season from November to April. Heavy precipitation often causes rivers to overflow their banks. This leads to house destruction and fatalities, as observed in the recent 2018 and 2019 floods. In this study, we explore a defense strategy for the east bank of the Shire River between Chobo and Jeke village (see Fig. 2, right side), which has experienced several flood events in the past years.

2.2. River water level and flood damage

According to the FLOPROS dataset (Scussolini et al., 2016), the current flood protection level of the case study area corresponds to a 2-year return period (T). Based on the GLOFRIS model (Winsemius et al., 2016), the water level of the Shire River (calculated from its bottom) for this return period is 1.26 m, whereas for a 5- and 20-year return period, the water levels are 1.5 m and 1.8 m, respectively (see Fig. 3a). This model also provides high-resolution damage estimations using inundation maps combined with a map of asset values and a depth-damage function to represent vulnerability. The area is protected against a 2-year flood (i.e. no damage), whereas the damage from 5- and 20-year return period floods is USD 9.3 million and USD 14.5 million respectively (see Fig. 3b). The flood maps of the 20-year return period can be found in the Supplementary material (Fig. A.1).

2.3. Forecast model

We employed forecast runs from the Global Flood Awareness System (GloFAS) (Alfieri et al., 2013). GloFAS is used operationally to provide flood early warnings to humanitarian organizations such as the Red Cross (Coughland de Perez et al., 2016). Forecasts were generated twice weekly with 11 ensemble members for the period 1997–2016 and with 51 ensemble members from January 2017 to June 2018. For the remainder of 2018 GloFAS forecasts were generated daily with 51 members. GloFAS uses ensemble forecasts from the European Centre of Medium-Range Weather Forecasts (ECMWF) with a 30-day forecast horizon. A climatology of daily discharge over the entire GloFAS river network is produced by deterministic hydrological simulations driven by meteorological forcing data from ERA5, ECMWF's latest global atmospheric reanalysis for the 1981–2017 period (Dee et al., 2011). The climatology includes a set of maps for the 2-, 5- and 20-year return levels, which are compared with GloFAS real-time forecasts to generate flood alerts. For further details about GloFAS, see Alfieri et al. (2013) and www.globalfloods.eu.

Our work compares forecasted discharge with discharge produced by the model, considered as pseudo-observations. Given that modelled discharge can differ significantly from real one, the so-called 'theoretical skill' is computed (Alfieri et al., 2014; Bischiniotis et al., 2019b). Forecast probabilities are based on the fraction of the ensemble members that exceed a predefined discharge threshold. For example, if 1 or 3 out of 11 members exceed this threshold, its probability of exceedance is 9% or 27% respectively.

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[1] DCCMS: http://www.metmalawi.com/climate/climate.php.

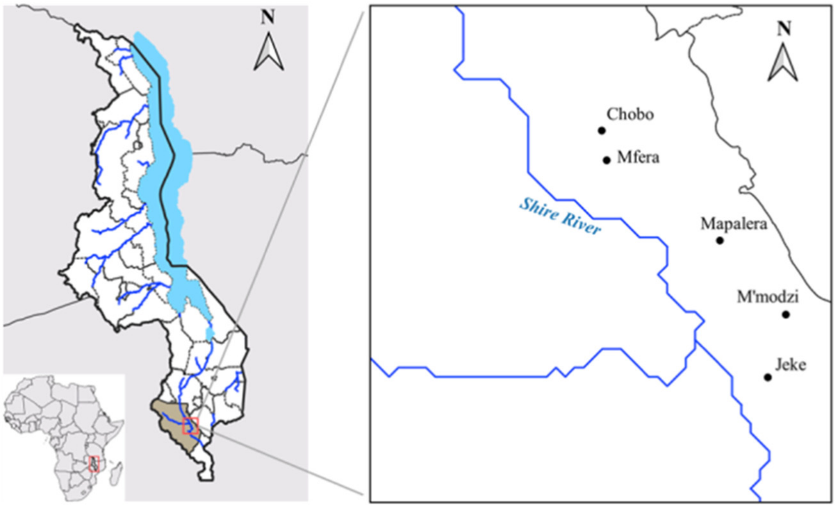

Fig. 2. Map of Malawi, where Chikwawa district is coloured in grey (left). The case study area is located on the east bank of the Shire River and includes the villages from Chobo to Jeke (right).

For the purposes of this study, we consider that when the forecasted discharge at a lead time of 7 days exceeds a given flood threshold (i.e. discharge of a predefined return period), with a predefined probability, a flood warning is issued and temporary actions are automatically triggered. The model is evaluated at a river point of the Shire River that is located in our case study area (Fig. 4, Location 1) at three river points of major rivers of Malawi that are not in the study area, aiming to explore the sensitivity of the results to different forecasted and modelled discharge time series (see Fig. 4: Location 2: Lilongwe River (Fig. 4, Location 2), Location 3: Ruo River, Location 4: Bua River. The evaluation of the model is described in Section 2.4.2.

2.4. Flood risk-reduction measures

There is wide range of public and private flood risk-reduction measures, with various cost, effectiveness and time characteristics, that can be applied before a flood occurs (Homberg and McQuistan, 2019). Permanent measures, such as dikes, dams and pumping stations, are the ones most frequently used for flood prevention.

Conversely, temporary measures are used either to reduce flood consequences (e.g. evacuation), or to reduce the flood hazard probability by increasing the protection levels for a limited period of time (e.g. constructing a temporary dike, strengthening the existing dike with sandbags, or clearing drainage channels). Of the many options that are available, we use dikes and a portable barrier, called muscle wall as examples of permanent and temporary measures, respectively. The dike and the muscle wall are comparable since they both a) reduce hazard occurrence probability by being constructed/placed on the ground (or on an existing dike crest to increase its height), and b) withstand the water level corresponding to a 20-year flood in the case study area (see Section 2.6). In our example, both dike and muscle wall are modelled along the Shire River for a total length L of 16 km (see Fig. 5).

2.4.1. Total losses of permanent measures

Permanent flood-prevention measures are designed on the basis of statistics for extreme events. They have predesignated lifetimes, and hence are often referred to as 'long-term' measures. Their total cost for their lifetime consists of initial construction investments and yearly maintenance expenditures. They provide protection up to a defined safety level, here dictated by a given discharge return time. In our example, we consider that if the modelled discharge is higher, a flood occurs. We refer to the damage provoked by the floods with a return period higher than the one of the safety level as 'unavoidable damage'. Hence, the total losses of permanent measures (TL_p) result from the aggregation of implementation and maintenance costs and the unavoidable damage over the entire lifetime period:

$$TL_P = C_p + \Sigma D_u \tag{1}$$

where C_p denotes the costs (i.e. initial investment and sum of annual maintenance costs), and ΣD_u is the sum of unavoidable damage that corresponds to floods with a return period higher than the safety level.

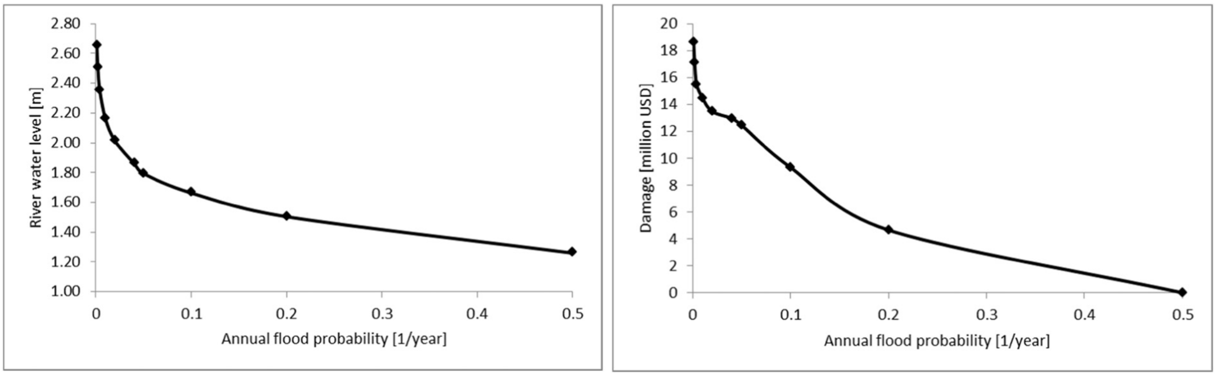

Fig. 3. Annual flood probability (1/T) for the river point in the case study area in relation to the corresponding river water level [m] (left), and flood damage [million USD] (right) based on GLOFRIS dataset.

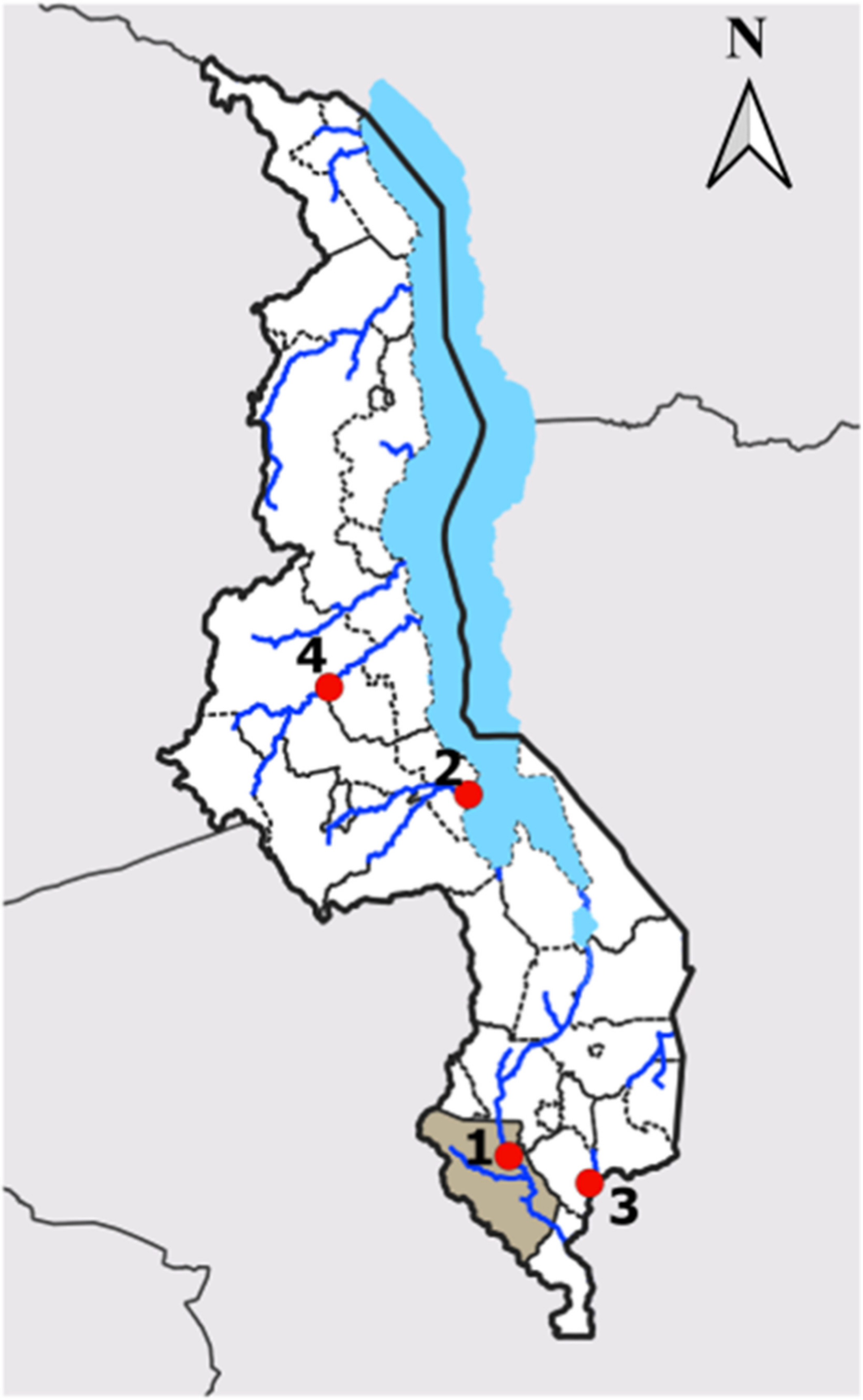

Fig. 4. GloFAS evaluation points (red circles): (Location 1) Shire River (16.03 S, 34.79 E) (case study area); (Location 2) Lilongwe River (13.75 S, 34.55 E); (Location 3) Ruo River (16.20 S, 35.25 E); (Location 4) Bua River (13.25 S, 33.75 E).

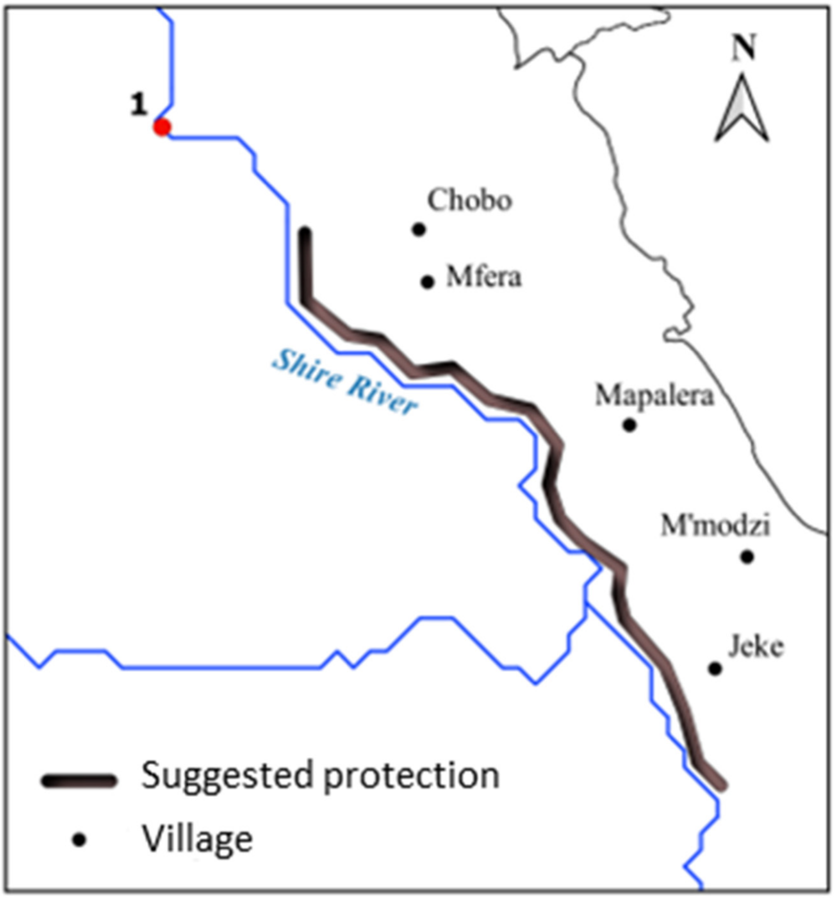

Fig. 5. Layout of the protection infrastructure. The black line shows the barrier (dike or muscle wall) along the Shire River that protects the case study area. Black dots show the villages within the case study area. The red dot shows the location where the GloFAS time series were evaluated.

Little published research exists regarding the costs of river dikes, particularly in low-income countries. The construction cost of a height increase of 1 m was estimated at 19.3–27.2 million USD/km in the Netherlands (Jonkman et al., 2013) and at 2.3 million USD/km in Vietnam for sea dikes (Danh and Khai, 2014). Aerts et al. (2018) estimated annual maintenance costs to be between 0.01% and 1% of the initial investment. The dike lifetime can vary from 10 to 50 years (Aerts et al., 2013; De Rocquigny, 2012). River dikes are generally less expensive than sea dikes and their investment costs are between 12.1 and 19.2 million USD/km per meter of height increase in high-income countries such as the US and the Netherlands (Dijkman, 2007; Smith et al., 2017). The costs of dikes in Vietnam are more representative of low-income countries. Therefore, assuming that construction costs for sea dikes in low-income countries are 10% of those in high-income countries (Jonkman et al., 2013), we set the construction costs of a river dike in Malawi to 1.6 million USD/km per meter of height increase, which is 10% of the mean value of the construction costs of river dikes in high-income countries (Dijkman, 2007; Smith et al., 2017). The lifetime of the dike is considered to be 25 years and its yearly maintenance costs amount to 1% of the initial investment. In our approach, costs are linearly proportional to dike height increase (e.g. Lenk et al., 2017; Bischiniotis et al., 2018). Dike height increases are based on water levels for the target return periods (Section 2.6 and Table 2). Here we assume that a discharge of a specific return period derived from GloFAS is translated into a river water level of the same return period. Finally, for an objective comparison with temporary measures, we scaled the costs of permanent measures to our study period, for which discharge-forecast time series are available (22 years).

2.4.2. Total losses of temporary measures

As with permanent measures, temporary measures have initial costs (e.g. purchase of necessary material, installation of the forecast system), but also costs associated with their implementation. The latter are dependent on the number of times an action is triggered. Flood damage depends on whether the measures reduce flood risk effectively (i.e. a flood warning is issued and appropriate risk mitigation actions are carried out in a timely manner). Hence, the calculation of the total losses of temporary measures requires the evaluation of the forecast model in terms of event-based metrics, which show the match between the forecasted and observed floods, as presented in contingency Table 1. T_1 is the return period that corresponds to the protection level in the current system (the "background" protection level), T_2 is a return period that corresponds to the provided protection level by implementing a temporary measure on top of the background protection level, and T is the forecasted/observed return period. When $T_1 < T < T_2$ a flood of Category 1 is forecasted observed and when $T < T_2$ a flood of Category 2 is forecasted/observed.

Table 2 shows the costs and damage accrued for different levels of forecast accuracy that the decision-maker uses to issue the flood warning that triggers action. For this, we use two different 'decision rationales' (DRs) in the evaluation. When DR_1 is followed, the temporary measure is employed, when a forecast is above the flood threshold (T_1). However, it could be that forecasted flood not only exceeds T_1, but also the threshold up to which the temporary measures provide protection (T_2) (i.e. Category 2 flood). Hence, the outcome of this case may be: I) no flood (implying that action was taken in vain), II) a flood between x and y (implying that action was correctly taken and

Table 1

Contingency table. CN = Correct Negative; FA_1 and FA_2 = false alarms of Category 1 and 2 flood; MS_1 and MS_2 = miss of Category 1 and 2 flood; CH_1 and CH_2 = correct hit of Category 1 and 2 flood; $CHMS_1$ and $CHMS_2$ = correct forecast of flood happening but wrong flood category.

	Background protection level $T_1 = x$ [years]	Forecast		
		$T < T_1$	$T_1 < T < T_2$ (warning for Category 1)	$T > T_2$ (warning for Category 2)
Observation	$T < T_1$	CN (correct no flood signal)	FA_1 (false alarm)	FA_2 (false alarm)
	$T_1 < T < T_2$ (Category 1 event)	MS_1 (flood missed)	CH_1 (Correct flood signal, category correctly forecasted)	$CHMS_1$ (Correct flood signal, category over-forecasted)
	$T > T_2$ (Category 2 event)	MS_2 (flood missed)	$CHMS_2$ (Correct flood signal, category under-forecasted)	CH_2 (Correct flood signal, category correctly forecasted)

potential damage was avoided), and III) a flood exceeding the y-year return level (implying that the action was taken but it could not provide adequate protection).

When DR_2 is followed, the temporary measure is only employed if the forecast is between T_1 and T_2 (i.e. Category 1 flood). In this case the outcome may be: a) no flood (implying that action was taken in vain), b) a flood between x and y (implying that action was correctly taken and potential damage was avoided), and c) a flood exceeding the y-year return level (implying that the action was properly declined since damage could not be avoided even if action had been triggered).

In our numerical example, event-based metrics are calculated by comparing the forecast at a lead time of 7 days to the modelled discharge at lead time 0. If the modelled discharge did not exceed the flood threshold during a year, this was considered as one no-flood event. A flood warning was issued and temporary actions were automatically triggered when the discharge was forecasted to exceed the threshold discharge with a certain probability. To explore the sensitivity in this we carry out the analysis using two probabilities: I) at least 9% and II) at least 27% was required to issue a flood warning (see Section 2.3). If the modelled discharge exceeded the flood threshold more than one time in a period of 60 days, it was counted as a single event, assuming that if action was triggered it would protect against the flood for its entire duration. Therefore, forecasted discharge is evaluated against the first modelled discharge that exceeded the flood threshold.

Hence, the total losses of the temporary measures include the initial costs I_T, the operational costs for temporary measures C_T multiplied by the number of times that they are triggered, the avoidable damage D multiplied by the number of times that a Category 1 flood occurs but action is not taken and the unavoidable damage D_U multiplied by the number of times a Category 2 occurs. The total losses for DR_1 and DR_2 are calculated by the following equations:

$$DR_1 : TL_T = I_T + CN \cdot 0 + (FA_1 + FA_2 + CH_1 + CHMS_1) \cdot C_T + MS_2 \cdot D_u + (CHMS_2 + CH_2) \cdot (C_T + D_u) \quad (2)$$

$$DR_2 : TL_T = I_T + (CN + FA_2) \cdot 0 + (FA_1 + CH_1) \cdot C_T + (CHMS_2 + MS_1) \cdot D + (MS_2 + CH_2) \cdot D_u + (CHMS_2) \cdot (C_T + D_u) \quad (3)$$

Table 3 shows the avoidable damage and the initial muscle wall costs I_T, which are derived from its commercial catalogue,[2] for the protection levels examined (see Section 2.6). We define the avoidable damage as the mean damage of the protection levels in question. This is calculated using Fig. 3b. The operational costs C_T are assumed to be 10% of the initial costs for each trigger.

2.5. Temporary measures against frequent low-impact and against rare high-impact events

Given the limited financial resources, temporary measures are often triggered only against high-impact events. For instance, humanitarian action of the Forecast-based financing project in Zambia is triggered only against events with a return period exceeding five years.[3] Although lower return period events have less severe impacts, they are more frequent and hence may lead to higher cumulative losses. For this reason, we compare the total losses of temporary measures when these are applied either against frequent low-impact (LF) (Category 1) or rare high-impact (HR) (Category 2) flood events. Again, to demonstrate our concept we use the muscle wall as our example of temporary actions, assuming that its use against events of a given category does not provide any protection against the events of the other category. In the real world various different measures might be taken, such as the placement of sandbags for flood categories that are not life threatening, and evacuation for higher inundation levels. For the comparison of measures against frequent, low-impact events and against rare high-impact events, we use DR_2, since the measures (in our case the height of the muscle wall) are directly linked to the flood category forecasted.

2.6. Background and provided protection levels

For objective comparison, we assume that permanent and temporary measures increase the protection level to the same extent. The combination of the background and newly provided protection level affects the flood occurrence probability, the costs of the measures taken, and the forecast accuracy required to trigger action. For instance, the higher the background protection level, the lower the flooding probability and the lower the likelihood that temporary measures will be triggered. In addition, the higher the provided protection level, the larger the cost difference between permanent and temporary measures (see Table 3). Finally, the smaller the difference between the background and provided protection level, the higher the forecast accuracy needed in order to trigger action (see DR_2 in Section 2.4.2).

To explore these sensitivities, we use: a) two provided protection levels (5-year and 20-year return period) on top of a background protection level same to the one of our case study area (2-year return period); b) a higher background protection level (5-year return period) in combination with a provided protection level that raises the protection to a 20-year return period (see Fig. 6).

In all cases, the total losses of increasing the background protection level with the dike (TL_P) are compared with the total losses by deploying the muscle wall (TL_T). For the case of a 2-year background level and 20-year provided protection, the total losses when using the

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[2] The commercial catalogue for the muscle wall can be found in this link: (https://indd.adobe.com/view/6e171f6c-c6b8-4fa4-98b0-990508c24e38).

[3] Practical information on Forecast-based Action: https://media.ifrc.org/ifrc/wp-content/uploads/sites/5/2019/03/0097_19_003_Broschuere_National-Society_210x297_EN.pdf.

Table 2

Cost and Damage for DR_1 (action against a Category 1 flood is triggered as soon as a flood higher than the current protection level is forecasted) and for DR_2 (action against a Category 1 flood is triggered only if a Category 1 flood is forecasted) for each pair of forecast/observation. C_T is the operational costs of temporary measures, D is the damage that is avoided if action is correctly triggered, and D_u is the damage that is unavoidable because it corresponds to higher return periods than those for which measures (permanent or temporary) can provide protection.

Background Protection level $T_1 = x$ [years]		Forecast		
		$T < T_1$	$T_1 < T < T_2$ (warning for Category 1)	$T > T_2$ (warning for Category 2)
DR_1 (Take action if a flood warning is issued {i.e. $T > T_1$})				
Observation	$T < T_1$	0	C_T	C_T
	$T_1 < T < T_2$ (Category 1 event)	D	C_T	C_T
	$T > T_2$ (Category 2 event)	D_u	$C_T + D_u$	$C_T + D_u$
DR_2 (Take action if a Category 1 flood warning is issued {i.e. $T_1 < T < T_2$})				
Observation	$T < T_1$	0	C_T	0
	$T_1 < T < T_2$ (Category 1 event)	D	C_T	D
	$T > T_2$ (Category 2 event)	D_u	$C_T + D_u$	D_u

dike are compared with the ones of the muscle wall as well as with the combination of measures, where the dike protects up to a 5-year return period and an additional increase of protection up to a 20-year return period with a muscle wall can be triggered by the forecast. Given that the two types of measures provide the same level of ultimate protection, the sum of the unavoidable damage (D_u) during the study time period is identical. Since the aim of this study is to compare the two types of measures, we do take into account the unavoidable damage in the calculation of the total losses, as this is the same for permanent and temporary measures.

For the comparison of temporary measures for events of different return periods, we assumed that frequent low-impact and rare high-impact events are those that correspond to events within the range T2-T5 and T5-T20, respectively.

3. Results

3.1. Floods and model evaluation

Fig. 7 presents the time series of the modelled discharge and the instances where the forecasted discharge exceeded the T2, T5- and T20 with at least 9% probability. Results are shown for the four river points examined (see Fig. 4). Fig. B.1 (Supplementary material) shows the same but forecast warnings are issued with at least 27% probability.

Table 4 presents the event-based metrics for the forecast-observation pairs introduced in Table 1. The results on the diagonal illustrate combinations where the forecast predicted the flood category correctly. Off-diagonal results indicate over- and under-forecasted flood categories. The total number of events varies across the four locations. For instance, there are seven events with a return period between 2 and 5 years at the Shire River, and only two at the Lilongwe River.

When at least 9% probability is used to issue a flood warning, we observe a systematic overestimation of flood occurrence at all locations. The forecasts for the Shire are the most accurate. When a higher probability to issue a flood warning is used (27%), over-forecasting is reduced, but the number of missed events increases. For example, no flood warning was issued (miss) for one event with return period between 2 and 5 years and two events with return period between 5 and 20 years at the Shire River. At the Bua River, two events with return period between 5 and 20 years were missed by the forecast in spite of systematic over-forecasting of the number of floods.

3.2. Permanent versus temporary measures for decision rationale 1

Fig. 8 presents the total losses when implementing permanent and temporary measures for all background and provided protection levels examined. The results indicate that increasing the background safety level from a 2-year return period to a 5-year level is financially more efficient using a permanent flood protection measure (dike) (6.75 million USD) than a temporary measure (muscle wall) (9.2–13.1 million USD). This is also the case when there are no misses by the forecasts (e.g. when a flood warning is issued with at least 9% probability at the Shire River). This can be explained by the small difference in the initial costs of permanent and temporary measures in combination with the high operational costs of the latter, which is a result of the relatively high frequency of triggered events including a significant number of false alarms.

When the background and provided safety levels are higher (i.e. a 5-year and 20-year return period) there are fewer floods against which protection is needed. This means that the costs of the permanent measures are more likely to be higher than the damage they prevent. For this reason, forecast-based measures are more likely to be more financially efficient than permanent ones. In our example, this is the case at the Shire and Ruo rivers, where there are no missed events (flood warnings issued with at least 9% probability). However, a large number of false alarms can make temporary measures less cost-effective due to excessive operational costs, as shown in the case of the Bua River.

When a protection level is upgraded from a 2-year to a 20-year return level, the likelihood of flood events against which action is taken increases relative to the previous scenarios. When at least 9% probability is used to issue a flood warning, the number of forecasted events is higher than the ones observed. However, despite the high number of false alarms, forecast-based measures are financially more efficient in all cases. This also applies even when a low-impact event (i.e. with return period between 2 and years) was missed (Ruo River), since its damage did not increase the total losses of the temporary defense

Table 3

River water level difference, dike total costs, muscle wall initial costs and avoidable damage for the three combinations of background and provided protection. When the background and the provided protection correspond to a return period T of 2 and 20 years respectively, the avoidable damage depends on the flood return period (i.e. T2-T5 or T5-T20). Fig. 3 is used to derive these numbers.

Background Protection	Provided Protection	River water level difference [m]	Dikes costs [USD/km] $(\cdot 10^3)$	Muscle wall initial costs (C_M) [USD/km] $(\cdot 10^3)$	Avoidable Damage (D) [USD] $(\cdot 10^3)$
T2	T5	0.24	422	230	4658
T5	T20	0.30	633	253	12,963
T2	T20	0.54	1055	300	4658|12,963

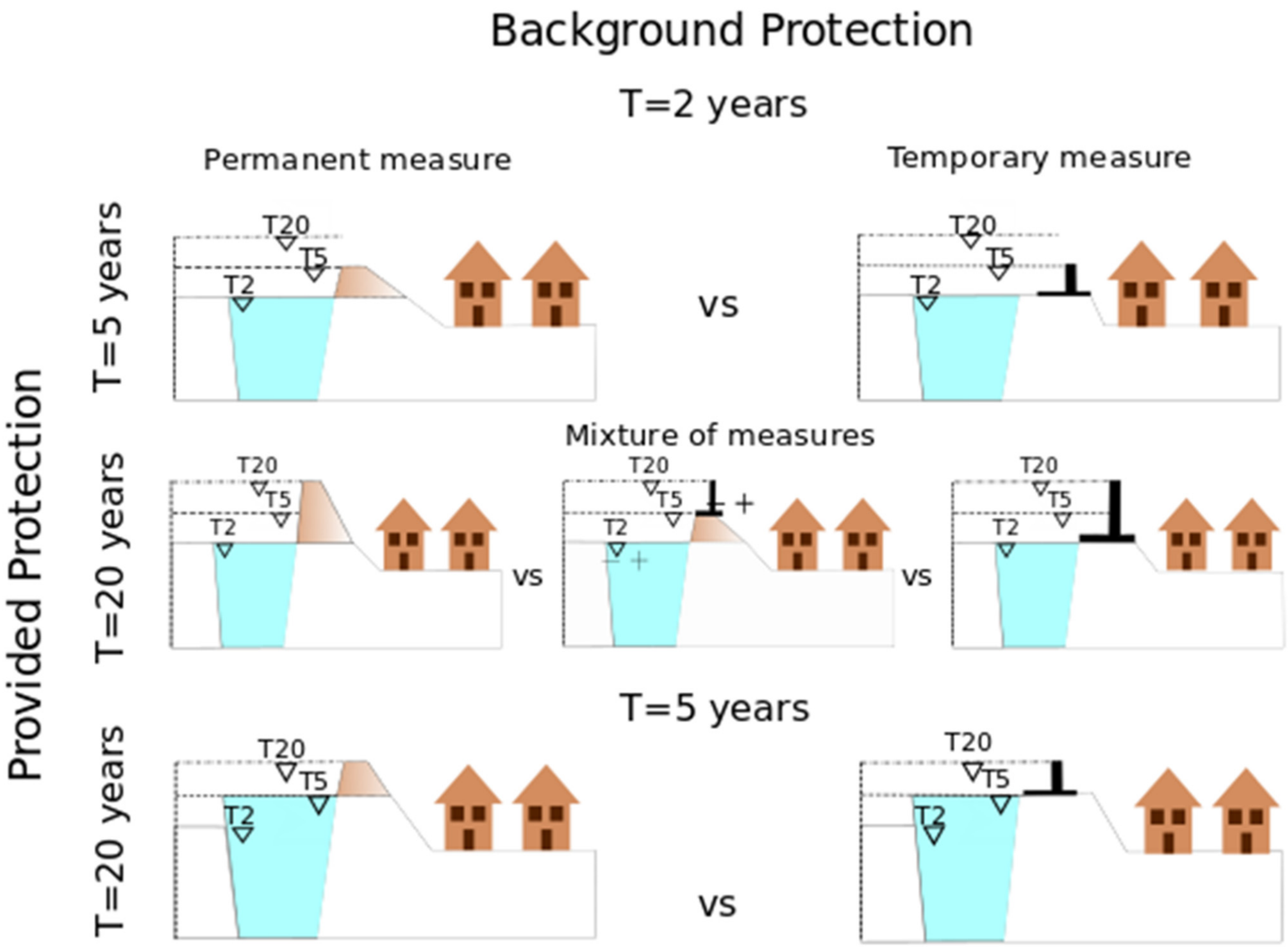

Fig. 6. Background and provided protection levels used in this study. In all cases the permanent measure (i.e. dike) is compared with the temporary measure (i.e. muscle wall). When background and provided protection corresponds to a $T = 2$- and $T = 20$-year return period, a mixture of dike and muscle wall is also evaluated.

strategy to levels exceeding the cost of permanent infrastructure. When the Ruo River time series is used, the most cost-effective configuration consists of a combination of dike to protect permanently up to T5, and muscle wall to temporarily protect up to T20 when the forecast issues a warning with at least 9% probability. Table C.1 (Supplementary information) presents a detailed calculation.

Fig. 9 shows the relative change required for each parameter to shift the most cost-effective strategy from permanent to temporary measures or vice versa. This sensitivity analysis is based on the GloFAS time series of the Shire River, and is carried out for both a 9% and 27% probability threshold. For an upgrade of a 2-year background level to a 5-year protection level, the shift from permanent to temporary measures can be achieved only with a substantial increase in the cost of permanent measure (1270%) or by a decrease in the cost of the temporary measure (either the initial or the operational costs) when they are triggered by flood warnings with at least 9% probability. When at least 27% probability was used, one event was missed by the forecasts. A decrease in the operational costs of the temporary measure is not sufficient to shift the strategy, because the sum of the damage of this missed event and of the initial costs of the temporary measures was higher than the costs of the permanent measures. Reducing the initial costs of the temporary measures by 73% makes the muscle wall financially more efficient than the dike. This demonstrates that the most cost-effective strategy is determined by the high initial costs of the temporary measure in combination with the high number of triggers (resulting from low exceedance levels and the tendency to over-forecast flood events).

When the background protection is higher (5-year T), a shift from temporary to permanent measures can be achieved only by changes in the costs of the measures when using at least 9% probability to issue a flood warning. When using at least 27% probability threshold, neither a change in the initial nor in the operational costs of the temporary measures can shift the optimal strategy, because the damage due to missed events is higher than the dike costs. A shift towards temporary measures would be accompanied either by a dramatic increase in the costs of permanent measures (+212%) or by a considerable decrease in avoidable damage (−83%).

With an upgrade of a low background protection level (2-year T) to a 20-year return level, temporary measures are preferable for the default configuration. A shift towards permanent measures is achieved by a decrease (increase) in the costs of permanent (temporary) measures when at least 9% probability is used to issue a flood warning. When at least 27% probability is used, a shift occurs either by an increase in the costs of the permanent measure or by a decrease in avoidable damage. This illustrates that permanent measures are more costly than temporary measures, although the latter are based on an inaccurate forecast system.

Finally, a combination of measures (e.g. a permanent dike up to a 5-year T and a temporary muscle wall up to a 20-year T) is more cost-effective than a muscle wall when reducing dike costs corresponding to an increase of safety level from 2- to 5-year T or muscle wall costs corresponding to an increase from 5- to 20-year T when issuing a flood warning with at least 9% probability. When a flood warning is issued with at least 27% probability, a mixture of measures is once again more cost-effective than only building a dike when the cost of a dike from 5- to 20-year T increases substantially (+127%) or the damage of this return period interval decreases significantly (−83%).

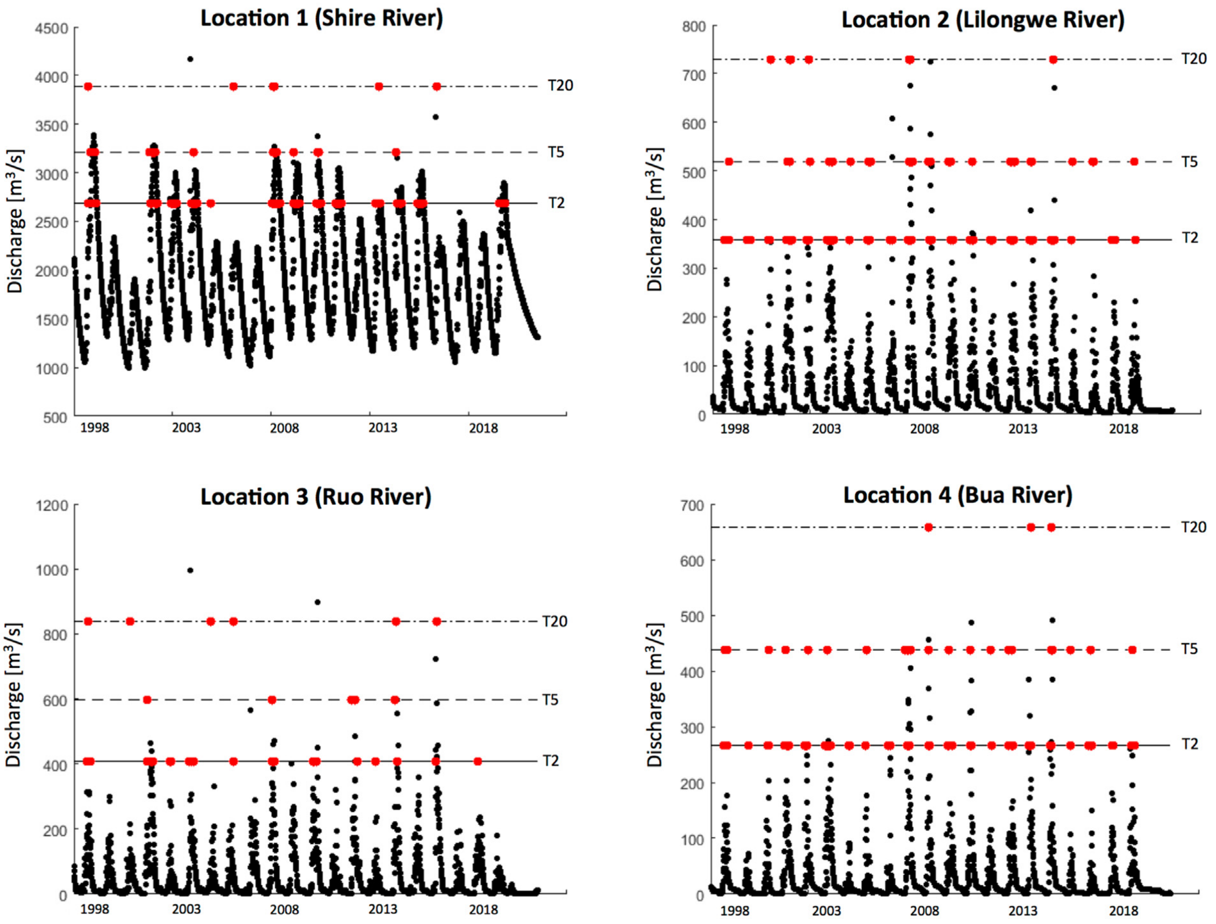

Fig. 7. Time series of modelled discharge (black circles) and instances where 7-day flood forecasts exceeded indicated return level thresholds with at least 9% probability (red circles) at four locations (see Fig. 4). Red circles on the 2-year line indicate that forecasted discharge is between 2- and 5-year return period; those on the 5-year line indicate that forecasted discharge is between 5- and 20-year return period; and those on the 20-year line indicate that forecasted discharge is higher than 20-year return period.

3.3. Permanent versus temporary measures for decision rationale 2

When action is only taken in response to alerts for floods of specific return periods, permanent measures are financially more efficient for all explored forecasted/modelled discharge time series (Fig. 10). This is mainly attributed to the model's inability to accurately forecast the return period of the events (see Table 4).

Comparing the results of temporary measures from Fig. 8 (DR_1) and 10 (DR_2), we see that, it is more cost-effective to act as soon as a flood warning is issued (i.e. DR_1), even when it is likely that the flood will exceed the coping capacity of the forecast-based actions. Table C.2 presents a detailed calculation.

3.4. Frequent low-impact and rare high-impact floods

Results in Fig. 11 show that the decision on whether it is financially more efficient to act against frequent low-impact events or rare high-impact events is highly affected by the forecast accuracy, which varies for events of different return periods. When the discharge time series of Shire, Lilongwe and Bua rivers are used, the lowest total losses occur with action against high-impact rare events, whereas acting against frequent low-impact events is most cost-effective when using the time series of the Ruo River. This demonstrates that a thorough economic analysis including forecast evaluation, action characteristics and potential damage from events of different return periods may shift the financially optimal strategy towards action against frequent low-impact events, which is contrary to the frequently used practice in which risk-reduction actions are only mandated for extreme events. See Table C.3 (Supplementary) for a detailed calculation.

4. Discussion

Our choice of the cost and benefit structure for the flood protection measures is simplified, aiming to serve the illustration of the underlying rationale of the comparison framework. Local data and recalibrated costs and benefits may change the outcomes. For instance, temporary measures such as the muscle wall are easily transportable and can be used in other locations, reducing the initial purchasing costs. False alarms can have additional costs (e.g. reputation loss, forecast confidence decrease) that may affect subsequent forecast-based actions through a reduced willingness to take action (Breznitz, 1984; LeClerc and Joslyn, 2015). Permanent measures can create a false sense of security that increases flood risk (Di Baldassarre et al., 2015). Finally, small-scale flooding can sometimes help fertilize arable land by bringing alluvium and moisture to the fields. The use of temporary measures can allow the small-scale flooding when this is beneficial. The use of different cost and benefits of the measures would require some adaptations, but the basic rationale would remain the same.

We assumed that permanent and temporary measures are equally effective in preventing floods, both having negligible probability of failure. Although this may be true for protection against low water levels, the failure probability increases for higher water levels. Furthermore, the effectiveness of the temporary measure is time-dependent: longer forecast lead times allow more time for effective implementation of the measures. However, forecast quality decreases with increasing

Table 4
Contingency table showing the number of forecast-observation pairs in each category [i.e. T < T2 (no flood), T2 < T < T5 (e.g. low-impact flood), T5 < T < T20 (e.g. high-impact flood) T > T20 (e.g. very high-impact flood)] for the four river locations shown in Fig. 4. The forecast probability used to issue a flood warning is at least 9% (27%).

Location 1 (Shire River)		Forecast			
		T < T2	T2 < T < T5	T5 < T < T20	T > T20
Observation	Q < T2 (no flood)	7 (9)	1 (0)	0 (0)	1 (0)
	T2 < T < T5 (low-impact flood)	0 (1)	4 (6)	2 (0)	1 (0)
	T5 < T < T20 (high-impact flood)	0 (1)	0 (1)	2 (3)	3 (0)
	T > T20 (very high-impact flood	0 (0)	0 (1)	1 (0)	0 (0)

Location 2 (Lilongwe River)		Forecast			
		T < T2	T2 < T < T5	T5 < T < T20	T > T20
Observation	Q < T2 (no flood)	1 (5)	2 (10)	11 (1)	2 (0)
	T2 < T < T5 (low-impact flood)	0 (0)	0 (2)	1 (0)	1 (0)
	T5 < T < T20 (high-impact flood)	0 (0)	1 (1)	0 (1)	2 (1)
	T > T20 (very high-impact flood	0 (0)	0 (0)	1 (1)	0 (0)

Location 3 (Ruo River)		Forecast			
		T < T2	T2 < T < T5	T5 < T < T20	T > T20
Observation	Q < T2 (no flood)	7 (13)	3 (1)	0 (0)	4 (0)
	T2 < T < T5 (low-impact flood)	1 (2)	0 (2)	3 (0)	0 (0)
	T5 < T < T20 (high-impact flood)	0 (1)	0 (1)	0 (0)	2 (0)
	T > T20 (very high-impact flood	0 (2)	2 (0)	0 (0)	0 (0)

Location 4 (Bua River)		Forecast			
		T < T2	T2 < T < T5	T5 < T < T20	T > T20
Observation	Q < T2 (no flood)	1 (7)	4 (8)	11 (1)	0 (0)
	T2 < T < T5 (low-impact flood)	0 (0)	0 (2)	2 (1)	1 (0)
	T5 < T < T20 (high-impact flood)	0 (0)	0 (2)	1 (1)	2 (0)
	T > T20 (very high-impact flood)	0 (0)	0 (0)	0 (0)	0 (0)

lead time, and therefore, an inherent trade-off between timeliness and quality exists. A careful calibration of the forecast-based systems requires extensive studies and physical modeling regarding the effectiveness of their measures as a function of various water levels, as well as consideration of the fact that forecast quality changes during the forecast time window.

Also, we did not apply any discounting procedure to account for time-varying net present value. The choice of discount rates strongly influences cost-benefit analyses of disaster risk management projects (Mechler, 2016). Temporary measures are obviously not triggered at fixed years, and thus our results would be also dependent on the timing of triggered actions. We have avoided this extra level of complexity in our fictitious exploration.

Estimating the expected losses of permanent and temporary measures requires a long time series of observational and forecast data. In our study, the available discharge forecast covers a period of only 22 years. This relatively short time series and the rarity of the events prevent a thorough evaluation of the forecast model, since conclusions based on expected values of event-based metrics (e.g. expected correct hits, false alarms, etc.) would not be robust. Therefore, we estimated the realized losses of the temporary measures for the period that forecasted discharge time series were available. However, these losses can differ significantly from expectations (Pope et al., 2017). For a robust design of a forecast-based system, a much observed/forecasted discharge time series than ours would be needed. Replacement with synthetic discharge and forecast series would avoid this problem but introduces the need for additional assumptions on reliability and stationarity, which is beyond the scope of this study.

A straightforward comparison of permanent and temporary flood risk-reduction measures is problematic when multiple decision makers with different mandates are governing the flood-prevention system. In Malawi, the Ministry of Agriculture, Irrigation and Water Development is responsible for permanent measures (e.g. building dikes), whereas the Department of Disaster Management Affairs and humanitarian agencies takes decisions regarding temporary, forecast-based responses. It is likely that each agency will apply different evaluation protocols. On the one hand, economic valuations such as cost-benefit analysis are typically used to justify large-scale infrastructure expenditures. This often introduces a bias towards wealthier areas, as in absolute terms the asset loss is higher than in poorer areas (Hallegatte et al., 2017). On the other hand, forecast-based early actions are typically evaluated in terms of their reduction of human losses and suffer. Comparison between the two types of measures makes sense when they are compared in a uniform evaluation framework. Actors coming together via national disaster risk management platforms, for example, can use the uniform evaluation framework to align their actions and seek the optimal combined approach. Via this overarching framework, donors can also bring coherence to their different funding mechanisms.

5. Conclusions

This work presents a methodology that compares permanent and temporary flood- prevention measures in terms of total financial losses. We created a hypothetical example to describe a number of decision scenarios using flood risk indicators for Chikwawa, Malawi, and forecasted discharge spanning from 1997 to 2018. The aim was to provide insights to improve existing approaches to flood risk management. Our study indicated that the choice between permanent and temporary measures is affected by the cost of measures, climatological flood risk, and forecast ability to produce accurate flood warnings. The results from our numerical example showed that the model used is skillful in providing correctly flood signals, but it has limited skill in forecasting accurately the flood return period. Therefore, temporary measures were never more cost-effective than permanent ones when they were triggered based on a forecast that specified the flood return period. When temporary measures were triggered based on flood warnings that did not specify the flood return period, action was taken in vain more times, but there were fewer events against which action was not taken at all. In this case, the results showed that when the existing measures could not protect against frequent low-impact events (from a 2-

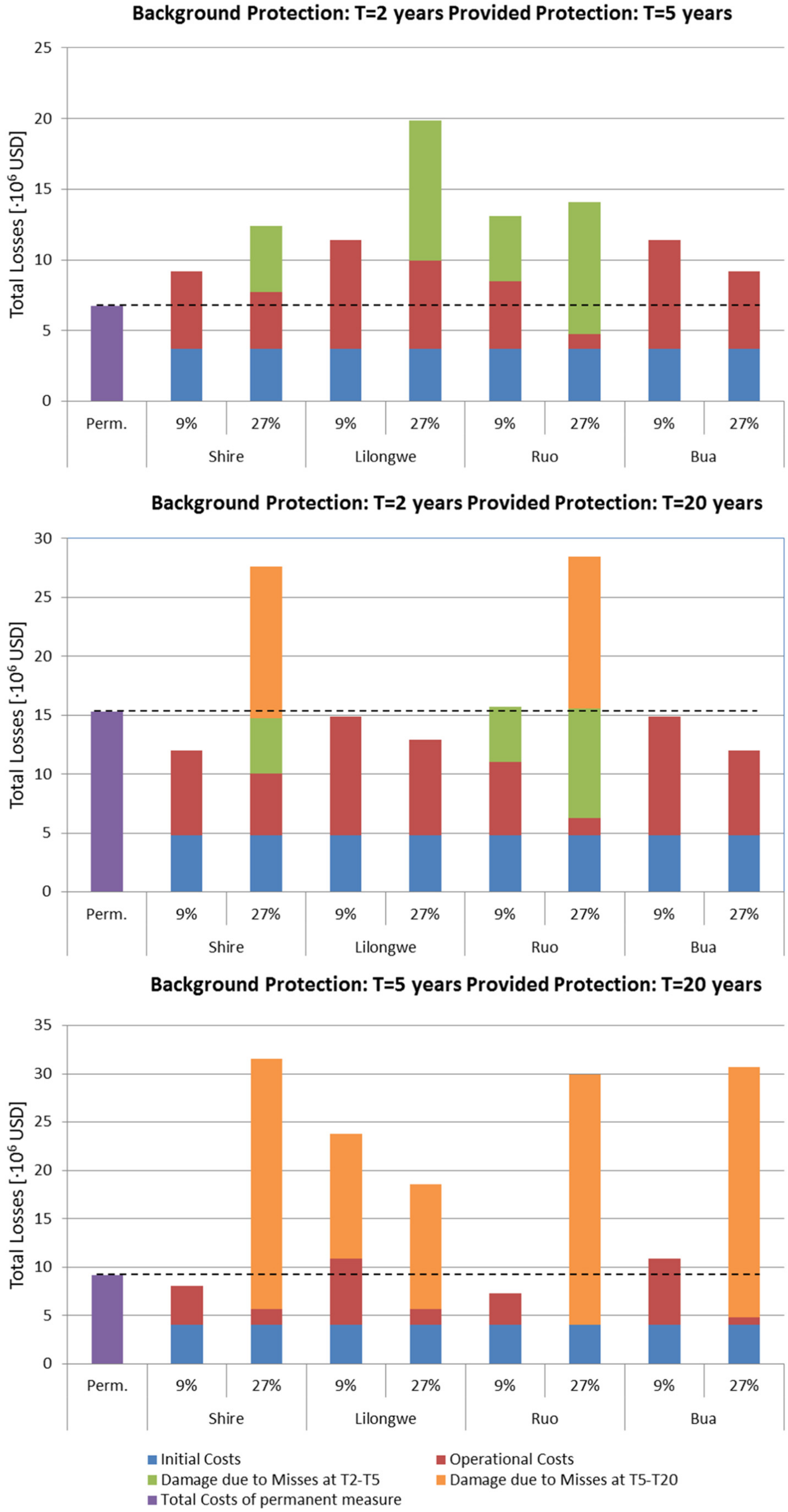

Fig. 8. Total Losses of permanent and temporary measures when DR_1 is followed. The horizontal dashed line is used for an easier comparison of the total losses of permanent measure with the total losses of the temporary measure.

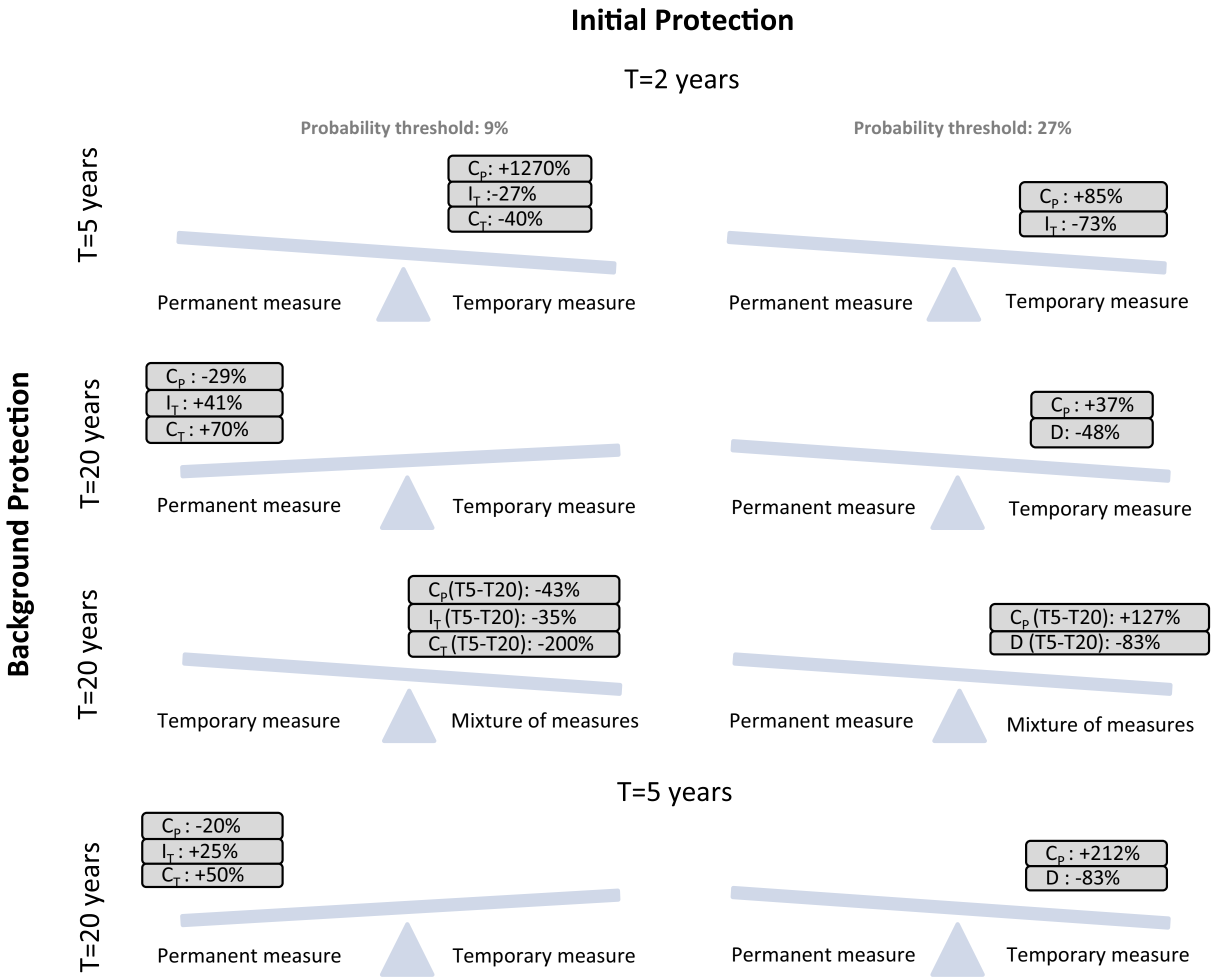

Fig. 9. Relative change required for each parameter to alter the most cost-effective strategy (permanent or temporary measures) identified in Fig. 8 for Location 1 (Shire river-Chikwawa). C_P: Costs of permanent measure, I_T: Initial costs of temporary measure, C_T: Operational costs of temporary measure, D: Avoidable Damage.

year up to a 5-year return period), the permanent increase of the safety level for these events was always more cost-effective than the temporary increase with forecast-based measures. When the existing measures could not protect against rare high-impact events (from a 5-year up to a 20-year return period), the increase of the safety level for these events was largely determined by the forecast ability to provide accurate warnings. We also demonstrated that the combination of permanent and temporary measures (i.e. in our example permanent measure from a 2-year up to a 5-year return period and temporary measure from a 5-year up to a 20-year return period) could be the most financially efficient strategy, particularly when the forecast is more skillful in capturing low-frequency events. This illustrates that forecast performance and available measures should be studied together in identifying the lowest-cost strategy. This should also be the case when choosing between taking forecast-based action against frequent low-impact or rare high-impact events, given that the interrelationships between measures characteristics, potential damage and forecast accuracy may give preference to a policy of taking action against the former, in comparison with recent practices, where action is triggered only against the latter.

This study highlights that forecast-based risk-reduction strategies should not be neglected in the process of identifying the optimal flood risk strategy. This study is relevant for both high-income countries with already high protection levels and low-income countries with minimal existing flood protection. However, the latter are where a careful allocation of available financial means is most urgently needed to save people and prevent humanitarian crises.

CRediT authorship contribution statement

Konstantinos Bischiniotis: Conceptualization, Data curation, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Hans de Moel:** Investigation, Methodology, Writing - original draft, Writing - review & editing. **Marc van den Homberg:** Data curation, Writing - original draft, Writing - review & editing. **Anaïs Couasnon:** Methodology, Writing - original draft, Writing - review & editing. **Jeroen Aerts:** Funding acquisition, Writing - review & editing, Project administration, Supervision. **Gabriela Guimarães Nobre:** Writing - original draft, Writing - review & editing. **Ervin Zsoter:** Software, Writing - review & editing. **Bart van den Hurk:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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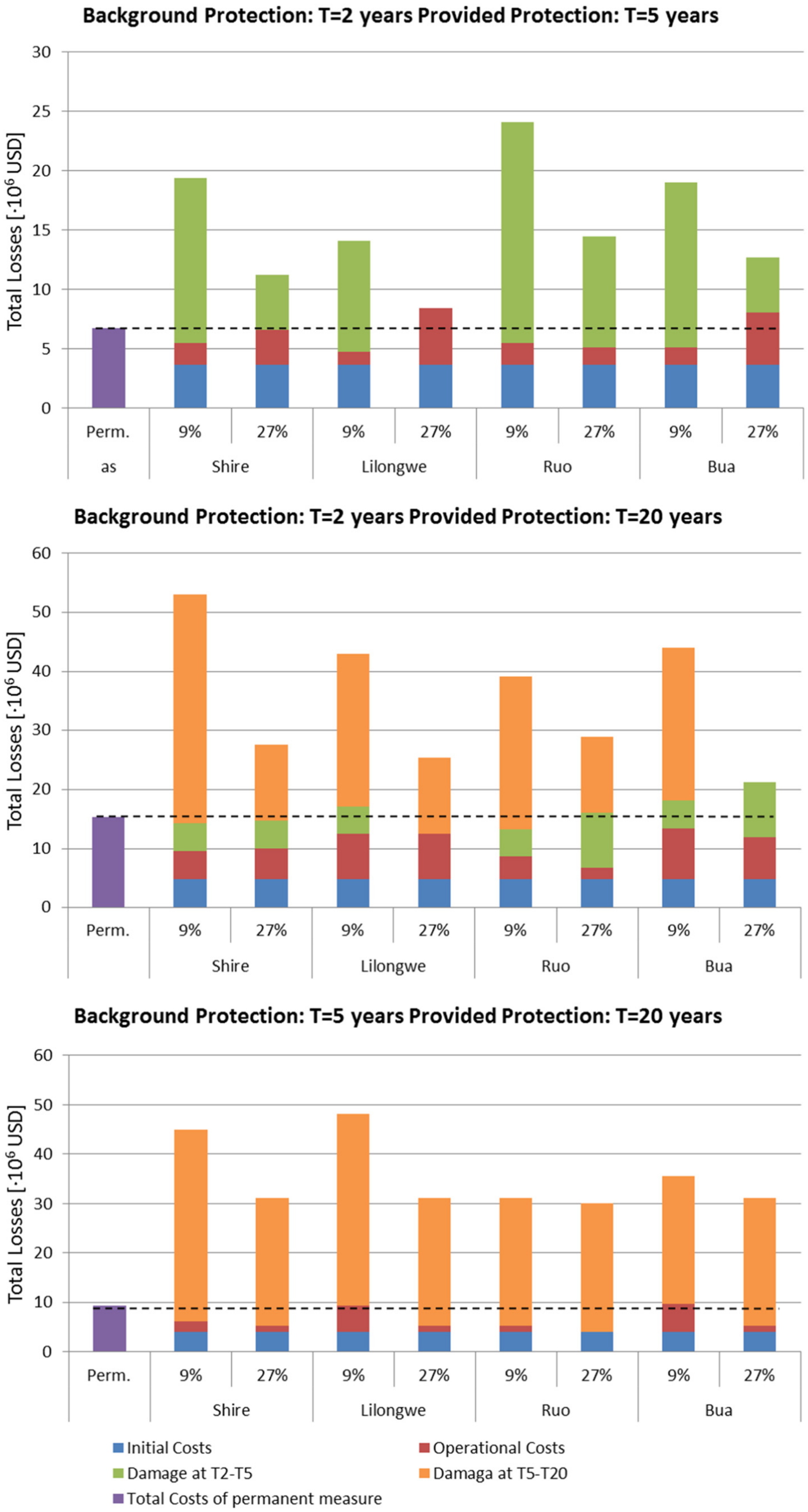

Fig. 10. Total Losses of permanent and temporary measures when DR_2 is followed. The horizontal dashed line is used for an easier comparison of the total losses of permanent measure with the total losses of the temporary measure.

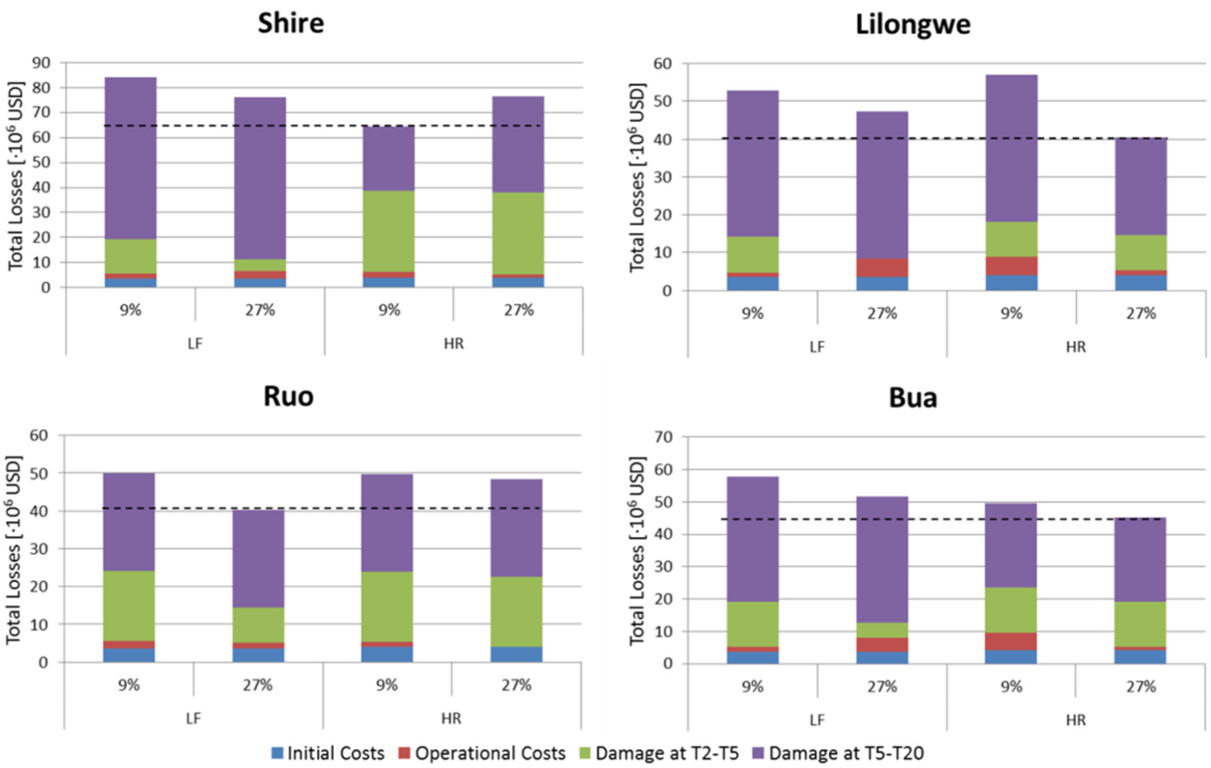

Fig. 11. Total losses when action is taken only against frequent low-impact (LF) or rare high-impact events (HR), using the modelled/forecasted discharge time series from Shire, Lilongwe, Ruo and Bua rivers.. The horizontal dashed line demonstrates the lowest total losses from all combinations.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.137572.

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