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A Cost Effective Solution to Reduce Disaster Losses in Developing Countries

Hydro-Meteorological Services, Early Warning, and Evacuation

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Abstract

In Europe, it can be estimated that hydro-meteorological information and early warning systems save several hundreds of lives per year, avoid between 460 million and 2.7 billion Euros of disaster asset losses per year, and produce between 3.4 and 34 billion of additional benefits per year through the optimization of economic production in weather-sensitive sectors (agriculture, energy, etc.). The potential for similar benefits in the developing world is not only proportional to population, but also to increased hazard risk due to climate and geography, as well as increased exposure to weather due to the state of infrastructure.

This analysis estimates that the potential benefits from upgrading to developed-country standards the hydro-meteorological information production and early warning capacity in all developing countries include: (i) between 300 million and 2 billion USD per year of avoided asset losses due to natural disasters; (ii) an average of 23,000 saved lives per year, which is valued between 700 million and 3.5 billion USD per year using the Copenhagen Consensus guidelines; and (iii) between 3 and 30 billion USD per year of additional economic benefits. The total benefits would reach between 4 and 36 billion USD per year.

Because some of the most expensive components of early warning systems have already been built (e.g., earth observation satellites, global weather forecasts), these investments are relatively modest, estimated here around 1 billion US per year, reaching benefit-cost ratios between 4 and 36.

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A Cost Effective Solution to Reduce Disaster Losses in Developing Countries: Hydro-Meteorological Services, Early Warning, and Evacuation

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The analysis presented here estimates that, in Europe, hydro-meteorological information and early warning systems save several hundred lives per year, avoid between 460 million and 2.7 billion euros of disaster asset losses per year, and produce between 3.4 and 34 billion additional benefits per year through the optimization of economic production in weather-sensitive sectors (agriculture, energy, and others). The potential for similar benefits in the developing world is not only proportional to population, but also to increased hazard risk due to climate and geography, as well as increased exposure to weather due to the state of infrastructure.

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- Between 300 million and 2 billion USD per year of avoided asset losses due to natural disasters;
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- Between 3 and 30 billion USD per year of additional economic benefits.

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Reaping these benefits would require additional investment in five domains: (1) local observation systems; (2) local forecast capacity; (3) increased capacity to interpret forecasts and translate them into warnings; (4) communication tools to distribute and disseminate information, data, and warnings; and (5) institutional capacity building and increased decision-making capacity by the users of warnings and hydro-meteorological information. Because some of the most expensive components of early warning systems have already been built (e.g., earth observation satellites and global weather forecasts), **these investments are relatively modest, estimated here around 1 billion US per year, reaching benefit-cost ratios between 4 and 36.**

The paper starts by investigating benefits from early warning systems in Europe, in terms of saved lives and reduced disaster asset losses. It then uses this evaluation to estimate the potential benefits of providing similar services in developing countries. Section 2 then assesses the other economic benefits that could be derived from the same hydro-meteorological information that is needed for early warning. These benefits are linked to a better optimization of economic production, and can be estimated in Europe to serve as the basis for an estimate for developing countries. Section 3 assesses the cost of providing this information, and Section 4 concludes with a cost-benefit analysis of doing so.

1. Benefits from early warning and preparation measures

This section investigates the socio-economic benefits from weather forecasts and early warning in Europe, and uses it as a benchmark to assess the benefits that could be generated by similar capabilities in developing countries.

Weather forecasts enable the anticipation of, and preparation for, extreme events like heat waves, cold spells, windstorms, thunderstorms and floods. Corresponding benefits accrue in two broad categories: the protection of persons and assets (prevention) and emergency preparation. Early warnings enable the protection of persons in many ways. Individuals can for instance avoid road trips when floods are forecasted, they can move vehicles out of flood zones and they can implement mitigation actions (e.g., sandbagging). Organizations and businesses can do the same. For instance, schools and businesses can be closed to avoid unnecessary trips and risks. In case of intense events, evacuation is also possible. Asset protection can also offer large benefits. Preparing a house before a hurricane (e.g. by covering windows) can reduce damage by up to 50% (Williams, 2002). A study in

Germany (Merz et al., 2004) shows that in the residential sector, one-third of the damage concerns the non-fixed contents, i.e. the house contents that could be saved, thanks to an early warning, by being moved out of vulnerable places (e.g. moved to the second floor). This proportion is only 10% in the infrastructure sector, but it grows to 60% in services and 80% in the manufacturing sector.

1.1. Illustration on Europe

1.1.1. Asset losses

Thieken et al. (2005, 2006, 2007) and Kreibich (2005) report on the Elbe and Danube floods in 2002. They show that 31% of the population of flooded areas implemented preventive measures. These measures include moving goods to the second floor of buildings (applied by more than 50% of the inhabitants who implemented prevention measures), moving vehicles outside the flood zone (more than 40%), protecting important documents and valuables (more than 30%), disconnecting electricity and gas supplies and unplugging electric appliances (more than 25%) and installation of water pumps (between 2 and 10%).

Among the inhabitants who did not implement any measure, 65% said that they had been informed too late, and about 20% said that they were not at home and could not do anything. For this population, it seems that an earlier warning would have allowed a better preparation and lower subsequent damage.

There is also a large potential for businesses. The International Commission for the Protection of the Rhine (2002) estimated that 50 to 75% of flood losses could be avoided thanks to emergency preparation measures. For instance, moving toxic materials and chemicals to safe places prevents local pollution (such as observed after hurricane Katrina flooded New Orleans). Machines and equipment can also be moved to avoid damage. For instance, large savings are possible in the transport sector, through moving transport equipments (trains, buses, etc.) out of dangerous areas. In addition, anticipating transport perturbations reduces the costs and complications of managing passengers blocked during their journey.

However, this potential is not easy to capture, especially because of the difficulties associated with disseminating the warning: according to Kreibich et al. (2007), 45% of businesses did not receive the warning directly from the authorities before the 2002 flood in Saxony, even though this warning was transmitted 20 hours before the flood.

In spite of this problem, almost 70% of all businesses implemented emergency prevention measures, often thanks to informal contacts that helped disseminate the warning. According to the study, 7% of all equipment was fully protected, and 75% partially protected, thanks to prevention measures. Concerning inventories and production, 10% could be fully protected, and 70% partially protected. However, Tapsell et al. (2008) estimate that the early warning and the subsequent prevention measures reduced flood costs by only 6%.

Studies show that the warning timing was critical: businesses that protected their equipment or inventories were those that received the warning early enough. This is confirmed by earlier findings by Day (1970), who found that avoided losses grow to near 35% when lead time exceeds 36 hours (see Figure 1). According to Carsell et al. (2004), a warning emitted 48 hours before a flood enables the overall damage to be reduced by more than 50%.

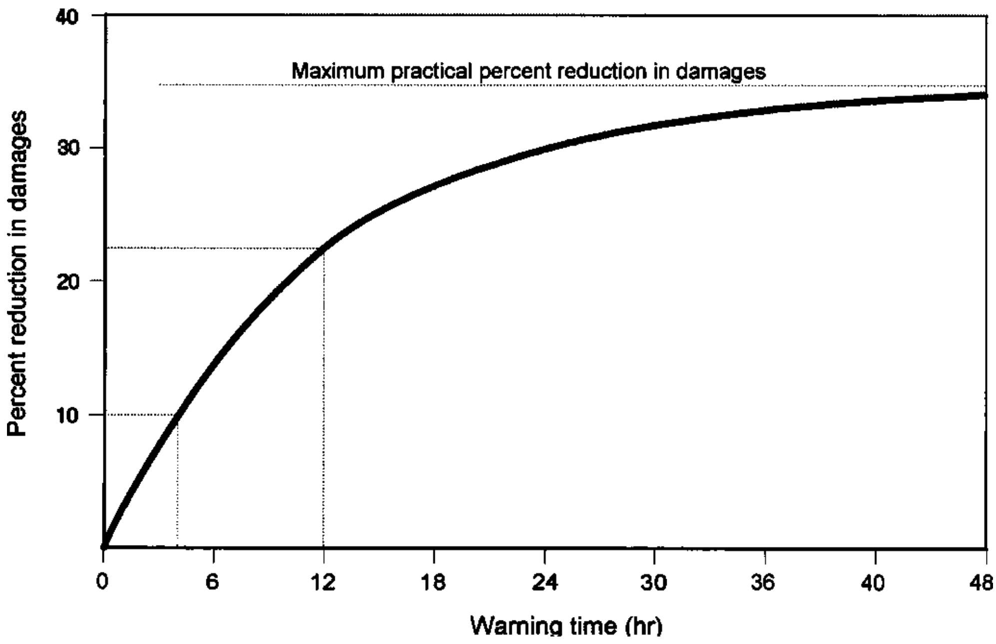

Figure 1: Day's curve for damage mitigation as a function of the forecast lead times. Source: Day et al., 1970.

Barredo (2009) finds that floods cost on average 4 billion euros per year Europe (EU27) (normalized costs calculated over the 1970-2006 period). Assuming that the warning reduces losses by 10%, and if only half of the floods are forecasted, the benefits from early warnings could reach 200 million euros per year. Using Carsell's estimate, and assuming that 75% of the floods can be forecasted, the benefits would reach 1,500 million euros per year[2].

According to Swiss Re (2006), storms have cost on average about 2.6 billion euros per year in Europe. If weather forecasts help reduce these losses by 10% or by 50% – thanks to the same types of actions than before a flood – the corresponding gains lie between 260 and 1,200 million euros per year. For floods and storms, the total could thus lie between 460 million and 2.7 billion per year. These gains represent between 0.003% and 0.017% of European GDP.

1.1.2. Human losses

It is more difficult to produce an economic estimate for individual safety. There are many weather-related threats to safety in Europe, such as floods (e.g., le Gars in France in 2002; Lower Silesia in 2005), winter storms (e.g., 1999 storms Lothar and Martin in France; Kyrill in France and Germany in 2011), heat waves (e.g., the 2003 summer) and cold spells (e.g., 1984-1985 in France; 2001 in Hungary; 2010 in Poland), and avalanches (e.g., in les Orres in France in 1998).

In Europe, severe winter-storms have a return period of about 10 years and often lead to dozens of casualties. The 2003 heat wave caused about 70,000 deaths in Europe, and the 2006 one led to

[2] We assume here that false alarms have no cost, which is not the case, especially in case of large scale evacuations.

about 2,000 deaths. Avalanches cause on average 32 deaths per year in France, for 4.5 million ski tourists[3].

It is difficult to assess how many lives prevention and early warning save each year, even though local actors consider these tools critical to ensure population safety. Examples of countries where early warning is considered seriously and where prevention emergency actions are well organized (e.g., Cuba) show that casualties can approach zero, apart from really exceptional events.

Other scenarios also need to be considered, such as technological catastrophes (accidents in a chemical plant or a nuclear plant). In these cases, the capacity to forecast winds, and thus the trajectory of the contamination cloud, can easily save hundreds of lives. The need to predict the trajectory of radioactive leaks was recently illustrated in Japan by the Fukushima nuclear accident. Even though the likelihood of using this capacity is fortunately very small, the damage avoided can be so large that this possibility needs to be accounted for in the social value of forecast capabilities.

Even in non-extreme situations, hydro-meteorological information plays a large safety role in many outdoor activities (e.g. sailing, hiking, skiing). Specialized services help thousands of people avoid being surprised at sea by a storm. These services have a large audience and probably help avoid hundreds of accidents each year.

Even more important, this information is used for maritime and air traffic.[4] Indeed, these operations depend on detailed weather information and, in the absence of meteorological information, it is unlikely that passenger air travel would be safe enough to be commercially viable in its current form.

Another component of forecast value is the ability to prepare emergency services before an event occurs. During the few hours before an intense weather event much can be done to increase the efficiency of emergency services. In 2002 during the floods in the Gard, for instance, 22 out of the 26 French helicopters able to conduct rescue airlifts were pre-positioned in the flood area, thanks to the forecasts. According to local emergency services, this pre-positioning saved about one hundred lives, compared with a situation in which it would have taken hours to move helicopters to the affected areas.

It is important to stress that the benefits from forecasts depend largely, and nonlinearly, on their accuracy and on the trust of the population. And threshold effects are important. For instance, if it were possible to predict exactly flash-floods, including their location, it would be possible to evacuate the at-risk areas, and reduce human losses to zero without any expensive investment in flood protections. But the decision to evacuate cannot be made if the probability of false alarm is too high (or if the warning area is too large): as, after a few unnecessary evacuations, the trust into the warning system is likely to disappear, and the warning system becomes useless. This problem is illustrated by the case of New Orleans, which had been unnecessarily evacuated twice (for hurricane George in 1998 and Ivan in 2004), making it more difficult to convince inhabitants to leave before hurricane Katrina. If the risk of false alarm becomes low enough to create and maintain trust and allow for significant prevention measures before disasters, a limited improvement in forecast accuracy can thus lead to a large increase in societal benefits. Trust should also be built through

[3] Source : Dossier d'information « Avalanche » du Ministère de l'Aménagement du Territoire et de l'Environnement, 2000, available on http://www.prim.net.fr.

[4] According to the « Bureau Enquête Accident », 7.5% of plane accidents have meteorological causes (http://www.bea-fr.org/etudes/stat9798/stats1997-1998.htm)

openness and communication from the specialists to the public, to explain the limits of forecasts and warning.

Taking into account these numbers, one can assume that hydro-meteorological information saves at least 200 lives per year in Europe, which is an extremely conservative estimate. A more likely estimate is about 800 lives per year.

Using the Copenhagen Consensus value of a human life (i.e., $1,000 and $5,000 DALY) and the global average life expectancy (70 years according to World Bank data in 2009), the value of a life saved at mid-life is between US$35,000 and US$175,000 (i.e. between 26,600 EUR and 133,000 EUR). With these numbers, the annual benefits of early warning systems in Europe can be estimated between 5 million euros (200 lives saved, $1,000 DALY) and 110 million euros (800 lives saved, $5,000 DALY).

Using standard values of the "statistical value of a human life" from the Boiteux Report on the transport sector in France[5], i.e. 1 million euros per life, the corresponding benefits can be estimated at between 200 and 800 million euros per year.[6]

1.2. Potential impact in developing countries

Adding up asset and human losses – using the Copenhagen Consensus numbers only – leads to an estimate of the annual benefits from early warning in Europe between 470 million and 2.8 billion euros per year.

These estimates are useful for our analysis because they provide an illustration of how much can be gained at the global level with current technologies and state-of-the-art modeling and observation systems. Of course, part of the potential benefits from early warning are already realized in the world (especially in developed countries such as Europe, the US, Japan, etc.). The questions are thus (i) How much of these benefits are already captured at global scale? (ii) How much would it cost to capture the full benefit potential?

It is difficult to estimate the existing availability of early warning. Some countries have introduced efficient systems in recent decades (e.g., Bangladesh and its hurricane early warning system). But in other places, basic observation systems are simply not in place to allow for implementing early warning.

Several institutions (including WMO, Golnaraghi 2012) review the ability of national hydro and meteorological services to fulfill their missions. Subbiah et al. (2008) distinguish four groups of countries. Group 1 includes countries with no basic hydro-meteorological services, where the benefits are likely to be close to zero; we assume that 10% only of potential benefits are already realized in these countries. Group 2 includes countries where hydromet services exist but are not fully operational; we will assume that these countries realize only 20% of the benefits achieved in Europe. Group 3 includes countries with well functioning hydromet services but with gaps in the chain from data production to early warning systems; there, we assume that only 50% of the

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[5] Instruction Cadre relative aux méthodes d'évaluation économique des grands projets d'infrastructure, 2005, http://www.statistiques.equipement.gouv.fr/IMG/pdf/Instruction_cadre_maj_2005_cle147216.pdf

[6] Another estimate is provided by Viscusi and Aldy (2003), who point out that the value of a statistical life (VoL) for U.S. labor market studies lies within a range of $4 million to $9 million. In developing countries the VoL presented in the survey by Viscusi and Aldy varies from $750,000 in South Korea to $4.1 million in India. (See Table 4, pp. 27-28).

European benefits are achieved. The last group includes countries where hydromet services and early warning systems are comparable to European ones, and where 100% of the European-type benefits are achieved.

There is no automatic relationship between these groups and country incomes, but richer countries are more likely to have functioning systems. As a consequence, we will assume that Groups 1 to 4 can be mapped to low income, low middle, high middle, and high income countries.

1.2.1. Avoided asset losses

Focusing first on asset losses, we assume that all countries face the same level of risk, and that early warning can provide the same relative benefits in terms of avoided disaster losses. In other terms, a European-like early warning system would allow to reduce disaster-related asset losses in all countries by between 0.003 and 0.017% of their GDP. This is conservative, for instance, because developing countries are affected by different hazards than industrialized countries (e.g., tropical storms).

The share of losses actually avoided is assumed to depend on the type of country: 10% of these benefits in low-income countries; 20% in lower middle income, 50% in upper middle income, and 100% in high income countries. The difference between the European potential and the share actually avoided provides an estimate of the additional benefits that could be achieved if hydro-meteorological services were upgraded to European standards (see Table 1).

This estimation suggests thus that generalizing the quality of hydromet services and early warning systems that can be found in developed countries could yield benefits *in terms of avoided asset losses* between 300 million and 2 billion USD per year in developing countries, thanks to lower disaster losses.

These values are supposed to increase like economic growth. Some analyses have concluded that disaster losses growth is slower than wealth growth (Skidmore and Toya, 2007; Mendelsohn et al., 2012). But in many countries, income growth also led to increased migrations and investments in areas at-risk, and a simple model shows that this trend may dominate the effect of risk-reduction measures (Hallegatte, 2011, 2012a).

This assessment is probably an underestimation because it does not take into account indirect losses from natural disasters, i.e. the loss in output that results from the loss in assets (see Hallegatte and Przyluski, 2011, on why and how to measure indirect losses). For large scale disasters, indirect losses can be of the same order of magnitude than direct losses (e.g., Tierney, 1997; Hallegatte, 2008).

Also, this assessment does not account for the possibility that reduced disaster losses can lead to accelerated economic growth (Hallegatte 2012b). This is an important assumption, since disasters can have long-lasting consequences on child development (Santos 2007, Alderman et al 2006), with large consequences on labor productivity and thus on growth and welfare. Moreover, disasters lead to significant migrations (e.g., Landry et al 2007 on Katrina in New Orleans). If disasters lead to out-migration, there will be consequences on economic growth, especially if—as suggested by the Katrina case, see Zissimopoulos and Karoly (2007)—high-skilled, high-productivity workers are more able to migrate than the average population. Strobl (2011) investigates this issue through the impact of hurricane landfall on county-level growth in the US. He finds that economic growth is reduced on average by 0.79% point in counties affected by a hurricane landfall, and increased by only 0.22% point the following year, suggesting the existence of long-lasting consequences.

And disaster can create poverty traps, by destroying assets and wiping out savings. These impacts can push households into situations where productivity is reduced, making it impossible for households to rebuild their savings and assets and return to pre-disaster income levels (Carter et al 2007, Dercon 2004, 2005, Lopez and Servén 2009, Van den Berg 2010). These poverty traps at the micro level could even lead to macro-level poverty traps, if investment capacities in a region are insufficient to cope with reconstruction needs (Hallegatte et al 2007, Hallegatte and Dumas 2008).

	GDP (million USD)	Potential (European-like) benefits		Ratio of current vs potential benefits	Estimation of actual benefits		Benefits from improved services	
		Low estimate	Likely estimate		Low estimate	Likely estimate	Low estimate	Likely estimate
Low income	413,000	12	69	10%	1	7	11	62
Lower middle income	4,300,000	122	714	20%	24	143	97	572
Upper middle income	15,300,000	433	2,542	50%	217	1,271	217	1,271
High income	43,000,000	1,217	7,145	100%	1,217	7,145	-	-
TOTAL	63,013,000	1,784	10,470		1,459	8,565	**324**	**1,904**

Table 1: Potential benefits from avoided asset losses thanks to early warning (with European-standard hydro-meteorological services), and share of these benefits actually realized with current services.

1.2.2. Human losses

In terms of life saved, the calculation is more difficult, because the lower quality of housing and infrastructure (including coastal and river flood protections) in developing countries means that the role of early warning is even more important than in developed countries.

According to the OFCA/CRED EM-DAT database, weather related extreme events killed on average 43,000 persons per year in developing countries between 1970 and 2011, and there is no visible trend in this figure (see Figure 2). Since the total population in 2011 in developing countries was approximately 5.7 billion persons, there is an annual death probability of 7.5 per million due to weather events.

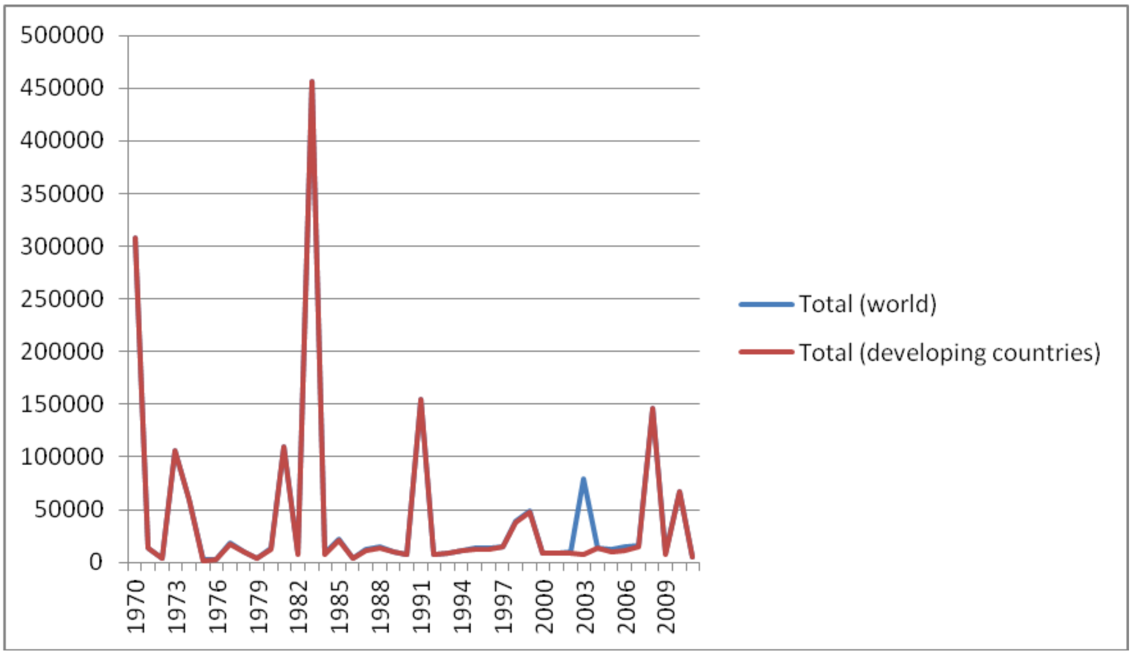

Figure 2: Number of people reported killed by weather-related natural disasters (1975-2011), in developing countries and at the world level. There is no significant trend in these series. Data from EM-DAT: The OFDA/CRED International Disaster Database.

In developed countries, the death toll is 2,500 persons per year (mostly from heat waves). The total population in developed countries is approximately 1.1 billion persons, and the annual death probability is 2.2 per million inhabitants. The ratio of the death probability in developing countries to the death probability in developed countries is thus equal to 3.4.

This difference is not due only to early warning: housing and infrastructure quality, disaster protection (dikes, drainage systems, etc.) are also important. Differences in climate (e.g., exposure to tropical storms) also make a difference. But early warning plays a huge role, as is illustrated by the case of Bangladesh and coastal floods. Paul (2009) reports on how hurricane Sidr caused many fewer deaths (about 3,400 deaths in 2007) than other similar storms (such that Gorky that killed more than 140,000 people in 1991). The main explanation is the good forecast of the storm, which allowed warning to be issued early, and the early warning and shelter systems.

According to Paul (2009):

> *The Cyclone Preparedness Program (CCP) was established in 1972 and was charged developing effective cyclone preparedness measures for residents of the Bangladesh coastal areas (Khan and Rahman, 2007). It was jointly set up by the Bangladesh Ministry of Disaster Management and Relief (MDMR) and the Bangladesh Red Crescent Society (BDRCS). CPP activities are centered around three infrastructures: a cyclone early warning system, public cyclone shelters for pre-disaster evacuation, and shelters to provide protection for cattle during storm surges.*

The CCP has been reinforced since cyclone Gorky in 1991, with better forecast and warning capacities, and twice as many volunteers being involved in the diffusion of warnings and evacuation orders. There is little high-technology in the early warning system:

> *Many Red Crescent volunteers, local government officials, workers from NGOs, and some villagers immediately joined the CCP volunteers. All traveled to threatened communities and disseminated cyclone warning and evacuation orders via*

megaphones, handheld bullhorns, bicycle-mounted loudspeakers, and house-to-house contacts. They also evacuated people in the path of the cyclone into cyclone shelters. In addition, fishing boats and trawlers over the North Bay of Bengal were instructed to immediately return to inland river ports.

This simple low-technology system saved many lives, in spite of the lack of maintenance of shelters, with only about 60% of them being usable. According to field data, more than 85% of households were aware of the storm warning and evacuation order (vs. 60% for Gorky in 1991), and 40% of potentially-affected households evacuated (i.e., 3.2 million out of 8 million coastal residents).

It is difficult to generalize the case of Bangladesh at global scale. Challenges to early warning and evacuation are different depending on the country (e.g., on the existence of transport infrastructure) and on the hazards (e.g., a storm is easier to forecast than the heavy precipitations responsible for deadly floods in Mumbai in 2005). Here, we will assume that generalizing the early warning and evacuation systems available in developed countries would make the death probability decrease from 7.5 per million to 4 per million (approximately a 50% reduction), making it still twice as large as in developed countries.

This means that the number of lives saved every year (with current population) would be 23,000 deaths per year. Assuming that each death is equivalent to 30 lost years, and taking the $1,000 and $5,000 values for DALYs, we obtain an annual benefit of 700 million USD per year or 3.5 billion USD per year (increasing with population and economic growth). This estimate is conservative, as we do not account for morbidity (injuries and disaster-caused illness), which might play a huge role (according to EM-DAT, more than 1 million persons have been injured by weather-related natural disasters between 1988 and 2007, most of them being in Asia), and we assume that growth in population and income does not translate into more disaster-related death (which is optimistic, see for instance Kellenberg and Mobarak, 2008).

Overall, the annual benefits of improved hydromet services and early warning systems in terms of avoided human losses can thus be estimated at between 700 million and 3.5 billion USD per year, growing with population and economic growth. Note that this value is highly dependent on the value used for saved lives, and that the $1,000 and $5,000 values used here for DALY are small, at least for some of the countries that are included in this analysis.

2. Economic benefits from hydromet information

Improving hydromet services would not only allow for better early warning systems. In practice, it would also produce economic benefits, in the form of useful services for industries and businesses and for households and individuals, even in normal conditions (i.e. during non-dangerous times).

In the agriculture sector, weather forecasts are used for planning purposes, e.g. to decide the dates of planting or fertilizer application. A few studies assessed the productivity gains from short to medium term weather forecasts. For instance, Wills et Wolfe (1998) investigate the use of forecasts to optimize lettuce production in the state of New York, and they find a $900 to $1,000 gain per hectare and per year, i.e. a 10% increase in productivity.

In the energy sector, weather forecasts are used to anticipate electricity demand, allowing to maximize the use of lower-cost but slowly-adjusting production units (e.g., nuclear, coal, or solid biomass) and reduce as much as possible the use of higher cost production units. But weather forecasts are also used to manage production. For instance, Roulston et al. (2003) estimate the value of weather information to optimize wind power production; they find a doubling in profits thanks to 1 and 2-day forecasts.

In transport, weather forecasts are used to optimize air traffic and ship routes, and to plan road salting and other preventive actions. A study by Leigh (1995) estimates benefits from weather information at the Sydney airport. He finds a benefit of 6.9 millions of Australian dollars per year, i.e. about 5 million American dollars. In the United Kingdom improved meteorological information services resulted in 20-25 % decrease in the use of road salt (Thornes 1990, cited in Leviäkangas, 2007). In Croatia, the socio-economic benefit of hydromet information related to the reduced number of accidents was estimated to be 4.3–8.7 million € per year (Leviäkangas, 2007).

In the construction sector, weather forecasts are used to optimize the use of labor resources, and to plan some temperature- or wind-sensitive operations. It avoids accidents (e.g., crane accident due to high wind) and improves building quality (e.g., by avoiding pouring concrete by very low temperatures).

In the tourism and health sector, weather is a predictor of future activities, useful to plan labor resources and inputs (e.g. anticipating the number of visitors in a touristic site, or the number of customers at a restaurant).

In these few examples, a significant impact of weather information on productivity is observed.[7] And the use of forecasts is growing worldwide, with many new businesses specialized in helping businesses to take this information into account. To estimate the orders of magnitude at stake, one can start from the economic value added in the world each year in the sectors considered as sensitive to weather conditions: agriculture, 2,000 billion USD; mining and energy, 7,000 billion USD; construction, 3,200 billion USD; and transport, 4,300 billion USD. Summing these numbers suggests that these sensitive sectors create more than 16,000 billion USD per year of added value, i.e. about 25% of world GDP.

And hydro-meteorological information goes beyond weather forecasts: observations and long data series are useful to design infrastructure, building, or even urban plans. In many countries, new constructions are prohibited in flood-prone areas (e.g., the 100-year flood plain in France), but the identification of such zones can be made impossible by the absence of appropriate data (see an illustration on Casablanca and Alexandria in World Bank, 2011). Hydro-meteorological information can also be used to monitor the environment over the long term, detect potentially harmful changes, and anticipate response measures (e.g., detecting as early as possible a change in rainfall to adjust drainage infrastructure, anticipating the arrival of a new pest in the agriculture sector).

Assuming that weather forecasts lead to value added gains between 0.1 and 1% in weather-sensitive sectors, these gains would be approximately equal to between 0.025 and 0.0025% of GDP. These estimates are small compared with the sectoral case studies presented above. And they are also small compared with estimated from ISDR et al. (2008), which propose estimates for 7 countries, namely Albania, Bosnia-Herzegovina, Macedonia, Moldova, Montenegro, and Serbia and Montenegro. In these countries, an economic analysis (carried out by VTT, based on available data and detailed surveys in each of the countries) estimated benefits from hydromet services between 0.09% (in Croatia) and 0.35% (in Moldova). Our numbers can thus be considered as conservative.

They are also conservative because they do not account for the “small” services that hydromet information provides to each of us in our daily life. Measuring the value of the private use of

[7] It is important to acknowledge the risk of bias in the literature, published studies being the ones that find a significant impact of weather information on economic activity. To my knowledge, no paper has been published on *a lack* of such impact.

forecasts is difficult. It means measuring the willingness of users to pay for the service they get from meteorological information. Knowing if one can go for a picnic without risking heavy rain has a value; being able to decide a few hours in advance if a dinner can be organized outside or inside has a value; deciding whether to take an umbrella when leaving for work in the morning also has a value. Each of these values remains small, but these decisions happen all the time and millions of people are making them. The aggregated value may thus be significant. Lazo et al. (2009) conducted a survey of U.S. households to estimate their willingness to pay for the weather information that is currently provided to them, and for potential improvement of this information. The survey focused on normal conditions, and excluded extreme events and safety aspect from the analysis, so there is no double counting with the previous section. The survey arrived at a median estimate of US$280 per year and per household, with more than 80% of households ready to pay more than US$30. Assuming that each European household is ready to pay at least 20 euros per year, again a conservative estimate, the societal benefit from weather information would be around 4 billion euros per year. With a value of 80 euros, the estimate reaches 15 billion euros.

For Europe, it is thus a very conservative estimate to assume that the value of hydromet information lies between 3.4 and 34 billion euros per year. At global scale, a similarly conservative estimate is that the potential benefits would be between 16 billion and 160 billion USD per year.

As with risk mitigation, part of these benefits has already been realized. Here, we want to assess the additional benefits if the services provided in developed countries were generalized. To do so, we use the same assumption that for risk mitigation, assuming that 10% of these benefits are realized in low income countries, 20% in lower middle income, 50% in upper middle income, and 100% in high income countries (see Table 2).

The result is that a generalization of hydromet services at high income country levels would generate additional economic benefits ranging between 3 and 30 billion USD. This estimate is an underestimation because it does not account for the bigger dependency of poor-country economies to environmental stress and weather extreme events.

	GDP (million USD)	Potential (European-like) benefits		Ratio of current vs potential benefits	Estimation of actual benefits		Benefits from improved services	
		Low estimate	Likely estimate		Low estimate	Likely estimate	Low estimate	Likely estimate
Low income	413,000	103	1,033	10%	10	103	93	929
Lower middle income	4,300,000	1,075	10,750	20%	215	2,150	860	8,600
Upper middle income	15,300,000	3,825	38,250	50%	1,913	19,125	1,913	19,125
High income	43,000,000	10,750	107,500	100%	10,750	107,500	-	-
TOTAL	63,013,000	15,753	157,533		12,888	128,878	**2,865**	**28,654**

Table 2: Potential economic benefits from improved hydrometeorological services, and share of these benefits actually realized with current services (these benefits exclude the benefits from early warning, presented in Table 1).

It is also an underestimation because it does not account for health impact, and for the fact that higher productivity in agriculture would increase food security, with health and economic benefits.

In that case, therefore, there are probably economic benefits that are even larger than the direct impact of early warning: economic benefits in normal conditions from hydromet information developed for disaster mitigation would yield 3 to 30 billion USD per year.

3. How to improve early warning, and at what cost?

Improving hydromet services and early warning systems implies multiple components. Some of the required measures are investments; some are linked to operational expenses and require sustainable funding. Other important components are linked to the institutional setting and to the training of the producers and of the users of hydromet information.

One important aspect of hydromet production information is that all countries do not need to invest in all the component of the forecast chain. Remote sensing information is provided by satellites that are launched and financed by developed countries (e.g., Meteosat 5 on Africa, operated by EUMETSAT; the Metop system, also operated by EUMETSAT; NOAA 19, financed by the US government). Global modeling is also carried out regularly by many services is the world (e.g., most European services such as Meteo-France and MetOffice, the European center ECMWF, US institutions like NOAA). And even observation can be rationalized thanks to regional integration: a radar network is much less expensive if designed at regional rather than national scale.

What is really needed in developing countries is thus:

(i) The local observation system, based on ground, in-situ observations, for weather data (e.g., temperature, precipitation), hydrological data (runoff data), topological data (e.g., elevation database to link runoff forecast with flood extension), socio-economic data (e.g., population density and transportation capacity to decide on evacuation).

(ii) Forecasting capacity, i.e. the translation of low-resolution model forecast into high-resolution forecast, using statistical downscaling and correction or additional models.

(iii) Interpretation capacity, to translate model output into actual forecast and warnings, taking into account known model bias and specific local conditions that models cannot integrate.

(iv) Communication tools, to make sure the alert reaches the individuals in charge to implementing prevention measures (including the public who is supposed to evacuate), and evacuation and emergency plans.

(v) Users' decision-making capacities, to make sure warnings are actually used (including for evacuation).

The ability to improve forecast capacity, and to provide forecasts that are appropriate and used on the ground, will depend on the local scientific "capacity", including the existence of university and research program. An example of how capacity can be improved is provided by the AMMA program (African Monsoon Multi-disciplinary Analysis[8]), an international research program that resulted in (i) better observation systems in Africa; (ii) creation of local research team on hydrometeorology, health and agriculture; (iii) creation of new degrees in relevant disciplines in African universities.

[8] More information on http://www.amma-international.org.

Finally, the ability to implement prevention measures will depend on local infrastructure and capacity. Lack of transport capacity (when public transportation is not accessible and poor households do not have individual transport vehicle) can make the entire system less efficient. Also, limited investments can make it possible to implement prevention measures, but financial constraints may make them impossible. For instance, hard-protection to windows and cofferdam can be extremely efficient to reduce wind or flood damages to houses and cost only a few dozen USD. They may nevertheless be too expensive to be broadly available in some regions.

The five categories of action may also be designed very differently depending on the local contexts. For instance, communication through TV, radio and cell phones can be extremely efficient, but in some countries low-tech options (such that the bicycle mounted loudspeakers used in Bangladesh) can be useful complement. When trust does not exist between the population and forecast producers, local contact points (such that the Red Cross volunteers) can help building it.

Here, we focus on the cost of the 5 elements listed above, without consideration for the more general capacity in the country, assuming that it will not be a constraint to evacuation efficiency (keeping in mind that we still assume that even with early warning and evacuation systems, the death ratio will be twice as large in developing countries than in developed countries, because of the lower building quality and transportation infrastructures).

The cost of strengthening hydromet service depends on the size of the country and of the context.[9] The range can be from a few million USD to hundreds of millions. The NMS can be as small as 5-8 forecasters converting results of global forecasting centers in the national alerts and forecasts supported by very limited infrastructure in the country. In this case the operating costs can be comparable or exceed the investment costs of setting up the system. This is not typical case. Usually, in developing countries there are many dozens (or several hundred) of low paid staff dealing with extensive but dilapidated infrastructure (buildings, observation sites, instruments, etc.).

In Russia, the first hydromet project WB invested into was over USD172M, the second (currently under preparation) is estimated at USD 141M. Still this is a fraction of the total needs (and real costs). In Mexico, the World Bank is planning to invest USD109M. Recent investments in Poland and Turkey were about USD62M and 26M. According to an analysis on South Eastern Europe (ISDR et al., 2008), the estimated financing needed to strengthen national hydromet services in seven countries, without regional cooperation and coordination, would be around €90.3 million. With deeper cooperation, the cost is around €63.2 million. This cost includes investment for in-situ measurement, upper-air sounding, radars, communication, and dissemination of data, information, forecast and warning. It includes also maintenance over a five-year period.

Moreover, as demonstrated by the case of Bangladesh, forecast capacity is not sufficient and needs to be complemented with decision-making system to translate a forecast into a warning, and communication tools (possibly with volunteers on the ground to diffuse the evacuation orders).

To be conservative, we will thus assume that the cost of providing appropriate early warning and evacuation orders in developing counties would be equal to about $50 million per country over a 5-year period (including maintenance and operational costs). For a set of 80 developing countries, including most of the world population, the cost would be equal to $2 billion over five years, i.e. an annual cost of $800 million per year.

[9] Invaluable information has been provided by Vladimir Vtsirkunov, from World Bank/GFDRR.

Box 1. Examples of local-scale case studies

A few project-scale cost-benefits have been made at local scale, and their result support the global analysis presented here. Subbiah et al. (2008) provides for instance numbers for Bangladesh, Sri Lanka, Vietnam, Thailand, Indonesia, Philippines, and India. They find that out of the 9 case studies they investigate, benefit-cost ratios ranging from 0.93 to more than 500. Only one project has a benefit-cost ratio below one.

The World Bank conducted an analysis of risk management in Tunis, Casablanca, and Alexandria, and provided cost-benefit analyses of multiple risk mitigating measures (including seismic risks). In all cases, implementing a warning system was considered as the most (or one of the most) cost-effective measures. In Tunis, for instance, the benefit-cost ratio of such a measure exceeds 5, while hard protection and building retrofit have benefit-cost ratio between 1 and 2 (see figure 3).

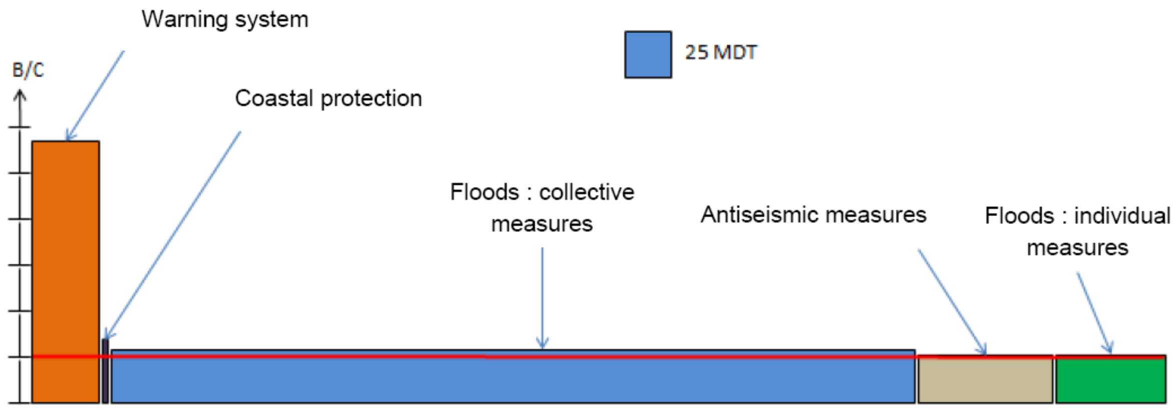

Figure 3: Benefit-cost ratios of various risk-mitigation measures in Tunis. One MDT is one million of Tunisian Dinar (1 DT is worth approximately US$0.66). Source: World Bank (2011).

It is important for hydro-meteorological services to be well connected to their users to ensure they produce the information that is required for early warning and evacuation (and for operational management). Also, users of information need to know how to use the information, especially for forecasts that are always uncertain. Deciding when to evacuate a flood-prone area necessitates an analysis of the cost of a false alarm (including the loss of confidence, which can lead the population not to evacuate the next alert), the cost of missing a dangerous flood, and the probability of error. The easiest way to achieve this is to include hydro-meteorological services in the government services that will use the hydro-meteorological information and decides on evacuation and preparation measures (e.g., the Ministry of Interior in most countries).

Producing hydromet information and making decisions on when to evacuate and invest in preparation measures requires specific skills that are not always available in developing countries. In addition to investments in hydromet and risk management services themselves, it is thus necessary to invest in population skills, for instance through the creation of a specific university program that will train students on hydromet information production, risk management, and decision-making. Training about 40 individuals per year in 40 countries would represent 1600 persons per year would cost less than 200 million USD per year.

4. Conclusions

This analysis demonstrates the large potential of investments in hydro-meteorological services and early warning and evacuation schemes to reduce the human and economic losses due to natural disasters. It also stresses the existence of other significant socio-economic benefits, which can potentially exceed the benefits in terms of disaster risk reduction.

A ballpark estimate of the cost of improvement of hydromet and warning services to make it possible to implement early warning systems in developing countries is thus lower than $1 billion a year. With benefits in terms of disaster risk reduction between 1 and 5.5 billion USD per year, and economic benefits between 3 and 30 billion USD, we reach benefit-cost ratios between 4 and 35 with co-benefits.

Since this analysis compares annual investment and spending to annual benefits, it does not depend on the discount rate. There might however be a several-year delay between an increase in spending and the corresponding increase in benefits. But such a delay should not change in a qualitative manner the result of the analysis proposed here.

Type of benefits	Annual benefits (million USD)		Annual cost (million USD)	Benefit-cost ratio	
	Minimum	Maximum		Minimum	Maximum
Reduced asset losses from disasters	300	2,000	1,000	4	35
Reduced human losses from disasters	700	3,500			
Other economic benefits	3,000	30,000			
Total	4,000	35,500			

Table 3: Summary of benefits from and costs of upgraded hydro-meteorological services.

This analysis is done at global scale, using very simple assumptions that are only capable of providing orders of magnitude. Before real investments are made, local and context-specific analyses are necessary, at project scale. In some regions, for instance, the main risk is linked to heavy precipitation, and meteorological radars will be extremely useful to provide warning with a time-lead of a few hours. Such radars will be much less needed where risks are not related to heavy precipitation but – say – to droughts or temperature extremes.

Even though the implementation would need to be done country by country – with detailed analyses of each investment – one can make a strong case for increased investment (and international attention) into early warning systems to save lives and improve economic efficiency.

Of course, the benefits from early warning systems would be maximized if they are designed in conjunction with other disaster risk management policies and investments, such as those proposed and evaluated in Mechler (2005) or in the companion paper by Kunreuther and Michel-Kerjan (2012).

Indeed, there is no single measure that can provide full protection against all natural hazards. The highest and strongest dikes have a failure probability, and risk can never be fully cancelled, by any measure and at any cost. Moreover, some approaches are more efficient to cope with frequent, low-intensity events while others are best to manage rare, high-intensity events. For instance, it is easy to avoid the frequent floods that occur in Mumbai almost every year through improvements in the drainage system. But it is almost impossible to prevent floods in case of exceptional rainfall like in July 2005 (Ranger et al., 2011). To cope with such exceptional events, the early warning and evacuation systems proposed in this paper can play a very efficient role. But early warning cannot do anything against frequent events: entire parts of Mumbai cannot be evacuated several times every year.

This is why risk management should be done through a policy mix, with several policies targeting different return periods, as suggested in Figure 4. Using the wording suggested in Hallegatte and Przyluski (2010), some of these policies will target direct disaster impacts and try to minimize them (disaster risk reduction actions), while others will target indirect disaster impacts and try to increase resilience (resilience building actions).

To minimize the cost of risk management, and maximize its benefits, the different policies of the mix should be designed together. With very strong physical protections – like in the Netherlands – there is no need for an evacuation system, an insurance scheme or specific building norms against floods. Where financial constraints make such protection unaffordable – like in Bangladesh – it is even more critical to implement an efficient early warning and evacuation scheme.

There is thus no "optimal" risk management policy mix, and different approaches are possible. Rich countries may decide to focus on physical protections, while poor countries may prefer to invest in early warning and evacuation. Depending on which approach is selected, the at-risk areas may be affected more or less often, with more or less damages. As seen with Katrina, over-reliance on physical protection and the absence of evacuation can lead to large-scale disasters.

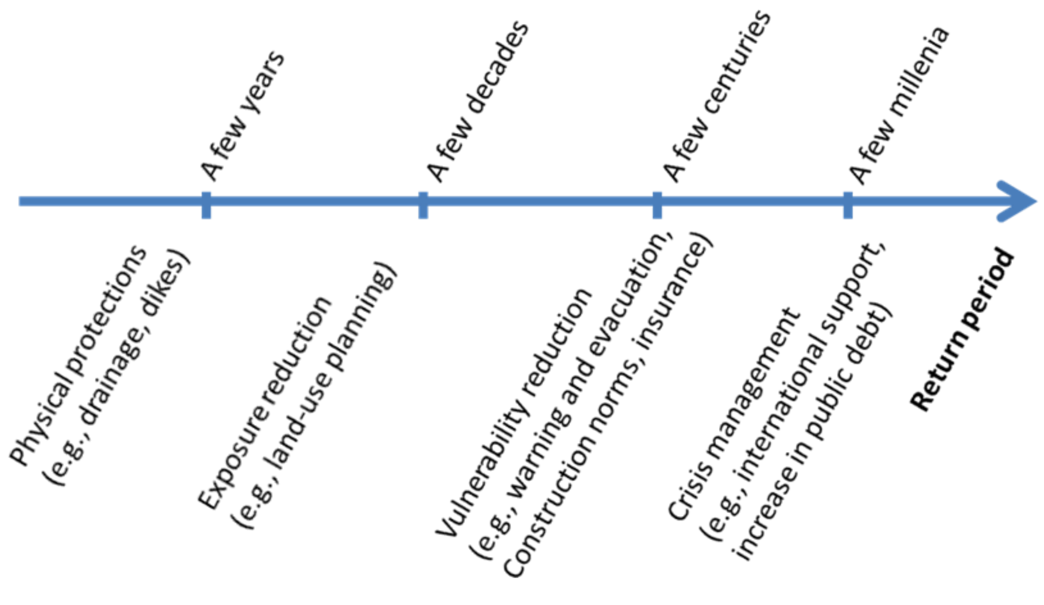

Figure 4: An example of risk-management policy mix, in which physical protections avoid frequent events; land-use planning limit population and asset exposure if protections are overtopped; early warning, evacuation, insurance reduce vulnerability, increase resilience and help affected regions rebound; and finally crisis management and international solidarity help cope with the largest events.

Importantly, a change in one component of the risk management policy mix may require changes in the other components. For instance, if the protection level provided by physical infrastructure is reduced by climate change or subsidence, the criteria used to decide when to evacuate at-risk areas may have to be revised; and insurance scheme financial viability may be threatened.

In practice, however, doing so is made extremely difficult by institutional fragmentation and coordination issues. Developing such a risk-management package would require in most countries a concerted effort by the ministry in charge of water and coastal management (for the dikes and drainage system), the ministry in charge of land-use and urbanization and various local authorities (for land-use planning), the ministry of interior (often in charge of warning, evacuation, and crisis management), the ministry of finance (for insurance and emergency finance), and the ministry of foreign affairs (if external support in case of disasters is concerned). Strong efforts need to be devoted to organizing a dialogue of these actors in a constructive way, to make the best use of each disaster risk reduction action that can proposed – from the improved building norms of Kunreuther and Michel-Kerjan to the hydromet information and early warning systems proposed here.

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