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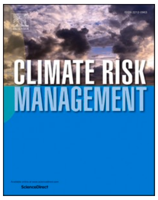

A reality check for the applicability of comprehensive climate risk assessment and management: Experiences from Peru, India and Austria

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ABSTRACT

Climate-related risks are a major threat to humanity, affecting the lives and livelihoods of communities globally. Even with adaptation, climate change is projected to increase the severity of risks, leading to impacts and residual risks, also termed losses and damages. Frameworks and approaches using Climate Risk Management (CRM), an integration of Disaster Risk Reduction, Climate Change Adaptation, and sustainable development, are being devised to support the comprehensive management of increasing climate-related risks. Here we discuss to what extent comprehensive CRM has been implemented in three specific cases – in Peru, India and Austria. The approach is conceptually represented and evaluated using a CRM framework. The cases deal with risks associated with glacial lake outburst floods, sea level rise, tropical cyclones, salinization, riverine floods and agricultural droughts. Ultimately, we synthesise policy and research recommendations to help understand what is feasible for CRM approaches applied in practice. We find that successful CRM implementation in practice benefits from being flexible, and participatory from beginning to end, whilst considering compounding risks, and the spectrum of (just and equitable) incremental to transformational adaptation measures necessary for attending to current and projected future increases in climate-related risks.

1. Introduction

Climate-related events and processes (e.g., floods, cyclones, sea level rise and heat waves) pose a major threat to communities all over the world, especially for the 3.3–3.6 billion people currently living in vulnerability hotspots (O'Neill et al., 2022). Multiple risks interacting (also known as cascading or compounding risks) increase the complexity of assessing and managing risks (Simpson et al., 2021). With intensifying climate change in combination with unequal socio-economic development, climate-related risks and impacts are expected to further increase in the future, leading to adaptation limits in natural and human systems. Losses and damages are

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expected to increase and disrupt lives and livelihoods, as current risk management and adaptation across the globe has been assessed to be fragmented, reactive and small-scale (Berrang-Ford et al., 2021; O'Neill et al., 2022).

In an effort to integrate Disaster Risk Reduction (DRR), Climate Change Adaptation (CCA) and sustainable development assessments, comprehensive Climate Risk Management (CRM) concepts have been developed, to support actions to reduce risks, minimise the impacts of climate-related risks and to increase resilience and adaptive capacity (e.g., Mechler et al., 2019b; Schinko and Mechler, 2017). It aims to manage the risk components of vulnerability, exposure and physical hazards (Leis & Kienberger, 2020). However, applications of conceptual CRM approaches on real-world cases are still scarce (Hallwright & Handmer, 2021; Leitner et al., 2020; Mechler et al., 2019b; Schinko et al., 2016).

Here, we build on a comprehensive CRM framework developed with GIZ (German Agency for International Cooperation) for application in India and other regions (Mechler et al., 2019b; Mechler et al., 2021) and discuss applications to three real-world risk cases in Peru, India and Austria. The strength of utilising the three cases is that they operate on different geographical scales and socio-economic contexts, allowing for an extensive examination of comprehensive CRM under distinct circumstances. The risks range from glacial lake outburst floods, sea level rise, salinization and cyclones, to riverine flooding and agricultural droughts.

The aim of this paper is to discuss three case studies of risk management practices and infer to what extent comprehensive CRM has been implemented in each case. We use a conceptual CRM framework as guidance to assess if comprehensive CRM has been achieved. Based on the specific results and common insights from the three cases, we will be able to (1) evaluate to what degree comprehensive CRM has been implemented in real world circumstances, (2) draw out comparative similarities and differences, strengths and weaknesses in the deployment of the CRM framework in the different cases, (3) synthesise policy and research recommendations towards an achievable comprehensive CRM in practice.

The paper is structured as follows: the second section provides the conceptual background, covering climate-related risks, adaptation (limits), incremental and transformational change, and an introduction of the GIZ CRM framework. The third section describes the data and methodological approach used in this study. In the fourth section, we outline the three case studies from Peru, India and Austria. Finally, in the fifth and sixth sections we discuss and conclude on the implications of this study for comprehensive CRM in practice.

2. Conceptual background

Climate-related risks are determined through the interactions of hazards, exposure and vulnerability - and their respective drivers (IPCC, 2022). Climate-related risks can be characterised as: acceptable (risks are so low there is no need for risk reduction or adaptation measures), tolerable (certain adaptation measures and risk management are needed and there might be residual damage) (Klein et al., 2014), and intolerable (no risk reduction measures or adaptive action are available and "an actor must either live with the risk of escalating loss and damage, or transform behaviour to avoid the risk") (Dow et al., 2013). This distinction is related to individual risk perceptions and levels of risk aversion. Intolerable risks are often linked to reaching adaptation limits.

Despite there not being one common definition of adaptation limits, scholars most often identify limits to be reached when adaptation action cannot prevent intolerable risks (Dow et al., 2013; Thomas et al., 2021). Certain circumstances, such as social, cultural, economic, technological or biophysical, condition the adaptive capacity of a system or action (Adger et al., 2007; 2009; Dow et al., 2013). Thomas et al. (2021) reports governance, institutional, policy and financial limits to be most pronounced in scientific literature, while biophysical limits are less commonly mentioned. A distinction is made between soft and hard adaptation limits, where the former is often defined as having the possibility to change over time with socio-economic and/or technological shifts, while the latter is unchangeable (Dow et al., 2013; Klein et al., 2014; Mechler et al., 2020; Thomas et al., 2021).

Due to increasing levels of intolerable risk and losses and damages,[1] the need for transformational change[2] in the context of disaster risk reduction and climate adaptation has gained traction (e.g., Godfrey-Wood and Naess 2016; Moore et al., 2014; O'Brien, 2012; Pelling et al., 2014; Termeer et al., 2017; Thomalla et al., 2018). However, societies hit by climate change currently adopt transformational adaptation only to a limited degree (Fedele et al., 2020). In a global stocktake of human adaptation to climate change, Berrang-Ford et al. (2021) found adaptation responses (documented in academic literature) to be largely incremental, and transformational adaptation was uncommon, also in high-risk cases. Transformational change is often described as system-wide or fundamental change with potential to alter paradigms, values and worldviews, as opposed to incremental change which operates within the system and where changes are made within existing structures (Deubelli & Mechler, 2021; IPCC, 2012, 2018; Manuel-Navarrete & Pelling, 2015, p 560; Park et al., 2012; Termeer et al., 2017). Transformational adaptation can be implemented in

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[1] The term Loss and Damage (L&D) with capitalised letters is used in political discourse, while losses and damages with lower case letters refers to the potential impacts once climate-related risks materialise (Mechler et al., 2019a). Losses and damages are generally divided into economic and non-economic (or monetary and non-monetary) losses and damages, where the latter include, for example, the loss of life, cultural and spiritual heritage, Indigenous knowledge, and impacts on health, human mobility, territory, biodiversity and ecosystem functions (Fankhauser et al., 2014; UNFCCC, 2013), as well as a sense of place and social cohesion (Roberts & Andrei, 2015: Serdeczny, 2019). Non-economic losses and damages, which make up a large portion of climate-related losses and damages, are seldom identified and measured and are consequently frequently excluded from both assessments and policy documents (Chiba et al., 2019; McNamara & Jackson, 2019; Mechler et al., 2020; Thomas & Benjamin, 2019; Tschakert et al., 2017; van der Geest & Warner, 2020).

[2] The term transformational change is used when referring to the outcome of the change process itself. Transformative change describes the change process.

anticipation of future climate-related challenges (Campos et al., 2016; Deubelli & Mechler, 2021; Mechler & Schinko, 2016; Termeer et al., 2017), or occur as a response to an incremental adaptation limit being reached (Deubelli & Mechler; 2021; Kates et al., 2012). Exactly what transformational adaptation should entail is still ambiguous and context-specific, and poor approaches can lead to harm and negative impacts for affected actors (Eriksen et al., 2021; Mach & Siders, 2021; Nightingale et al., 2021). Ajibade & Adams (2019) promotes an intentional and ethical approach to transformational adaptation, which centres participatory methods, flexibility, and decentralised governance, with a specific focus on justice and equity.

The comprehensive CRM framework upon which our CRM framework builds was developed with GIZ for application on national and state-level, to support assessment and management of climate-related risks, and deal with vulnerabilities, residual risks and losses and damages (Mechler et al., 2019b; Mechler et al., 2021). The framework follows a 6-step process, integrates DRR, CCA and policy and actions against residual risk, includes both incremental and transformational interventions and combines top-down approaches with bottom-up information through participatory methods. The 6-step process is meant to operationalize CRM while allowing for adjustments and improvements to the framework over time with increased insights.

3. Data & methodological approach

For this study we used and further developed a CRM framework built with GIZ for application in India in the context of L&D (Mechler et al., 2019b). Learning from the experiences since the introduction of the CRM framework, we further extended the previous 6-step approach by two more steps (steps 7 and 8 in Fig. 1). This allows for better highlighting that a CRM framework consists of, broadly speaking, two closely interlinked elements: (i) climate risk assessment (Steps 3–6) and (ii) decision making, implementation and monitoring of CRM measures (Steps 1–2 and 7–8).

The purpose of the resulting CRM framework is to facilitate management of climate risks in a comprehensive way. The purpose of step 1 and 2 of the framework is to identify information needs and objectives, and understand risk hotspots and capacities, in order to be able to answer the questions: what is the existing state of knowledge, who are the stakeholders, and what are their priorities and needs? In step 3 of the framework, a methodology is developed to assess the risk, paying due attention to differential vulnerabilities, exposures and adaptive capacities caused by intersectionality issues (i.e., how differences based on gender, ethnicity, income, location etc. are interacting). Following, in step 4 a qualitative and quantitative assessment of the current risk landscape is completed, also considering potential compounding risks. In step 5, risk tolerance and limits are evaluated, including adaptation limits and residual risks (resulting in both economic and non-economic losses and damages), and in step 6, adaptation and risk management options to avert, minimise and address the risks are identified, including both incremental and transformational changes. Step 7 introduces policy and decision making, with establishing funding of climate risk management policies and measures. Finally, in step 8, climate risk management policies and measures are implemented, monitored and evaluated. The CRM cycle is embedded in a learning loop framework (see e.g., Lavell et al., 2012), which allows for a system-wide transformative adjustment of the overall CRM processes, as well as implicit mental and analytical models in the medium to long-term. The cycle is complemented with two monitoring and evaluation cycles, where the first one takes place regularly to evaluate and incrementally improve methods and measures, and the

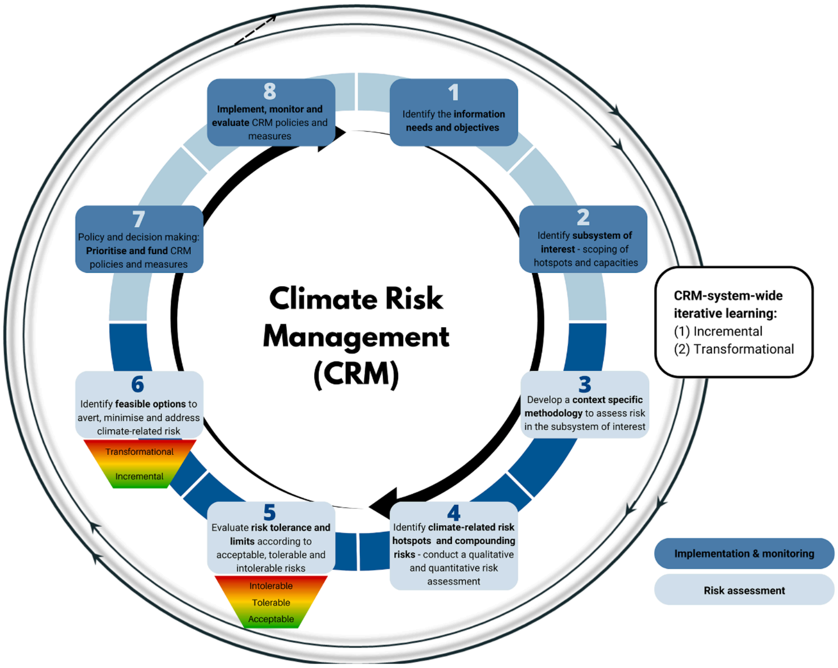

Fig. 1. Comprehensive Climate Risk Management (CRM) framework developed for and utilised in this study.

second one aims to be a longer-term learning process and answer whether the CRM cycle needs transformational changes. Embedding CRM into learning, monitoring and evaluation processes allows for addressing temporality issues, i.e., how are risks and response capacities changing over time due to climate change and socio-economic development. What follows more is that the individual steps of the CRM cycle do not necessarily have to take place linearly in the given sequence. For example, after step 8, step 4 and / or step 5 may be directly invoked as the implementation of certain CRM measures and policies affect risk assessment and risk tolerance evaluation.

The purpose of this paper is to analyse three cases of climate risk management and to which extent comprehensive CRM has been implemented in each case. For this purpose, we utilise our comprehensive CRM framework (Fig. 1). The cases are based on different socio-economic and geographical contexts; in South America, Asia and Europe, and include distinct spatial scales; from local in Peru (Carhuaz), to district in India (Nagapattinam), to national scale in Austria. The reasoning behind selecting complementary cases was to encompass several different sudden and slow-onset risks, socio-economic conditions, and experiences in approaching CRM, in order to provide a thorough discussion of CRM practises.

While the Peru study originally did not use the CRM framework as presented here, we post processed the information and approach, and present insights in light of a CRM. Literature utilised for the Peru case study were Reynolds et al. (1998), INDECI (2004; 2010a; 2010b), Carey et al. (2012), Frey et al. (2014), Schneider et al. (2014), Fluixá-Sanmartín et al. (2018), and Huggel et al. (2020b). The India case followed a 6-step CRM framework developed by Mechler et al. (2019b), which our framework is building on. Further literature utilised were a GIZ report conducted in 2017–2019 (unpublished), Adelphi (2015), and CRM initiatives from various state agencies. The Austria case study was based on work by Schinko et al. (2016), Mochizuki et al. (2018), Leis & Kienberger (2020), Leitner et al. (2020), and Schinko & Bednar-Friedl (2022), and partly follows a 4-step CRM cycle.

4. Case study analysis

In this section the three real-world climate risk management case studies are described and assessed.

4.1. Case study 1

Glacial lake hazard management and adaptation, Lake 513, Cordillera Blanca, Peru.

The assessment of case study 1 stems from 40 years of glacial lake outburst flood (GLOF) risk management at Lake 513, located in the Cordillera Blanca in Peru, see Fig. 2.

The more than 260,000 inhabitants of the Santa River Valley (also known as Callejón de Huaylas) in Cordillera Blanca are highly exposed to multiple mountain hazards such as avalanches, landslides and glacial lake outburst floods (GLOFs) (Frey et al., 2018). The livelihoods of the rural upland population consist mostly of small-hold farming and pastoralism (Carey et al., 2012). Whilst local knowledge about the region passed on through generations provides resilience, poverty, marginalisation and social inequalities render the rural population vulnerable to hazards, as they are lacking both anticipation capacities, as well as capacities to respond and

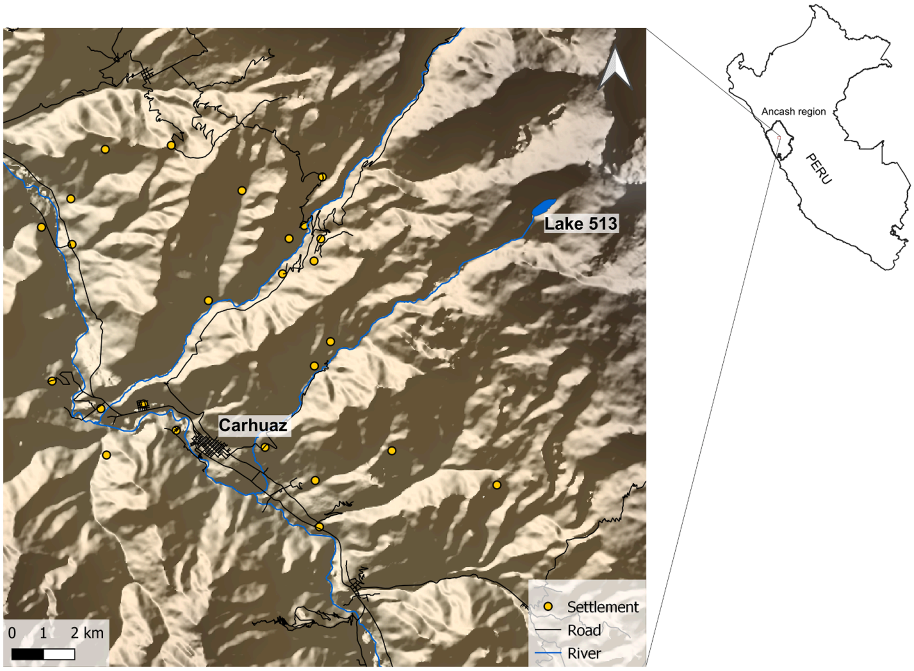

Fig. 2. Map over Peru case study region, including Lake 513 and catchment, the city of Carhuaz, and other settlements.

recover, while simultaneously often being forced to occupy more risk-prone areas. Additionally, a survey showed how residents in Nueva Florida, Huaraz perceived other risks as more severe, such as social and economic instability and changing their livelihoods, and were therefore reluctant to relocate from hazard-exposed areas (Huggel et al., 2020a). Corruption and an unstable government for several decades have weakened public institutions and public trust in decision makers and state agencies, including the glaciology division, thereby increasing vulnerability to glacier hazards (Carey et al., 2012).

One of the critical glacial lakes is Lake 513, located at 4428 m asl. at the foot of Mt Hualcán, upstream of the city of Carhuaz. The 25,000 inhabitants of the city, as well as the upstream settlements, crucial roads connecting the valley, houses, irrigation canals, agricultural land and animals are located in the risk zone of GLOFs from Lake 513 (Carey et al., 2012). Lake 513 started forming in the 1970s when glacier retreat of Glacier 513 uncovered a depression in its former bed (Portocarrero, 2014). It grew rapidly, reaching a critical state in 1988, when the freeboard at the dam was less than 1 m high, due to both increased lake volume and sinking of the moraine dam. While most of the lake was dammed by stable bedrock, the upper part of the lake was dammed by an unstable, ice-cored terminal moraine, posing an imminent risk to inundate the city of Carhuaz (Reynolds et al., 1998). The high-mountainous surroundings make the lake highly susceptible to rock and ice avalanches, which, when impacting the lake, can cause large displacement waves that can lead to an overtopping of the dam and erosion of the morainic material, thereby triggering GLOFs.

The Glaciology and Hydrological Resources Unit (UGRH), now called AEGL (Área de Evaluación de Glaciares y Lagunas) first identified Lake 513 as hazardous in 1988, which motivated risk reduction measures through government funding and engineering efforts. After the installation of a siphon in 1988, which did not significantly lower water levels, a second siphon was proposed. A 2000% inflation in Peru during the 1980s, together with intensifying terrorist activities in the region obstructed hazard management and halted the installation of a second siphon. Fortunately, private funding from Austria and the UK enabled the installation of the second siphon in 1989, lowering the water level by 5 m (Reynolds et al., 1998). Nevertheless, in 1991, an ice avalanche caused a GLOF with large displacement waves overtopping the dam, which, however, caused no serious damage due to the previous siphon instalments (Carey et al., 2012).

This GLOF event spurred further risk reduction measures: a 155 m tunnel was drilled through the bedrock to divert water, lowering the water by another 15 m. This led to the water being dammed only by bedrock instead of ice-cored moraine. Local authorities considered the lake to be safe (Reynolds et al., 1998; Carey et al., 2012). In 1997, an INAGGA report stated that despite the lake being safe, climate change could increase glacier instability and therefore the probability for large avalanches. Since avalanches are unpredictable, the report concluded that the only way to assure protection was to implement hazard zoning. Nevertheless, this suggestion was not implemented (Carey et al., 2012).

In April 2010, another GLOF event occurred due to a large rock-ice avalanche, causing a 25 m high push-wave, overtopping the dam by 5 m, with an overflow volume of approximately 1 million m^3 (Schneider et al., 2014). The flood affected the health of 100 people and nearly 700 animals, damaged the potable water system and 110 km of irrigation canals, disrupting water supply to Carhuaz and Acopampa for 15 days (the water system had been created without a risk assessment (INDECI 2004; 2010a)), and damaged houses, bridges and roads, including the main highway (INDECI, 2010a; 2010b; Carey et al., 2012). 5 ha of irrigated crop land and 6 ha of agroforestry and grazing land were directly affected (INDECI 2010b). In the aftermath of the GLOF in 2010, authorities from PRONAA (the National Food Assistance Program) delivered 1.2 metric tons of food and supplies to households most affected by the debris flow and heavy machinery began to clear debris and repair roads. Freshwater was delivered to Carhuaz and Acopampa communities through emergency distribution points (Carey et al., 2012).

The GLOF in 2010 made it evident that some residual risks were left after the construction of the drainage tunnel. Complete emptying of the lake would be the only way to reduce GLOF risk to zero, but this was and is not a feasible option due to water resources management issues, national park regulations, and the cultural understanding of landscape elements of the local population. On the other hand, without the lowered lake level, the volume and peak discharges of the flood wave would have been one order of magnitude larger (Schneider et al., 2014), leading to a major disaster with severe damages and potentially loss of lives.

After the 2010 GLOF, another rise in engagement in hazard management of Lake 513 was seen for Carhuaz local residents, authorities, and engineers, as well as international researchers. A new study of the lake was conducted and an international meeting was held by UGRH (Haeberli et al., 2010). However, local residents were not inclined to move out of exposed areas. This was due to other risks arising from relocation which the residents valued as more severe (Carey, 2008; Carey et al., 2012). Carey et al. (2012) suggested the proposed adaptation measure to relocate from exposed areas had social and cultural adaptation limits among local residents, which authorities and researchers failed to address. The authors indicated that the adaptation measure was met with doubt and contempt as it brought new risks of diminished local autonomy and power, relocation from homelands, and loss of identity and social status and networks (Carey et al., 2012).

A project to implement an early warning system (EWS) for the catchment developed. The project was a joint collaboration between the city of Carhuaz, University of Zurich and CARE Peru, and funded by the Swiss Agency for Development and Cooperation (Frey et al., 2014). Schneider et al. (2014) simulated the entire process chain of the 2010 GLOF event using physically-based numerical models. Modelling results and fieldwork resulted in a GLOF hazard map for the whole catchment (Schneider et al., 2014) that was also used for the design of the EWS (Frey et al., 2014). Community-based workshops using the CVCA tool by CARE (https://careclimatechange.org/cvca/) were organised, in order to understand vulnerabilities and capacities, as well as divergent risk perceptions and priorities of local residents and decision makers. Ethnographers were invited for months-long research visits to strengthen understanding of the different communities' risk perceptions, social structures and power relations. A strong and present concern for water availability became evident from the results of this research (Huggel et al., 2020b).

The installation of the EWS system was thought to complement the structural measures of the tunnel at Lake 513. The EWS was designed to register GLOF triggers and included an alarm system and evacuation routes. Its design and implementation were finalised in 2015. The system was officially handed over to the municipality of Carhuaz and functioned until 2016, when a severe drought hit the central tropical Andes and no rain fell during October and November. Farmers in the catchment depend on rain during these months and started to become desperate. The perception that the rain gauges and antennas of the EWS system were causing the lack of rain began spreading. Local residents requested to remove the system, and on 24 November about 200 residents gathered at Lake 513 and dismantled the stations. The dismantling affected the monitoring and warning sections of the EWS, but owing to the permanent wardens of the water intake installation in Pampa Shonquil, certain service could continue.

Investigations of this event revealed that political conflicts, and distrust and biases against external institutions had a strong impact on local residents' lack of acceptance of the EWS. Moreover, risk perceptions of local residents differed vastly from those of researchers, authorities and engineers. The risk of water scarcity was acknowledged by local residents as more severe than the risk of GLOFs from the lake (Huggel et al., 2020b). Further, the exclusion of sub-groups of local residents from decision-making, and tensions between communities interplayed in the outcome. Knowledge disparities and inadequate inclusion of traditional knowledge and narratives also played a part (Carey et al., 2012; Huggel et al., 2020b; Motschmann et al., 2020).

In 2014 another 30 m tunnel through the bedrock dam at Lake 513 was proposed to control the discharge and lower the water volume further. Controlling the discharge would allow for water storage during wet season and increase water supply during dry season. One main reason why the construction of the new tunnel, combined with a controlled water discharge has not been realised yet, is that the National Park regulations only allows for the implementation of risk reduction measures, but not for installations of water management infrastructure. The construction of a tunnel would therefore be possible, but only without a gate to regulate the runoff and water level. However, in view of the local population, the water management aspect has a much higher priority than the GLOF risk reduction aspect.

4.2. Case study 2

Tropical cyclones and compounding slow onset effects of sea level rise and salinization in Nagapattinam, Tamil Nadu, India.

The 6-step CRM framework presented in the conceptual background was originally developed with GIZ to inform and support national institutions to assess and determine their response to climate-related risks in terms of comprehensive risk management, including transformation (Mechler et al., 2021). It has been taken forward by the National Institute for Disaster Management (NIDM) for training and planning purposes and applied to other states in India, such as in Himachal Pradesh (see GoHP, 2020). We present the framework as applied to managing climate-related risks for rural households in Nagapattinam.

The Nagapattinam district in Tamil Nadu is located on the Southeast Indian coast (see Fig. 3) and has a population of 1.6 million people, of which 77% are considered rural. The high dependence on agriculture for earnings (82% of the population) makes the district vulnerable to climate variability. Fishery is the economic backbone, and tourism also plays a key role in the region. Nagapattinam is highly exposed to cyclonic storms, which often includes storm surges, strong winds of 320–350 km/h, and torrential rain of 30–40 cm/day, with high potential to cause both severe structural damage and loss of lives. More than half of the villages and towns in this district have a very high exposure level to cyclonic hazards. Around 37 villages are in a very high and high hazard category with respect to tsunami (Abarna et al., 2023). Similarly, Karuppusamy et al. (2021) report that around 60% of coastal villages have a high vulnerability score for multi-hazards. The coastline is 187 km and most of the 11 administration blocks are located below or between 0 and 5 m above sea level. Therefore, gradual sea level rise is exacerbating cyclonic impacts. A study by Muthusankar et al., (2013) found that about 0.6 million people will be impacted by a wave of around 5 m following a cyclonic storm. Salt water intrusion, heat extremes and drought are leading to salinization of soil and groundwater, affecting both drinking water and agricultural land (see Abarna et al., 2023). Between 1981 and 2000, 62 cyclonic storms crossed the Tamil Nadu coast, 7 of which having occurred in the last decade. The cyclones and the tsunami of 2004 had the most devastating impacts, when over 6000 lives were lost (out of which 1776 were children). A large number of the casualties came from the fishing community. Severe damage was caused to houses, schools, and public health centres (GIZ, unpublished). A total of 1,320 ha of agricultural and non-agricultural land was ultimately affected (Ramalingam et al., 2007). In summary, several studies have reported that the coastal stretch of this district has a very high to high level of exposure to multiple hazards, including cyclonic storms, coastal flooding, tsunamis, salinization, sea level rise, etc. (Abarna et al., 2023; Karuppusamy et al., 202; Muthusankar et al., 2013). Further, the Indian Department of Science and Technology - DST (2020) reported that this district is highly vulnerable to climate variability.

These incidents spurred several climate risk management efforts in Nagapattinam, among others an integrated climate risk and vulnerability assessment under GIZ. To first establish the baseline hydro-climatic and socio-demographic context, as well as hazard, exposure and vulnerability conditions, the State Disaster Management Plan (Tamil Nadu State Disaster Management Authority, 2018), Tamil Nadu State Action Plan on Climate Change (TNSAPCC, 2019) and other literature were utilised. An initial inception meeting with 13 participants was then carried out, to stake out the priorities, key risks and adaptation needs.

Levels of livelihood and infrastructure risk were identified for the baseline (1981–2010) and mid-century (2021–2050) time periods, the latter based on climate scenarios RCP 4.5 and RCP 8.5. Livelihood risk was projected to increase for the mid-21st century, for both scenarios, with all of the blocks moving into higher risk categories. In total, 3 blocks moved into extremely high-risk conditions for RCP 8.5. Flood discharge, drought weeks, warm days, and heat stress for animals and humans were all projected to increase towards mid-century. For mid-century, infrastructure risk was projected to increase for half the blocks with RCP 4.5, and fewer in RCP 8.5, due to a larger increase in floods and precipitation under RCP 4.5 compared to RCP 8.5.

No changes in cyclone trajectories were considered due to high uncertainties in modelling future trajectories, however, future losses were estimated based on a mean increase of 9% in maximum cyclonic wind speeds and 30% increase in cyclonic rainfall rate in the North Indian Ocean under a 4 °C warming scenario (after Yoshida et al., 2017). No changes in vulnerability were included for the

Fig. 3. Location of Tamil Nadu state (yellow) and the district of Nagapattinam (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mid-21st century risk index, due to the lack of a robust approach to project changes in vulnerability at this scale.

In order to receive the perspective of local residents, a focus group meeting (56 participants) and two community level field-surveys (with 62 participants from fishing communities and 69 participants from agricultural communities) were executed. The community surveys highlighted flooding and cyclones as the greatest threats, compounded by other climatic and non-climatic stressors. For farmers, a combination of heavy rainfall, storm surges, and winds associated with cyclonic storms was identified to cause damage to crops and houses. There was a strong perception (98%) that climate change had an effect on agricultural profitability. For fishing communities, cyclonic storms were identified as the driver of risk, in terms of strong wind rather than rainfall, and tsunamis were the primary non-climatic physical driver. Increasing numbers of boats and exploitation of fish stocks were key compounding factors, leading to declining catch numbers and loss of income (see Nambi & Bahinipati, 2012). Reportedly it took 2–5 years for farmers to

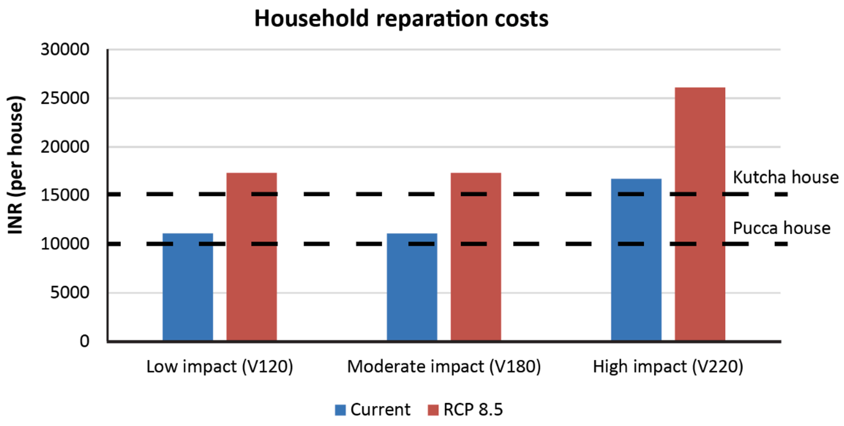

Fig. 4. Current and future potential losses to houses from cyclonic storms (INR per house), showing comparison with level of compensation (dashed lines) provided by the government in response to Cyclone Gaja in 2018 for kutcha (non-concrete constructions) and pucca (concrete constructions) houses. (Figure from GIZ, unpublished).

return to normal conditions after a severe cyclonic storm. Salinization was a major issue, with both health effects from consumption of saline water, and crop failure. The fishing community perceived high impact and economic losses across all blocks from cyclones. The participants indicated there is a loss of 2–4 months' worth of working days following a moderate impact cyclonic event, which accounts to around INR 15,000–20,000 (equiv. to ~ EUR 170–230). Migration and psychological stress were identified as important non-monetary impacts related to climate risk, in both communities.

Monetary losses were calculated for damage to crops and related loss of earnings, and for damage to houses. Combined with information on average annual incomes and land holding size, average household losses at block level were estimated at INR 6,957 (equiv. to ~ EUR 80) per acre. By mid-21st century under a future scenario of increasing compound risks under RCP 8.5, including an increase in cyclonic rainfall rates (after Yoshida et al., 2017), 8 out of 11 blocks in Nagapattinam could face losses from tropical cyclone events equivalent to what would be expected currently only within high and very high-risk zones. Household damage under different velocity cyclone events were modelled under current and future (RCP 8.5) conditions. When compared to reported compensation levels received from the government in the aftermath of Cyclone Gaja (based on community surveys and media articles), it can be clearly demonstrated that compensation falls considerably short of the household repair costs faced after high impact events (Fig. 4). This shortfall will significantly increase in the future if compensation levels are not increased in line with the expected change in cyclonic strength under RCP 8.5, especially for the highest impact events. An adaptation scenario was also included, revealing that damage could be partly avoided through a 10% increase in the percentage of concrete houses, with reduced losses of 25% for low impact, and up to 33% for high impact events. After Gaja the state government provided financial support within Pradhan Mantri Awas Yojana to construct pucca houses in cyclone affected areas (see https://tnsdma.tn.gov.in/app/webroot/img/gos/sdrf/G.O.648.pdf). However, above a certain wind speed no houses can be saved. Additionally, mud houses (kutcha) are better suited for extreme heat.

A wide spectrum of potential risk reduction, preparedness and risk financing measures can be applied in order to reduce vulnerability and risk to communities in Nagapattinam. Focus was given to bottom-up scaling of measures that were already proposed and/or initiated by the community. More options were identified for farmers than for fishing communities, with for example using water from bonds, borewells and hand pumps, and embankments and tillage to reduce soil salinity. Likewise, Dhanya and Ramachandran (2016) conducted a survey among farmers in the Kancheepuram district, one of the coastal districts in Tamil Nadu, and revealed proposed adaptation measures from farmers included construction of small check dams, revive farm ponds, livelihood diversification, altering farm operation and crop calendar, crop weather insurance, early warning systems, and drought/salt tolerant seeds. For fishermen, transformative adaptation could include migration, and investment in human capital. However, incremental actions such as repairing nets and boats and using loans were more common. For farmers, incremental adaptation could include altering crop calendars and compensation schemes from the government. Forced transformation included switching livelihoods. Income diversification was encouraged, so when there's high soil salinity after a storm or tsunami which disrupts uptake of agricultural activities, other activities can still generate income.

For farmers, four specific concrete recommendations for adaptation were further elaborated in greater detail: (1) Introduction and increased use of bioshields (coastal vegetation) to protect against storm surges and wind. (2) Reducing salinization through improved data collection and groundwater modelling, leading to improved soil and water management. (3) Encouraging use of traditional crops/ species which succeed in saline soils, for example through subsidies from the government. (4) Higher uptake of crop insurances, through awareness and information campaigns. After Pradhan Mantri Fasal Bima Yojana (a scheme by the national government to provide crop insurance to farmers at a low premium rate) launched in 2016, various states observed a rise in the amount of cultivated land under insurance, ~21% for Tamil Nadu in 2017–2018 (Rajeev & Nagendran, 2019). A survey of 200 households in Nagapattinam and Thiruvarur districts completed in 2021[3] found farmers are currently undertaking several coping and adaptation mechanisms, for example diversification of income, selling (non) agricultural assets, seasonal migration, crop diversification, and soil and water management options.

The GIZ study focussed on assessing and informing, not implementation, so it did not cover steps 7 and 8 of our CRM framework. However, continued work in the district can provide some information on these steps. Various government agencies and initiatives are working to prioritise, implement, monitor and evaluate CRM policies and measures (see Bahinipati et al., 2021 for details).

4.3. *Case study 3*

Assessing and managing water-related risks (riverine flooding and agricultural drought) in Austria at a national level.

The Austrian case study is a nationwide analysis of the current state of CRM for riverine floods and agricultural droughts, which are the most prominent climate-related risks in Austria (Leitner et al., 2020). Recent flooding events on record occurred in 2002, 2005, 2013 and 2018, with the first three contributing to several billion Euro in damage (Leitner et al., 2020). Insured losses attributed to agricultural drought between 2013 and 2019 were on average EUR 123 million per year (Austrian Hail Insurance, 2019).

Precipitation is the main driver of both flood and drought hazards. Annual precipitation varies widely within the country, due to topographic differences and several climate regimes with a stronger continental influence towards the east, from 500 mm per year in the northeast, to greater than 2000 mm per year in the Alps (Leis & Kienberger, 2020). The Austrian Panel on Climate Change found in its national assessment that climate-related risks will increase in the future, both due to climatic changes and changes in socio-economic conditions. The assessment recommended upgrading adaptation efforts (APCC, 2014).

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[3] The household survey was carried out as part of the research project sponsored by Indian Council of Social Science Research (G-3/2017–18/ ICSSR/RP), New Delhi.

Table 1

Case studies summarised according to the 8-step CRM framework described in section 3.2. Steps 1, 2, 7 and 8 represent the decision making, implementation and monitoring steps, and steps 3, 4, 5 and 6 the climate risk assessment steps.

	Peru	India	Austria
Step 1. Status quo- Identify the information needs and objectives	**1988** - **2010** Clarification of needs together with local municipality and state and non-state actors through workshops and meetings.	Identify stakeholders and information needs through stakeholder mapping and desk-based review. Target group is decision-makers at district level. Overall findings also relevant at state level.	Identification of relevant CRM actors and governance structures through desktop research and structured qualitative interviews (n = 14) (Leitner et al., 2020).
Step 2. Identify subsystem of interest - Scoping of hotspots and capacities	**1988** Lake mapping and assessment in Cordillera Blanca.Annual control of GLOF risk for Lake 513 by UGRH. **2010** Subsystem of interest already identified when project started.	Risk hotspots, data coverage and availability, as well as needs and expectations of stakeholders identified, through desk-based review, inception workshop and focus group meetings.	Two stakeholder maps, one for floods, one for droughts. Stakeholder-activity matrix (Leitner et al., 2020).
Step 3. Develop a context specific methodology to assess the risk in the subsystem of interest	**1988** - **2010** Community based assessment, geographical boundaries of catchment, which processes to include.	Developed methodology based on information retrieved in step 1 and 2. Climate risk analyses for current and future projections, considering also future changes in population.	Development of a Stochastic fiscal debt modelFurther developing the CRM circle.
Step 4. Identify climate-related risk hotspots - Conduct a qualitative and quantitative risk assessment	**1988** GLOF assessment by experts. **2010** Community workshops using CVCA tool, ethnographers stayed with community, fieldwork, numerical modelling, hazards and risk mapping.	Indicator-based risk assessment based on 54 indicators for hazard, exposure and vulnerability.Soil and Water Assessment Tool (SWAT) modelling for water/drought stress and floods. Temperature and precipitation projections from CORDEX regional climate model. Projected cyclone activity from Yoshida et al. (2017).Exposure from satellite imagery and Census India (Census, 2011) data, with population trends extrapolated from 1991 to 2011 to mid-21st century. Vulnerability assessment data (sensitivity and adaptive capacity) (Census, 2011), focus group meeting and community field-surveys.	Risk- and vulnerability assessment (spatially explicit, 14 primary and 35 sub-indicators, (Leis & Kienberger 2020).Application of a probabilistic model (Schinko et al., 2016) and a stochastic debt assessment (Mochizuki et al., 2018) for fiscal flood risk assessment.
Step 5. Evaluate risk tolerance and limits according to acceptable, tolerable and intolerable risks	–	System's capacity to reduce and adapt to risks was evaluated through:- Focus group meeting to learn from past experiences and losses.- Expert judgement and evaluation.	Evaluation of fiscal flood risk projections against the Austrian disaster fund.
Step 6. Identify feasible options to avert, minimise and address climate-related risk	Several short-term and longer-term measures were identified and implemented, often in relation to lake outbursts.	Evaluation of a wide range of incremental and transformational adaptation options. Focus group meetings helped identify community perceptions and needs. A variety of adaptation measures were undertaken at farm and household-level.	Suggestion to implement a varied portfolio of instruments, each applicable for a certain layer of climate-related risk (Schinko et al., 2016), combining short-term and long-term responses and adaptation (Leis & Kienberger, 2020) and aligning DRR and CCA (Leitner et al., 2020).
Step 7. Policy and decision making: Prioritise and fund CRM policies and measures	**1988** - **2010** Part of budget of municipality to maintain EWS.	Various agencies are working to prioritise and fund CRM policies and measures.	Role-play simulations for identifying a feasible portfolio of CRM measures at the local level in Austria (Schinko & Bednar-Friedl, 2022).
Step 8. Implementation, monitoring and evaluation of CRM policy and measures	–	Various government agencies are responsible to implement CRM policy and measures.	Role-play simulations for identifying roles and responsibilities in Austrian CRM (Schinko & Bednar-Friedl, 2022).

Investigations of the current state of comprehensive CRM of flooding and agricultural droughts in Austria are underway. Efforts to define high- and low CRM-related activity and institutional overlaps through detailed activity matrices and governance maps for the Austrian situation showed some activities clustered in certain phases, for example in climate risk analysis, while other sub-phases had low or no activity, such as preparedness and response/coping (see Leitner et al., 2020, Appendix Table 1). There was also a lack of detailed awareness amongst stakeholders of the activities of others, and no clear linkage between CCA and DRR. However, some initiatives, such as the Natural hazards and Climate Check for Austrian municipalities, are working in this direction (Lexer et al., 2018). Future climate risks are increasingly considered, for example with the mandatory inclusion of potential climate change consequences in the Austria flood risk management plan from 2021 onwards. However, future climatic and socio-economic developments are inadequately considered in risk management as of yet, especially for agricultural drought risk management (Leitner et al., 2020). The study by Leitner et al. (2020) included a literature review and relevant stakeholder involvement in the form of 14 interviews and two workshops. Two stakeholder maps, one for drought risks and one for floods, were plotted in a participatory manner. Moreover, two stakeholder activity matrices were created, with a special regard to CRM-relevant activities and following a 4-phase CRM cycle (which integrates Disaster Risk Management (DRM) and CCA activities into (1) inventory, (2) climate risk analysis, (3) CRM measures identification, and (4) CRM measures implementation) adapted from Schinko et al. (2016).

While flood discharge in Austria has increased recently, it is still within the natural flood variability according to climate projection analysis (Blöschl et al., 2015; Leis & Kienberger, 2020). When predicting flood trends there is uncertainty, especially associated with precipitation projections. However, studies have begun to attribute an expected increase in extreme events with anthropogenic climate change (Chimani et al., 2016), with e.g., higher winter runoff expected in the Alps (Blöschl et al., 2018). Concerns of lack of data, as well as uncertainty in data and scenarios were also emphasised by some of the 14 stakeholders interviewed by Leitner et al. (2020).

In order to accurately map climate-related flood risks in Austria, Leis & Kienberger (2020) applied a spatial Climate Risk and Vulnerability Assessment (CRVA), using a combination of the IPCC AR5 risk framework (IPCC, 2014) and the MOVE risk framework (Birkmann et al., 2013). The assessment resulted in maps of homogenous regions of risks and vulnerability, hot- and coldspots, as well as typologies of risk and vulnerability. The risk and vulnerability assessment included 14 primary indicators and 35 socio-economic sub-indicators, chosen mainly by relevance of indicators for flood hazard assessment and applicability to vulnerability. The vulnerability indicators included for example transport infrastructure, ecosystem services, land use, early warning systems, education and accessibility (see Leis & Kienberger, 2020, Table 1 for complete indicator list). From the study, hotspots of socio-economic vulnerability to floods emerged in the northern and eastern regions of Austria, whilst when including a hazard proxy (max 5-day precipitation, including projections with RCP 4.5 and RCP 8.5), risk hotspots were identified in central-northern and eastern Austria. With future scenarios, an expected increase in max 5-day precipitation was visible for the east (RCP 4.5) and central-northern Austria (RCP 8.5). Coldspots included eastern and southeast areas, and valleys in the west. A main challenge from the study was validation of the results, and the authors recommended a strong stakeholder involvement to further derive complexities and uncertainties.

Climate-related risks may also impose severe stress on public budgets, potentially requiring a change in how these fiscal risks are currently dealt with. To shed more light on this aspect, Schinko et al. (2016) probabilistically projected flood-induced fiscal risk and compared it with budgetary allocations to the Austrian disaster fund, the country's main policy vehicle for coping with disaster impacts. The authors found that the fund's endowment is sufficient to cover the expected losses in 2015. However, this changes until 2030, when contrasting the development of expected annual flood losses, Schinko et al. (2016) found that neither in 2030 nor in 2050 will this endowment be sufficient to cover expected annual losses, and severe stress could be put on the disaster fund's financial resilience.

In a follow-up study, Mochizuki et al. (2018) applied a stochastic debt model and assessed the potential flood risk in Austria to the public debt and the national disaster fund. Their results indicate that public debt under no fiscal consolidation is estimated to increase from the current level of 84.5% relative to GDP in 2015 to 92.1% in 2030, with macroeconomic variability adding further risk to the country's baseline public debt trajectory. The study finds that the estimated public contingent liability due to expected flood risk is small relative to the size of the economy. The existing earmarked DRR funding will likely reduce the risk of frequent and low impact floods, yet the current budgetary arrangement may be insufficient to deal with rising risk of extreme floods in the future. This prompts the need for further discussions regarding potential reforms of the disaster fund.

Instead of relying on a single risk management tool, as is still often the case in for example flood risk management practice with a strong emphasis on structural building measures, Schinko et al. (2016) suggested employing a more comprehensive and integrative approach to CRM. The authors argued that, as there are different kinds of climate-related risks, some occurring frequently with only minor impacts while others occurring fairly infrequently but with devastating consequences (low and high return period events, respectively), Austria, as well as other countries, should employ a varied portfolio of instruments, each carefully chosen to be applicable for a certain layer of climate-related risk and, based on the evidence available, iteratively adjusted over time.

To close prevailing science–policy–implementation gaps in Austrian CRM, Schinko & Bednar-Friedl (2022) co-developed and conducted a role-play simulation centred on riverine-flood risk with local stakeholders in the city of Lienz and the city of Innsbruck. This is because these gaps are often a result from insufficiently clear roles and responsibilities, diverging stakeholder interests, priorities and risk perceptions, and inexistent or incipient cooperation mechanisms. After taking part, the diverse societal stakeholders were found to better understand: (i) the interacting dimensions and drivers of riverine-flood risks; (ii) the diverging risk perceptions; and (iii) each other's interests and needs in addressing such risks at the individual and institutional level.

Recommendations for improvement include improving the Austrian disaster fund, by allowing building back better after a catastrophe, and complementing the fund with natural catastrophe insurance systems to deal with private losses. Tackling even higher layers of climate risk, characterised by flood risk return periods of 500 years and beyond, Schinko et al. (2016) suggested to foster national and international risk financing and risk absorption schemes, such as the European Union Solidarity Fund (EUSF) or regional risk pools. These scientific insights have however not yet been picked up by CRM practice in Austria. To overcome the current challenges towards a comprehensive CRM approach in Austria, Leitner et al. (2020) suggested the creation of a legally-anchored national risk council where climate change would be classified as one of the risks.

5. Discussion

We now proceed to discuss to what extent comprehensive CRM has been achieved in the three cases, and share comparative similarities and differences, strengths and weaknesses in the deployment of the CRM framework in the different cases. We finish with a synthesis of policy and research recommendations towards an achievable CRM in practice.

5.1. Aim I. Evaluate to what degree comprehensive CRM has been implemented in real world circumstances

In order to assess whether comprehensive CRM has been implemented in the three case studies, the 8-step comprehensive CRM framework (described in section 3.2) was applied to each case; the results are summarised in Table 1.

Since the risk management in the Peru case study did not follow a specific CRM framework, it is perhaps the most interesting to compare to our conceptual CRM framework. The initial risk management in 1980–90 s was an ad-hoc, straight forward approach, mainly consisting of engineering measures focused on reducing the hazard from the lake. It did not address exposure and vulnerability. Neither was there an explicit identification of information needs and objectives on record (Step 1 of the CRM framework). Rather, it was the imminent threat of a GLOF (which became evident through mapping of Lake 513) that spurred initial action. The management cycle started with the identification of adaptation options, available funding and policy decisions, both for the siphons and tunnel in the 1980–90 and the EWS in 2010. (CRM step 6 and 7). It demonstrates how actual risk management does not always follow the CRM steps in the described order. Political settings, the priorities of the local government, funding, and path-dependency will play a role in where and when CRM commences.

It would likely not have been possible to implement the entire CRM framework for Lake 513 in the 1980s, due to both lacking funds and political tension. Nevertheless, risk management was successful in significantly lowering GLOF risk for the city of Carhuaz and upstream settlements. This became evident also with the GLOF in 2010, which without the siphons and tunnel would have resulted in a major disaster (Carey et al., 2012). The implementation of an EWS aimed at complementing the structural measures by managing the remaining risk by a reduction of exposure and vulnerability. With the destruction of the EWS stations, the effectiveness of this measure was reduced greatly, but not completely eliminated, since efforts and measures on improving risk understanding, communication, and response capacity still had an effect. Risk management in the 2010s was much more comprehensive than in the 1980s, and did in fact coincide with steps 1, 2, 3, 4, 6 and 7 of the CRM framework (see Table 1), although not accounting for differential vulnerabilities and exposure (step 3) and compounding risks (step 4).

The risk management at Lake 513 did not specifically include an evaluation of the risk tolerance and limits (step 5). However, several adaptation limits can be identified related to economic, cultural, institutional and political conditions. Terrorist activities and a 2000% inflation in the 1980s obstructed hazard management and initially halted the installation of a second siphon. Moreover, management of the UGRH shifted seven times among five different state agencies between 1973 and 1990. This altered the agency's mission, reduced public support and caused funding shortages, all of which influenced why drainage of the lake ultimately took six years (1988–1994) (Carey, 2010; Carey et al., 2012). Step 8 of the CRM framework, containing implementation, monitoring and evaluation of CRM policy and measures, was largely not found for the Peru case study. The implementation of the EWS was finalised in 2015, and handed over to the municipality in Carhuaz in 2016, shortly before a group of local residents gathered to dismantle it. The dismantled EWS could either qualify as another adaptation limit being reached, or as failed comprehensive climate risk management. Local residents risk perceptions not coinciding with that of researchers, authorities and engineers, exclusion of parts of the affected population, insufficient inclusion and weight given to Indigenous and local knowledge and narratives, and political and institutional distrust all played a role in the outcome of this event. An identification of information needs and objectives (step 1) prior to deciding the direction of risk management with clear inclusion of all affected actors in the decision making, and monitoring and evaluation of the implemented CRM measure (step 8) could possibly have resulted in a different outcome.

Meanwhile, the India case followed a 6-step CRM framework developed by Mechler et al. (2019b) and which formed the basis for the 8-step CRM framework employed in this study. In the Indian case, all six steps were evidently followed (see Table 1), although with a few limitations. The small sample size of field surveys, due to the project's time and budget limitations, meant that survey results on block-level were rather indicative than representative. Furthermore, stakeholders' reservation to answer sensitive questions about earnings, investments and (sometimes illegal) secondary sources of income led to gaps, and possibly distortions, in the data. A third limitation was the high uncertainty in predicting future vulnerability and exposure. Ultimately, there was no inclusion of vulnerability projections, and the projected risk index was only based on changes in hazard and exposure (extrapolated population trends). Attempts were made to use population and development scenarios under Shared Socioeconomic Pathways (SSPs), but the currently available data was too coarse for a block- or village-level analysis. Another important aspect to consider is that major non-climatic events, such as tsunamis, can also lead to fundamental shifts in local socio-economic development. A fourth limitation was the high uncertainty in projecting cyclone activity. Small changes in cyclone trajectories over time could lead to significant changes in land area affected by cyclones, yet were not considered.

The GIZ report did not cover steps 7 and 8 which have since been added to the CRM framework. Adding these two steps puts a stronger emphasis on decision making, monitoring and evaluation processes, while the earlier 6-step approach was slightly biased towards risk assessment steps. Without including step 7 and 8 there is no guaranteed continuation of funding for adaptation measures, as well as monitoring and evaluation of CRM policies and measures in place. However, further investigations show that various agencies currently do work in the direction of funding, implementing and monitoring CRM policies and measures, building at least partially on the report findings. Moreover, farmers in Nagapattinam are currently undertaking a wide range of adaptation measures against climate risks, many of which were addressed in the GIZ report.

The Austria case diverges from the other cases presented in this paper in that it is a nation-wide CRM assessment, and covers a country which is considered to be part of the Global North, where, for example, the discourse on adaptation limits takes a different shape. Nevertheless, large economic losses are already attributed to climate-related droughts and flood hazards (Austrian Hail Insurance 2019; Leitner et al., 2020), and risks are expected to increase in the future. All eight steps of our CRM framework have been addressed by different studies for Austria, though not every study covered all steps. Leis & Kienberger (2020) were determining hazards, exposure and vulnerability on a country-wide level, rather than local or regional, which lead to a coarser resolution than in the other cases. However, the authors were still able to stake out areas of higher socio-economic vulnerabilities and risks. The assessment of climate-related risk (step 4) and risk tolerance (step 5) was also attended to in terms of flood risk projections in relation to the Austrian disaster fund and public debt (Mochizuki et al., 2018; Schinko et al., 2016). The case study suggested the implementation of varied responses and adaptation measures, to avert or minimise risk (step 6), and discussed (by employing the concept of risk layering) how to prioritise measures (step 7). It did not, however, cover specific adaptation options or other ways of averting risk. Finally, steps 7 and 8 were also attended to through local role-play simulations of flood and drought risk management (Schinko & Bednar-Friedl, 2022). For Austria, lack of awareness amongst stakeholders of the activities of each other, as well as a general lack of access and availability of data and uncertainty in data and scenarios was revealed. A comprehensive CRM, connecting the fields of DRR and CCA, is not yet established in Austria. However, if areas of currently low CRM-activity, as well as uncertainties and unknowns are considered it could lead to more robust decision-making.

5.2. Aim II. Draw out comparative similarities and differences, strengths and weaknesses in the deployment of the CRM framework in the different cases

The case studies were all analysed based on their way of addressing climate-related risk (including the risk components hazard, exposure and vulnerability, and compounding risks), as well as losses and damages, whether risk management included participatory methods, whether both economic and non-economic losses and damages were accounted for, and whether both incremental and transformational adaptation measures were considered.

The way of addressing risk, and the risk components hazard, exposure and vulnerability, as well as losses and damages differed in the three cases. Up until the dismantlement of the EWS, no assessments of future vulnerability and exposure were completed for the Peru case, which rather focused on the present and future threat of GLOF hazards. However, Motschmann et al. (2020) did cover projected vulnerability and exposure for the catchment. The case mentioned several economic (destruction of houses, water service infrastructure etc.) and a few non-economic (effects on human health) losses and damages. The GIZ report for the India case brought up several benefits of using a risk rather than vulnerability assessment (the latter most commonly used in state action plans in India). It allows for inclusion of and separation between all/most factors contributing to climate-related loss and damage, whereas traditional vulnerability assessments often lead to a broad identification of districts being highly vulnerable, without the ability to find out what drives the vulnerability, and how adaptation measures or risk reduction can be adjusted accordingly to reduce impact. The assessment of losses undertaken in Nagapattinam focused on losses due to crop damage, and physical damage to houses. While this may well represent the quantifiable losses that are of most direct significance to the rural population, a more comprehensive CRM approach would need to consider additional losses, both monetary and non-monetary. This includes, on the one hand, quantifiable losses from disruption to trade routes, or due to loss of secondary sources of income (such as tourism), and on the other hand, losses that may be more difficult to quantify, relating, for instance, to mental and physical health impacts. In Austria, risk and risk tolerance were assessed and investigated, however only in terms of economic losses for the public sector, non-economic losses were not considered.

The Peru and Austria cases focused on risk reduction of one or a couple of climate-related hazards, rather than having a system wide focus on risk management, including compounding or cascading risks. This can be explained by policy, institutional and financial constraints, together with the fact that systems thinking and compounding risks are rather new concepts in climate risk management. However, the India case considered both rapid and slow-onset climate-events, and investigated the compound effects of flooding and cyclones together with rising temperatures, water scarcity and salinization. This allowed for a proposal of an integrated response mechanism which includes both climate change adaptation and disaster risk management.

Participatory methods are a crucial part of comprehensive CRM, including the planning stage, during the initial phases of a project when identifying needs and objectives, during decision making and for knowledge sharing. In the Peru case, participatory measures and efforts to collaborate with residents included stakeholder workshops, but were insufficient in including all perspectives, needs, knowledge bases and relationships. The Nagapattinam case study included both a top-down and, a more limited, bottom-up approach. Scientists from the region performed community surveys, to enhance the level of trust among participants. However, sample sizes of the field surveys would have needed to be larger, to achieve a more comprehensive and representative stakeholder inclusion across all district blocks. Identification of stakeholders, risk hotspots and risk indicators was arguably comprehensive. Stakeholders were identified with stakeholder mapping, and thereafter needs and objectives were outlined. The study identified risk hotspots, which ultimately led to the decision of the district as a focus area. However, data availability and coverage also mandated the selection. In regards to participatory approaches in the Austria case, stakeholder involvement was present in the form of interviews and workshops (Leitner et al., 2020; Schinko & Bednar-Friedl, 2022), and the flood vulnerability and risk maps were validated in a small workshop with stakeholders. Identifying needs and objectives (step 1) in the three cases was done by a combination of desk-based reviews, stakeholder mapping, workshops and interviews, however none of the cases state if stakeholders were involved in the actual decision-making.

For Lake 513, there is no mention of transformational risk management. Likewise, none of the Austria literature explicitly mentions transformational change in terms of adaptation measures. This can be due to the Austrian CRM discourse focusing on incremental adjustments to established risk management approaches, as current levels of climate-related risk are generally not perceived as intolerable or as transgressing societal adaptation limits. However, in Nagapattinam, the risk assessment covered a multitude of both incremental and transformational adaptation measures for farmers and fishermen.

5.3. Aim III. Synthesise policy & research recommendations towards an achievable comprehensive CRM in practice.

The three cases have different spatial as well as socio-economic contexts. The complexity of the different cases allowed us to understand where the CRM framework is more and less favourable, which elements are important across cases, and which elements are case specific.

The Peru case helped raise the issue of when and where a CRM framework is implemented. In this case, risk management was rather kick-started due to a hazardous event. This is the case for multiple other risk-prone regions. Moreover, also evident from the Peru case was that in real-world CRM, all steps are not always followed, or even applicable. Risk management might start at any step in the cycle, contain only parts of the cycle or have elements not included in the framework. Another outcome of this study was how risk tolerance levels are both context specific and subjective. Risk tolerance assessments will need stronger consideration in the future, including the appropriate methodologies, transdisciplinary research approaches and inclusion of a wide range of stakeholders. A consideration of social, political and cultural conditions is crucial for a successful implementation of CRM, with a leading role given to local residents. CRM should be participatory (including in decision making) from beginning to end, in order to adequately account for the knowledge, needs and desires of all involved partners.

Both the India and Austria case study used RCP 4.5 and 8.5 for future projections. We would recommend including a low-emissions scenario as well, in order to show challenges that arise even if we manage to contain global warming to 1.5 °C. Similar for all three cases were difficulties in predicting future risk, including projected vulnerability, exposure and hazard. Future assessments should take this into consideration, since adaptation measures implemented now should ideally avert risk also in the long-term.

The distinction between transformational and incremental change and adaptation measures is largely not used in the case studies, with the exception of the India case. Rather, the changes and adaptation measures that were available and viable were also implemented. However, due to increasing levels of intolerable risk and losses and damages, as indicated in our case study insights, transformational change will likely become a larger part of CRM practises in the future. We want to emphasise that, if applying transformative change, it should be equitable, just and sustainable (Ajibade & Adams, 2019; Gram-Hanssen et al., 2021). A systems thinking approach, including compounding risks, can allow for a more holistic view of the situation at hand, and can prevent risk management aimed at one hazard from increasing risk elsewhere in the system.

5.4. Learnings and limitations of the study

What is important to consider for similar future research exercises is that the conceptual CRM framework is deliberately kept generic to render it universally applicable. This means that it does not accommodate for all context specific aspects of real-world risk management examples by default. Hence, before use, the framework has to be contextualised for each specific case. Our positionality and unconscious biases are also important to consider: we are primarily researchers from Global North, assessing risk management in two locations in the Global South, based on a conceptual CRM framework which was developed by us and European colleagues. For future research we therefore suggest to further develop the CRM framework with expertise from the Global South, and to maximise the involvement of local researchers and practitioners in further applications of the framework.

6. Conclusions

We applied a conceptual CRM framework to real world cases of risk management in three different geographical contexts and scales, to infer to what extent comprehensive CRM has been implemented in each case, and to identify the benefits and challenges encountered. We find that not all real word cases implemented all 8 steps of the CRM framework. Based on our ex-post analysis we conclude that cases which did so were able to derive clear policy recommendations to foster integration of DRR and CCA towards comprehensive CRM and associated risk management and adaptation measures. Cases where not all steps have been implemented show a high degree of policy fragmentation but can nevertheless be highly successful in certain risk reduction efforts. Future CRM practice will benefit from following a framework as presented here - contextualised to the respective case - that provides adequate guidance and structure to successfully implement comprehensive CRM, while still being flexible enough to enter the process at any of the eight given steps. Moreover, future policy and research measures should take into consideration risk projections as well as external conditions, such as other climate- and non-climate-related risks emerging or changing socio-economic or political contexts, which can create limits to CRM. Future CRM approaches will benefit from being participatory from beginning to end, considering compounding risks, and exploring different adaptation pathways, including (just and equitable) transformative adaptation measures necessary for adhering to current and projected future increases in climate-related risks.

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.

Data availability

No data was used for the research described in the article.

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