Progress in Disaster Science 23 (2024) 100337

Contents lists available at ScienceDirect

Progress in Disaster Science

journal homepage: www.elsevier.com/locate/pdisas

Managing residual flood risk: Lessons learned from experiences in Taiwan

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ARTICLE INFO

Keywords:
Residual risk
Flood mitigation
Risk perception
Spatial planning
Flood maps
Risk transfer

ABSTRACT

Flood risk has dramatically increased over the decades and is complicated by climate change. Nevertheless, the residual risk of flooding remains scarcely addressed in practice and theory. This paper is to document the lessons learned from managing residual risk in Taiwan. Through a semi-structured interview process, fourteen stakeholders from the flood management in academia, government, and local communities shared their perspectives on residual risk covering various aspects, including flood risk mapping, social representations, and some management strategies. Land use regulation and community-based disaster prevention were highlighted as preparedness measures and recognized for their effectiveness to mitigate flood residual risk. However, there is still an insufficient consideration of flood maps as public communication tools rather than mere decision-informing documents. Besides, all the interviewed stakeholders agreed that marginal flood risk awareness limits the recognition and discussion of residual risk as a problem of its own. Misconceptions and the lack of communication between stakeholders were identified as the main barriers too. Interviewees pointed out that citizens are unaware of risks mainly either due to their inexperience or over-trust in the safety of flood protection structures. Overall, this work may inform residual flood risk management for Taiwan and elsewhere enduring similar extreme floods.

1. Introduction

Extreme hazard events can reshape landscapes, swing the course of history, and halt countless livelihoods [19,23,103]. Among all natural hazards, floods are the most recurrent ones, accounting for 43% of all-natural disasters in the last three decades since 1993 [14]. In this period, the cumulative outcomes of flooding include 2787 million people worldwide who have required immediate assistance [13] and 70 thousand million USD in economic damages due to property, crops, and livestock [13]. This condition is liable to the considerable increase in the frequency and intensity of high-magnitude extreme floods, and could be exacerbated shortly due to unregulated urban expansion [9,42] and effects of climate change, such as sea level rise, more intensive precipitation levels, and higher river discharges [34,41,56].

The magnitude of a flood event can be represented by the recurrence interval, the percent change of occurring in any given year. For instance, a 100-year flood has a 1% chance of recurring each year. This probability of occurrence is relevant as it is commonly used to set the protection level of for different "flood control" measures. As flood control measures, such as levees, are designed to a certain level of protection (which is 100 years in Taiwan for large rivers for instance), above which they can breach or overtop. The risk from floods greater than the design standard of the levees, i.e. level above which levees can overtop or breach, is called residual risk [84].

Floods are non-stationary by nature [56], consequently entailing their associated risks to also remain in a continuous state of flux [9] due to hydro and climatological uncertainties [53]. As such, it is hardly ever possible to guarantee protection against any conceivable flood, i.e., risk can only be reduced but not eliminated [77,86]. For many years, structural (protection or defense) measures have been central to flood risk management, with urban development tending to increase in lands protected by flood control infrastructure [116]. With climate change, current urbanization rates in high hazard zones and aging infrastructure, this residual risk is increasing worldwide. Nonetheless, despite its permanent role in flood risk assessment, residual risk is not well addressed in the literature nor explicitly acknowledged [1,34,54].

Underpinned by an embedded character, there is no established understanding to address residual risk. As a concept, residual risk was first formalized by Krutilla [47] as part of conceptual research on flood insurance to limit the private and social cost of floodplain use. Plate [77] elaborated a conceptual framework for flood risk management where residual risk was integrated as part of the reinforcing loop of

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https://doi.org/10.1016/j.pdisas.2024.100337
Received 20 March 2024; Received in revised form 29 May 2024; Accepted 3 June 2024
Available online 7 June 2024

protection actions. Hereafter, qualitative research has taken the form of case studies where theoretical propositions on residual risk relation with spatial planning intervention [51,100], hazard identification barriers [43], and flood insurance affordability [29] have been developed. However, the lack of consistent understanding has ostracized some studies' ability to produce systematically generalizable knowledge [113]. Whereas in the realm of applied risk management, residual risk has been discussed through modeling and identification of flood risk for extreme floods in large-scale catchments [11,22,76,84,86,98,115]. Among these, a few studies have developed tools for the identification and mitigation of residual risk, such as multi-scenario compound risk assessment methodologies [12,31], cost-effectiveness assessments at the building scale [2,79], and integration of social research data [25] and dynamic adaptive behavior in risk forecasting [32,108]. Nonetheless, further advancements from recent years may have gone unnoticed since residual risk started being addressed as part of flood risk assessment's hazard and vulnerability uncertainty analyses [1,34,54].

Overall, the frequency of extreme floods is on the rise and there's a shortage of research documenting the perceptions and management actions taken to address residual flood risks. Ignoring residual risk of floods beyond the design event or resulting from poor condition of flood control infrastructure can have catastrophic consequences. This difficulty for residual risk to be independently recognized within flood risk management systems makes case-to-case knowledge transfer sluggish. In this paper, we highlight the urgency of this topic by a methodologically case study of Taiwan's flood risk management stakeholders and their ordeal addressing residual risk through semi-structured interviewing. We developed three main themes regarding the social representations, the identification through mapping, and the management of residual flood risk. Our research objective was to explore if and how residual flood risk is understood, characterized, and managed in Taiwan. With the lessons learned identified, it is expected this work's conjectures may complement already existing knowledge and serve useful to other areas enduring similar extreme floods. At the same time, we look forward to our work to boost consistent systematicity practices among akin case studies to improve residual risk management.

2. Materials and methods

Risk is a contextual interdisciplinary issue [54,77], of a metaphysical nature to some extent [5]. For floods, risk swifts along the continuous reshaping of human settlements and changing environmental conditions [54] and "changes" in the eyes of different observers [52]. As suggested by van Asselt and Renn [97], risks defy simple concepts of causation due to their uncertainty, complexity, and ambiguity. To better address risks, they proposed three principles, i.e. communication and inclusion, integration of knowledge and experience, reflection on what the actors are doing. We adopted these principles and used case study research [114] to complement existing knowledge of management strategies for residual risk. This methodology is suitable because of its capacity to address contemporary issues in–depth and within their real-world context, especially when blurry boundaries stretch between the issue and its context [114]. This research followed Yin's [114] methodological guideline to ensure the trustworthiness of our process and pursue the consolidated criteria for reporting qualitative research (COREQ) [89] to present our findings.

2.1. The case: Taiwan

Flood risk is global, but the most flood-exposed people live in South and East Asia [81]. In the region, Taiwan is among the most prone to the strike of floods. This comes as the result of Taiwan's unique geo-fluvial and hydrological conditions, where the frequent earthquakes and tropical storms occur. The integration of these factors highlights challenges and opportunities to more resilient flood management practices.

Taiwan is an island located along the Northwest Pacific tropical cyclone basin on the western edge of the Pacific Ocean with an extension of 36,000 sq. km, whose tectonic location created an even terrain distribution between mountain ranges, mid-altitude hills and plateaus, and floodplains. Taiwan is often exposed to heavy rainfall and severe flooding events. The average annual precipitation has been recorded at 2500 mm. In the last century, Taiwan experienced more than 350 typhoons and 1000 rainfall events [87]. Occurring in 2009, Typhoon Morakot was the latest extreme event that hit the island, with an accumulated precipitation of 2777 mm within 72 h, causing 677 deaths and US$3.3 billion in economic losses [96]. Typhoon Morakot produced rainfall levels with a return-period over 200 years. The rainfall intensity triggered landslides at mid-altitude hills that buried more than 400 people at once, breached 36.2 km of levees along major rivers, and left close to a million people in the floodplains off fresh running water [92,96]. The aggregation of hydrological and geological characteristics with climate change in Taiwan leads to massive flow peaks, rapid river rising, and pernicious flood conditions, as revealed in the **2024** Taiwan Climate Report [111].

The development of legislative reforms and management strategies aimed to lessen the impacts of floods in Taiwan has been intertwined with the historical occurrence of natural disasters [92]. Fig. 1 offers a chronological view of the Taiwan's main regulatory frameworks for the management of flood hazards and disasters. Prior to the year 2000, Taiwan's flood management systems relied heavily on levees and reservoir catchments as in the pre-amendment versions of Taiwan's Water Act [59]. The occurrence of the devastating typhoon events, for instance, Typhoon Nari, sparked a set of legislative changes that decentralized flood risk management into the central, regional, and local levels (Disaster Prevention and Protection Act, [62]), stiffened the control of allowed activities near core waterworks like reservoir areas and sea embankments (Water Act, [59]), and presented a transition from hazard protectionism to avoidance (Special Act for Flood Management, [57]). Typhoon Morakot in 2009 called for a more structured river basin management (Special Statute for the Comprehensive Management of River Basins, [58]), as well as more streamlined processes for the remediations works of those drainage systems and their related soil preservation works (Special Act for Flood Management, [57]). These two regulations held the status of Special Regulations with a limited implementation period and hence have been abolished, but their relevance remains as they were the first pieces of legislation to recognize and respond to climate change and possible extreme climatological events. At one, efforts towards planning a nationwide residential flood insurance program were ongoing [36]). And at the same time, there was a promotion of non-engineered actions like nature-based solutions (Wetland Conservation Act, [63]), the maintenance of natural coastal systems (Coastal Zone Management Act, [64]), the promotion of flood prevention in the built environment through runoff allocation and outflow control strategies (Water Act, [59]), and the reinforcement of adaptation capacities related to disaster response (Climate Change Response Act, [61]).

In terms of actors, Taiwanese governance linked to natural flood hazards follows a complexly layered structure going from the Prime Minister's Office down through ministries, councils, commissions, and special institutions [26]. Among the ministries, the Ministry of Economic Affairs (MOEA) is responsible for the promotion of water-related business and policies for the area in between river embankments and its corresponding river basins. Derived from this ministry, the central Water Resources Agency (WRA) and its ten regional River Administrations [104] are the institutions in charge for these duties. Parallelly, the Ministry of the Interior (MOI) has among its responsibilities the mitigation and prevention of floods in areas outside the active river basin, including its land use planning and development [65,66]. Legislatively, land use regulation occurs in two different jurisdictions. While the WRA offers indications how only fish farming and agriculture can be conducted in the floodplain (RES9; [57,59]), the MOI provide guidance of some of the flood control infrastructure measures to be adopted by

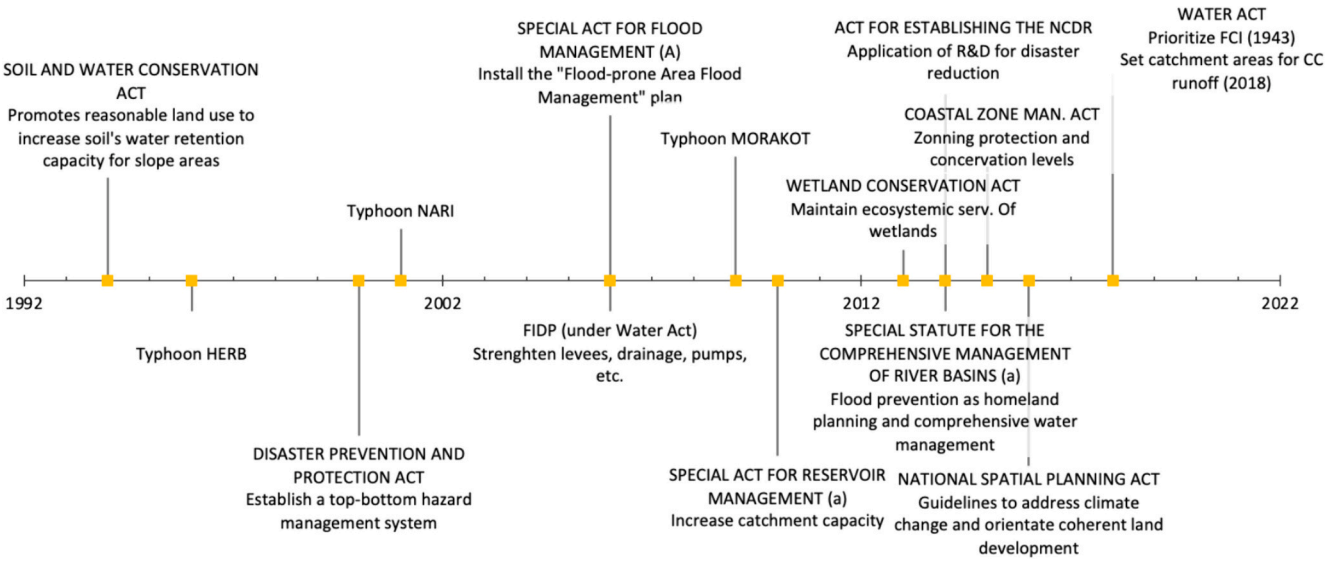

Fig. 1. Chronology for flood risk management policy Taiwan. Note: (a) means already abolished policy; NCDR stands for National Science and Technology Center for Disaster Reduction.

county and city governments. These measures include stilts houses, rainwater harvesting systems, and water retention systems [67,107]. Other activities, such as maintenance and preservation of the coastal environment are mediated by the Ocean Affairs Council and involve joint actions by the MOI and MOEA. Whereas, on a local level, city governments take charge of the implementation of policies related to watercourses drainages and flood hazards preparations, as well as disaster response and recovery **[68,69]**). These local institutions are in charge of executing national plans involving minor river basins, as well as the district-scale mapping of flood risks. More in-detail information on the governance of natural hazards in Taiwan is found at Wang et al. **[102]** .

Currently, Taiwan's flood management vision conjugates engineering and non-engineering measures. About structural control, Taiwan's 26 largest rivers are protected against 1% annual exceedance probability flood events. This excludes the Danshui River whose protection level is 0.5% exceedance probability or 200-year flood protection **[106]** . Regarding planning, the "Forward-Looking Infrastructure" program is the most emblematic output, as it looks for the optimization of water environments by strengthening the current control infrastructure and expanding complementary protection from low-impact development networks. Statistically, reductions of up to 96% of flooded areas have been attributed to the public works completed within this program **[104,105]** . Additionally, other non-engineering initiatives are displayed on the ground and have taken anchor in preparedness programs like the Flood Prevention Communities. At a core, these communities build "strong regional resilience through the development of social capital and effective emergency preparedness" **[110]** , by following relief ratios of 7:2:1, i.e., seven-parts of self-help, two-parts of mutual aid, and one-part of public assistance [68] **[]** ; although, outcomes have been recorded as non-uniform.

2.2. Data collection and analysis

A semi-structured interviewing process with stakeholders from Taiwan's flood risk management sphere was used. A formal assembly of evidence, including coded responses for risk management themes can be found in the Supplementary materials.

The interview process involved public officials, academicians, and local leaders with an active role in flood disaster management and mitigation. Seventeen stakeholders were invited to take part in the interview process, among which eleven (64%) completed an interview, one (6%) did not reply, two (12%) declined to be interviewed, and three (18%) agreed to be interviewed only off-record. Answers from the latter were annotated to the highest fidelity possible and integrated into the case study as field notes. Among the fourteen interviewed stakeholders, seven (50%) of the stakeholders were interviewed by video call, and seven (50%) stakeholders were interviewed face-to-face. The average duration of each interview was sixty-one minutes, where the shortest interview lasted 30 min and the longest lasted seventy-four minutes.

The pivotal inclusion criteria for the stakeholder identification were their experience in managing large-scale natural disasters. The latest extreme flooding event in Taiwan was typhoon Morakot in 2009. Thus, we looked for stakeholders who could share their internalized lessons from this and prior events, as well as their current perspectives on how these lessons are being applied to residual risk mitigation. The fourteen interviewees possess different types of expertise, which were divided into five categories and assigned independent identification codes. See Table 1. Additionally, as can be seen, seven of our stakeholders were academicians or researchers and accordingly tagged into "flood research". In this respect, it is worthy to note that Taiwanese political institutions, research organizations, and private enterprises have

Table 1
Categories and unique identifiers for participating stakeholders.

Stakeholder category	Category definition	#	Category ID	Unique stakeholder ID
Flood policy	Involved in setting and engaging with relevant flood policies.	3	POL	POL1; POL2; POL3
Flood research	Involvement in research projects related to floods.	7	RES	RES4; RES5; RES6; RES7; RES8; RES9; RES10
Flood risk planning	Involvement in the development and implementation of plans to minimize flood risk.	1	FRP	FRP11
Spatial Planning	Active involvement in spatial and land-use planning that influence flooding.	2	SP	SP12; SP13
Local leader	Organization and response to flood affairs at the community level.	1	LL	LL14

extensive collaboration networks framed upon the central government's research grants and its "Industry-Academia Collaboration" program [60,91]. These circumstances provide researchers with close knowledge of public policy and off-the-paper implications, thus off-setting any potential off-balance in the stakeholder sample.

Independently whether interviews followed a virtual or physical method, the same semi-structured process using a consistent set of interview questions was applied to all the stakeholders. Every question and their respective justification are available in Table 2. En-suite, a follow-up through telephone or email communication was conducted. This served stakeholders who wanted to expand their responses or fact-check their statements.

When asking the respondents to highlight the different flood risk management tools having the greatest impact in Taiwan's case, a sample of the tools considered in Fraser et al. [30] was provided and employed to structurally catalog their experiences. This sample included tools like zoning, risk transfer, spatial planning, risk communication, and hazard identification. Likewise, these topics reflect the main interests of a larger research project, RREFlood (Belmont Forum, [7]). Given the wide range of stakeholders' expertise, questions four to eight were formulated to case-by-case dig deeper into the former topics. Furthermore, a brief conceptualization of residual risk looked forward to breaking the communication barrier the term "residual risk" might possess, considering the scarce use it is given [28].

Table 2
Stakeholder interview questions and their justification.

No.	Question	Purpose
Q1	Could you please detail your organization's association with Taiwan's flood disaster management? Please describe the work that you do that is relevant to flood prevention and mitigation.	Establish the background and connection of the stakeholder to the Taiwan disaster management network.
Q2	Contemporary flood risk management employs a full suite of tools. Which flood risk management tools are used in Taiwan for flood risk management and which should be used more intensively?	Determine the main lines of thought (research objectives) to be developed throughout the case study.
Q3	Are you familiar with the concept of residual risk? If so, have you or your organization worked, or are currently working, on flood residual risk management?	Identify the stakeholder's knowledge and understanding of residual risk.
Q4	How relevant do you consider the role of flood inundation maps in land use planning and flood risk management in general? Is risk mapping currently being fully addressed?	
Q5	Flood insurance is a risk transfer mechanism to be compensated for the adverse consequences of flooding. Locally, what are the barriers stopping flood insurance from becoming a national policy?	
Q6	Describe the present and past role of emergency preparedness in Taiwan's flood management vision.	Aims to identify best practices of risk management from a stakeholder's perspective on risk feedback, reduction, and preparedness
Q7	The "levee effect" is strongly internalized in different territories, including Taiwan. How can risk communication be improved beyond this point and what is already stated in the regulation?	
Q8	Zoning is a legislative risk isolation mechanism although it has barriers to its enforcement, e.g., mixed economic and cultural value of land. Describe how Taiwan faces this top-down approach.	
Q9	In the last fifteen years, what have been the most remarkable changes in flood mitigation, preparedness, response, and recovery in Taiwan?	
Q10	Typhoon Morakot was the latest extreme flood in Taiwan. Several imprints and lessons were left. Concerning its current state, could Taiwan be better prepared for the strike of another extreme event?	Determine the process along which progress has been made.

The data analysis procedure followed a three-stage deductive coding process, based on our research objectives of exploring if and how residual flood risk is understood, characterized, and managed in Taiwan. As conceptual frameworks devoted to residual risk are scarce and mostly limited to the quantification rather than qualitative characterization of residual flood risk, the three proposed principles, i.e. communication and inclusion, integration of knowledge and experience, reflection on what the actors are doing by van Asselt and Renn [97], were used as the core to develop the three main themes as shown below and in Fig. 2 regarding the social representations, the identification through mapping, and the management of residual flood risk. Initially, we transcribed interview recordings, manually coded them, and integrated them. This includes the interview notes from sessions where recording consent was not granted. At this stage, we abide by the standards of Nowell et al. [72] and Joffe [40] for coding and theme identification. Meanwhile, the coding process, theme identification, and address of rival explanations passed through two iterations by the authors looking forward to preserving the validity of evidence analysis. A full list of coded responses for all stakeholder themes can be found in the Supplementary Data section Tables A.1 and A.2. Fig. 2 provides a general look at the flow scheme of the coding process:

1. Understanding risk conceptions (Social representations) - Coding of the stakeholders' answers to their roles and association with Taiwan's flood risk management (Q1), their fundamental knowledge of residual risk (Q3), and their exposure to extreme flood events (Q9, Q10) provide background to understand the meaning that the interviewees, as individuals, have given to flood risk. This socially constructed knowledge takes part in political psychology and may steer the direction of risk management [40,83].
2. Residual risk identification - Coding of responses to the more immediate structure of flood risk management in Taiwan (Q2), and to risk determination and mapping (Q4), as a representation of the most-preliminary stage in risk management [77]. This serves to delimitate the boundaries outside which residual risk lies.
3. Rationalization of risk management strategies - Feeding of relevant coded responses to the some of the most common risk management strategies: insurance (Q5), preparedness (Q6), communication (Q7), and land use regulation (Q8). We rationalize the applications these have taken to address the risk of extreme flood events.

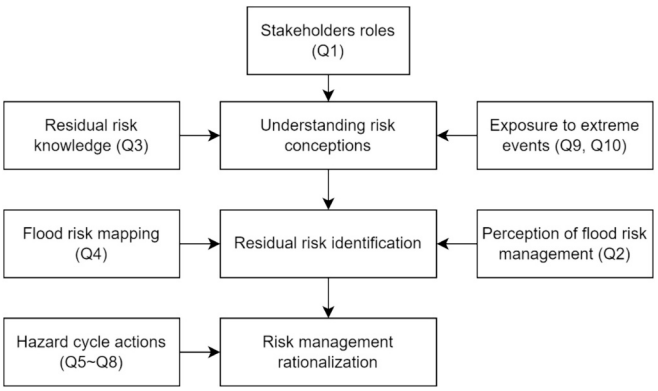

Fig. 2. Data analysis process.

3. Results

3.1. Social representations of residual risk

The interviewing process shed light on the stakeholder's social representations of residual risk knowledge, citizens' risk awareness, and risk communication. Stakeholders shared a common understanding of residual risk, extrapolating concepts based on own their diverse professional backgrounds. Beyond conceptual definitions, different tiers of stakeholders offered social representations linked to the modeling of compound disasters, land use planning, and engineering-focused flood management styles.

> *"We can accomplish engineering projects to reduce 20% the chance of flooding versus a business-as-usual situation. However, we may still need to acknowledge that an 80% chance that the flood may happen will remain. […] We can implement a variety of strategies, but the risk will never reach 0%." — FRP11*

> *"We have worked with disaster resilience but not with residual risk. Although, I consider the term was implicit in our resilience planning research. […] people outside this sphere had very little incentive to know about". —RES6*

Here, the relation between stakeholder's knowledge on residual risk and their hands-on experience reflected to be brittle (RES4, RES5, RES6, RES10, FRP11, SP13) as many interviewees couldn't confirm any explicitly direct-working experience to residual risk. Moreover, they highlighted some barriers stopping the development of expertise, including the absence of regulatory incentives, a populist environment, and the need for stronger institutions [93] (RES6, RES9, RES10).

Likewise, public risk awareness, though not astonishingly, permeated the reflections of all interviews. Stakeholders conceived citizens as either ignorant of flood risk or them deliberately deciding to ignore such risks, regardless of whether risks corresponded to extreme or slow-onset events (POL3, RES6, RES7, RES9). On one side, citizens' unawareness of risk was attributed to their inexperience, as recent years have been characterized by not having severe flooding events, like typhoon Morakot (RES9). While alternatively, it was proposed that citizens *"overtrusted the safety of levees"* (POL3). Independently, on both views, flood control infrastructure maintained a central role in reinforcing an investment-trust "*vicious relationship,"* as reflected below. Thus, public involvement and consequentially risk communication was emphasized in equal measure, as follows:

> *"Common citizens probably think that non-engineering measures can't solve the flooding problem… but only through the implementation of engineering measures. Flooding at some point is not only a physical but a metaphysical issue, a matter of perception. The public itself is not concerned about the risk of flooding when only flood control infrastructure measures are taken". —POL2*

> *"We have communicated the principles of flood resilience through concepts that were familiar to the public (…), and the population opened itself to these new solutions but still expected the government to intervene and not have any flooding". —RES9*

As seen by the stakeholders, risk communication is regarded as the complex cohesive material in a risk reduction and preparedness process led by the government and to be followed by the people. Above, "opened" and "intervene" reflect the unbalanced dynamics in the purposeful two-way exchange of risk information that flood risk communication is meant to be. On one side, risk communication opened itself and experienced a major leap forward after Typhoon Morakot in 2009. The catastrophic event acted as a catalyst in the mindset shift towards supporting more flood risk preparedness and mitigation rather than control measures (RES7; RES9; FRP11; SP13) and expanded the use of emerging telecommunications. Particularly, community-based risk communication was characterized as a suitable platform to inform flooding risks and engage citizens with low-impact development practices (RES6).

On the other hand, interviewees informed about the distention of a mistrust atmosphere. In this environment, people were tagged as resilient-dependent (RES9; RES10; FRP11) and the government as callous and unaccountable (RES6; RES9; RES10), which has eventually led to an unhealthy expectation towards engineering-focused interventions (RES9; RES10; FRP11). The fixation on engineering-focused measures was argued to be boosted by their efficiency in the reduction of flood impacts in the short and middle term, as seen below:

> *"Right now, we are trading to have a temporarily very convenient, stable environment at the cost of a low probability of a very disastrous flooding event. On the other hand, if we adopt this resilience-based flood management the paradigm may change. Tolerating the inconvenience of smaller floods and learning from them in order for us to obtain the capacity to deal with high impact floods. It's just a different way of thinking. I 'd say most people in Taiwan they rather have a shorter, safe, stable condition and they rely on the government to provide the infrastructure". —RES6*

Lastly, risk communication is a topic that cannot be accounted for or measured straightforwardly [45]. Thus, it wasn't surprising to present to stakeholders materializing risk communication in terms of flood maps and jargon-use.

> *"In the city, floods with a half-tire height are very serious, meanwhile in the countryside, a half-tire height might be normal for a flood (…) Both are communicated using the same maps". —RES9*

> *"Professional and government agencies need to tell the truth to correct people's misconceptions of the full protection of flood control infrastructure (…) what a 200, 100, 50 YRP flood actually means. (…) They insist on the speech that such a structure cannot be breached. They would mention that the height of a levee will protect them from flooding, and people without any technical background will believe in them". —RES6*

Here, both references craft the subjective experience of floods within non-academic environments, where the use of specialized jargon and administrative-oriented flood maps have crippling roles for flood risk perception in relation to flood maps (RES6; RES9; FRP11). The flood risk notices provided by the authorities "beautify" their achievements and fail to convey an objective notion of flood control infrastructure transience and the prevalence of residual risk associated with different rainfall scenarios (RES6; RES9; FRP11; LL14). Similarly, the existence of information asymmetry and its effects on caving public trust in risk management institutions may be called upon attention. For instance, a flood inundation map produced by the central agency and another one produced by the city level government are both simultaneously communicated to citizens, without any clarification about the prevalence of one over the other (POL2; RES6). This is expanded in the next section.

3.2. Risk mapping

> *"Flood maps are a basic part of the residual risk conversation because they are a sample of the area that (we) cannot protect, […] that despite all the effort to prevent flooding, still continues to be underwater". — FRP11*

Maps are an illustrative medium through which risk underlying causes and determinants are communicated to the broader audience. When flood maps are not comprehensive (e.g., not including potential levee breaching), certain issues are institutionalized and remain unaddressed. Different countries utilize flood maps for various purposes,

including emergency management, land use planning, and insurance [84]. In Taiwan, Flood inundation maps (FIMs) take the role of risk identification tools and depict the extent and depth of flood water under various scenarios. The production of maps follows an administrative scale, where some scenarios depict flooded areas during low-probability events, e.g.,450 mm/1 h. However, according to our interviewees (POL2; RES7; RES10), the current maps are ill-equipped to scope extreme events like storm surge-rainfall compound risk (RES10) or global circulation model's climate change effects [17].

> *"Maps are only scenarios; they represent very specific circumstances. […] we should (instead) regard FIMs from a managerial perspective. That is to say, you know that this site is flooded, so you need to think about the most appropriate strategy to add it to the National Spatial Plan". —RES9*

As they are currently conceived, FIMs should play a role in the hierarchization of interventions to address slow- and sudden-onset flood events, as scheduled by the National Spatial Plan agenda. Nonetheless, the aforementioned role is rather advisory than of any regulatory status [71,107].

> *"Current flood maps are insufficient in many aspects (…) they should integrate diverse land use types and the duration of floods (…) which may have sparked the creation of local flood maps". —FRP11*

Here, the existence of alternative flood maps prepared by research centers, local governments, and universities is recognized (POL2; RES7; RES10). These maps production is more well-suited, flexible to internal use scales, and incorporates emerging research more rapidly [49,74,85] (RES10). While, FIMs production is more systemic and need to follow standards set by the MOEA [17]. The coexistence of both maps carried apprehension by stakeholders as there were mismatches between analogous flooded areas, especially attributing them to climate change-driven uncertainty. Collectively, the simultaneous provision of heterogeneous information may caveat trust to effective risk communication and boost private underinvestment in preparedness and mitigation policies.

Overall, stakeholders expressed additional widely shared representations for the improvement of mapping techniques, focusing on modeling software suitability, interdisciplinarity, and communication tailoring. This comprehends, a) concerns about simulators' lack of real-time conditions modules (RES7; RES8), b) diversification of mapping techniques with socio-economic sciences (RES4; RES10; FRP11), and c) one-size-fits-all flood-mapping of extensive watersheds at the expense of low-resolutions and fit (RES7; RES10). Further discussion on tailored maps revealed that residual risk and extreme flooding may have different interpretations depending on whether it is experienced in urban or rural areas. Equally, the adoption of FIMs at community, rather than administrative scales was also proposed, especially where different social strata and land use areas prevailed. These mentioned issues are the boundaries (limitations) outside which characterizing residual risk lies. Due to their higher resolutions, community framed FIMs could worsen the over-trust people has on flood control infrastructure (RES7), yet under the same principle, they hand a valuable opportunity:

> *"(Community FIMs) create clear communication signs (…) display information in an attractive way (…) where are the existing improvement projects, and even the relevant facilities such as roadside flooding alarms and their placement. The expectation is to inform the public better about their own public space". —RES7*

3.3. Risk management strategies

In the eyes of most if not all interviewed stakeholders, managing extreme floods in Taiwan could only be described as challenging, especially due to the prevalence of flood control infrastructure over preparedness and mitigation strategies. In recent years, the conjugation of large budgets allocating for flood control infrastructure and an extended period of time without any severe flooding events established a niche-reinforcement loop for levee-effect feelings (RES9; SP13) although there is a promotion of non-engineered actions as described in section 2.1. Meanwhile, the adoption of non-engineering pilot measures was described as limited, especially when their benefits could not be immediately perceived (RES9). The following sections elaborate on the opportunities and barriers that preparedness, flood insurance, and land use regulation present as strategies to address flood residual risk, as emphasized by the interviewees.

3.3.1. Preparedness

The vision for flood preparedness in Taiwan's disaster management was described as to *"address any protection level exceeding the flood control infrastructure design*" (POL2; RES9), especially through the flood resilience improvement and community disaster prevention program. The program has clear blueprints, cruising from systems thinking perspectives to participatory decision-making -according to stakeholders- making it autonomous, low-maintenance, and easily adoptable in the management of flood residual risk (RES7; RES9).

> *"Originally, the community disaster prevention project was conceived as autonomous. On one side, the control infrastructure keeps regular floodings at bay, and preparedness and mitigation measures are kept as contingency for unaccounted severe events". —RES9*

Here, disaster prevention communities offer a prevention mechanism with smooth top-down and bottom-up synergies, as study cases in Taipei demonstrate [18,44,109]. Its bottom-up component provides an opportunity to the population to self-acknowledge their role in risk reduction management and effectively communicate their needs to responsible officers (POL2; RES9; FRP11). The use of exchange and dialogue, instead of traditional pedagogical ways, was praised to gain public cooperation, particularly from community leaders (RES7; RES9). Top-bottom interactions, on the other side, contributed to expanding the ancestral and empirical knowledge of risk managers. Which was argued may enable the development of tailor-fit in cooperation with vulnerable communities, as the example below may depict:

> *"Awareness is the most important thing to keep in mind. But I also realize that education about the professions involved in this field is very important (…) expanding towards nurturing the expertise and knowledge of professionals on how to plan for these expected high-consequence floods". —RES6*

Complementarily, preparedness building against residual risk might be integrated into other strategies like comprehensive river basin management or emergency planning. Although, comments about these were negligible in our interviews.

3.3.2. Flood insurance

Our interviews described flood insurance as likely to navigating through a perfect storm. Its success demands highly specific conditions including seamless cooperation between government and private institutions, insuring institutions liquidity, and enough legislative support (POL2; RES6; RES9). These aspects are raised in the following quote:

> *"Four complications may arise (for insurance). The first one is science and politics. After scientific aspects are calculated, the government may not be too transparent to explain them (…) Then there is the possibility of being influenced by populism (…) which will require people and companies to invest additional resources to promote insurance. Third, comes the management authority with low human capital (…) Finally, the last barrier is the liquidity and treasury backups required to put insurance forward". —RES9*

Here, an argument establishing how Taiwan's political structure may be liable for holding back the national flood insurance program was established. The influence of populism in such cases can be positive or negative, given that political consensus supporting insurance could be attained with enough public awareness and pressure. The opposite may also happen, as explained in the subsequent paragraphs. Under these circumstances, political willingness to take responsibility for insurance regulation is very low (FRP11).

Likewise, Taiwan presents an almost perennial floodplain, a barrier whose conditions cannot be modified but only adapted into (POL2; RES9; FRP11), although not with full success. For instance, having a recurrent prone area causes reverse selection, which is a condition where "*only people with liabilities signed up for insurance premiums, and the state incurred a liquidity deficit to cover eventual liabilities (RES5).*" The situation generates a dissonance between the risk private insurers can afford to uptake and the risk citizens are willing to pay for.

> *"Flooding in Taiwan occurs almost exclusively in the flood-prone area (…) therefore companies refuse to sell insurance to the citizens living there". —FRP11*

Because of the factors above, precedents of insurance in Taiwan have not been able to last the passage of time [62]. Chronologically these antecedents were weather-based insurance, agricultural insurance, and (still available) flooding subsidies (RES4; RES5; RES9; FRP11). Weather-based insurance established a fixed precipitation threshold over which premiums were paid. Such an approach presented public rejection when areas with contrasting land-uses experienced the same rainfall levels, underwent different consequences, but received the same compensation (FRP11). Agricultural insurance, proposed years later, surpassed the land-differentiation barrier by offering crop-based premiums. Although this insurance could not find a successful transfer mechanism to urban centers (RES4; RES9; FRP11) due to low resolutions in economic loss maps (RES4; FRP11). Alternatively, flood subsidies are not addressed in depth since they do not constitute legitimate risk transfer mechanisms. Relief policies like this do not require a premium payment from home-owners, and instead have the government retain all the risk (POL2).

Lastly, interviewees addressed potential recommendations for insurance premiums estimation. To some stakeholders, premiums should focus only on incidence probabilities and event losses (RES5), while to others, holistic approaches that included frontline personnel costs and human capital losses were the best choice (POL3; RES4). However, in a tacit agreement, it was established that flood insurance required an interdisciplinary approach involving urban planning and media studies to foster positive economic incentives and consistent risk awareness, correspondingly.

3.3.3. Land use regulation

Our interviews exhibited a heavy gravitation of land use regulation and building codes conversations towards the conflicts with industrial development (RES7; RES9; SP13). For instance, the flood elevation principle, *"the requirement for all the foundations of building to be raised to the same base (flood) elevation (SP12)"*, was brought up as a measure to face extreme floods. But stakeholders stated that some of these measures have not been enforced, as *"it is the duty of local government to do so, and local government have not set specific department to follow up these matters in many of the provinces (SP13)"*.

> *"Whenever land restriction and economic development are pushed at the same time, the economy comes on top, (…) and land planning cannot be evenly enforced". —RES9*

According to the stakeholders account, land conservation and preservation for flood risk management initiatives would frequently occur outside urban centers, where land use reorganization can be cheaper and bureaucratically faster (RES9; FRP11; SP12). Similarly, economic and political interests for industry and housing development would also be vested in the same lands due to their flatness, closeness to amenities and lower land market value, and hence, the rise of conflict. The perceived opportunities that industrial parks offered to nearby populations, as well as the newly taxable lands that local governments could profit from would be some of the factors explaining the favoritism (POL1; RES9). More often than not, the associated economic and political pressures hindered the follow-up of prevention-wise land use regulation mandates (POL1; RES9), as exemplified below:

> *"Repopulation of areas with newly enhanced flood infrastructures is very common in Taiwan. People ignore the cumulative threats that these controls pose and swiftly move back to these flood plain areas, which by the way were regarded as unsafe by the population itself. These are unavoidable situations for which the public need to be educated on how to protect themselves, especially under the threat of climate change. In short, the risk is not being well communicated and that is evidenced by the rising housing prices in the area". —RES9*

In a closer look, these stakeholders warned that land use designation driven by private interest keeps misinforming the public and spread false security feelings (FRP11; SP13). To this, stakeholders emphasized the need for assertive communication of land use designation criteria as the axis around which land use regulation could be healthily promoted (FRP11). New (re-)developments inside flood prone areas are an example of the failure to effectively communicate risks, which degenerates into the exceedance of planned residential capacity, reduction of soil permeability, and consequent decrease of flood resilience. A cyclic source and an effective formula for flooding (FRP11; SP13).

Furthermore, traits of management asymmetry and organizational deficiencies were identified in the depiction of budget assignment and governance autonomy issues due to the *"legislative split between land management and water conservancy, (both) under different bureaucratic divisions"* (SP12; SP13; LL14).

In overview, land use regulations were inarguably determined to require stricter enforcement. At the same time, nonetheless, Taiwan's spatial planning have been recognized in having simplified the review of land use permits and enforcing them more effectively, especially along the rural floodplain where unauthorized developments took place more often (SP12, SP13).

4. Discussion

Flood risk management has undergone significant changes over the last two decades in developed countries, especially under the new challenges posed by unprecedented climate. In previous decades, the main measure to reduce flood risk was the construction of hydraulic works to target a necessary level of security. These actions led to overconfidence in the engineering works and the maintenance and development of inappropriate actions that increased the exposure and vulnerability levels of communities, increasing the residual flood risk. Not until recently, throughout increasing discussions and actions, there has been a refocus of the current state-of-affairs, as well as a step forward for the integration of effective spatial land management and public participation to reduce the latent risks of extreme floods not only induced by climate change but also originating from the potential failure of protective structures or any kind of human mismanagement.

The stakeholder experiences reviewed in this study overview the development of residual risk management practices in Taiwan. The concept of residual risk is understood by those involved in natural hazards risk management despite most of them not having any direct hands-on experience with the subject. The social representations of residual risk shared among stakeholders range from the elaboration of preparedness strategies, passing by the physical effects of compound disasters, to views of what publicly shared liabilities of risk prevention and mitigation could be. These representations were found to be consistent with literature, as Chen [16]; Harries [33]; and Lemée et al.

[50] reported representations of climate change-driven disasters and risk preparedness plans in their own case studies of extreme flood events.

Moreover, this study explores current approaches Taiwan has undertaken to address residual flood risk, as any component of part of the hazard management cycle's preparedness and mitigation. The most disseminated practices by far are community-based flood prevention and land use regulation practices, whereas instruments like flood insurance and flood maps are being discussed to play a more active role in the management of residual risk. Such reality echoes with the recently described social representations. It also matches accordingly with the reviews prepared by Serra-Llobet et al. [84]; and Wagner et al. [100], which determined that community disaster prevention initiatives and flood-related land use planning are among the most-well spread approaches in managing the risks and residual risks.

4.1. Flood maps with public communication and land use regulations

Flood maps are a common tool in flood risk management. While management of flood risk through flood maps has been widely discussed in the literature [4,10,90], very few have been published on the implications of these maps in managing residual risk [39,84]. Flood maps made today can create very different scenarios of exposure and vulnerability that local and national governing agencies will have to face when managing flood risks in the future. The way these maps depict (or not) residual risk beyond the floodplain -behind levees- and the way they are linked to different non-structural measures such as land use regulation, flood insurance, emergency management strategies or risk communication can have tremendous implications for managing residual flood risks [84].

FIMs published by the Water Resources Agency in Taiwan are widely used in administrative affairs regarding emergency planning, resource allocation, and risk communication. In their guiding role, FIMs have been subject to many improvements particularly their hydrograph and geospatial processing in the past ten years [21]. However, despite their technical improvements, FIMs still face challenges being displayed as risk awareness tools, as well as integrating effectively land use regulations and global circulation models in their scenarios. Moreover, social vulnerability variables and indexes have not been integrated to influence decisions. As a result, decisions to reduce flood risk are mainly based on the potential consequences of a specific flood event rather than targeting the causes of risk.

FIMs visualize the areas that conventional flood control measures are unable to protect under various scenarios. This makes the communication of (residual) flood risk using FIMs a challenge. Pronounced by political interests, FIMs communication in Taiwan has emphasized more on conveying messages and less on education. This approach not only builds on the levee effect conception, but it also destabilizes the role of FIMs as an objective source of information. Likewise, additional barriers to the general population's engagement with flood maps were attributed to the rigidity of risk communications and frequent use of specialized jargon.

In return, the distribution of user friendly, lingua franca written flood maps are exercises that Taiwan could assimilate and profit from. These practices have been shown to positively influence citizens' mitigation intentions [6,48,80]. For instance, [6] concluded that when distributing flood maps, a description of a "1% flood occurring in any year" conveyed flood uncertainty more effectively than a description of a "100-year flood".

Second to emergency planning, spatial planning has the largest base of users for flood maps [20]. The use of flood maps in spatial planning in Taiwan is limited to advisory connotations as flood management and spatial planning are regulated by decoupled entities, the WRA and the MOI, respectively. Closer in detail, our interviews reflected that the WRA actively involves in flood preparedness and land use planning activities behind levees, even when these areas might be outside the WRA governance domains. This displays the importance of horizontal institutional coordination to bridge the adaptation gap in waterways under risk of levee failure or embankment over-breaching.

Nonetheless, given the evidence that both risk managers and spatial planners have shared liabilities, it could be strongly argued that there is a need for legislation to bind land use and FIMs, so that people's vulnerability is not compromised [94]. Serra-Llobet et al. [84] uses cases from France and North America to show that governance-based regulatory maps can reduce exposure and vulnerability to extreme flood hazards if local governance and culture differences are accounted for.

4.2. Lessons learned for managing residual flood risk

To date, measures that address flood residual risk in Taiwan have presented mixed results, depending on the approach taken. This is by targeting residual risk directly, as it occurs with flood resilient communities, or by addressing it as holistic flood risk management perspective, as with scenario-based flood maps. Implications from our study to managing residual flood risk include enablers and barriers as described below.

Initially, slow-onset events like climate change require to be better integrated into the flood risk management system. The current modeling of FIMs has tackled previous challenges including the failure of flood control infrastructure and simulation of extreme event scenarios, e.g., 600 mm/24 h rainfall scenarios. Currently, the national guideline for the implementation of FIMs requires the consideration of a 10–15% design factor which account for climate change variability effects [17], although it was noted that the Taiwanese research community had little comprehension about the factor calculation from our interviews. However, in terms of the flood risk management of coastal region, the Coastal Zone Protection Plan at present only evaluates sea barriers for a protection of 50-year return period storm surges [35]. Such design considerations would not be enough to stand future sudden-onset events with 20–40% increments in intensity [35,37]. Likewise, our interviewees agreed extensively how such modeling conditions might not be representative of nowadays nor future scenarios, neglecting the social and economic vulnerability needs of current and future coastal settlements.

Second, environmental and risk management-related legislation in Taiwan has recently included new amendments for the institutionalization of outflow control and runoff allocation of new developments [59]. These amendments are one decisive step forward to address climate change and urban development, as their implementation has a reduction of up to 96% of flooding in previously affected areas [104,105]. On the same page, there seems a mismatch between local flood management plans and general urban plans to regulating land uses. Besides, building codes are an aspect that are considered to have world-class rigorousness when related to fire and earthquake disasters [24,78], but they do not meet the same standards in terms of flood risks. Thus, considering the room for improvement, the promotion of stronger building codes constitutes a rational adaptation step between other two strategies of raising flood control barriers and forbidding development in the floodplain options. Serra-Llobet et al. [84] looked on the association of building codes with regulatory flood maps and discussed different pathways on floodplain risk management among regions with various governance and cultural landscapes. The analogous characteristics in top-down management and flood disaster subvention policy in France could be a suitable proxy to Taiwan and provide a starting point for a building code policy transfer case-study [70] and deeper research would be beneficial.

Following, community-based initiatives have been cemented as an effective strategy in Taiwan to raise the public awareness about flood impacts [95]. Flood resilient communities [109] and citizen science-based early warning systems [112] are punctual examples. These strategies implementation so far has had mixed outcomes in

communicating flood risks at the local scale, particularly in coastal areas. This is reflected among our interviews where it was argued how despite personalized door-to-door and public hearing types of communication, the public has a prevailing preference for transferring flood risk to the authorities instead of acting upon it. Interestingly, Wu [109] contests that the low effectiveness of people-centered flood management does not have an entirely negative connotation. They recognize people-centered flood risk management as cumulative [75], not always moving forward but *"allowing local residents and organizations to accumulate valuable experience that can be used to address hazards and risks"* [109]. In this regard, it is contributed that the development of a clear framework, including public hearings crafted to boost public trust [3,88,99,101], could enhance the public understanding of (residual) flood risk and increased their willingness to participate in community-based preparedness initiatives.

Next, due to the absence of regulatory flood maps, discussion on flood insurance in Taiwan is limited. Not like the flood insurance programs in other countries, such as the US and Japan [27,46], the existing flood insurance in Taiwan is part of a disaster relief bundle package, also including fire and earthquake risks. The current insurance premium and compensation are not related to the flood risk or based on any estimation of flood damages. WRA planned to introduce a mandatory national flood insurance program to offset the financial losses of residents in flood-prone areas in Taiwan about 15 years ago but could not land successfully because of insurers unwillingness to retain risk and difficulties in the specification of financial loss modules resolution [15,36]. According to Hung [38], people generally acknowledge that the typhoon-flood insurance is beneficial but the willingness to adopt flood insurance decreases due to satisfaction with government's flood prevention constructions, risk amplification effects [80], and the institutionalization of sizeable post-disaster subsidies from the government. Despite its status as a "low-regret measure" to yield benefits regardless of the outcoming climate scenarios, it is evident that the case for insurance in Taiwan requires seamless coordination of government and private institutions [8,73]. Under such circumstances, the challenge to insure residual flood risk in Taiwan is formally worsened due to the existence of an almost-perennial floodplain, which generates a dissonance between the risk private insurers can afford to uptake and the risk citizens are willing to pay for. Looking at the bigger picture, one can argue that the substantial price tag of implementing a flood insurance program in Taiwan could be largely outweighed by insurance potential benefits on risk redistribution and risk communication [82], especially as a region characterized by a certain level of economic development [55]. Nonetheless, it is also necessary to acknowledge that arguments of value regarding insurance must not be carelessly issued wherever practical data on the topic is not available, as Wagner et al. [100] have noticed.

Finally, it should be noted that this study has limitations. We surveyed a small number of stakeholders among which there was a high share of researchers and data was collected for specific sub-catchment areas. As a result, our findings are context sensitive and call for further research. Future studies should focus on a broader geographic region or make comparisons across multiple sub-catchment areas in different regions. These areas should comprehend more holistic institutional, socio-political, economic, and geographic contexts, as well as heterogeneous experiences with residual risk management practices.

5. Conclusions

In this study, we explored the flood residual risk management cycle, highlighting some of the successes and works-still-in progress that Taiwan has concerted to mitigate the residual flood risks. We start by surveying the social representations that flood risk stakeholders have collectively built around flood residual risk, passing through the identification of low-probability floods, and arriving to an exploration of the pros and cons in measures to reduce flood vulnerability.

Our assessment indicated a lumpy landscape in the perception and understanding of residual flood risk, where the population was gauged to present low risk awareness levels, whereas stakeholders held solid conceptualizations even when they lacked abundant hands-on experience with the flood residual risk. This status presents several opportunities as it reflects that the concept of residual risk is being processed in societal terms. This, in consideration that the residual risk concept was structurally acknowledged but not just until recent time [7,94]. Additionally, incomplete knowledge is a frequent status for systems drowned in fuzziness and it can be carried on through observed-project management practices. Thus, in-depth stakeholder perception research may present an opportunity to understand the content and structure of residual risk representations and explore the mechanisms for how risk representations can be passed down onto the general public. Especially in a geographic location like Taiwan where flood risk concentrates in dense dwellings. Notwithstanding, there remain considerations to be made, this being the applied integration of building codes and regulatory flood maps within a spatial planning context to reduce exposure in high hazard zone.

Following, we concluded that flood maps in Taiwan have enough technical sophistication to identify the potential flooding. The maps' production is standardized but to attend to specific needs, alternative "unofficial" maps depicting compound disasters and global circulation models have emerged. The simultaneous existence and free access to both maps promote information asymmetry -especially among scholars- and presents the chance to caveat trust in public institutions. In the linkage of flood maps to residual risk, the recognition that both elements are at conflict due to the ontological very nature of maps is a must. Hence, any content or form improvements —these being swiftness to inform during emergency situations or downscaling of maps to user-friendly scales— should be thought of in systems, accounting for misleading safety conceptions.

As a bundle, flood risk management measures aim to find an equilibrium in effectively addressing frequent lighter floodings while keeping extreme magnitude events at bay. Flood preparedness, insurance, and land use regulation reduced the vulnerability of the population at risk of residual flooding. In Taiwan, community disaster prevention initiatives and spatial planning were highly praised for their effectiveness although short-termism and self-promotion posed barriers against them. In this regard, a full commitment to address the risk of (almost-) all floods would be based on two-way efficient communication between the public institutions and their shareholders. The government would require an increased management transparency, open to multi- and interdisciplinary research. Meanwhile, private parties strengthen their willingness to share flood risk burden along with the government, transitioning from passive dependency to comprehensive integration.

CRediT authorship contribution statement

Hsiao-Wen Wang: Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Daniel Sebastián Castillo Castro:** Writing – original draft, Validation, Methodology, Formal analysis, Data curation. **Guan-Wei Chen:** Validation, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Hsiao-Wen Wang reports financial support was provided by National Science and Technology Council. If there are other authors, they 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

Data will be made available on request.

Acknowledgements

This work was supported by the Belmont Forum Collaborative Research Actions: “Residual Risk of Extreme Floods: A Challenge for Achieving Sustainable Development Goals”, National Science and Technology Council in Taiwan with the Grant Number 110-2621-M-006-004-MY3. We also acknowledge the Water Sustainability Lab of the National Cheng Kung University and its members who provided further non-financial support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pdisas.2024.100337.

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