Progress in Disaster Science 14 (2022) 100232

Contents lists available at ScienceDirect

Progress in Disaster Science

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

An assessment of structural measures for risk reduction of hydrometeorological disasters in Sri Lanka

Kanchana Ginige [a,*], Kalindu Mendis [b], Menaha Thayaparan [b]

[a] Department of Architecture and Built Environment, Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne NE1 8ST, United Kingdom
[b] Department of Building Economics, Faculty of Architecture, University of Moratuwa, Moratuwa, Sri Lanka

ARTICLE INFO

Keywords:
Climate change adaptation
Disaster risk reduction
Hydrometeorological hazards
Structural measures
Sri Lanka

ABSTRACT

Sri Lanka has a high incidence of natural hazards with hydrometeorological hazards being the most prevalent. Despite the fact that structural measures such as flood walls and embankments play a vital role in disaster mitigation, it is observed that there is a gap in the development of effective, sustainable, and state of the art structural measures in Sri Lanka. This paper, in this context, aims to assess the nature of existing structural measures in the country in order to highlight what improvements are needed, and the costs and benefits of the necessary improvements. This is achieved through a comprehensive literature review followed by the analysis of twelve semi-structured interviews conducted with experts in the subject of structural measures for disaster mitigation. The findings reveal that Sri Lanka has sufficient types of structural measures in relation to floods, landslides, and coastline erosion compared to other developing countries. However, age and outdated technology are critical issues that hinder the expected performance of the measures. Moreover, it is observed that sufficient structural measures for mitigating the risk of drought related disasters are not in place in Sri Lanka compared to measures for other hydrometeorological hazards. The key benefits of improving structural measures in the country are identified as land development, economic growth, and increased stability of cities, and the main costs and challenges are high initial capital cost, high maintenance and repair cost, and the negligible residual value of structural measures. The findings of this study will lead to gaining a comprehensive understanding of gaps and weaknesses in structural measures in Sri Lanka and will influence policymakers and other respective practitioners in disaster mitigation to effectively enhance the existing portfolio of such measures.

1. Introduction

Disasters triggered by natural hazards affect millions of people every year, resulting in a high number of fatalities, negative economic impacts, and the relocation of communities [1,2]. According to Jayawardena [3], hydrometeorological disasters cause more than 75% of the damage to human life and property among the three major types of natural hazards in the world, geological, hydrometeorological, and biological. Hydrometeorological hazards include floods, droughts, coastal erosion, cyclones of all types, landslides, avalanches, heat waves, cold waves, and debris flow. Sri Lanka experiences hydrometeorological hazards of floods, landslides, and droughts mainly [4] and has seen a substantial rise in the frequency and severity of similar hazards over the last few decades [5]. Besides, recent studies have revealed that the erosion of the coastal zone of Sri Lanka is a long-standing problem although not systematically monitored or documented [6,7,8]. Events triggered by hydrometeorological hazards have had major impacts on Sri Lanka's economy [9,10]. Based on available data, between 2009 and 2018, around 1.98 million Sri Lankans were affected every year by these hazards [11].

According to Cannon [12], a natural hazard becomes a disaster only when the former meets vulnerable people. Developing countries such as Sri Lanka are, hence, more vulnerable to the risks of disasters. According to Srinivas & Nakagawa [13], developing countries fail to function and respond effectively to many natural hazards that confront them because of inadequate infrastructure and emergency services, high population densities in unplanned settlements, and low economic capacities to endure the impacts. In addition, the observed changes in the frequency, severity, spatial extent, and duration of weather and climatic extremes, including hydrometeorological hazards are likely to increase disaster

* Corresponding author at: Department of Architecture and Built Environment, Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne NE1 8ST, United Kingdom.
E-mail addresses: kanchana.ginige@northumbria.ac.uk (K. Ginige), mendisapkd.20@uom.lk (K. Mendis), mthayaparan@uom.lk (M. Thayaparan).

https://doi.org/10.1016/j.pdisas.2022.100232
Received 6 January 2022; Received in revised form 6 May 2022; Accepted 8 May 2022
Available online 13 May 2022

vulnerability of communities [3,14]. According to Wagenaar et al. [15], in Sri Lanka, deforestation, urbanisation, unlawful landfilling, and construction that blocks waterways and riverbanks further increase the country's vulnerability to disasters.

The severe impacts of natural hazards can be prevented through structural mitigation measures such as engineering techniques and hazard-resistant construction, and non-structural measures such as policies, awareness building, knowledge development, public commitment, and methods and practices such as participatory mechanisms [16,17,18,19]. According to the World Bank and the United States Geological Survey, a US$40 billion investment in prevention, mitigation, and preparedness strategies could reduce a predicted US$400 billion in economic losses from natural hazards over the 1990s by US $280 billion [20]. Therefore, the United Nations Paris Agreement [21] asserts that relevant authorities should acknowledge the significance of preventing, mitigating, and addressing loss and damage caused by climate change, as well as the role of sustainable development in lowering the risk of loss and damage. Of the two types of measures, structural measures have prevailed to a great degree over non-structural ones during a period of increased risk [22]. However, it is observed that detailed research inquiries in relation to structural measures are less frequent in the context of Sri Lanka compared to non-structural measures. Despite research on flood management [23,24,15,25], there are fewer studies on structural measures relating to floods [26,27] and coastal erosion [28] in Sri Lanka. In addition, there is a dearth of literature on structural measures in relation to droughts and landslides, despite the fact that they are among the top three hydrometeorological hazards in Sri Lanka. Considering the aforementioned facts, this paper aims to examine the nature of existing structural measures for reducing the disaster risks caused by hydrometeorological hazards in Sri Lanka in order to highlight any improvements that are needed, and their costs and benefits. Disasters triggered by hydrometeorological hazards are referred to as hydrometeorological disasters in this paper here onwards. Accordingly, the following key research questions are raised in relation to structural measures for hydrometeorological disasters in Sri Lanka:

- What are the types of existing structural measures?
- What is the condition of the existing measures?
- What improvements are needed?
- What are the associated costs and benefits?

2. Literature review

According to UNDRR terminology, "Structural measures are any physical construction to reduce or avoid possible impacts of hazards, or the application of engineering techniques or technology to achieve hazard resistance and resilience in structures or systems" [29]. Structural measures alter the characteristics of natural hazards and reduce the probability of hazards occurring in the location of interest [30]. As a result, they reduce the impact of natural hazards [31]. Tasseff et al. [32] reveal that structural measures can be categorised into "hard" and "soft" measures and can also be temporary or permanent. Some examples of commonly used structural measures are dams, reservoirs, embankments, channel improvements, levees, gabion walls, and floodwalls which are combinedly used in order to reduce the adverse effects of floods [33,34].

2.1. Engineering school of vulnerability reduction

According to Cannon's vulnerability analysis, disaster mitigation is possible not only by modifying the hazard, but also by reducing the vulnerability. To reduce vulnerability, it is essential to implement social protection mechanisms through various types of technological interventions, such as structural measures [12]. McEntire et al. [35] introduce four ideal types for vulnerability reduction: physical science school, engineering school, structural school, and organisational school. As per McEntire et al.'s model, the physical science school emphasises living in safe environments and focuses on risk reduction and exposure to hazards. The engineering school focuses on the built environment and ways to improve resilience through construction practices and fabrication methods. The structural school focuses more on traditional notions of vulnerability than the other three, emphasising susceptibility based on socioeconomic and demographic factors such as race, ethnicity, gender, age, and other factors. The organisational school emphasises on the significance of preparedness, leadership, management, and the capacity to adapt, reinvent, and be creative. The theoretical basis of this study relates to McEntire et al.'s engineering school among the four approaches of vulnerability reduction to emphasise the importance of structural measures in disaster risk reduction. Bosher et al. [36], Lewis and Mioch [37], Poteyeva et al. [38], and Tipple [39] who are the major proponents of this school of thought of McEntire's, assert that if the buildings are constructed as per the building regulations and standards, as well as if there are adequate structural mitigation measures, impacts of natural hazards would inevitably subside.

Recent studies have shown that structural measures have a large potential for significantly reducing the impact of future hazards [40,41,42]. According to Magana [43], by means of structural measures, countries become less vulnerable and more resilient to natural hazards. The effective application of science and engineering principles in the development of the built environment is clearly evident in the natural hazard-threatened cities of the developed world [44]. One such example is Japan. In the aftermath of the massive and devastating Tsunami in 2011, the Japanese government made a strong commitment to rebuilding the affected region to a high level of safety. Based on simulations of future Tsunami heights, massive infrastructure projects have been carried out in the region, including the construction of huge seawalls and levees, hardened riverbanks and levees, and new and/or elevated roads and highways [45]. However, while these engineering protective measures would undoubtedly provide a safer built environment in hazard-prone areas [36], the vast amount of resources and ability to construct these are not always available, particularly in developing countries [3]. Lincke and Hinkel [42] assessed the cost-effectiveness of structural measures against sea-level rise considering population growth and found that structural adaptation measures are feasible for 13% of the global coastline.

2.2. Challenges of developing structural measures

Although the trend seems stable on developing more structural measures to mitigate the impacts pf natural hazards, several factors remain as barriers to constructing them, such as the increasingly complicated task of finding suitable places to build them, environmental pressure, the economic crisis [22], and the possibility of leading to a false sense of security and encouraging development in unsafe areas [46].

Starominski-Uehara [47] argues, despite mitigating flooding to some extent, dams offer no guarantee that flooding in downstream areas will not occur. Dams store water upstream of rivers to prevent flood damage to the downstream area. Therefore, they need to be built in the upper reaches of the river and have a space for water limiting the construction of the structures to mountainous areas only [34]. Structural measures such as underground dams are very inexpensive to install and can be quite effective in providing stored water during periods of drought. However, they might be associated with issues such as leakages or not providing expected water volumes, or poor water quality in some cases [48]. In addition, van Westen et al. [49] declare that landslide hazard is one of the more difficult ones to address, as this may involve extensive risk analysis and geotechnical investigations, in addition to risk maps, which may not be readily available in most countries. Terraced slopes are the most widely utilised structural measure against landslides across the world [50].

Moreover, development of structural measures usually entails high costs, and could constrain the implementation of non-structural strategies [51]. Starominski-Uehara [47] reveals that structural measures, in spite of their inherent limitations, should consider the uncertainty of externalities in causing damage to dense and exposed communities. However, while the damage caused by natural hazards is severe in developing countries, the structural measures to solve this problem are presently insufficient [52]. Therefore, these measures should be continually expanded and managed properly.

When a natural hazard occurs with catastrophic results, the affected population immediately notices a lack of security and equally quickly demands structural measures to solve the problem. Historically, this situation has been increasingly repeated in societies where population pressure and urbanisation positively correlate with the increase in disasters triggered by natural hazards, and as a result, a significant amount of resources has been allocated with the intention of mitigating the disaster risk [53]. The development of structural measures needs to achieve a desirable balance between the scale of measures and their economic benefits [54]. The scale of the structural measures is defined according to the standards of different return periods, and different scales have different economic costs [55,56]. A structural measure with a higher return period scale (such as one hundred years) usually has the potential to reduce disaster losses substantially over its life time but as Wang et al. [56] ascertain that such measures require higher economic investments and may not be the most appropriate overall solution for vulnerability reduction.

Further, there are sustainability related issues in relation to building these structures. Most of the structural measures are still built with carbon intensive materials like concrete and steel although more sustainable materials such as timber and biomaterials are now looked at as alternatives. The application of bioengineering techniques is being considered in Sri Lanka as well [57].

2.3. Types of structural measures in Sri Lanka

In Sri Lanka, different structural measures namely reservoirs, dams, diversions, channel improvements, terrace systems, retaining walls, and levees have been adopted throughout the country [28,57,58,27]. Among all the structural measures, dams can be considered as mostly used structural measures against floods [47]. Dam construction in Sri Lanka is not new to the country because the country possesses a strong hydraulic civilisation [59]. For centuries, coastal protection measures such as seawalls and rock revetments have been employed to safeguard and prevent further loss of coastal areas that serve as economic basis [60]. Breakwaters, seawalls, and dykes are onshore structures with the key function of protecting low-lying coastal areas, human habitation, and infrastructure against coastal flooding from waves, unusually high tides, storm surge, and in some cases like a Tsunami [61]. Magana [43] claims that droughts are one of the costliest natural hazards on the globe and further stress that droughts are expected to be more frequent and severe unless structural measures to reduce the water crisis are implemented.

2.4. Issues pertaining to structural measures in Sri Lanka

Although structural measures play a vital role in disaster management, different shortcomings and negative aspects can be identified which lead to different types of challenges in Sri Lanka as discussed below.

2.4.1. Ageing

Although, there are structural measures for floods in Sri Lanka and they stand for effective flood management within the country, their performance has deteriorated due to the ageing of these structures with time [26]. Besides, Japan International Cooperation Agency (JICA) [4] claims that some of these structural measures such as Kelani, Gin, and Nilwala flood barriers desperately need replacements or rehabilitations to ensure their functions in the event of a flood, as most of them were implemented before the 1980s. Therefore, there is a need for effective structural measures against floods in the context of Sri Lanka.

2.4.2. Poor practices

Abeykoon et al. [28] reveal that due to the prevailing economic state of the country, it has implemented low-cost coastal protective structures, while failing to conduct a comprehensive study on their effectiveness and their negative impacts on the coastal zone of Sri Lanka. Moreover, though it has been revealed that coastal erosion in Sri Lanka is a long-standing problem [6,8], monitoring and documentation seem to be poorly handled [28]. Moreover, significant concerns such as leakages and building flaws due to poor construction, insufficient capacity, blockage of water flow, and the risk of collapse were also discovered in these existing structural measures, which severely influence the whole disaster management process in Sri Lanka [26].

2.4.3. Damage to the ecosystem

According to Rathnayake and Suratissa [62], the construction of structural measures sometimes has damaging implications on the natural environment. For example, the Uma Oya multipurpose project has posed a significant environmental risk because of various activities such as excavations, rock blasting, and cut and fill. Furthermore, environmental difficulties such as soil erosion, groundwater contamination, negative impacts on aquatic and semiaquatic species, changes in wildlife survival, and saline intrusion into the water have occurred as a result of the Mahaweli reservoir building project.

2.4.4. Inadequacy of structural measures

It is observed that there is a gap in the development of effective, state of the art structural measures to mitigate the risk of natural hazards in Sri Lanka. Despite the existence of some structural measures for risk reduction of hydrometeorological disasters in Sri Lanka, whether they are adequate and effective are questionable due to a variety of reasons, including the insufficient use of new technology available, issues related to financing and physical planning, and lack of awareness of the benefits of the structural measures [26,63].

2.4.5. Damage to adjacent structures

According to Rathnayake and Suratissa [62], another negative consequence of structural measures is the damages caused by their construction to infrastructure in adjacent locations. The Uma Oya project is again shown as an example in this regard because its tunnelling activities have had a negative impact on the nearby water wells and infrastructure.

The findings of the literature show that there is a variety of structural measures against hydrometeorological disasters across the world, as well as the importance of those measures in disaster risk reduction. Although there are structural measures in Sri Lanka to some level, there are difficulties with ageing, maintenance, and monitoring. Besides, despite the abundance of disaster management studies, the literature on structural measures against hydrometeorological disasters in the Sri Lankan context is limited.

3. Methodology

To achieve the aim of this study, four research questions were established as: “what are the types of existing structural measures?”, “what is the condition of the existing measures?”, “what improvements are needed?”, and “what are the associated cost and benefits?” in relation to structural measures against hydrometeorological disasters in Sri Lanka. A narrative literature review was first carried out to build the foundation for the research as well as the theoretical understanding needed to fulfil the research questions.

Following the literature review, a set of expert interviews were conducted with the intention of bridging the knowledge gap identified in relation to structural measures in Sri Lanka.

According to Ritchie et al. [64], a qualitative research approach is ideal for gathering opinions and information from people based on their experience and will be useful in situations where an in-depth analysis of the data gathered is required. Such analysis was necessary in this study in order to understand the improvements to the structural measures and associated costs and benefits in the context of Sri Lanka. Moreover, Creswell [65] suggests a qualitative research approach when the variables to be investigated are unknown or when the literature is not comprehensive enough. According to Creswell [65], the qualitative approach is well suited to analyse exploratory data and to gather new knowledge. Furthermore, in comparison to quantitative surveys, a study of this nature could be best approached through a qualitative survey due to the significant population variance [66]. Accordingly, a qualitative interview survey strategy was adopted for this study.

The experts were selected using the snowball sampling method, a non-probability sampling method. In snowball sampling, the study respondents are invited to help find other possible respondents and become “de facto” research assistants [67]. When this sampling method is used, no specific sample size is required [68]. However, Guest et al. [69] have verified that 6–12 interviews appear to be a perfect balance for the number of qualitative interviews required to attain data saturation, while 80% of the codes are identified within the first 6 interviews. The concept of “saturation” – the point at which incoming data yields little or no new information – is a well-accepted benchmark for determining sample sizes for qualitative research [69,70]. Based on the principles of saturation, 12 in-depth interviews were conducted for this study. All the interviewees were selected based on their practice or research-based knowledge and experience in disaster management in the built environment, particularly in relation to structural measures against hydrometeorological disasters in Sri Lanka. In addition, availability for interviewing, and willingness to take part in the interviews were also considered in the selection. Table 1 summarises the profile of the respondents. The 12 experts were affiliated to organisations that perform a key role in the development and maintenance of structural measures for hydrometeorological disasters in Sri Lanka. In this regard, Disaster Management Centre, which is an overarching authority for all types of disaster management in Sri Lanka, Sri Lanka Army which usually involve in the construction of structural measures for all types of disasters, Irrigation department which is the key agency managing floods and droughts in Sri Lanka, Coast Conservation and Costal Resource Management Department is the main authority dealing with coastal erosion and flood, NBRO which is a research organisation undertaking several projects related to landslides were mainly selected to gather primary data. In addition, a research centre related to disaster risk reduction in a state university was approached to get more insight to the research study.

The interview guideline was developed using the information gleaned from the literature review. According to Rowley [71], semi-structured interviews allow the participants to explain the significance of a subject through their thoughts, experiences, and viewpoints. Less structured interview questions allow to raise further questions instantly, whenever required [72]. The interview guideline was divided into sections following the research questions in order to identify the existing structural measures in Sri Lanka, their current state, the required improvement in them, and finally, the benefits and costs associated with them. Each semi-structured interview (via physical visits/online meetings/telephone conversations) was conducted for 60–90 min.

Finally, the collected data was analysed using code-based content analysis (Inductive coding) with a focus on the research questions. This method considered as the most commonly used method in qualitative content analysis, where the researcher relies upon the data to accomplish new insights [73]. In the method, the respondents' narratives with verbatim quotations were retrieved from the gathered data and related to the phenomenon being investigated. The retrieved narratives were classified into several ‘codes’ based on similar themes. These codes were named using content characteristic words, phrases, or sentences. Following the extraction of narratives, primary codes, sub codes and the links between them were explored in relation to the research questions.

4. Results

Research findings revealed that the Irrigation Department, NBRO, and Coast Conservation and Coastal Resource Management Department of Sri Lanka have the legal obligation of deciding, designing, constructing, as well as maintaining structural measures for floods, landslides, and coastal erosion respectively. According to a report published by the Ministry of Environment Sri Lanka, currently, there is a National Drought Plan (published in 2020) but there is no single organisation or entity to take charge of drought management [74]. Besides, the responsibilities are “diffused” among many organisations. As a result, there are no-proactive programmes to mitigate drought in the country

Table 1
Profile of the respondents.

Respondent	Organisation	Job title/ position	Years of experience	Details of the Projects	
				Type	Involvement
R1	Sri Lanka Army	Project engineer	10	Flood and landslide mitigation projects	Managing the initial design and planning phase
R2	Irrigation Department	Director	22	Flood and drought mitigation projects	Conducting hydraulic analyses, design work, and evaluations Coordinating project teams
R3	Irrigation Department	Director	21	Flood and drought mitigation projects	Managing the initial design and handling the permitting work processes
R4	Coast Conservation and Coastal Resource Management Department	Chief Engineer	21	Coastline protection projects	Planning and designing
R5	National Building Research Organisation (NBRO)	Scientist	9	Landslide mitigation projects	Planning
R6	NBRO	Director	29	Landslide mitigation projects	Planning, monitoring, team leading
R7	Coast Conservation and Coastal Resource Management Department	Civil Engineer	10	Coastline protection projects	Designing and supervision of work
R8	Irrigation Department	Civil Engineer	12	Flood mitigation projects	Site management
R9	Irrigation Department	Technical Officer	10	Flood mitigation projects	Planning, designing, and construction supervision
R10	Disaster Management Centre (DMC)	Director	25	Flood, landslides, and drought mitigation projects	Consultation, research work
R11	Irrigation Department	Technical Officer	6	Flood mitigation projects	Planning, designing, and construction supervision
R12	Research Centre at a State University	Research Scholar	3	Flood mitigation research	Research work

and most of the drought interventions have been mainly reactive. While agreeing with that, R2, R3, R8, R9, R10, and R11 declared that the Irrigation department is mainly handling drought management, despite the fact that there is no legally vested power in them for drought management. Structural measures used in Sri Lanka are discussed in the next section.

4.1. Structural measures in Sri Lanka

Based on literature and primary data, the types of structural measures implemented in Sri Lanka were identified and classified as shown in Table 2. As per Table 2, the structural measures were mainly categorised based on the natural hazards; floods, coastal erosion/floods, droughts, and landslides. Adhering to Tasseff et al.'s [32] classification, the structural measures were then identified as "hard or soft" and " permanent or temporary".

Table 2 shows that the structural flood mitigation measures are widely available in Sri Lanka while there is a lack of structural measures against droughts. Moreover, structural measures such as dikes, polders, earth ramparts, and bridge abutments are not used in the local context compared to the global context. Besides, the majority of the structural measures in Sri Lanka are hard and permanent structural measures. The majority of the respondents mentioned that if there is an emergency disaster situation only the temporary structural measures are constructed, if not always the permanent structures are constructed and appreciated (R1, R2, R4, R5, R6, R9, and R12). It can be seen that there are common structural measures used in the country, which are highlighted (in bold) in Table 2. In addition, some of the structural measures are used for multi-purposes. Elaborating on that R3 stated that *"the reservoirs are normally built up in the upstream area on a river to retain the water flow in flood situation as well as it can be used for multi-purposes such as for power generation, water storage for drought events, industrial and domestic water requirement, and groundwater recharge"*. Anvarifar et al. [75] reported that traditionally, many flood mitigation measures in the Netherlands also serve other functions such as housing, transportation, recreation, and so on. In the majority of cases, the only visible function is the secondary function of the flood mitigation measure [88].

4.2. The existing condition of the structural measures in Sri Lanka

As per the empirical findings, the existing conditions of structural measures in Sri Lanka are affected by factors such as obsolescence, lack of maintenance, rehabilitation and replacement, and insufficiency. It was declared by all the respondents that Sri Lanka has enough types of structural measures against natural hazards, compared to other developing countries. However, according to JICA [4], the main problem with these existing structural measures in Sri Lanka, is their age. The study clarified that the existing structural measures badly need replacements or rehabilitation in order to ensure they function as expected in the event of a hydrometeorological hazard, as most of them were installed more than 40 years ago. Accordingly, it is evident through empirical research findings that the majority of flood defences against natural hazards are obsolete as these were built before 1980s. Some of these outdated flood defences are currently overtopping, resulting in a sudden, dangerous water rise. Furthermore, the unoccupied marshy areas near the flood defences were also developed and occupied by the community back then [R2, R3, and R11]. Hence, these structural measures should be upgraded in light of the current population, development, and new technologies in order to obtain the real benefits from such measures.

In addition, the respondents revealed structural measures such as copper damming using sheet piling and temporary filters against floods, landslide resilient houses, shotcrete structures, and Nature-based Solutions (NbS) against landslide hazards are utilised in Sri Lanka in order to

Table 2
Structural measures against hydrometeorological disasters in Sri Lanka.

Natural Hazard	Structural measures	Classifications				Literature Sources
		Hard	Soft	Permanent	Temporary	
Flood	Water retarding basin	✓		✓		1, 6, 8, 23
	Channel improvement	✓		✓		1, 8, 13
	Embarkment	✓		✓		1, 3, 10, 11, 21, 20, 21, 24
	Levee/Marginal embarkment	✓		✓		1, 2, 4, 5, 6, 8, 10, 12, 18, 31
	Dam	✓		✓		2, 5, 6, 8, 12, 13, 21, 18, 19
	Reservoir	✓		✓		6, 8, 13, 17, 23
	Drainage pipe networks	✓		✓		6, 16, 17
	Pumping station	✓		✓		8, 17
	Dredging		✓	✓		6
	Floodgate	✓		✓		2, 3, 6, 8
	Combinations	✓		✓		6, 8
	Floodwall /flood barrier	✓		✓		3, 16, 11, 14
	Copper damming using sheet piling		✓		✓	–
	Temporary filters		✓		✓	–
	Sandbags		✓		✓	7, 15, 19, 21
Coastal erosion / flood	Geotextile bags		✓	✓		10
	Rock revetments	✓		✓		2, 10
	Breakwater	✓		✓		2, 10, 21
	Groins	✓		✓		10
	Floodwall /flood barrier	✓		✓		14
	Beach nourishment		✓		✓	10
Drought	**Reservoir**	✓		✓		9, 23
Landslide	**Drainage pipe networks**	✓		✓		29
	Channel improvement	✓		✓		22
	Anchoring systems	✓		✓		22
	Retaining walls	✓		✓		22
	Soil nailing	✓		✓		22
	Deep shafts/dowels	✓		✓		22
	Landslide resilient houses	✓		✓		–
	Shotcrete structures	✓		✓		–
	Nature-based Solutions (NbS)	✓		✓		–

Literature Sources: 1 - [31], 2 - [61], 3 - [75], 4 - [76], 5 - [77], 6 - [33], 7 - [78], 8 - [34], 9 - [43], 10 - [60], 11 - [79], 12 - [80], 13 - [22], 14 - [81], 15 - [82], 16 - [83], 17 - [84], 18 - [47], 19 - [32], 20 - [85], 21 - [86], 22 - [49], 23 - [46], 24 - [87]

mitigate disaster impacts. According to R5, NbS can be effectively used for risk mitigation in larger areas prone to landslide hazards, where traditional mitigation options are less cost-effective. However, there is still a limited use of those techniques in landslide-prone areas such as Galabada in Rathnapura and Badulusirima in Badulla (R5 and R6).

According to Table 2, it is clear that enough structural measures for drought events are not in use in Sri Lanka compared to other hydro-meteorological hazards. Droughts are one of the most frequent hydro-meteorological disasters identified in the Disaster Management Act No. 13, 2005 of the Government of Sri Lanka [74]. While highlighting the severity of droughts in Sri Lanka, De Alwis and Noy [89] claimed that on average, the economic costs associated with said events to healthcare have been estimated to be US$52.8 million yearly, with 78% of the costs originating from droughts.

As highlighted by R3, the construction of underground dams is considered the best option against drought disasters worldwide. Similarly, Telmer and Best [48] specified that underground dams are very inexpensive to install but can be quite effective in providing stored water during periods of drought. Interviewed experts claimed that underground dams are located in Sri Lanka by nature. Nonetheless, the country lacks methods for protecting those structures (R2, R3, R8, and R9). R2 further elaborated that *"there are no groundwater extraction limitations in our country. Anyone can get water supply by digging a well at any place"*. A drought is basically managed by groundwater and groundwater storage, as managed natural infrastructure, could be a multipurpose, more decentralised, cost-effective, and sustainable alternative to "grey" infrastructure, such as traditional-built dams [90]. Therefore, relevant authorities should take necessary actions to protect such gifts given by the nature of the country.

Besides, R4 emphasised that *"we have not applied structural measures until now focusing on disasters like Tsunami, due to the huge cost, and also since Tsunami is a rarely happened incident, Sri Lankan government cannot allocate that much huge finance to construct flood defences against Tsunami"*. Further, there are a lot of technologically sophisticated structural measures in developed countries [91,56], which are currently not applied in Sri Lanka. Therefore, there is a need to look into the application of those effective structural measures in order to reduce the adverse effects of natural hazards prevailing in the country. Nevertheless, non-structural measures such as a buffer zone along coastal line and an early warning system were implemented to minimise the impact of Tsunamis in Sri Lanka (R10 and R12). There was no early warning System for tsunamis in the Indian Ocean prior to 2004. Following the devastation of the 2004 Tsunami, numerous countries banded together to build an efficient Tsunami early warning system in the Indian Ocean region. In 2008, an end-to-end Tsunami early warning system was built, which became fully operational in 2013 and covered all affected countries, including Sri Lanka [92]. However, the effectiveness of the existing early warning system for Tsunami was questioned several times [93]. The next section discusses what is more required in structural measures in hydrometeorological disasters in Sri Lanka.

4.3. Structural measures in Sri Lanka - what more is required?

According to the study, major replacements and rehabilitation, regular maintenance, the construction of more structural measures, raising awareness of the importance of building structural measures, the use of advanced technologies, budget allocation, project prioritisation, and a consistent decision-making framework are the major concerns in improving the structural measures against hydrometeorological disasters in Sri Lanka.

Agreeing to JICA [4], the majority of the respondents acknowledged that major flood control measures in the Kelani, Gin, and Nilwala River Basins were initiated before the 1980s and after that, no new major flood control measures were introduced (R1, R2, R3, R8, R9, and R11). At present, the existing structural measures such as dikes, flood gates, and pump houses are old and need to be replaced or rehabbed in order to operate properly. In Sri Lanka, reservoirs that were built primarily for water supply in drought events as well as for day-to-day activities, play a significant role in flood mitigation because they also are a way of flood control. However, many reservoirs are old and need to be refurbished to ensure the necessary protection from them. Moreover, R2 stated, *"we have already proposed location-specific flood protection structures such as continuous major bunds and dry dams to different places in Sri Lanka"*. In addition, flood control reservoirs and dry dams for Kalu river upstream, extended flood bunds for Kelani river and Mahaweli river downstream, and upstream reservoirs for Nilwala river are being proposed.

Structural measures against coastal erosion such as jetty – protect and stabilise man-made constructions such as maritime works, seawalls – reduce the effects of strong waves and to defend the coast around a town from sea erosion, and dikes – protect low-lying areas from flooding from the sea, are recommended by the experts as suitable to Sri Lanka (R4 and R7). In contrast, R1, R5, R6, and R9 stressed, *"rather than going for new structural measures, protecting the existing is much crucial"*.

Almost all the respondents agreed that there is an inadequacy of structural measures and there are critical issues with structural measures, such as ageing and lack of awareness of the benefits of structural measures by responsible authorities as well as the by the public.

When enquiring further about what could be done to improve structural measures in the country, R1 claimed that *"financial barriers are the most common barriers and the maintenance of structural measures is not happening properly in our country. Also, we do not have the advanced technologies that other countries have. However, we do have enough human resources"*. Besides, the majority of the respondents emphasised that less priority has been given to projects related to building structural measures and project prioritisation differs from one government to another. Due to the lack of usage of advance technologies, the structural measures that are currently available in Sri Lanka have limited flexibility to adapt to new climate related challenges in future.

Social pressure is another major challenge, which comes prior to the construction of structural measures. As an example, normally the benefits of a structural measure are achieved by people who live a little further away from the construction premises, but not by those who live very close. Hence, the people who live nearby do not feel compelled to sacrifice their daily living style. R3 declared that *"in this kind of situation, it is really hard to convince society about the importance of building a structural measure for a country"*.

Some experts highlighted the reason for most of the challenges associated with building structural measures is the lack of a consistent decision-making framework (R2, R4, R5, R6, and R10). According to Meyer et al. [94], economic evaluation of alternative structural measures for decision support has a considerable tradition in Europe and the United States. Different approaches like cost-benefit analysis (CBA) or cost-effectiveness analysis (CEA) can be applied for the economic evaluation of such measures. However, such an approach has not been undertaken so far in the Sri Lankan decision-making process with regard to structural measures.

Nevertheless, according to Hartmann and Juepner [55], structural measures have different scales which are defined according to the standards of different return periods, and different scales have different economic costs. Thus, the relationship between costs and benefits should be analysed to acquire the most economical structural measure in disaster management. The next section will address the benefits and costs related to structural measures.

4.4. Structural measures in Sri Lanka - Benefits and costs

Natural hazards may cause substantial devastation to any country's economy, environment, infrastructure, and property. The findings of the literature indicated the importance of implementing structural measures in order to decrease the adverse impact of natural hazards. However, there may be both benefits and costs in any type of investment or implementation. As a result, the respondents were asked about the benefits and costs of structural measures against natural hazards in order to assess the implications of having them in Sri Lanka. All of the respondents' ideas are summarised in Fig. 1.

Fig. 1 depicts the benefits and costs of structural measures for mitigating floods, landslides, droughts, and coastal erosion as shown in green and red dots, respectively. Different types of cost and benefits are mapped with the related natural hazards. As per Fig. 1, majority of the benefits and costs are commonly applicable to structural measures for any of the identified hazards. However, there are unique benefits as well as costs of structural measures associated with some hazards. Some of the unique benefits include facilitating fishing and recreational activities, and beach development; sea-front development from structural measures for coastal erosion; water circulation from flood and drought mitigation measures; and improvement of drainage systems and replenishment of groundwater resources from flood mitigation measures. Some of the specific costs include: creation of unsuitable micro-environment after the new construction of flood mitigation measures and limited travel along the beach due to the structural measures against coastal erosion.

When considering the costs (negative consequences) associated with structural measures, all the respondents professed that structural measures comprise an initial cost for design and construction plus the maintenance and repair costs through its life cycle. In addition to these costs, some experts claimed that there can be residual operational costs such as training, practice deployments, staff costs, storage, transportation, supervision, and security associated with structural measures (R2, R7, R9). Partington [95] claimed that the cost of maintenance, repair, and operation is necessary over the life of a structural measure to keep it functional. Similarly, the majority of respondents agreed that the degree and complexity of maintenance operations, as well as the requirement for specialised maintenance, are critical to the proper operation of any structural measure.

Moreover, the majority of the respondents pointed out that the damage to human life and property from a structural measure which has exceeded its return period could be more, compared to the situation with no such structural measure. With the ageing of the structural measures, the maintenance costs are likely to increase, and hence, ensuring effective maintenance is important until the end of the return period which is generally the end of the lifecycle to minimise costs. As maintenance costs incurred beyond the return period is not cost effective, rehabilitating will be usually demanded at the end of the return period. Also, not constructing or maintaining the structures properly could lead to unexpected disasters as well.

Highlighting the issues related to resettlement and social costs of the new construction, R3 stated, *"When there is new construction on structural measure, resettlements must be arranged for the community who live there. In those situations, we cannot provide the real value of their land. As an example, even though the market value of the alternative land and the property provided will be equal or even more than their previously owned property if the ownership of the property comes from generation to generation, there is much more value than the market price of that land for the owner"*.

In addition, respondents claimed that sometimes, professionals would advocate more towards non-structural measures rather than structural measures because they believe that building structural measures tend to change the pattern of the environment. For instance, there are natural habitats associated with floods and if floods are controlled by structural defences, they will indirectly harm the indigenous species that live in such waterlogged areas. Elaborating more on this, R2 stated, *"There are flood-dependent animals, and their breeding season starts just after a flood happens. Hence, environmentalists argue that controlling floods through* structural *measures is a cost to the environment"*. Nevertheless, Kim et al. [34] suggested that in order to defend against urban flooding, structural and non-structural measures must be carried out at the same time. Moreover, R12 highlighted that only a certain level of protection against hydrometeorological disasters can be achieved through structural measures. Hence, it is important to consider the residual risk when developing structural measures. This involves clearly defining the design level of protection that the structural measure can reliably achieve, specifying the local conditions that may affect the level of

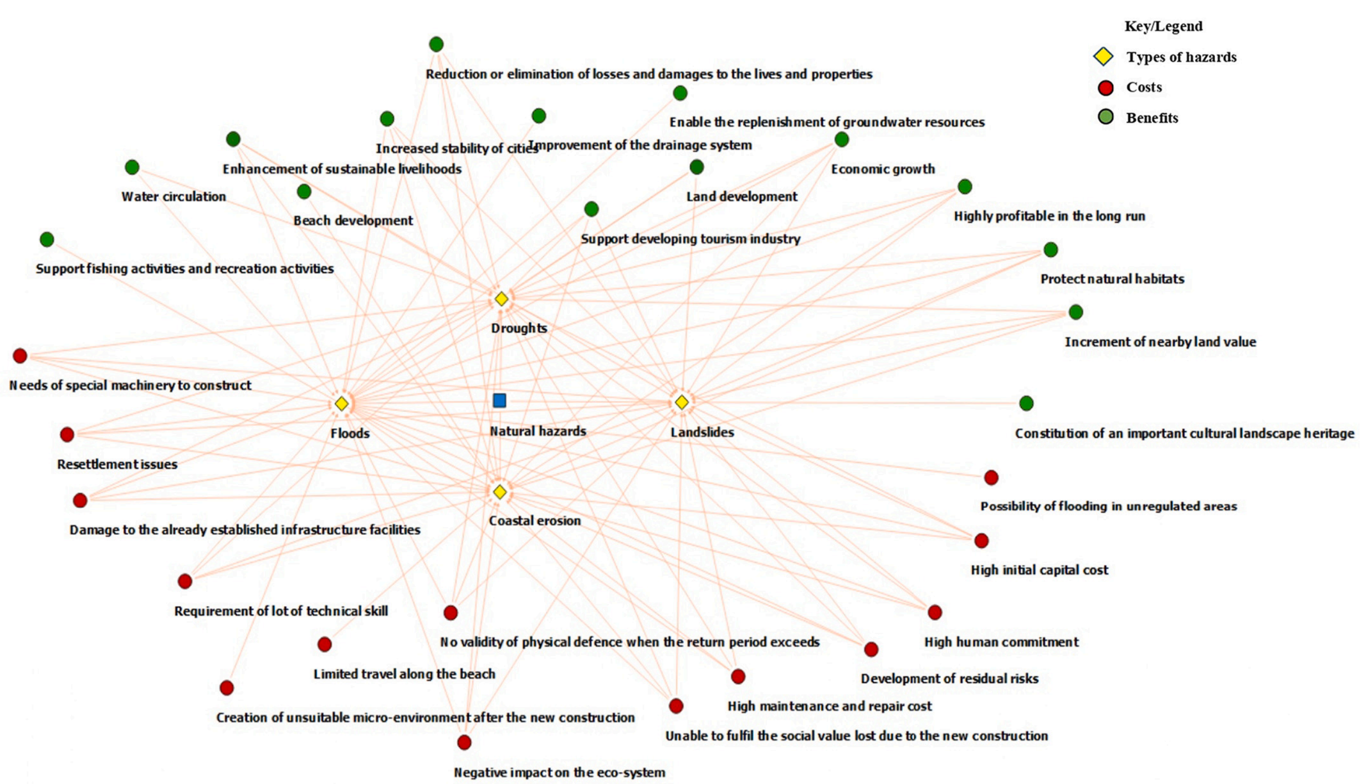

Fig. 1. Mapping of benefits and costs associated with structural measures.

protection, determining the disaster risks in the protected area related to the performance and capacity of the structural measure, and educating the community about the limitations of the measure [96].

Emphasising the value of constructing structural measures above all the costs related, R3 stated, *"deaths from a natural hazard are just numbers until they become names of people you know or names of people you love. Therefore, there is an uncountable benefit associated with structural measures against natural hazards"*. While agreeing with that, R8 and R9 detailed that a Netherlands team assessed the economic damage caused by floods and landslides that occurred in 2017, which affected almost the entire country, and there they quantified that the total cost of the damage was higher than constructing a full protection system. Therefore, it is undoubted that structural measures are highly beneficial, as the costs are clearly outweighed by the benefits.

Besides, all the interviewees expressed that the construction of structural measures facilitates the development of the country. For example, Rathnapura (translated into English as 'City of Gems' because it is the centre of the country's *gem* trade), one of the main cities in Sri Lanka is frequently impacted by severe floods and landslides. According to Dilhani and Jayaweera [97], the main causes of flooding in Rathnapura town are the very high annual rainfall in the area and its location in the floodplains of Kalu River. The river, which is 76.5 km long from Rathnapura to Kalutara is unable to create higher velocities to discharge floods with only 11.70 m (38.4 ft) Mean Sea Level (MSL) riverbed elevation at Rathnapura and a gradient of only 0.15 m per km (1/6700) [98]. Additionally, the city is affected by 1 into 10-year major flood event that causes significant destruction to lives and property. During this flood event, approximately 80% of the land within the city lies under floodwater for an average period of 2–5 days. In 2017, a total number of 206 families and 1203 people were affected by the major floods [99]. Since that, the occurrence of floods has had a significant influence on the city's growth since the damage that is connected with flood risk ranges from infrastructure, buildings, loss of farmland to injuries, and loss of life. The experts (R2 and R3) mentioned that the Irrigation Department of Sri Lanka has proposed to construct a major flood dike from Warakatota bridge area to Ayurveda office, which will be beneficial for protecting the town itself from the annual flood. This proposal will contribute to the growth of, Rathnapura city, and ultimately the country. There, as a member of the expert committee, respondent R2 had been actively involved in the development of the proposal.

All in all, every expert highlighted that the costs of structural measures are paid in the short run, but the benefits are realised in the long run.

4.5. Discussion

The study investigated the nature of existing structural measures for hydrometeorological disasters in order to highlight any improvements that are required, and the costs and benefits. It was discovered that in the Sri Lankan context, there is a significant need for structural mitigation measures to reduce the impacts of natural hazards. According to the respondents, most projects lack prior planning owing to a lack of coordination and collaboration with related stakeholders, as well as lack of time available for further research of the scenario in order to develop thorough plans. This limits the construction of effective structural mitigation measures. Therefore, the need to understand how to develop efficient structural measures is becoming increasingly urgent. As per the Vulnerability Plus (V+) theory developed by Zakour, and Swager [100], the effectiveness of structural measures should be improved in order to reduce disaster vulnerability while also providing the community with the capacity to respond resiliently to natural hazards.

In 2009, the Iranian Hydrologic Engineering Centre estimated the expected values of damage reduction without and with flood protection measures in the Karun river's entire reaches. Without constructing a dam, the annual expected value of damage was US$7.74 million. The annual expected value of damage reduction from the Dam 1 and Dam 2 alternatives was estimated to be US$6.64 million and US$5.9 million, respectively [101]. Similarly, respondents emphasised the importance of constructing structural measures against natural hazards, referring to the fact that the economic damage caused by floods and landslides in Sri Lanka in 2017 was more than the cost of constructing a full protection system.

Moreover, while agreeing with Denton et al. [102], all the experts asserted that the most appropriate and effective structural measures must be identified and prioritised. In doing so, the costs and benefits of these measures over their life cycle must be assessed [103]. However, such a holistic assessment has not been incorporated in the decision-making process in relation to the construction of structural measures in Sri Lanka so far.

5. Conclusions

Sri Lanka, being a disaster-prone country, has a considerably high incidence of hydrometeorological disasters for a variety of reasons, as documented in both the literature and empirical evidence. Hydrometeorological disasters affect many people in Sri Lanka each year, resulting in fatalities, severe economic impacts, and relocation of communities. In this context, hydrometeorological disaster mitigation has emerged as one of the country's top priorities. Structural measures, which are one of the disaster mitigation techniques, are used to alter the features of hydrometeorological hazards and reduce the probability and/or effect of the hazard occurring in the place of interest. Therefore, structural measures for hydrometeorological disasters in Sri Lanka were studied in order to determine what is required for the country to decrease the detrimental impacts of disasters.

In comparison to other developing countries, the empirical research findings indicated that Sri Lanka has sufficient types of structural measures against floods, landslides, and coastline erosion. However, because most of the current structural measures were installed before the 1980s, they are in desperate need of replacement or rehabilitation in order to function efficiently. Moreover, compared to other natural hazards, sufficient structural measures against drought occurrences are limited in Sri Lanka. Both the research and empirical evidence show that constructing underground dams is an effective method of averting droughts. Although these measures are available in Sri Lanka, the country lacks ways for preserving these structures.

There are several technologically sophisticated structural measures that are currently not deployed in Sri Lanka. Therefore, there is a need to investigate the application of those effective structural measures in order to mitigate the negative impacts of hydrometeorological hazards prevalent in the country. It was also discovered that, in addition to the insufficiency of structural measures in terms of types, there are other major concerns such as ageing and a lack of knowledge of the benefits of structural measures among responsible authorities and the public. Undoubtedly, structural measures have significant building costs, but the benefit of establishing structural measures for a society is always all-encompassing. Therefore, to assert the aforementioned facts and establish the most cost-effective structural measure for a specific situation, all the costs and benefits including non-financial implications must be analysed in detail. Using development appraisal techniques such as CBA or CEA, are appropriate. However, it is not evident that the decision-making process in relation to the development of structural measures in Sri Lanka is based on such systematic and detailed analyses. Hence, a study on developing a comprehensive decision-making framework based on CBA in relation to structural measures is recommended as a future research direction.

Credit author statement

Kanchana Ginige: Conceptualization, Funding acquisition, Project administration, Methodology, Supervision, Writing-Reviewing and

Editing.

Kalindu Mendis: Methodology, Investigation, Data curation, Formal analysis, Writing-original, Visualisation.

Menaha Thayaparan: Methodology, Supervision, Writing-Reviewing and Editing.

Declaration of Competing Interest

The study has been funded by Northumbria University, UK. 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.

References

[1] Barnes B, Dunn S, Wilkinson S. Natural hazards, disaster management and simulation: a bibliometric analysis of keyword searches. Nat Hazards 2019;97:813–40. https://doi.org/10.1007/s11069-019-03677-2.

[2] Dube E, Wedawatta G, Ginige K. Building-Back-Better in post-disaster recovery: Lessons learnt from cyclone Idai-Induced floods in Zimbabwe. Int. J. Disaster Risk. Sci. 2021;12:700–12. https://doi.org/10.1007/s13753-021-00373-3.

[3] Jayawardena AW. Hydro-meteorological disasters: causes, effects and mitigation measures with special reference to early warning with data driven approaches of forecasting. Procedia IUTAM 2015;17:3–12. https://doi.org/10.1016/j.piutam.2015.06.003.

[4] Japan International Cooperation Agency. Data collection survey on disaster risk reduction sector in Sri Lanka. 2017.

[5] Amaratunga D, Malalgoda C, Haigh R, De Silva A. How do we organise for disaster risk reduction and resilience? A study on disaster reduction and management governance profile of Sri Lanka. United Kingdom: University of Huddersfield; 2020.

[6] Lakmali EN, Deshapriya WGA, Jayawardene KGAI, Raviranga RMP, Ratnayake NP, Premasiri HMR, et al. Long term coastal erosion and shoreline positions of Sri Lanka. Surv Fish Sci 2017;3. https://doi.org/10.18331/SFS2017.3.2.1.

[7] Mehvar S, Dastgheib A, Bamunawala J, Wickramanayake M, Ranasinghe R. Quantitative assessment of the environmental risk due to climate change-driven coastline recession: a case study in Trincomalee coastal area. Sri Lanka Clim Risk Manag 2019;25:100192. https://doi.org/10.1016/j.crm.2019.100192.

[8] Ratnayake NP, Ratnayake AS, Azoor RM, Weththasinghe SM, Seneviratne IDJ, Senarathne N, et al. Erosion processes driven by monsoon events after a beach nourishment and breakwater construction at Uswetakeiyawa beach. Sri Lanka SN Appl Sci 2018;1:52. https://doi.org/10.1007/s42452-018-0050-7.

[9] Lehner B, Doll P, Alcamo J, Henrichs T, Kaspar F. Estimating the impact of global change on flood and drought risks in Europe: a continental. Integr Anal Clim Change 2006;75:273–99. https://doi.org/10.1007/s10584-006-6338-4.

[10] Steele P, Knight-John M, Rajapakse A, Wickramasinghe KSK. Disaster management policy and practice: Lessons for government, civil society, and the private sector in Sri Lanka. Colombo: Institute of Policy Studies of Sri Lanka; 2007.

[11] Basnayake A, Jayasinghe L, Nauki T, Weerathunga S. Disaster management in Sri Lanka: A case study of administrative failures. 2019.

[12] Cannon T. Vulnerability analysis and the explanation of “natural” disasters. In: Varley A, editor. Disasters, Development and Environment. John Wiley & Sons, Ltd; 1994. p. 13–30.

[13] Srinivas H, Nakagawa Y. Environmental implications for disaster preparedness: lessons learnt from the Indian ocean tsunami. J Environ Manage 2008;89:4–13. https://doi.org/10.1016/j.jenvman.2007.01.054.

[14] Lavell A, Oppenheimer M, Diop C, Hess J, Lempert R, Li J, et al. Climate change: New dimensions in disaster risk, exposure, vulnerability, and resilience, managing the risks of extreme events and disasters to advance climate change adaptation. Cambridge University Press, United Kingdom; 2012.

[15] Wagenaar DJ, Dahm RJ, Diermanse FLM, Dias WPS, Dissanayake DMSS, Vajja HP, et al. Evaluating adaptation measures for reducing flood risk: a case study in the city of Colombo, Sri Lanka. Int J Disaster Risk Reduct 2019;37:101162. https://doi.org/10.1016/j.ijdrr.2019.101162.

[16] United Nations Office for Disaster Risk Reduction. Online glossary: mitigation [WWW Document]. 2021. https://www.undrr.org/terminology/mitigation.

[17] United Nations. Transforming our world: the 2030 agenda for sustainable development [WWW document]. 2015. https://sdgs.un.org/2030agenda.

[18] United Nations. Sendai framework for disaster risk reduction 2015–2030. 2015.

[19] Ginige K, Amaratunga D, Haigh R. Developing capacities for disaster risk reduction in the built environment: capacity analysis in Sri Lanka. Int J Strateg Prop Manag 2010;14:287–303. https://doi.org/10.3846/ijspm.2010.22.

[20] Shreve CM, Kelman I. Does mitigation save? Reviewing cost-benefit analyses of disaster risk reduction. Int J Disaster Risk Reduct 2014;10:213–35. https://doi.org/10.1016/j.ijdrr.2014.08.004.

[21] United Nations. Paris agreement. Paris. 2016.

[22] Perez-Morales A, Asuncion Romero-Diaz M, Gil-Guirado S. Structural measures against floods on the Spanish Mediterranean coast. Evidence for the persistence of the “escalator effect.”. Geogr Res Lett 2021;47:33–50. https://doi.org/10.18172/cig.4901.

[23] Chamber of Construction Industry. Seminar on Flood Control & Disaster Responsiveness in proposed Western Megapolis. Colombo, Sri Lanka. 2017.

[24] Palliyaguru R, Amaratunga D. Managing disaster risks through quality infrastructure and vice versa. Struct Surv 2008;26:426–34. https://doi.org/10.1108/02630800810922766.

[25] Wickramaratne S, Ruwanpura J, Ranasinghe U, Walawe-Durage S, Adikariwattage V, Wirasinghe SC. Ranking of natural disasters in Sri Lanka for mitigation planning. Int J Disaster Resil Built Environ 2012;3:115–32. https://doi.org/10.1108/17595901211245198.

[26] Dasandara M, Ernst R, Kulatunga U, Rathnasiri P. Investigation of issues in structural flood management measures in Sri Lanka. J Constr Dev Ctries 2021. In press.

[27] Sivakumar S. Flood mitigation strategies adopted in Sri Lanka a review. Int J Sci Eng Res 2015;6:607–11.

[28] Abeykoon LCK, Thilakarathne EPDN, Abeygunawardana AP, Warnasuriya TWS, Egodauyana KPUT. Are coastal protective hard structures still applicable with respect to shoreline change in Sri Lanka. 2021 (vol. No. 1240). Tokyo.

[29] United Nations Office for Disaster Risk Reduction. Structural and non-structural measures [WWW Document]. 2022. https://www.undrr.org/terminology/structural-and-non-structural-measures (accessed 5.4.22).

[30] National Research Council. Implementing flood risk management strategies. In: Levees and the National Flood Insurance Program: Improving policies and practices. Washington, DC: National Academies Press; 2013. p. 97–126.

[31] Abdella K, Mekuanent F. Application of hydrodynamic models for designing structural measures for river flood mitigation: The case of Kulfo River in southern Ethiopia. Model Earth Syst Environ 2021. https://doi.org/10.1007/s40808-020-01057-5.

[32] Tasseff B, Bent R, Van Hentenryck P. Optimization of structural flood mitigation strategies. Water Resour Res 2019;55:1490–509. https://doi.org/10.1029/2018WR024362.

[33] Garrote J, Bernal N, Diez-Herrero A, Martins LR, Bodoque JM. Civil engineering works versus self-protection measures for the mitigation of floods economic risk. A case study from a new classification criterion for cost-benefit analysis. Int J Disaster Risk Reduct 2019;37. https://doi.org/10.1016/j.ijdrr.2019.101157.

[34] Kim K, Han D, Kim D, Wang W, Jung J, Kim J, et al. Combination of structural measures for flood prevention in Anyangcheon river basin. South Korea Water 2019;11. https://doi.org/10.3390/w11112268.

[35] McEntire D, Gilmore Crocker MPH, C, Peters E.. Addressing vulnerability through an integrated approach. Int J Disaster Resil Built Environ 2010;1:50–64. https://doi.org/10.1108/17595901011026472.

[36] Bosher L, Dainty A, Carrillo P, Glass J. Built-in resilience to disasters: a pre-emptive approach. Eng Constr Archit 2007;14:434–46.

[37] Lewis D, Mioch J. Urban vulnerability and good governance. J Conting Crisis Manag 2005;13:50–3.

[38] Poteyeva M, Denver M, Barsky LE, Aguirre BE. In: Rodrıguez H, Quarantelli EL, Dynes RR, editors. Search and rescue activities in disasters. Springer, New York, NY: Handbook of Disaster Research; 2006. p. 200–16.

[39] Tipple G. Housing and urban vulnerability in rapidly-developing cities. J Conting Crisis Manag 2005;13:66–75.

[40] Diaz DB. Estimating global damages from sea level rise with the Coastal Impact and Adaptation Model (CIAM). Clim Change 2016;137:143–56. https://doi.org/10.1007/s10584-016-1675-4.

[41] Hinkel J, Lincke D, Vafeidis AT, Perrette M, Nicholls RJ, Tol RSJ, et al. Coastal flood damage and adaptation costs under 21st century sea-level rise. Proc Natl Acad Sci 2014;111:3292–7. https://doi.org/10.1073/pnas.1222469111.

[42] Lincke D, Hinkel J. Economically robust protection against 21st century sea-level rise. Glob Environ Chang 2018;51:67–73. https://doi.org/10.1016/j.gloenvcha.2018.05.003.

[43] Magana V. Considerations for a research program on drought in Mexico. Tecnol Y Ciencias Del Agua 2016;7:115–33.

[44] Allotey NK, Arku G, Amponsah PE. Earthquake-disaster preparedness: the case of Accra. Int J Disaster Resil Built Environ 2010;1:140–56. https://doi.org/10.1108/17595901011056613.

[45] Maly E, Suppasri A. The Sendai framework for disaster risk reduction at five: lessons from the 2011 great East Japan earthquake and tsunami. Int J Disaster Risk Sci 2020;11:167–78. https://doi.org/10.1007/s13753-020-00268-9.

[46] Wenger C, Hussey K, Pittock J. Living with floods: Key lessons from Australia and abroad, synthesis and integrative research. Gold Coast, QLD: Final Report; 2013.

[47] Starominski-Uehara M. How structural mitigation shapes risk perception and affects decision-making. Disasters 2021;45:46–66. https://doi.org/10.1111/disa.12412.

[48] Telmer K, Best M. Underground dams: A practical solution for the water needs of small communities in semi-arid regions. 2004.

[49] van Westen CJ, Jetten V, Sliuzas R, Brussel M, Alkema D, van den Bout B, et al. Caribbean handbook on risk management. 2016.

[50] Parrotta JA, Agnoletti M. Traditional Forest-related knowledge: Sustaining communities. Springer, Dordrecht: Ecosystems and Biocultural Diversity; 2012.

[51] Gerber BJ. Disaster management in the United States: examining key political and policy challenges. Policy Stud J 2007;35:227–38. https://doi.org/10.1111/j.1541-0072.2007.00217.x.

[52] Son C-H, Baek J-I, Ban Y-U, Ha S-R. The effects of mitigation measures on flood damage prevention in Korea. Sustainability 2015;7:16866–84. https://doi.org/10.3390/su71215851.

[53] Tariq MAUR, van de Giesen N. Floods and flood management in Pakistan. Phys Chem Earth, Parts A/B/C 2012;47–48:11–20. https://doi.org/10.1016/j.pce.2011.08.014.

[54] Kundzewicz ZW, Hegger DLT, Matczak P, Driessen PPJ. Flood-risk reduction. Proc Natl Acad Sci U S A 2018;115:12321–5.
[55] Hartmann T, Juepner R. The flood risk management plan between spatial planning and water engineering. J Flood Risk Manag 2017;10:143–4. https://doi.org/10.1111/jfr3.12101.
[56] Wang H, Zhou J, Tang Y, Liu Z, Kang A, Chen B. Flood economic assessment of structural measure based on integrated flood risk management: a case study in Beijing. J Environ Manage 2021;280. https://doi.org/10.1016/j.jenvman.2020.111701.
[57] Balasuriya ADH, Jayasingha P, Christopher WAPP. Application of bioengineering to slope stabilization in Sri Lanka with special reference to Badulla district. Prof Geol 2018;55:47–51.
[58] Jayawardane AKW. Disaster mitigation initiatives in Sri Lanka. 2005.
[59] Wijesundara C, Dayawansa N. Construction of large dams and their impact on cultural landscape: a study in Victoria reservoir and the surrounding area. Trop Agric Res 2011;22:211. https://doi.org/10.4038/tar.v22i2.2830.
[60] Masria A, Iskander M, Negm A. Coastal protection measures, case study (Mediterranean zone, Egypt). J Coast Conserv 2015;19:14. https://doi.org/10.1007/s11852-015-0389-5.
[61] AECOM. A methodology for incorporating climate change adaptation in infrastructure planning and design flood management. United Kingdom. 2015.
[62] Rathnayake U, Suratissa DM. Uma Oya multi purpose development project. Water New Zeal: Sri Lanka; Flood management and social impacts; 2016.
[63] Mudalige J. Comparison study of existing flood research activities. 2011.
[64] Ritchie J, Lewis J, Nicholls CM, Ormston R. Analysis in practice. In: Qualitative Research Practice: A Guide for Social Science Students and Researchers. SAGE Publications Ltd; 2014. p. 295–343.
[65] Creswell JW. Research design: Qualitative, quantitative, and mixed methods approaches. 4th ed. California: SAGE Publications; 2014.
[66] Jansen H. The logic of qualitative survey research and its position in the field of social research methods. Forum Qual Sozialforsch / Forum Qual Soc Res 2010;11. https://doi.org/10.17169/fqs-11.2.1450.
[67] Biernacki P, Waldorf D. Snowball sampling. Sociological Methods and Research SAGE Publications 1981:141–63.
[68] Naderifar M, Goli H, Ghaljaie F. Snowball sampling: a purposeful method of sampling in qualitative research. Strides Dev Med Educ 2017;14:1–4. https://doi.org/10.5812/sdme.67670.
[69] Guest G, Bunce A, Johnson L. How many interviews are enough?: an experiment with data saturation and variability. Field Methods 2006;18:59–82. https://doi.org/10.1177/1525822X05279903.
[70] Guest G, MacQueen KM. Handbook for Team-Based Qualitative Research. AltaMira Press; 2008.
[71] Rowley J. Conducting research interviews. Manag. Res Rev 2012;35:260–71.
[72] Berg BL. Qualitative research methods for the social sciences. Boston: Allyn and Bacon; 2009.
[73] Hsieh H-F, Shannon SE. Three approaches to qualitative content analysis. Qual Health Res 2005;15:1277–88. https://doi.org/10.1177/1049732305276687.
[74] Ministry of Environment Sri Lanka. National Drought Plan for Sri Lanka. 2020.
[75] Anvarifar F, Voorendt MZ, Zevenbergen C, Thissen W. An application of the Functional Resonance Analysis Method (FRAM) to risk analysis of multifunctional flood defences in the Netherlands. Reliab Eng Syst Saf 2017;158:130–41. https://doi.org/10.1016/j.ress.2016.10.004.
[76] Atta-ur-Rahman, Khan AN. Analysis of flood causes and associated socio-economic damages in the Hindukush region. Nat Hazards 2011;59:1239–60. https://doi.org/10.1007/s11069-011-9830-8.
[77] Dufty N. Using social media to build community disaster resilience. Aust J Emerg Manag 2012;27:40–5. https://doi.org/10.3316/informit.046981962746932.
[78] Jha AK, Bloch R, Lamond J. Integrated flood risk management: Structural measures, in: Cities and flooding: A guide to integrated urban flood risk management for the 21st century. Washington, DC: The World Bank; 2012. p. 638. https://doi.org/10.1596/978-0-8213-8866-2.
[79] Ogunyoye F, Stevens R, Underwood S. Temporary and demountable flood protection guide. 2011. Bristol.
[80] Pathirage C, Seneviratne K, Amaratunga D, Haigh R. Knowledge factors and associated challenges for successful disaster knowledge sharing. In: Global Assessment Report on Disaster Risk Reduction 2015; 2014.
[81] Poussin JK, Wouter Botzen WJ, Aerts JCJH. Effectiveness of flood damage mitigation measures: empirical evidence from French flood disasters. Glob Environ Chang 2015;31:74–84. https://doi.org/10.1016/j.gloenvcha.2014.12.007.
[82] Rahman S, Akib S, Khan MTR, Shirazi SM. Experimental study on tsunami risk reduction on coastal building fronted by sea wall. Sci World J 2014;2014. https://doi.org/10.1155/2014/729357.
[83] Rahman NA, Tarmudi Z, Rossdy M, Muhiddin FA. Flood mitigation measres using intuitionistic fuzzy dematel method. Malaysian J Geosci 2017;1:01–5.
[84] Singkran N. Flood risk management in Thailand: shifting from a passive to a progressive paradigm. Int J Disaster Risk Reduct 2017;25:92–100. https://doi.org/10.1016/j.ijdrr.2017.08.003.
[85] Tiggeloven T, de Moel H, Winsemius HC, Eilander D, Erkens G, Gebremedhin E, et al. Global-scale benefit-cost analysis of coastal flood adaptation to different flood risk drivers using structural measures. Nat Hazards Earth Syst Sci 2020;20:1025–44. https://doi.org/10.5194/nhess-20-1025-2020.
[86] Tokida KI, Tanimoto R. Lessons for countermeasures using earth structures against tsunami obtained in the 2011 off the Pacific coast of Tohoku earthquake. Soils Found 2014;54:523–43. https://doi.org/10.1016/j.sandf.2014.07.001.
[87] Wood D, Kubatko EJ, Rahimi M, Shafieezadeh A, Conroy CJ. Implementation and evaluation of coupled discontinuous Galerkin methods for simulating overtopping of flood defenses by storm waves. Adv Water Resour 2020;136:1–28. https://doi.org/10.1016/j.advwatres.2019.103501.
[88] Stalenberg B. Design of floodproof urban riverfronts [Doctoral Thesis]. TU Delft 2010. http://resolver.tudelft.nl/uuid:258042d2-104f-4d59-b845-66d8e758b91b. [Accessed February 2021].
[89] De Alwis D, Noy I. The cost of being under the weather: Droughts, floods, and health care costs in Sri Lanka. Wellington. 2017.
[90] Shivakoti BR, Villholth KG, Pavelic P, Ross A. Strategic use of groundwater-based solutions for drought risk reduction and climate resilience in Asia and beyond. 2019.
[91] Velasco M, Russo B, Cabello À, Termes M, Sunyer D, Malgrat P. Assessment of the effectiveness of structural and nonstructural measures to cope with global change impacts in Barcelona. J Flood Risk Manag 2018;11:S55–68. https://doi.org/10.1111/jfr3.12247.
[92] Jayasekara RU, Jayathilaka GS, Siriwardana C, Amaratunga D, Haigh R, Bandara C, et al. Identifying gaps in early warning mechanisms and evacuation procedures for tsunamis in Sri Lanka, with a special focus on the use of social media. Int J Disaster Resil Built Environ 2021. https://doi.org/10.1108/IJDRBE-02-2021-0012. ahead-of-print.
[93] Haigh R, Sakalasuriya MM, Amaratunga D, Basnayake S, Hettige S, Premalal S, et al. The upstream-downstream interface of Sri Lanka's tsunami early warning system. Int J Disaster Resil Built Environ 2019;11:219–40. https://doi.org/10.1108/IJDRBE-07-2019-0051.
[94] Meyer V, Priest S, Kuhlicke C. Economic evaluation of structural and non-structural flood risk management measures: examples from the Mulde River. Nat Hazards 2012;62:301–24. https://doi.org/10.1007/s11069-011-9997-z.
[95] Partington R. Does the government spend more on flood defences for the south? The Gaurdian; 2019.
[96] https://ec.europa.eu/environment/water/flood_risk/pdf/flooding_bestpractice.pdf. [Accessed March 2022].
[97] Dilhani KAC, Jayaweera N. A study of flood risk mitigation strategies in vernacular dwellings of Rathnapura. Sri Lanka Built-Environment Sri Lanka 2016;12:1. https://doi.org/10.4038/besl.v12i1.7611.
[98] Japan International Cooperation Agency. Comprehensive study on disaster management in Sri Lanka. 2009.
[99] Urban Development Authority. Ratnapura development plan (2019–2030). Sri Lanka. 2019.
[100] Zakour MJ, Swager CM. Chapter 3 - vulnerability-plus theory: the integration of community disaster vulnerability and resiliency theories. Butterworth-Heinemann 2018:45–78. https://doi.org/10.1016/B978-0-12-809557-7.00003-X.
[101] Heidari A. Structural master plan of flood mitigation measures. Nat Hazards Earth Syst Sci 2009;9:61–75. https://doi.org/10.5194/nhess-9-61-2009.
[102] Denton F, Wilbanks TJ, Abeysinghe AC, et al., 2014. Climate-resilient pathways: adaptation, mitigation, and sustainable development. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 1101–1131.
[103] Genovese E, Thaler T. The benefits of flood mitigation strategies: effectiveness of integrated protection measures. AIMS Geosci 2020;6:459–72. https://doi.org/10.3934/geosci.2020025.