

# 1 **An Assessment of Structural Measures for Risk Reduction of Hydrometeorological** 2 **Disasters in Sri Lanka**

## 3 **Abstract**

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 However, age and outdated technology are critical issues that hinder the  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

25 **Keywords:** Climate change adaptation, Disaster Risk Reduction, Hydrometeorological  
26 hazards, Structural measures, Sri Lanka

## 27 **1.0 Introduction**

28 Disasters triggered by natural hazards affect millions of people every year, resulting in a high  
29 number of fatalities, negative economic impacts, and the relocation of communities  
30 (Anonymous, 2021; Barnes et al., 2019). According to Jayawardena (2015),

31 hydrometeorological disasters cause more than 75% of the damage to human life and property  
32 among the three major types of natural hazards in the world, geological, hydrometeorological,  
33 and biological. Hydrometeorological hazards include floods, droughts, coastal erosion,  
34 cyclones of all types, landslides, avalanches, heat waves, cold waves, and debris flow. Sri  
35 Lanka experiences hydrometeorological hazards of floods, landslides, and droughts mainly  
36 (Japan International Cooperation Agency, 2017) and has seen a substantial rise in the frequency  
37 and severity of similar hazards over the last few decades (Amaratunga et al., 2020). Besides,  
38 recent studies have revealed that the erosion of the coastal zone of Sri Lanka is a long-standing  
39 problem although not systematically monitored or documented (Lakmali et al., 2017; Mehvar  
40 et al., 2019; Ratnayake et al., 2018). Events triggered by hydrometeorological hazards have  
41 had major impacts on Sri Lanka's economy (Lehner et al., 2006; Steele et al., 2007). Based on  
42 available data, between 2009 and 2018, around 1.98 million Sri Lankans were affected every  
43 year by these hazards (Basnayake et al., 2019).

44 According to Cannon (1994), a natural hazard becomes a disaster only when the former meets  
45 vulnerable people. Developing countries such as Sri Lanka are, hence, more vulnerable to the  
46 risks of disasters. According to Srinivas & Nakagawa (2008), developing countries fail to  
47 function and respond effectively to many natural hazards that confront them because of  
48 inadequate infrastructure and emergency services, high population densities in unplanned  
49 settlements, and low economic capacities to endure the impacts. In addition, the observed  
50 changes in the frequency, severity, spatial extent, and duration of weather and climatic  
51 extremes, including hydrometeorological hazards are likely to increase disaster vulnerability  
52 of communities (Jayawardena, 2015; Lavell et al., 2012). According to Wagenaar et al. (2019),  
53 in Sri Lanka, deforestation, urbanisation, unlawful landfilling, and construction that blocks  
54 waterways and riverbanks further increase the country's vulnerability to disasters.

55 The severe impacts of natural hazards can be prevented through structural mitigation measures  
56 such as engineering techniques and hazard-resistant construction, and non-structural measures  
57 such as policies, awareness building, knowledge development, public commitment, and  
58 methods and practices such as participatory mechanisms (Anonymous2010; United Nations,  
59 2015b, 2015a; United Nations Office for Disaster Risk Reduction [UNDRR], 2021). According  
60 to the World Bank and the United States Geological Survey, a US\$40 billion investment in  
61 prevention, mitigation, and preparedness strategies could reduce a predicted US\$400 billion in  
62 economic losses from natural hazards over the 1990s by US\$280 billion (Shreve & Kelman,

2014). Therefore, the United Nations Paris Agreement (United Nations, 2016) 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 (Perez-Morales et al., 2021). 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 (Chamber of Construction Industry, 2017; Palliyaguru & Amaratunga, 2008; Wagenaar et al., 2019; Wickramaratne et al., 2012), there are fewer studies on structural measures relating to floods (Dasandara et al., 2021; Sivakumar, 2015) and coastal erosion (Abeykoon et al., 2021) 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?

## 2.0 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” (UNDRR, 2022). Structural measures alter the characteristics of natural hazards and reduce the probability of hazards occurring in the location of interest (National Research Council, 2013). As a result, they reduce the impact of natural hazards (Abdella & Mekuanent, 2021). Tasseff et al. (2019) 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,

95 reservoirs, embankments, channel improvements, levees, gabion walls, and floodwalls which  
96 are combinedly used in order to reduce the adverse effects of floods (Garrote et al., 2019; Kim  
97 et al., 2019).

## 98 **2.1 Engineering School of Vulnerability Reduction**

99 According to Cannon's vulnerability analysis, disaster mitigation is possible not only by  
100 modifying the hazard, but also by reducing the vulnerability. To reduce vulnerability, it is  
101 essential to implement social protection mechanisms through various types of technological  
102 interventions, such as structural measures (Cannon, 1994). McEntire et al. (2010) introduce  
103 four ideal types for vulnerability reduction: physical science school, engineering school,  
104 structural school, and organisational school. As per McEntire et al.'s model, the physical  
105 science school emphasises living in safe environments and focuses on risk reduction and  
106 exposure to hazards. The engineering school focuses on the built environment and ways to  
107 improve resilience through construction practices and fabrication methods. The structural  
108 school focuses more on traditional notions of vulnerability than the other three, emphasising  
109 susceptibility based on socioeconomic and demographic factors such as race, ethnicity, gender,  
110 age, and other factors. The organisational school emphasises on the significance of  
111 preparedness, leadership, management, and the capacity to adapt, reinvent, and be creative.  
112 The theoretical basis of this study relates to McEntire et al.'s engineering school among the  
113 four approaches of vulnerability reduction to emphasise the importance of structural measures  
114 in disaster risk reduction. Boshier et al. (2007), Lewis and Mioch (2005), Poteyeva et al. (2006),  
115 and Tipple (2005) who are the major proponents of this school of thought of McEntire's, assert  
116 that if the buildings are constructed as per the building regulations and standards, as well as if  
117 there are adequate structural mitigation measures, impacts of natural hazards would inevitably  
118 subside.

119 Recent studies have shown that structural measures have a large potential for significantly  
120 reducing the impact of future hazards (Diaz, 2016; Hinkel et al., 2014; Lincke & Hinkel, 2018).  
121 According to Magana (2016), by means of structural measures, countries become less  
122 vulnerable and more resilient to natural hazards. The effective application of science and  
123 engineering principles in the development of the built environment is clearly evident in the  
124 natural hazard-threatened cities of the developed world (Allotey et al., 2010). One such  
125 example is Japan. In the aftermath of the massive and devastating Tsunami in 2011, the  
126 Japanese government made a strong commitment to rebuilding the affected region to a high

127 level of safety. Based on simulations of future Tsunami heights, massive infrastructure projects  
128 have been carried out in the region, including the construction of huge seawalls and levees,  
129 hardened riverbanks and levees, and new and/or elevated roads and highways (Maly &  
130 Suppasri, 2020). However, while these engineering protective measures would undoubtedly  
131 provide a safer built environment in hazard-prone areas (Bosher et al., 2007), the vast amount  
132 of resources and ability to construct these are not always available, particularly in developing  
133 countries (Jayawardena, 2015). Lincke and Hinkel (2018) assessed the cost-effectiveness of  
134 structural measures against sea-level rise considering population growth and found that  
135 structural adaptation measures are feasible for 13% of the global coastline.

## 136 **2.2 Challenges of developing structural measures**

137 Although the trend seems stable on developing more structural measures to mitigate the  
138 impacts of natural hazards, several factors remain as barriers to constructing them, such as the  
139 increasingly complicated task of finding suitable places to build them, environmental pressure,  
140 the economic crisis (Perez-Morales et al., 2021), and the possibility of leading to a false sense  
141 of security and encouraging development in unsafe areas (Wenger et al., 2013).

142 Starominski-Uehara (2021) argues, despite mitigating flooding to some extent, dams offer no  
143 guarantee that flooding in downstream areas will not occur. Dams store water upstream of  
144 rivers to prevent flood damage to the downstream area. Therefore, they need to be built in the  
145 upper reaches of the river and have a space for water limiting the construction of the structures  
146 to mountainous areas only (Kim et al., 2019). Structural measures such as underground dams  
147 are very inexpensive to install and can be quite effective in providing stored water during  
148 periods of drought. However, they might be associated with issues such as leakages or not  
149 providing expected water volumes, or poor water quality in some cases (Telmer & Best, 2004).  
150 In addition, van Westen et al. (2016) declare that landslide hazard is one of the more difficult  
151 ones to address, as this may involve extensive risk analysis and geotechnical investigations, in  
152 addition to risk maps, which may not be readily available in most countries. Terraced slopes  
153 are the most widely utilised structural measure against landslides across the world (Parrotta &  
154 Agnoletti, 2012).

155 Moreover, development of structural measures usually entails high costs, and could constrain  
156 the implementation of non-structural strategies (Gerber, 2007). Starominski-Uehara (2021)  
157 reveals that structural measures, in spite of their inherent limitations, should consider the

158 uncertainty of externalities in causing damage to dense and exposed communities. However,  
159 while the damage caused by natural hazards is severe in developing countries, the structural  
160 measures to solve this problem are presently insufficient (Son et al., 2015). Therefore, these  
161 measures should be continually expanded and managed properly.

162 When a natural hazard occurs with catastrophic results, the affected population immediately  
163 notices a lack of security and equally quickly demands structural measures to solve the  
164 problem. Historically, this situation has been increasingly repeated in societies where  
165 population pressure and urbanisation positively correlate with the increase in disasters triggered  
166 by natural hazards, and as a result, a significant amount of resources has been allocated with  
167 the intention of mitigating the disaster risk (Tariq & van de Giesen, 2012). The development  
168 of structural measures needs to achieve a desirable balance between the scale of measures and  
169 their economic benefits (Kundzewicz et al., 2018). The scale of the structural measures is  
170 defined according to the standards of different return periods, and different scales have  
171 different economic costs (Hartmann & Juepner, 2017; Wang et al., 2021). A structural measure  
172 with a higher return period scale (such as one hundred years) usually has the potential to reduce  
173 disaster losses substantially over its life time but as Wang et al. (2021) ascertain that such  
174 measures require higher economic investments and may not be the most appropriate overall  
175 solution for vulnerability reduction.

176 Further, there are sustainability related issues in relation to building these structures. Most of  
177 the structural measures are still built with carbon intensive materials like concrete and steel  
178 although more sustainable materials such as timber and biomaterials are now looked at as  
179 alternatives. The application of bioengineering techniques is being considered in Sri Lanka as  
180 well (Balasuriya et al., 2018).

### 181 **2.3 Types of Structural measures in Sri Lanka**

182 In Sri Lanka, different structural measures namely reservoirs, dams, diversions, channel  
183 improvements, terrace systems, retaining walls, and levees have been adopted throughout the  
184 country (Abeykoon et al., 2021; Balasuriya et al., 2018; Jayawardane, 2005; Sivakumar, 2015).  
185 Among all the structural measures, dams can be considered as mostly used structural measures  
186 against floods (Starominski-Uehara, 2021). Dam construction in Sri Lanka is not new to the  
187 country because the country possesses a strong hydraulic civilisation (Wijesundara &  
188 Dayawansa, 2011). For centuries, coastal protection measures such as seawalls and rock

189 revetments have been employed to safeguard and prevent further loss of coastal areas that serve  
190 as economic basis (Masria et al., 2015). Breakwaters, seawalls, and dykes are onshore  
191 structures with the key function of protecting low-lying coastal areas, human habitation, and  
192 infrastructure against coastal flooding from waves, unusually high tides, storm surge, and in  
193 some cases like a Tsunami (AECOM, 2015). Magana (2016) claims that droughts are one of  
194 the costliest natural hazards on the globe and further stress that droughts are expected to be  
195 more frequent and severe unless structural measures to reduce the water crisis are  
196 implemented.

## 197 **2.4 Issues pertaining to structural measures in Sri Lanka**

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

### 201 **2.4.1 Aging**

202 Although, there are structural measures for floods in Sri Lanka and they stand for effective  
203 flood management within the country, their performance has deteriorated due to the ageing of  
204 these structures with time (Dasandara et al., 2021). Besides, Japan International Cooperation  
205 Agency (JICA) (2017) claims that some of these structural measures such as Kelani, Gin, and  
206 Nilwala flood barriers desperately need replacements or rehabilitations to ensure their functions  
207 in the event of a flood, as most of them were implemented before the 1980s. Therefore, there  
208 is a need for effective structural measures against floods in the context of Sri Lanka.

### 209 **2.4.2 Poor practices**

210 Abeykoon et al. (2021) reveal that due to the prevailing economic state of the country, it has  
211 implemented low-cost coastal protective structures, while failing to conduct a comprehensive  
212 study on their effectiveness and their negative impacts on the coastal zone of Sri Lanka.  
213 Moreover, though it has been revealed that coastal erosion in Sri Lanka is a long-standing  
214 problem (Lakmali et al., 2017; Ratnayake et al., 2018), monitoring and documentation seem to  
215 be poorly handled (Abeykoon et al., 2021). Moreover, significant concerns such as leakages  
216 and building flaws due to poor construction, insufficient capacity, blockage of water flow, and  
217 the risk of collapse were also discovered in these existing structural measures, which severely  
218 influence the whole disaster management process in Sri Lanka (Dasandara et al., 2021).

### 219 **2.4.3 Damage to the ecosystem**

220 According to Rathnayake and Suratissa (2016), the construction of structural measures  
221 sometimes has damaging implications on the natural environment. For example, the Uma Oya  
222 multipurpose project has posed a significant environmental risk because of various activities  
223 such as excavations, rock blasting, and cut and fill. Furthermore, environmental difficulties  
224 such as soil erosion, groundwater contamination, negative impacts on aquatic and semiaquatic  
225 species, changes in wildlife survival, and saline intrusion into the water have occurred as a  
226 result of the Mahaweli reservoir building project.

### 227 **2.4.4 Inadequacy of structural measures**

228 It is observed that there is a gap in the development of effective, state of the art structural  
229 measures to mitigate the risk of natural hazards in Sri Lanka. Despite the existence of some  
230 structural measures for risk reduction of hydrometeorological disasters in Sri Lanka, whether  
231 they are adequate and effective are questionable due to a variety of reasons, including the  
232 insufficient use of new technology available, issues related to financing and physical planning,  
233 and lack of awareness of the benefits of the structural measures (Dasandara et al., 2021;  
234 Mudalige, 2011).

### 235 **2.4.5 Damage to adjacent structures**

236 According to Rathnayake and Suratissa (2016), another negative consequence of structural  
237 measures is the damages caused by their construction to infrastructure in adjacent locations.  
238 The Uma Oya project is again shown as an example in this regard because its tunnelling  
239 activities have had a negative impact on the nearby water wells and infrastructure.

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



### 246 **3.0 Methodology**

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

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

255 According to Ritchie et al. (2014), a qualitative research approach is ideal for gathering  
256 opinions and information from people based on their experience and will be useful in situations  
257 where an in-depth analysis of the data gathered is - required. Such analysis was necessary in  
258 this study in order to understand the improvements to the structural measures and associated  
259 costs and benefits in the context of Sri Lanka. Moreover, Creswell (2014) suggests a  
260 qualitative research approach when the variables to be investigated are unknown or when the  
261 literature is not comprehensive enough. According to Creswell (2014), the qualitative approach  
262 is well suited to analyse exploratory data and to gather new knowledge. Furthermore, in  
263 comparison to quantitative surveys, a study of this nature could be best approached through a  
264 qualitative survey due to the significant population variance (Jansen, 2010). Accordingly, a  
265 qualitative interview survey strategy was adopted for this study.

266 The experts were selected using the snowball sampling method, a non-probability sampling  
267 method. In snowball sampling, the study respondents are invited to help find other possible  
268 respondents and become “de facto” research assistants (Biernacki & Waldorf, 1981). When  
269 this sampling method is used, no specific sample size is required (Naderifar et al., 2017).  
270 However, Guest et al. (2006) have verified that 6-12 interviews appear to be a perfect balance  
271 for the number of qualitative interviews required to attain data saturation, while 80% of the  
272 codes are identified within the first 6 interviews. The concept of "saturation" – the point at  
273 which incoming data yields little or no new information – is a well-accepted benchmark for  
274 determining sample sizes for qualitative research (Guest et al., 2006; Guest & MacQueen,  
275 2008). Based on the principles of saturation, 12 in-depth interviews were conducted for this  
276 study. All the interviewees were selected based on their practice or research-based knowledge

277 and experience in disaster management in the built environment, particularly in relation to  
 278 structural measures against hydrometeorological disasters in Sri Lanka. In addition,  
 279 availability for interviewing, and willingness to take part in the interviews were also considered  
 280 in the selection. Table 1 summarises the profile of the respondents. The 12 experts were  
 281 affiliated to organisations that perform a key role in the development and maintenance of  
 282 structural measures for hydrometeorological disasters in Sri Lanka. In this regard, Disaster  
 283 Management Centre, which is an overarching authority for all types of disaster management in  
 284 Sri Lanka, Sri Lanka Army which usually involve in the construction of structural measures  
 285 for all types of disasters, Irrigation department which is the key agency managing floods and  
 286 droughts in Sri Lanka, Coast Conservation and Coastal Resource Management Department is  
 287 the main authority dealing with coastal erosion and flood, NBRO which is a research  
 288 organisation undertaking several projects related to landslides were mainly selected to gather  
 289 primary data. In addition, a research centre related to disaster risk reduction in a state university  
 290 was approached to get more insight to the research study.

291

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 Organization (NBRO)	Scientist	9	Landslide mitigation projects	Planning
R6	NBRO	Director	29	Landslide mitigation projects	Planning, monitoring, team leading

<b>R7</b>	Coast Conservation and Coastal Resource Management Department	Civil Engineer	10	Coastline protection projects	Designing and supervision of work
<b>R8</b>	Irrigation Department	Civil Engineer	12	Flood mitigation projects	Site management
<b>R9</b>	Irrigation Department	Technical Officer	10	Flood mitigation projects	Planning, designing, and construction supervision
<b>R10</b>	Disaster Management Centre (DMC)	Director	25	Flood, landslides, and drought mitigation projects	Consultation, research work
<b>R11</b>	Irrigation Department	Technical Officer	6	Flood mitigation projects	Planning, designing, and construction supervision
<b>R12</b>	Research Centre at a State University	Research Scholar	3	Flood mitigation research	Research work

292 Table 1: Profile of the Respondents

293 The interview guideline was developed using the information gleaned from the literature  
294 review. According to Rowley (2012), semi-structured interviews allow the participants to  
295 explain the significance of a subject through their thoughts, experiences, and viewpoints. Less  
296 structured interview questions allow to raise further questions instantly, whenever required  
297 (Berg, 2009). The interview guideline was divided into sections following the research  
298 questions in order to identify the existing structural measures in Sri Lanka, their current state,  
299 the required improvement in them, and finally, the benefits and costs associated with  
300 them. Each semi-structured interview (via physical visits/online meetings/telephone  
301 conversations) was conducted for 60–90 minutes.

302 Finally, the collected data was analysed using code-based content analysis (Inductive coding)  
303 with a focus on the research questions. This method considered as the most commonly used  
304 method in qualitative content analysis, where the researcher relies upon the data to accomplish  
305 new insights (Hsieh & Shannon, 2005). In the method, the respondents' narratives with  
306 verbatim quotations were retrieved from the gathered data and related to the phenomenon being  
307 investigated. The retrieved narratives were classified into several 'codes' based on similar  
308 themes. These codes were named using content characteristic words, phrases, or sentences.  
309 Following the extraction of narratives, primary codes, sub codes and the links between them  
310 were explored in relation to the research questions.

311 **4.0 Results**

312 Research findings revealed that the Irrigation Department, NBRO, and Coast Conservation and  
 313 Coastal Resource Management Department of Sri Lanka have the legal obligation of deciding,  
 314 designing, constructing, as well as maintaining structural measures for floods, landslides, and  
 315 coastal erosion respectively. According to a report published by the Ministry of Environment  
 316 Sri Lanka, currently, there is a National Drought Plan (published in 2020) but there is no single  
 317 organisation or entity to take charge of drought management (Ministry of Environment Sri  
 318 Lanka, 2020). Besides, the responsibilities are "diffused" among many organisations. As a  
 319 result, there are no-proactive programs to mitigate drought in the country and most of the  
 320 drought interventions have been mainly reactive. While agreeing with that, R2, R3, R8, R9,  
 321 R10, and R11 declared that the Irrigation department is mainly handling drought management,  
 322 despite the fact that there is no legally vested power in them for drought management. structural  
 323 measures used in Sri Lanka are discussed below section.

324 **4.1 Structural measures in Sri Lanka**

325 Based on literature and primary data, the types of structural measures implemented in Sri Lanka  
 326 were identified and classified as shown in Table 2. As per Table 2, the structural measures were  
 327 mainly categorised based on the natural hazards; floods, coastal erosion/floods, droughts, and  
 328 landslides. Adhering to Tasseff et al.'s (2019) classification, the identified structural measures  
 329 were then identified as "hard or soft" and "temporary or permanent".

Natural Hazard	Structural measures	Classifications				Literature Sources	
		Hard	Soft	Permanent	Temporary		
<b>Flood</b>	Water retarding basin	✓		✓		1, 6, 8, 23	
	<b>Channel improvement</b>	✓		✓		1, 8, 13	
	Embankment	✓		✓		1, 3, 10, 11, 21, 20, 21, 24	
	Levee/Marginal embankment	✓		✓		1, 2, 4, 5, 6, 8, 10, 12, 18, 31	
	Dam	✓		✓		2, 5, 6, 8, 12, 13, 21, 18, 19	
	<b>Reservoir</b>	✓		✓		6, 8, 13, 17, 23	
	<b>Drainage pipe networks</b>	✓		✓		6, 16, 17	
	Pumping station	✓		✓		8, 17	
	Dredging		✓	✓		6	
	Floodgate	✓		✓		2, 3, 6, 8	
	Combinations	✓		✓		6, 8	
	<b>Floodwall /flood barrier</b>	✓		✓		3, 16, 11, 14	
	Copper damming using sheet piling		✓			✓	-
	Temporary filters		✓			✓	-
	Sandbags		✓			✓	7, 15, 19, 21
Geotextile bags		✓	✓			10	

<b>Coastal erosion / flood</b>	Rock revetments	✓	✓	2, 10	
	Breakwater	✓	✓	2, 10, 21	
	Groins	✓	✓	10	
	<b>Floodwall /flood barrier</b>	✓	✓	14	
	Beach nourishment		✓	✓	10
<b>Drought</b>	<b>Reservoir</b>	✓	✓	9, 23	
<b>Landslide</b>	<b>Drainage pipe networks</b>	✓	✓	29	
	<b>Channel improvement</b>	✓	✓	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 - (Abdella and Mekuanent, 2021), 2 - (AECOM, 2015), 3 - (Anvarifar et al., 2017), 4 - (Atta-ur-Rahman and Khan, 2011), 5 - (Dufty, 2012), 6 - (Garrote et al., 2019), 7 - (Jha et al., 2012), 8 - (Kim et al., 2019), 9 - (Magana, 2016), 10 - (Masria et al., 2015), , 11 - (Ogunyoye et al., 2011), 12 - (Pathirage et al., 2014), 13 - (Perez-Morales et al., 2021), 14 - (Poussin et al., 2015), 15 - (Rahman et al., 2014), 16 - (Rahman et al., 2017), 17 - (Singkran, 2017), 18 - (Starominski-Uehara, 2021), 19 - (Tasseff et al., 2019), 20 - (Tiggeloven et al., 2020), 21 - (Tokida and Tanimoto, 2014), 22 - (van Westen et al., 2016), 23 - (Wenger et al., 2013), 24 - (Wood et al., 2020)

330 Table 2: Structural Measures against Hydrometeorological Disasters in Sri Lanka

331 Table 2 shows that the structural measures against flood mitigation measures widely exist in  
332 Sri Lanka among other hydrometeorological disasters, while there is a lack of structural  
333 measures against drought disasters. Moreover, structural measures such as dikes, polders, earth  
334 ramparts, and bridge abutments are not used in the local context compared to the global context.  
335 Besides, the majority of the structural measures in Sri Lanka are hard and permanent structural  
336 measures. The majority of the respondents mentioned that if there is an emergency disaster  
337 situation only the temporary structural measures are constructed, if not always the permanent  
338 structures are constructed and appreciated (R1, R2, R4, R5, R6, R9, and R12). It can be seen  
339 that there are common structural measures used against natural hazards, which are emphasised  
340 in Table 2. In addition, some of the structural measures are used for multi-purposes. Elaborating  
341 on that R3 stated that *“the reservoirs are normally built up in the upstream area on a river to*  
342 *retain the water flow in flood situation as well as it can be used for multi-purposes such as for*  
343 *power generation, water storage for drought events, industrial and domestic water*  
344 *requirement, and groundwater recharge”*. Anvarifar et al. (2017) reported that traditionally,  
345 many flood mitigation measures in the Netherlands also serve other functions such as housing,  
346 transportation, recreation, and so on. In the majority of cases, the only visible function is the  
347 secondary function of the flood mitigation measure (Stalenberg, 2010).

#### 348 4.2 The existing condition of the structural measures in Sri Lanka

349 As per the empirical findings, the existing conditions of structural measures in Sri Lanka were  
350 influenced by the factors such as obsolescence, lack of maintenance, rehabilitation and  
351 replacement, and insufficiency. It was declared by all the respondents that Sri Lanka has  
352 enough types of structural measures against natural hazards, compared to other developing  
353 countries. However, according to JICA (2017), the main problem with these existing structural  
354 measures in Sri Lanka, is ageing with time, and the unavailability of sufficient structural  
355 measures. The study further clarified that the existing structural measures badly need  
356 replacements or rehabilitation in order to ensure they function as expected in the event of a  
357 hydrometeorological hazard, as most of them were installed more than 40 years ago.  
358 Accordingly, the issue is witnessed through empirical research findings that the majority of  
359 flood defences against natural hazards are obsolete as these were built before 1980s. Some of  
360 these outdated flood defences are currently overtopping, resulting in a sudden, dangerous water  
361 rise. Furthermore, the unoccupied marshy areas near the flood defences were also developed  
362 and occupied by the community back then [R2, R3, and R11]. As a result, these structural  
363 measures should be upgraded in light of the current population, development, and new  
364 technologies in order to obtain the real benefits from such measures.

365 In addition, the respondents revealed structural measures such as copper damming using sheet  
366 piling and temporary filters against floods, landslide resilient houses, shotcrete structures, and  
367 Nature-based Solutions (NbS) against landslide hazards are utilised in Sri Lanka in order to  
368 mitigate disaster impacts. According to R5, NbS can be effectively used for risk mitigation in  
369 larger areas prone to landslide hazards, where traditional mitigation options are less cost-  
370 effective. However, there is still a limited use of those techniques in landslide-prone areas such  
371 as Galabada in Rathnapura and Badulusirima in Badulla (R5 and R6).

372 According to Table 2, it is clear that enough structural measures for drought events are not in  
373 use in Sri Lanka compared to other natural hazards. Droughts are one of the most frequent  
374 hydrometeorological disasters identified in the Disaster Management Act No. 13, 2005 of the  
375 Government of Sri Lanka (Ministry of Environment Sri Lanka, 2020). While highlighting the  
376 severity of droughts in Sri Lanka, De Alwis and Noy (2017) claimed that on average, the  
377 economic costs associated with said events to healthcare have been estimated to be US\$52.8  
378 million yearly, with 78% of the costs originating from droughts.

379 As highlighted by R3, the construction of underground dams is considered the best option  
380 against drought disasters worldwide. Similarly, Telmer and Best (2004) specified that

381 underground dams are very inexpensive to install but can be quite effective in providing stored  
382 water during periods of drought. Interviewed experts claimed that underground dams are  
383 located in Sri Lanka by nature. Nonetheless, the country lacks methods for protecting those  
384 structures (R2, R3, R8, and R9). R2 further elaborated that *“there are no groundwater*  
385 *extraction limitations in our country. Anyone can get water supply by digging a well at any*  
386 *place”*. A drought is basically managed by groundwater and groundwater storage, as managed  
387 natural infrastructure, could be a multipurpose, more decentralised, cost-effective, and  
388 sustainable alternative to “grey” infrastructure, such as traditional-built dams (Shivakoti et al.,  
389 2019). Therefore, relevant authorities should take necessary actions to protect such gifts given  
390 by the nature of the country.

391 Besides, R4 emphasised that *“we have not applied structural measures until now focusing on*  
392 *disasters like Tsunami, due to the huge cost, and also since Tsunami is a rarely happened*  
393 *incident, Sri Lankan government cannot allocate that much huge finance to construct flood*  
394 *defences against Tsunami”*. However, there are a lot of technologically sophisticated structural  
395 measures in developed countries (Velasco et al., 2018; Wang et al., 2021), which are currently  
396 not implemented in Sri Lanka. Therefore, there is a need to look into the application of those  
397 effective structural measures in order to reduce the adverse effects of natural hazards prevailing  
398 in our country. Nevertheless, non-structural measures such as a buffer zone along coastal line  
399 and an early warning system were implemented to minimise the impact of Tsunamis in Sri  
400 Lanka (R10 and R12). There was no early warning System for tsunamis in the Indian Ocean  
401 prior to 2004. Following the devastation of the 2004 Tsunami, numerous countries banded  
402 together to build an efficient Tsunami early warning system in the Indian Ocean region. In  
403 2008, an end-to-end Tsunami early warning system was built, which became fully operational  
404 in 2013 and covered all affected countries, including Sri Lanka (Jayasekara et al., 2021).  
405 However, the effectiveness of the existing early warning system for Tsunami was questioned  
406 several times (Haigh et al., 2019). The next section discusses what is more required in structural  
407 measures in hydrometeorological disasters in Sri Lanka.

#### 408 **4.3 Structural measures in Sri Lanka - what more is required?**

409 According to the study, major replacements and rehabilitation, regular maintenance, the  
410 construction of more structural measures, raising awareness of the importance of building  
411 structural measures, the use of advanced technologies, budget allocation, project prioritisation,

412 and a consistent decision-making framework are the major concerns in improving the structural  
413 measures against hydrometeorological disasters in Sri Lanka.

414 Agreeing to JICA (2017), the majority of the respondents acknowledged that major flood  
415 control measures in the Kelani, Gin, and Nilwala River Basins were initiated before the 1980s  
416 and after that, no new major flood control measures were introduced (R1, R2, R3, R8, R9, and  
417 R11). At present, the existing structural measures such as dikes, flood gates, and pump houses  
418 are old and need to be replaced or rehabbed in order to operate properly. In Sri Lanka, reservoirs  
419 that were built primarily for water supply production in drought events as well as in day-to-day  
420 life, play a significant role in flood mitigation because they also have a flood control volume.  
421 Many reservoirs are old and needed to be refurbished to ensure protection from them.  
422 Moreover, R2 stated, “we have already proposed location-specific flood protection structures  
423 such as continuous major bunds and dry dams to different places in Sri Lanka”. In addition,  
424 flood control reservoirs and dry dams for Kalu river upstream, extended flood bunds for Kelani  
425 river and Mahaweli river downstream, and upstream reservoirs for Nilwala river are being  
426 proposed.

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

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

436 When further digging into what could be done to improve structural measures in the country,  
437 R1 claimed that “*financial barriers are the most common barriers and the maintenance of*  
438 *structural measures is not happening properly in our country. Also, we do not have the*  
439 *advanced technologies that other countries have. However, we do have enough human*  
440 *resources*”. Besides, the majority of the respondents emphasised that less priority has been  
441 given to projects related to building structural measures and project prioritisation differs from  
442 one government to another. Due to the lack of usage of advance technologies, the structural



443 measures that are currently available in Sri Lanka have limited flexibility to adapt to new  
444 climate related challenges in future.

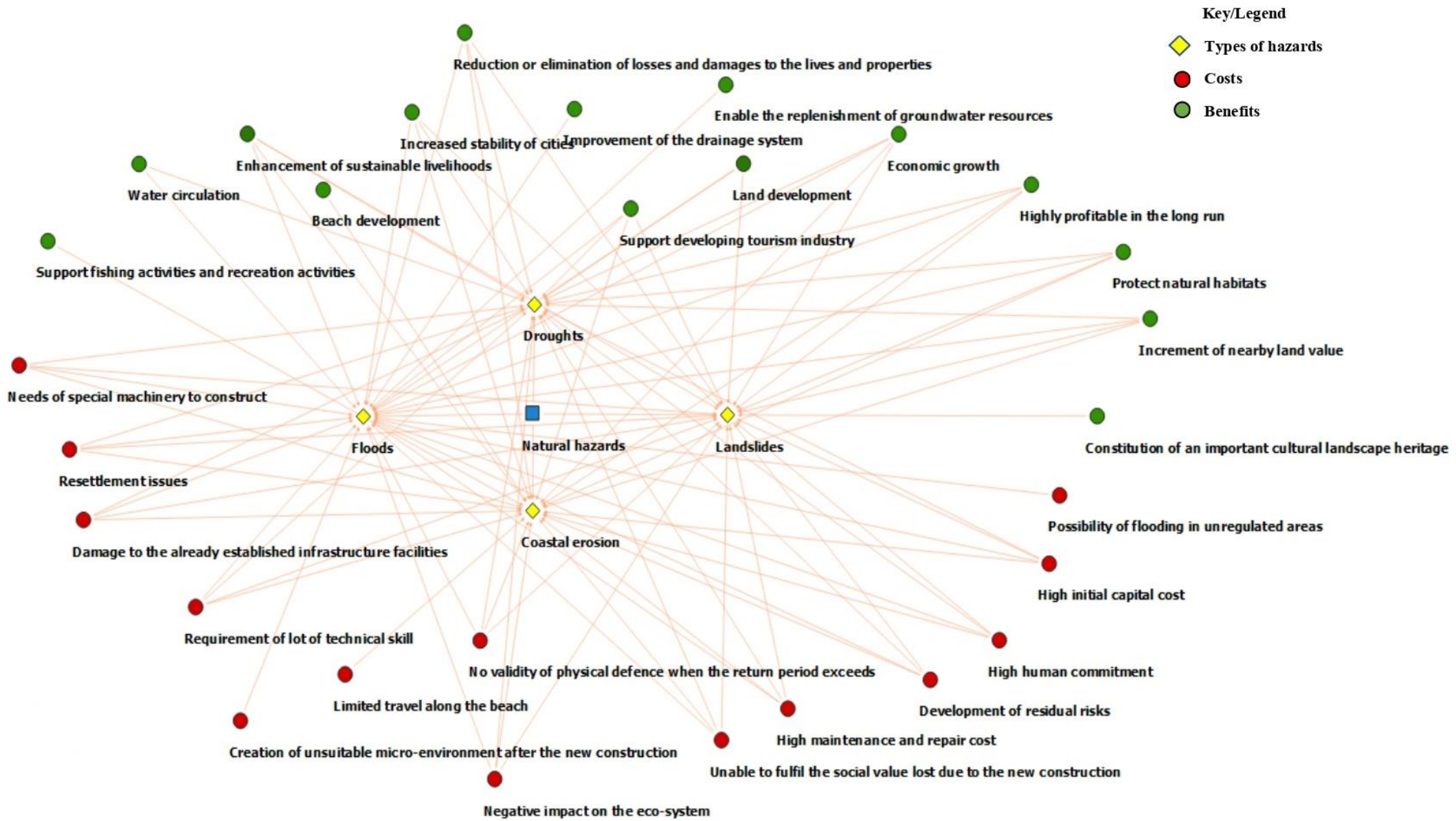
445 Social pressure is another major challenge, which comes prior to the construction of structural  
446 measures. As an example, normally the benefits of a structural measure are achieved by people  
447 who live a little further away from the construction premises, but not by those who live very 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

451 Some experts highlighted the reason for most of the challenges associated with building  
452 structural measures is the lack of a consistent decision-making framework (R2, R4, R5, R6,  
453 and R10). According to Meyer et al. (2012), economic evaluation of alternative structural  
454 measures for decision support has a considerable tradition in Europe and the United States.  
455 Different approaches like cost-benefit analysis (CBA) or cost-effectiveness analysis (CEA) can  
456 be applied for the economic evaluation of such measures. However, such an approach has not  
457 been undertaken so far in the Sri Lankan decision-making process with regard to structural  
458 measures.

459 Nevertheless, according to Hartmann and Juepner (2017), structural measures have different  
460 scales which are defined according to the standards of different return periods, and different  
461 scales have different economic costs. Thus, the relationship between costs and benefits should  
462 be analysed to acquire the most economical structural measure in disaster management. The  
463 next section will address the benefits and costs related to structural measures.

#### 464 **4.4 Structural measures in Sri Lanka - Benefits and costs**

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



472  
473

Figure 1: Mapping of benefits and costs associated with structural measures

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

486 When considering the costs (negative consequences) associated with structural measures, all  
487 the respondents professed that structural measures comprise an initial cost for design and  
488 construction plus the maintenance and repair costs through its life cycle. In addition to these  
489 costs, some experts claimed that there can be residual operational costs such as training,  
490 practice deployments, staff costs, storage, transportation, supervision, and security associated  
491 with structural measures (R2, R7, R9). Partington (2019) claimed that the cost of maintenance,  
492 repair, and operation is necessary over the life of a structural measure to keep it functional.  
493 Similarly, the majority of respondents agreed that the degree and complexity of maintenance  
494 operations, as well as the requirement for specialised maintenance, are critical to the proper  
495 operation of any structural measure.

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

504 Highlighting the issues related to resettlement and social costs of the new construction, R3  
505 stated, *"When there is new construction on structural measure, resettlements must be arranged*

506 *for the community who live there. In those situations, we cannot provide the real value of their*  
507 *land. As an example, even though the market value of the alternative land and the property*  
508 *provided will be equal or even more than their previously owned property if the ownership of*  
509 *the property comes from generation to generation, there is much more value than the market*  
510 *price of that land for the owner".*

511 In addition, respondents claimed that sometimes, professionals would advocate more towards  
512 non-structural measures rather than structural measures because they believe that building  
513 structural measures tend to change the pattern of the environment. For instance, there are  
514 natural habitats associated with floods and if floods are controlled by structural defences, they  
515 will indirectly harm the indigenous species that live in such waterlogged areas. Elaborating  
516 more on this, R2 stated, *"There are flood-dependent animals, and their breeding season starts*  
517 *just after a flood happens. Hence, environmentalists argue that controlling floods through*  
518 *structural measures is a cost to the environment"*. Nevertheless, Kim et al. (2019) suggested  
519 that in order to defend against urban flooding, structural and non-structural measures must be  
520 carried out at the same time. Moreover, R12 highlighted that disaster protection is never  
521 absolute; only a certain level of protection against hydrometeorological disasters can be  
522 achieved. As a result, for each structural measure, the concept of residual risk should be  
523 considered. That is, clearly define the design level of protection to which the structural measure  
524 can be reliably defended, or local conditions that may weaken it, determine disaster risks in the  
525 protected area related to the performance characteristics, overtopping, and failure probability  
526 of the structural measure, and explain it to the public.

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

536 Besides, all the interviewees expressed that the construction of structural measures facilitates  
537 the development of the country. For example, Rathnapura (translated into English as 'City of

538 Gems' because it is the centre of the country's gem trade) is one of the main cities in Sri Lanka  
539 frequently impacted by severe floods and landslides. According to Dilhani and Jayaweera  
540 (2016), the main cause of flooding in Rathnapura town is the very high annual rainfall falling  
541 in the catchment of 604 km<sup>2</sup> above Rathnapura and its location in the flood plains of Kalu  
542 River. The riverbed elevation at Rathnapura is only 11.70 m (38.4 ft) Mean Sea Level (MSL)  
543 and the length of the river course up to Kalutara is 76.5 km from Rathnapura. The gradient of  
544 the riverbed is only 0.15 m per km (1/6,700) (JICA, 2009). This shows the inadequacy of  
545 creating higher velocities to discharge floods. Additionally, the city is affected by 1 into 10-  
546 year major flood event that causes significant destruction to lives and property. During this  
547 flood event, approximately 80% of the land within the city lies under floodwater for an average  
548 period of 2 – 5 days. In 2017, a total number of 206 families and 1203 people were affected by  
549 the major floods (Urban Development Authority, 2019). Since that, the occurrence of floods  
550 has had a significant influence on the city's growth since the physical damage is connected with  
551 flood risk ranges from infrastructure, buildings, loss of farmland, injuries, and loss of life. The  
552 experts (R2 and R3) mentioned that the Irrigation Department of Sri Lanka has proposed to  
553 construct a major flood dike from Warakatota bridge area to Ayurveda office, which will be  
554 beneficial for protecting the town itself from the annual flood. This proposal will contribute to  
555 the growth of Rathnapura city, ultimately the country's growth. There, as a member of the  
556 expert committee, respondent R2 had been actively involved in the development of the  
557 proposal.

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

#### 560 **4.5 Discussion**

561 The study investigated the nature of existing structural measures for hydrometeorological  
562 disasters in order to highlight any improvements that are required, and the costs and benefits.  
563 It was discovered that in the Sri Lankan context, there is a significant need for structural  
564 mitigation measures to reduce the impacts of natural hazards. According to the respondents,  
565 most projects lack prior planning owing to a lack of coordination and collaboration with related  
566 stakeholders, as well as a lack of time available for further research of the scenario in order to  
567 develop thorough plans. This limits the construction of effective structural mitigation  
568 measures. Therefore, the need to understand how to develop efficient structural measures is  
569 becoming increasingly urgent. As per the Vulnerability Plus (V+) theory developed by Zakour,

570 and Swager (2018), the effectiveness of structural measures should be improved in order to  
571 reduce disaster vulnerability while also providing the community with the capacity to respond  
572 resiliently to natural hazards.

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

581 Moreover, while agreeing to Denton et al. (2014), all the experts asserted that the most  
582 appropriate and effective structural measures must be identified and prioritised. Then, the costs  
583 and benefits of these measures over the long-term must be assessed prior to choosing the most  
584 effective set of structural measures to manage natural hazards (Genovese & Thaler, 2020).  
585 However, such an assessment has not been carried out prior to the construction of structural  
586 measures against natural hazards in the Sri Lankan decision-making process thus far.

## 587 **5.0 Conclusions**

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

598 In comparison to other developing countries, the empirical research findings indicated that Sri  
599 Lanka has sufficient types of structural measures against floods, landslides, and coastline  
600 erosion. However, because most of the current structural measures were installed before the

601 1980s, they are in desperate need of replacement or rehabilitation in order to function  
602 efficiently. Moreover, compared to other natural hazards, sufficient structural measures against  
603 drought occurrences are limited in Sri Lanka. Both the research and empirical evidence show  
604 that constructing underground dams is an effective method of averting droughts. Although,  
605 these measures are available in Sri Lanka, the country lacks ways for preserving these  
606 structures.

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

## 622 **References**

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

626 Abeykoon, L.C.K., Thilakarathne, E.P.D.N., Abeygunawardana, A.P., Warnasuriya, T.W.S.,  
627 Egodaunya, K.P.U.T., 2021. Are coastal protective hard structures still applicable with respect  
628 to shoreline change in Sri Lanka (No. 1240). Tokyo.

629 AECOM, 2015. A methodology for incorporating climate change adaptation in infrastructure  
630 planning and design flood management. United Kingdom.

631 Allotey, N.K., Arku, G., Amponsah, P.E., 2010. Earthquake-disaster preparedness: The case  
632 of Accra. *Int. J. Disaster Resil. Built Environ.* 1, 140–156.  
633 <https://doi.org/10.1108/17595901011056613>

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

637 Anvarifar, F., Voorendt, M.Z., Zevenbergen, C., Thissen, W., 2017. An application of the  
638 Functional Resonance Analysis Method (FRAM) to risk analysis of multifunctional flood  
639 defences in the Netherlands. *Reliab. Eng. Syst. Saf.* 158, 130–141.  
640 <https://doi.org/10.1016/j.ress.2016.10.004>

641 Atta-ur-Rahman, Khan, A.N., 2011. Analysis of flood causes and associated socio-economic  
642 damages in the Hindukush region. *Nat. Hazards* 59, 1239–1260.  
643 <https://doi.org/10.1007/s11069-011-9830-8>

644 Balasuriya, A.D.H., Jayasingha, P., Christopher, W.A.P.P., 2018. Application of  
645 bioengineering to slope stabilization in Sri Lanka with special reference to Badulla district.  
646 *Prof. Geol.* 55, 47–51.

647 Barnes, B., Dunn, S., Wilkinson, S., 2019. Natural hazards, disaster management and  
648 simulation: a bibliometric analysis of keyword searches. *Nat. Hazards* 97, 813–840.  
649 <https://doi.org/10.1007/s11069-019-03677-2>

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

652 Berg, B.L., 2009. *Qualitative Research Methods for the Social Sciences*, Allyn and Bacon,  
653 Boston.

654 Biernacki, P., Waldorf, D., 1981. Snowball sampling, in: *Sociological Methods and Research*.  
655 SAGE Publications, pp. 141–163.

656 Black, K., 2007. Research: Considerations in writing a literature review. *New Soc. Work.* 12,  
657 12–30.

658 Boshier, L., Dainty, A., Carrillo, P., Glass, J., 2007. Built-in resilience to disasters: A pre-



659 empty approach. *Eng. Constr. Archit.* 14, 434-46.

660 Cannon, T., 1994. Vulnerability analysis and the explanation of “natural” disasters, in: Varley,  
661 A. (Ed.), *Disasters, Development and Environment*. John Wiley & Sons, Ltd, pp. 13–30.

662 Chamber of Construction Industry, 2017. Seminar on Flood Control & Disaster  
663 Responsiveness in Proposed Western Megapolis. Colombo, Sri Lanka.

664 Creswell, J.W., 2014. *Research design: Qualitative, quantitative, and mixed methods*  
665 *approaches*, 4th ed. SAGE Publications, California.

666 Dasandara, M., Ernst, R., Kulatunga, U., Rathnasiri, P., 2021. Investigation of issues in  
667 structural flood management measures in Sri Lanka. *J. Constr. Dev. Ctries.*

668 De Alwis, D., Noy, I., 2017. *The cost of being under the weather: Droughts, floods, and health*  
669 *care costs in Sri Lanka*. Wellington.

670 Denton F, Wilbanks TJ, Abeysinghe AC, et al., 2014. Climate-resilient pathways: adaptation,  
671 mitigation, and sustainable development. *Climate Change 2014: Impacts, Adaptation, and*  
672 *Vulnerability. Part A: Global and Sectoral Aspects. Working Group II to the Fifth Assessment*  
673 *Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 1101–  
674 1131.

675 Diaz, D.B., 2016. Estimating global damages from sea level rise with the Coastal Impact and  
676 Adaptation Model (CIAM). *Clim. Change* 137, 143–156. [https://doi.org/10.1007/s10584-016-](https://doi.org/10.1007/s10584-016-1675-4)  
677 [1675-4](https://doi.org/10.1007/s10584-016-1675-4)

678 Dilhani, K.A.C., Jayaweera, N., 2016. A study of flood risk mitigation strategies in vernacular  
679 dwellings of Rathnapura, Sri Lanka. *Built-Environment Sri Lanka* 12, 1.  
680 <https://doi.org/10.4038/besl.v12i1.7611>

681 Dufty, N., 2012. Using social media to build community disaster resilience. *Aust. J. Emerg.*  
682 *Manag.* 27, 40–45. <https://doi.org/10.3316/informit.046981962746932>

683 Garrote, J., Bernal, N., Diez-Herrero, A., Martins, L.R., Bodoque, J.M., 2019. Civil  
684 engineering works versus self-protection measures for the mitigation of floods economic risk.  
685 A case study from a new classification criterion for cost-benefit analysis. *Int. J. Disaster Risk*  
686 *Reduct.* 37. <https://doi.org/10.1016/j.ijdr.2019.101157>

687 Genovese, E., Thaler, T., 2020. The benefits of flood mitigation strategies: effectiveness of  
688 integrated protection measures. *AIMS Geosci.* 6, 459–472.  
689 <https://doi.org/10.3934/geosci.2020025>

690 Gerber, B.J., 2007. Disaster management in the United States: Examining key political and  
691 policy challenges. *Policy Stud. J.* 35, 227–238. [https://doi.org/https://doi.org/10.1111/j.1541-  
692 0072.2007.00217.x](https://doi.org/https://doi.org/10.1111/j.1541-0072.2007.00217.x)

693 Guest G, Bunce A, Johnson L., 2006. How many interviews are enough?: An experiment with  
694 data saturation and variability. *Field Methods* 18, 59–82.  
695 <https://doi.org/10.1177/1525822X05279903>

696 Guest G, MacQueen KM., 2008. *Handbook for Team-Based Qualitative Research*. AltaMira  
697 Press.

698 Haigh, R., Sakalasuriya, M.M., Amaratunga, D., Basnayake, S., Hettige, S., Premalal, S.,  
699 Jayasinghe Arachchi, A., 2019. The upstream-downstream interface of Sri Lanka’s tsunami  
700 early warning system. *Int. J. Disaster Resil. Built Environ.* 11, 219–240.  
701 <https://doi.org/10.1108/IJDRBE-07-2019-0051>

702 Hartmann, T., Juepner, R., 2017. The flood risk management plan between spatial planning  
703 and water engineering. *J. Flood Risk Manag.* 10, 143–144. <https://doi.org/10.1111/jfr3.12101>

704 Heidari A., 2009. Structural master plan of flood mitigation measures. *Nat Hazards Earth Syst*  
705 *Sci* 9, 61–75. <https://doi.org/10.5194/nhess-9-61-2009>.

706 Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S.J., Marzeion, B.,  
707 Fettweis, X., Ionescu, C., Levermann, A., 2014. Coastal flood damage and adaptation costs  
708 under 21st century sea-level rise. *Proc. Natl. Acad. Sci.* 111, 3292–3297.  
709 <https://doi.org/10.1073/pnas.1222469111>

710 Hsieh, H.-F., Shannon, S.E., 2005. Three approaches to qualitative content analysis. *Qual.*  
711 *Health Res.* 15, 1277–1288. <https://doi.org/10.1177/1049732305276687>

712 Jansen, H., 2010. The logic of qualitative survey research and its position in the field of social  
713 research methods. *Forum Qual Sozialforsch / Forum Qual Soc Res* 11,  
714 <https://doi.org/10.17169/fqs-11.2.1450>

715 Japan International Cooperation Agency, 2009. Comprehensive study on disaster management  
716 in Sri Lanka.

717 Japan International Cooperation Agency, 2017. Data Collection Survey on Disaster Risk  
718 Reduction Sector in Sri Lanka.

719 Jayasekara, R.U., Jayathilaka, G.S., Siriwardana, C., Amaratunga, D., Haigh, R., Bandara, C.,  
720 Dissanayake, R., 2021. Identifying gaps in early warning mechanisms and evacuation  
721 procedures for tsunamis in Sri Lanka, with a special focus on the use of social media. *Int. J.*  
722 *Disaster Resil. Built Environ.* ahead-of-print. <https://doi.org/10.1108/IJDRBE-02-2021-0012>

723 Jayawardane, A.K.W., 2005. Disaster mitigation initiatives in Sri Lanka.

724 Jayawardena, A.W., 2015. Hydro-meteorological Disasters: Causes, Effects and Mitigation  
725 Measures with Special Reference to Early Warning with Data Driven Approaches of  
726 Forecasting. *Procedia IUTAM* 17, 3–12. <https://doi.org/10.1016/j.piutam.2015.06.003>

727 Jha, A.K., Bloch, R., Lamond, J., 2012. Integrated flood risk management: Structural measures,  
728 in: *Cities and Flooding: A Guide to Integrated Urban Flood Risk Management for the 21st*  
729 *Century*. The World Bank, Washington, DC, p. 638. [https://doi.org/10.1596/978-0-8213-8866-](https://doi.org/10.1596/978-0-8213-8866-2)  
730 [2](https://doi.org/10.1596/978-0-8213-8866-2)

731 Kim, K., Han, D., Kim, D., Wang, W., Jung, J., Kim, J., Kim, H.S., 2019. Combination of  
732 structural measures for flood prevention in Anyangcheon river basin, South Korea. *Water* 11.  
733 <https://doi.org/10.3390/w11112268>

734 Kundzewicz, Z.W., Hegger, D.L.T., Matczak, P., Driessen, P.P.J., 2018. Flood-risk reduction.  
735 *Proc. Natl. Acad. Sci. U. S. A.* 115, 12321–12325.

736 Lakmali, E.N., Deshapriya, W.G.A., Jayawardene, K.G.A.I., Raviranga, R.M.P., Ratnayake,  
737 N.P., Premasiri, H.M.R., Senanayake, I.P., 2017. Long term coastal erosion and shoreline  
738 positions of Sri Lanka. *Surv. Fish. Sci.* 3. <https://doi.org/10.18331/SFS2017.3.2.1>

739 Lavell, A., Oppenheimer, M., Diop, C., Hess, J., Lempert, R., Li, J., Muir-Wood, R., Myeong,  
740 S., 2012. *Climate change: New dimensions in disaster risk, exposure, vulnerability, and*  
741 *resilience, Managing the Risks of Extreme Events and Disasters to Advance Climate Change*  
742 *Adaptation*. Cambridge University Press, United Kingdom.

743 Lehner, B., Doll, P., Alcamo, J., Henrichs, T., Kaspar, F., 2006. Estimating the Impact of  
744 Global Change on Flood and Drought Risks in Europe: A Continental, Integrated Analysis.  
745 *Clim. Change* 75, 273–299. <https://doi.org/10.1007/s10584-006-6338-4>

746 Lewis, D., Mioch, J., 2005. Urban vulnerability and good governance, *J. Contingencies Crisis*  
747 *Manag.* 13, 50-53.

748 Lincke, D., Hinkel, J., 2018. Economically robust protection against 21st century sea-level rise.  
749 *Glob. Environ. Chang.* 51, 67–73. <https://doi.org/10.1016/j.gloenvcha.2018.05.003>

750 Magana, V., 2016. Considerations for a Research Program on Drought in Mexico. *Tecnol. Y*  
751 *Ciencias Del Agua* 7, 115–133.

752 Maly, E., Suppasri, A., 2020. The Sendai Framework for Disaster Risk Reduction at Five:  
753 Lessons from the 2011 Great East Japan Earthquake and Tsunami. *Int. J. Disaster Risk Sci.* 11,  
754 167–178. <https://doi.org/10.1007/s13753-020-00268-9>

755 Masria, A., Iskander, M., Negm, A., 2015. Coastal protection measures, case study  
756 (Mediterranean zone, Egypt). *J. Coast. Conserv.* 19, 14. [https://doi.org/10.1007/s11852-015-](https://doi.org/10.1007/s11852-015-0389-5)  
757 [0389-5](https://doi.org/10.1007/s11852-015-0389-5)

758 McEntire D, Gilmore Crocker MPH C, Peters E. Addressing vulnerability through an  
759 integrated approach. *Int J Disaster Resil Built Environ* 2010;1:50–64.  
760 <https://doi.org/10.1108/17595901011026472>.

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

765 Meyer, V., Priest, S., Kuhlicke, C., 2012. Economic evaluation of structural and non-structural  
766 flood risk management measures: examples from the Mulde River. *Nat. Hazards* 62, 301–324.  
767 <https://doi.org/10.1007/s11069-011-9997-z>

768 Ministry of Environment Sri Lanka, 2020. National Drought Plan for Sri Lanka.

769 Mudalige, J., 2011. Comparison Study of Existing Flood Research Activities.

770 Naderifar, M., Goli, H., Ghaljaie, F., 2017. Snowball sampling: A purposeful method of  
771 sampling in qualitative research. *Strides Dev. Med. Educ.* 14, 1–4.  
772 <https://doi.org/10.5812/sdme.67670>

773 National Research Council, 2013. Implementing flood risk management strategies, in: *Levees*  
774 *and the National Flood Insurance Program: Improving Policies and Practices*. National  
775 Academies Press, Washington, DC, pp. 97–126.

776 Ogunyoye, F., Stevens, R., Underwood, S., 2011. *Temporary and demountable flood protection*  
777 *guide*. Bristol.

778 Palliyaguru, R., Amaratunga, D., 2008. Managing disaster risks through quality infrastructure  
779 and vice versa. *Struct. Surv.* 26, 426–434. <https://doi.org/10.1108/02630800810922766>

780 Parrotta, J.A., Agnoletti, M., 2012. *Traditional Forest-related Knowledge: Sustaining*  
781 *Communities, Ecosystems and Biocultural Diversity*. Springer, Dordrecht.

782 Pathirage, C., Seneviratne, K., Amaratunga, D., Haigh, R., 2014. Knowledge factors and  
783 associated challenges for successful disaster knowledge sharing, *Global Assessment Report on*  
784 *Disaster Risk Reduction 2015*.

785 Partington, R., 2019. Does the government spend more on flood defences for the south? *The*  
786 *Gaurdian*.

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

790 Poteyeva, M., Denver, M., Barsky, L.E., Aguirre, B.E., 2006. Search and rescue activities in  
791 disasters, in Rodri ´guez, H., Quarantelli, E.L., Dynes, R.R. (Eds), *Handbook of Disaster*  
792 *Research*. Springer, New York, NY, 200-216.

793 Poussin, J.K., Wouter Botzen, W.J., Aerts, J.C.J.H., 2015. Effectiveness of flood damage  
794 mitigation measures: Empirical evidence from French flood disasters. *Glob. Environ. Chang.*  
795 31, 74–84. <https://doi.org/10.1016/j.gloenvcha.2014.12.007>

796 Rahman, N.A., Tarmudi, Z., Rosdy, M., Muhiddin, F.A., 2017. Flood mitigation measres  
797 using intuitionistic fuzzy dematel method. *Malaysian J. Geosci.* 1, 01–05.

798 Rahman, S., Akib, S., Khan, M.T.R., Shirazi, S.M., 2014. Experimental study on tsunami risk  
799 reduction on coastal building fronted by sea wall. *Sci. World J.* 2014.  
800 <https://doi.org/10.1155/2014/729357>

801 Rathnayake, U., Suratissa, D.M., 2016. Uma Oya multi purpose development project, Sri  
802 Lanka; Flood management and social impacts. *Water New Zeal.*

803 Ratnayake, N.P., Ratnayake, A.S., Azoor, R.M., Weththasinghe, S.M., Seneviratne, I.D.J.,  
804 Senarathne, N., Premasiri, R., Dushyantha, N., 2018. Erosion processes driven by monsoon  
805 events after a beach nourishment and breakwater construction at Uswetakeiyawa beach, Sri  
806 Lanka. *SN Appl. Sci.* 1, 52. <https://doi.org/10.1007/s42452-018-0050-7>

807 Ritchie, J., Lewis, J., Nicholls, C.M., Ormston, R., 2014. Analysis in practice, in: *Qualitative*  
808 *Research Practice: A Guide for Social Science Students and Researchers.* SAGE Publications  
809 Ltd, pp. 295–343.

810 Rowley, J., 2012. Conducting research interviews. *Manag. Res. Rev.* 35, 260–271.

811 Shivakoti, B.R., Villholth, K.G., Pavelic, P., Ross, A., 2019. Strategic use of groundwater-  
812 based solutions for drought risk reduction and climate resilience in Asia and beyond.

813 Shreve, C.M., Kelman, I., 2014. Does mitigation save? Reviewing cost-benefit analyses of  
814 disaster risk reduction. *Int J Disaster Risk Reduct* 10, 213–35.  
815 <https://doi.org/10.1016/j.ijdrr.2014.08.004>.

816 Singkran, N., 2017. Flood risk management in Thailand: Shifting from a passive to a  
817 progressive paradigm. *Int. J. Disaster Risk Reduct.* 25, 92–100.  
818 <https://doi.org/10.1016/j.ijdrr.2017.08.003>

819 Sivakumar, S., 2015. Flood mitigation strategies adopted in Sri Lanka a review. *Int. J. Sci. Eng.*  
820 *Res.* 6, 607–611.

821 Son, C.-H., Baek, J.-I., Ban, Y.-U., Ha, S.-R., 2015. The Effects of Mitigation Measures on  
822 Flood Damage Prevention in Korea. *Sustainability* 7, 16866–16884.  
823 <https://doi.org/10.3390/su71215851>

824 Srinivas, H., Nakagawa, Y., 2008. Environmental implications for disaster preparedness:  
825 Lessons learnt from the Indian ocean tsunami. *J. Environ. Manage.* 89, 4–13.

826 <https://doi.org/10.1016/j.jenvman.2007.01.054>

827 Stalenberg, B., 2010. Design of floodproof urban riverfronts. TU Delft.

828 Starominski-Uehara, M., 2021. How structural mitigation shapes risk perception and affects  
829 decision-making. *Disasters* 45, 46–66. <https://doi.org/10.1111/disa.12412>

830 Steele, P., Knight-John, M., Rajapakse, A., Wickramasinghe, K.S.K., 2007. Disaster  
831 management policy and practice: Lessons for government, civil society, and the private sector  
832 in Sri Lanka. Institute of Policy Studies of Sri Lanka, Colombo.

833 Tariq, M.A.U.R., van de Giesen, N., 2012. Floods and flood management in Pakistan. *Phys.*  
834 *Chem. Earth, Parts A/B/C* 47–48, 11–20. <https://doi.org/10.1016/j.pce.2011.08.014>

835 Tasseff, B., Bent, R., Van Hentenryck, P., 2019. Optimization of structural flood mitigation  
836 strategies. *Water Resources Res.* 55, 1490–1509. <https://doi.org/10.1029/2018WR024362>

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

839 Tiggeloven, T., de Moel, H., Winsemius, H.C., Eilander, D., Erkens, G., Gebremedhin, E.,  
840 Loaiza, A.D., Kuzma, S., Luo, T., Iceland, C., Bouwman, A., van Huijstee, J., Ligtoet, W.,  
841 Ward, P.J., 2020. Global-scale benefit-cost analysis of coastal flood adaptation to different  
842 flood risk drivers using structural measures. *Nat. Hazards Earth Syst. Sci.* 20, 1025–1044.  
843 <https://doi.org/10.5194/nhess-20-1025-2020>

844 Tipple, G., 2005. Housing and urban vulnerability in rapidly-developing cities, J.  
845 *Contingencies Crisis Manag.* 13, 66-75.

846 Tokida, K.I., Tanimoto, R., 2014. Lessons for countermeasures using earth structures against  
847 tsunami obtained in the 2011 off the Pacific Coast of Tohoku Earthquake. *Soils Found.* 54,  
848 523–543. <https://doi.org/10.1016/j.sandf.2014.07.001>

849 United Nations Office for Disaster Risk Reduction, 2021. Online glossary: mitigation [WWW  
850 Document]. URL <https://www.undrr.org/terminology/mitigation>

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

854 United Nations, 2015a. Transforming our world: the 2030 Agenda for Sustainable  
855 Development [WWW Document]. URL <https://sdgs.un.org/2030agenda>

856 United Nations, 2015b. Sendai Framework for Disaster Risk Reduction 2015-2030.

857 United Nations, 2016. Paris Agreement. Paris.

858 Urban Development Authority, 2019. Ratnapura development plan (2019-2030). Sri Lanka.

859 van Westen, C.J., Jetten, V., Sliuzas, R., Brussel, M., Alkema, D., van den Bout, B., Hazarika,  
860 M., 2016. Caribbean handbook on risk management.

861 Velasco, M., Russo, B., Cabello, À., Termes, M., Sunyer, D., Malgrat, P., 2018. Assessment  
862 of the effectiveness of structural and nonstructural measures to cope with global change  
863 impacts in Barcelona. *J. Flood Risk Manag.* 11, S55–S68. <https://doi.org/10.1111/jfr3.12247>

864 Wagenaar, D.J., Dahm, R.J., Diermanse, F.L.M., Dias, W.P.S., Dissanayake, D.M.S.S., Vajja,  
865 H.P., Gehrels, J.C., Bouwer, L.M., 2019. Evaluating adaptation measures for reducing flood  
866 risk: A case study in the city of Colombo, Sri Lanka. *Int. J. Disaster Risk Reduct.* 37, 101162.  
867 <https://doi.org/10.1016/j.ijdr.2019.101162>

868 Wang, H., Zhou, J., Tang, Y., Liu, Z., Kang, A., Chen, B., 2021. Flood economic assessment  
869 of structural measure based on integrated flood risk management: A case study in Beijing. *J.*  
870 *Environ. Manage.* 280. <https://doi.org/10.1016/j.jenvman.2020.111701>

871 Wenger, C., Hussey, K., Pittock, J., 2013. Living with Floods: Key Lessons from Australia and  
872 Abroad, Synthesis and Integrative Research, Final Report. Gold Coast, QLD.

873 Wickramaratne, S., Ruwanpura, J., Ranasinghe, U., Walawe-Durage, S., Adikariwattage, V.,  
874 Wirasinghe, S.C., 2012. Ranking of natural disasters in Sri Lanka for mitigation planning. *Int.*  
875 *J. Disaster Resil. Built Environ.* 3, 115–132. <https://doi.org/10.1108/17595901211245198>

876 Wijesundara, C., Dayawansa, N., 2011. Construction of large dams and their impact on cultural  
877 landscape: A study in Victoria reservoir and the surrounding area. *Trop. Agric. Res.* 22, 211.



878 <https://doi.org/10.4038/tar.v22i2.2830>

879 Wood, D., Kubatko, E.J., Rahimi, M., Shafieezadeh, A., Conroy, C.J., 2020. Implementation  
880 and evaluation of coupled discontinuous Galerkin methods for simulating overtopping of flood  
881 defenses by storm waves. *Adv. Water Resour.* 136, 1–28.  
882 <https://doi.org/10.1016/j.advwatres.2019.103501>

883 Yin, R.K., 2018. Designing Case Studies, in: *Case Study Research and Application*. SAGE  
884 Publications Ltd, Thousand Oaks, pp. 19–53.

885 Zakour, M.J., Swager, C.M., 2018. Chapter 3 - Vulnerability-plus theory: The integration of  
886 community disaster vulnerability and resiliency theories. Butterworth-Heinemann, pp. 45–78.  
887 <https://doi.org/https://doi.org/10.1016/B978-0-12-809557-7.00003-X>

888 [Anonymous., 2010] Details omitted for double-anonymized reviewing.

889 [Anonymous., 2021] Details omitted for double-anonymized reviewing.