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FUNCTIONAL CHARACTERISTICS OF AN EARLY WARNING SYSTEM TO MINIMISE THE RISKS OF DAM BREAKS IN SRI LANKA

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ABSTRACT

Dams have become a very important infrastructure that provides enormous benefits to the economy of the country. Even though dams are very important and significant structures within a country, their breaks can cause severe damage to the country's economy, society, and environment. Other than that, it can be impacted human life by causing deaths. As a come-up strategy, early warning systems can be used to reduce the severe impacts of dam breaks. Early warning systems (EWS) have been identified as a very important tool used to save lives and properties from disasters. Hence, this paper attempts to identify the functional characteristics of an EWS that can be used to reduce the impacts of dam breaks in Sri Lanka. An extensive literature survey was conducted to achieve the primary objective of this paper. Accordingly, the paper has identified the major purposes of dams, the causes for the dam breaks, and the impacts of dam breaks on the economy, society, and the environment. Then, the paper explores the functional characteristics of the EWS which is used for dam breaks. Finally, a conceptual framework has been developed with the key literature findings of the paper in order to minimise the social, economic, and environmental impacts created by dam breaks using early warning systems in Sri Lanka. As such, this paper will be a value addition to support the country's economy, society, as well as environment.

Keywords: *Causes; Dam Breaks; Early Warning System; Functional Characteristics; Impacts.*

1. INTRODUCTION

Dams can be identified as an obstruction created by steel, concrete, or earth to disturb or manage the flow of water by constructing across streams or rivers and can be defined as a structure used to create reservoirs (Manikowski and Strapasson, 2016). These engineering structures have a long history of application in general watershed restoration, erosion reduction, and soil conservation, and they are found in a wide range of locations around the world (Mekonnen, et al., 2015). Dams have always been associated with humanity's development process (Chen, et al., 2016). Hence, dams are classified as large or small, and this classification is directly related to the structure's intended purpose and

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use (Nascimento and Ribeiro Neto, 2017). Dams have served a variety of purposes over the years, and their widespread use is due to the scientific knowledge used in the design and safety of the structures (Martinz, et al., 2003). According to Lucas-Borja, et al. (2021) dams are used to manage soil erosion, moderate water, and sediment flows, and improve the land. Hence, dams serve a variety of purposes, regardless of their size; dams primarily provide energy production, and they are also used for flow control, navigation, agricultural supplies (mostly for small properties), and water accumulation (Nava, et al., 2021).

The collapse of an infinite or finite volume of fluid, particles, or their mixture onto a horizontal or inclined channel is referred to as a dam break (Chanson, 2006). According to Chanson (2006), it represents a wide range of practical problems with significant engineering implications. Among the most well-known examples are the collapses of water reserving dams and earth filling tailing dams (Di Cristo, et al., 2010). The failure of these dams could have disastrous consequences for both human life and property (Li and Zhao, 2018). Dam failure can be caused by a variety of factors (Gregoretti, et al., 2010). Further, Gregoretti, et al. (2010) asserted that the main causes of tail dam failure are unusual weather and poor dam management, whereas the stability of a landslide dam is influenced by reservoir level, seepage, dam material, and geometric dam configuration. Overtopping is the most common cause of dam failure, particularly for moraine dams and earthen embankments (Balmforth, et al., 2008).

As per Viseu and Almeida (2009), dam accidents, including structure failure, pose serious risks to people and property. Despite increased dam safety due to improved engineering knowledge and better construction quality, a completely risk-free guarantee is not possible, and an accident can occur due to natural hazards, human actions, or a dam's loss of strength capacity due to age (Chen, et al., 2016). Further, Chen, et al. (2016) highlighted that those all justify an increased focus on dam safety and valley management. Prospective dam failures, as well as public pressure for a safer environment, advocate dam risk assessment and reduction in downstream valleys in modern society (Green and Baird, 2020).

Climate change has increased the frequency of natural disasters such as flash floods, hurricanes, and landslides around the world in recent years (Hsiao, et al., 2021). Natural disasters have a significant impact on human society and can be caused by a variety of hazards (Chen, et al., 2016). Disasters lead to substantial casualties in terms of physical infrastructure, interruption of essential facilities, and harm to the means of livelihood in the affected areas (Rathnasinghe, et al., 2021). However, in a climate of increasing public security, it is becoming increasingly public scrutiny, and it is becoming increasingly inadequate to handle a single dam or a portfolio of dams in allocating limited resources for their operation, repair, or improvement (Li, et al., 2019). Even though the communities have the practice of identifying the risk of dam failures through environmental changes like water stream levels, there can be the risk of dam breaks due to non-environmental changes such as the aging of the dam, structure failures, etc. (Mehta, et al., 2020). The experts in dam authorities communicate about the dam failures through mathematical and scientific methods, however, communities cannot understand those due to their lack of knowledge on the causes and impacts of the dam failure as they adhered to assess the risk of dam failures through their self-assessments (Mehta, et al., 2020). Therefore, people are willing to have a pre-disaster risk identification method in order to increase the communication between communities and dam operators with the aim of reducing the hazard of dam breaks (Mehta, et al., 2020). As such establishing an early warning system (EWS) to indicate the dam failures is vital to manage the potential risks before the actual disaster occurs.

In Sri Lanka, there are dams of various sizes and types like gravity, embankment, arch, and arch-gravity dams (Navarathinam, et al., 2015; Manatunge, et al., 2009; Fujikura, et al., 2009). With the recent climate changes and the aging of the dams, Sri Lanka is at risk of dam breaks as highlighted by the Irrigation Department (Samarajiva, et al., 2006). Hence, it is high time to have an effective early warning system developed for dam breaks in Sri Lanka.

However as witnessed based on the scientific literature the EWSs that are developed mainly focused on flood risk management (Henriksen, et al., 2018), tsunami warnings (Rahayu, et al., 2020), and preparedness for other disasters (Collins and Kapucu, 2008; Leonard, et al., 2008). Hence, there is an inadequacy of research focusing on developing an EWS for the dam breaks. As the impact of dam breaks are significant, and the recent climate change can be one of the main causes of dam breaks, it is high time to research on the EWS for dam break. In this context, this study attempts to address the research gap by investigating the functional characteristics of effective EWS to reduce the disaster risks of dam breaks in Sri Lanka. The next section presents the research methodology. Then the analysis of the literature is presented followed by the conceptual framework that is developed for further research. Finally, conclusions and the way forward are provided.

2. RESEARCH METHODOLOGY

This research intends to answer the problem of "what are the functional characteristics of an effective EWS used to reduce the risk of dam breaks?" through a qualitative approach. Qualitative methods support to implement systematic analysis of evolving beliefs and are more suitable when the study has a trifling base of literature background (Naoum, 2007). Further, the qualitative method can be used to create new relationships with the variables to understand the complex processes and to illustrate the influence of society (Shah and Corley, 2006). Accordingly, an extensive literature review was conducted to address the research question. The review investigated the purposes of the dams, the causes and impacts of the dam breaks; and the functional characteristics of EWS. Based on the review of the literature a conceptual framework has been developed as a guide to steer through the problem with the contribution of primary data collection as the way forward.

3. REVIEW ON EWS FOR DAM BREAKS

This section intends to present the functional characteristics of EWS. First, it reviews the major purposes of dams and the causes and impacts of dam breaks followed by the functional characteristics of EWS. Finally, the conceptual framework developed based on the literature has been presented.

3.1 DAM CONSTRUCTION

As revealed by Youdeowei, et al. (2019) dams are introduced as engineering structures which are used for the storage, regulation, and diverting of water from rivers, and they are artificial man-made barriers built across the water. However, dams have become unique constructions all over the world (Chen, et al., 2016). According to the intended purpose and the usage, design strategies, and construction materials, various types of dams can be found in a wide range of locations around the world (Youdeowei, et al., 2019). Among them, earth dams, embankment dams, concrete dams, hydroelectric dams, tail dams, check dams, cascade dams, and arch-type dams are very popular (Nava, et al., 2021). The benefits of dam construction can be realised in the social systems, livelihood, and health of the people, and culture. Table 1 provides the direct and indirect purposes of dam construction.

Table 1: Purposes of dam construction

Main Purpose	Sub Purposes
Direct Purposes	Water supply for human activities
	Water supply for agricultural activities
	Water supply for industrial use
	Flood control
	Water storage
	Electrical energy production
	Changing the direction of rivers
	Control flow of sediments
Indirect Purposes	Preventing flood erosion
	Prepare barren lands for agriculture
	Depositing sand and clay near the river mouth
	Changing the flow of nutrients
	Increase food production
	Act as a centre for tourists
	Introduce new jobs
	Act as a source of fish

Adapted from: (Haghshenas, et al., 2016; Celic and Gul, 2021; Ribas and Pérez-Díaz, 2019; Hallouz, et al., 2018; Youdeowei, et al., 2019)

While serving a range of purposes in terms of social, economic, and environmental aspects, dam can be disastrous when they fail. The next section discusses the causes and impacts of dam breaks.

3.2 DAM BREAKS

Even though dams are constructed with well-improved engineering knowledge and construction qualities for different purposes, they can be broken and cause severe damage to humans and their properties (Haghshenas, et al., 2016). The overturning of the still water column in a reservoir as a result of the removal of the sluice gate will represent an ideal sudden dam break which can introduce a mechanism that involves creating and formulating rapid unsteady flow (Khoshkonesh, et al., 2019). Terrible damages may cause for both human life and the properties due to the failures associated with the dams (Li and Zhao, 2018). However, when compared to the dam constructions in the past more attention has been given to modern dam safety as modern dams are comparatively larger due to the industrialisation and increased density of population around the dams (Wang, et al., 2018). Therefore, it is vital to identify the causes and the negative impacts of dam break to create strategies to mitigate the risks associated with dam breaks.

3.2.1 Causes of Dam Breaks

Ribas, et al. (2021) have categorise the major causes involved in the dam breaks as internal and external causes. Despite the sophisticated engineering involved with dam construction, dam breaks can be caused due to internal causes such as design, technical, and management failures (Zhang, et al, 2009). The authors further highlighted that mechanical or electrical consequences and internal erosions can cause dam breaks. The key external cause is the climatic changes where the global warming that increases the atmospheric temperature can be a threat to dams as it will create floods due to the dissolution of glaciers and increased rainfall (You, et al., 2012). Besides, human actions such as man-made disasters are another major external cause of dam breaks (Ardeshirtanha and Sharafati, 2020). Figure 1 illustrates the main causes of dam breaks.

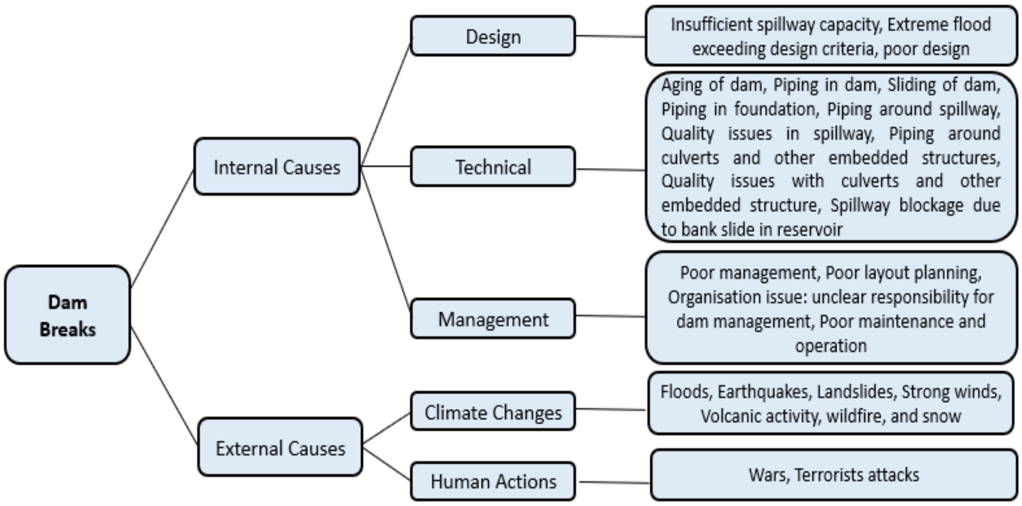

Figure 1: Causes of dam breaks

Adapted from: Zhang, et al. (2009); You, et al. (2012); Ribas, et al. (2021)

3.2.2 Impacts of Dam Breaks

The main impacts of the dam breaks can be classified as loss of human life, economic, social, and environmental losses (Wang, et al., 2018). Dam breaks adversely impact human life as it leads to the loss of human lives, their residencies, employment, and farming lands (Mehta, et al., 2020).

The economic losses caused by dam breaks can be divided into direct and indirect economic impacts (Zhang and Tan, 2014). The direct economic impacts are the financial impacts that can be directly measured in the flood-affected areas due to the reservoir dam break (Zhang and Tan, 2014). Basically, direct economic losses have been caused by agriculture (crops, fishery, forestry, animal husbandry), industry, commerce, and infrastructure (roads, railways, telecommunication, and tunnels) (Wang and Zhang, 2018). The direct economic loss has been measured as physical losses and income losses (Nigatu and Dinar, 2015). Physical losses are the physical value reductions in buildings, equipment, machinery, and all type of fixed or current assets which were affected by the dam break floods (Mo, et al., 2019). Mo, et al. (2019) further explored that the income losses are the profit losses that occurred due to the suspension of production and management activities as a result of the reservoir dam break and it mainly includes the agricultural income losses and industrial and commercial transport service losses. As revealed by Mo, et al. (2019) indirect economic impacts included the expenses of flood management efforts, losses from decreased agricultural production and factory production, and the rising costs of typical socioeconomic activities.

Like human life and the economy, dam breaks badly affect the environment and society too (Zhang and Tan, 2014). As such dam breaks affect the physical and mental health as a result of injury or stress, and a decrease in the quality of daily life (Zhong, et al, 2011). Other than that, damage to the cultural properties, art treasures, rare animals and plants, and even harmful political effects (i.e., national and social stability) can be identified as the social impacts due to the dam breaks (Mo, et al., 2019). The environmental and social impacts due to the reservoir dam breaks cannot be ignored as increased attention has been placed on the environment and society (Sun, et al., 2014). Accordingly, the effects on the channel morphology, living creatures and their habitats (including rivers, wetlands, topsoil, vegetation, and so on), and the cultural landscape, which cause significant damage to the environment through contaminations (e.g., River facilities and chemical storage facilities) can be identified as the environmental impacts caused with the reservoir dam breaks (Mo, et al., 2019).

Accordingly, there are severe impacts on humans, the economy, society, and the environment with the dam breaks (Lempérière, 2017). Hence, there is a vital need for an early warning system with the aim of reducing the risks of dam breaks.

3.3 EARLY WARNING SYSTEM (EWS)

An early warning system (EWS) is one of the most important tools used to prevent the impact of disasters (Zambrano, et al., 2017). Hence, EWS and risk communications are very important roles in the existence and recovery of the population impacted by the disasters (Fan, et al., 2018). According to Zambrano, et al. (2017), "early' refers to the prevention or reduction of disasters, potential damages, or hazards, "warning" describes the announcement given by describing the danger, and "system" is the component that puts all the information together. Therefore, EWS has been identified as a strategy used to save lives from disasters (Collins and Kapucu, 2008). Generally, EWS is a collection of abilities required to develop and transmit timely and relevant information in order for people, communities, and organisations endangered by hazards to plan and respond effectively having sufficient time to decrease the chance of injury or loss (UNISDR, 2009).

When developing an effective EWS, spatial and socio-cultural factors such as hazard and vulnerability mappings (Schlurmann, et al., 2011), community education and participation (Collins and Kapucu, 2008), indigenous and local knowledge (McAdoo, et al., 2008), and religious and language differences (Haigh, et al., 2020) should be considered. Other than that, the developers must have a solid knowledge and understanding of how to create effective warnings for the accurate risk scenarios associated with vulnerable people (Dutta and Basnayake, 2018). The authors further asserted that the effectiveness of the EWS can be achieved with the engagement of experienced experts to manage the system. Basically, EWSs are focused on the people (people-centric) by developing the risk knowledge, monitoring and warning service, dissemination of warning information, and public awareness and preparedness (Eckersley, et al., 2017). Hence, there are instruments and procedures connected with the

EWS which are coordinated by the international, regional, and national agencies (Fan, et al., 2018).

The installation of a variety of devices and technologies to guarantee early identification and monitoring of risks is typical of warning systems (Schlurmann, et al., 2011). As per Leonard, et al. (2008), EWSs are comprised of scientific and organisational capabilities for assessing acquired data to estimate the level of related risk exposure, potential consequences, and prompt notification mechanisms for people at risk. In addition to that, it is important to consider the coherency, capacity to convey timely predictions, efficient alarms, accurate detection, and warning messages, strong communication, reliable responses, and consistency in order to maintain the effectiveness of the EWS (Haigh, et al., 2020). Wehn and Evers (2015), also have further asserted that good risk communication has the ability to establish public confidence if it is based on honesty, clarity, comprehensiveness, and timeliness. Even though the major function of an EWS is to deliver the warning to the final destination (community level), the key concept behind that scenario is to filter the gathered information and translated them into recommended action through the technical process using the most suitable language in order to convey the warning in an understandable manner for the end-users (Hamza and Månsson, 2020). The next section explores the functional characteristics of an EWS.

3.4 FUNCTIONAL CHARACTERISTICS OF AN EARLY WARNING SYSTEM FOR DAM BREAKS

In order to achieve the goal of the EWS, there are five specific characteristics that must work in unison such as (i) Risk forecasting and evaluation, (ii) Detection and monitoring, (iii) Emergency response and action, (iv) Local dissemination, and (v) Public education (Samarajiva, et al., 2006).

Risk Forecasting and Evaluation

This is the system's scientific and technical dimension, which primarily relies on observation and prediction based on scientific expertise and advanced technologies such as mathematical modelling, remote sensing, etc. (Wu, et al., 2021). A significant amount of effort and resources have been invested on this characteristic, resulting in significant advances in EWS (Collins and Kapucu, 2008).

Many hazard warnings are prompted by local officials as well as affected local residents, alerting families, and neighbours (Delenne, et al., 2012). As a result, other than the experts, people also act as a valuable source of hazard detection information (Cools, et al., 2016). However, dam inspection staff, as well as villagers close to the dam, should always be trained to identify the dam breaks in a timely manner and to look for early signs of distress conditions such as unusually high-water levels in the canals or muddy discharge from seepage (Steenbergen and Willems, 2013). Therefore, when a villager identifies any hazard, they must inform relevant authorities to activate early warnings (Wattanasit and Khwannimit, 2021).

Detection and Monitoring

An accurate and dependable method of detecting hazards is the foundation of an effective and comprehensive public safety programme (Binder, 1979). As revealed by You, et al. (2012), in the field of dam safety, hazard detection begins with a thorough examination of the dam's physical integrity. An effective inspection/monitoring system must include the collection of relevant data to ensure that monitors receive accurate safety status indications, as well as timely data collection/sensing systems to allow authorities time to analyse data and issue warnings if necessary (Eckersley, et al., 2017). High tech extreme (considering complex factors) and low tech extreme (observations) are included in the routine inspections. However, due to structural and financial limitations, routine inspections are solely undertaken using low-tech extreme such as visual inspection (Fujikura, et al., 2009). This might lead to dam failures, for instance, Kantale dam failure (unusually heavy flow from a sluice barrel) was also first notified by a villager and informed to the Irrigation Engineer (Samarajiva, et al., 2006). Increasing the time lag between hazard detection and hazard events allows enough time to warn and evacuate vulnerable communities, as well as take mitigation actions to minimise property damage (Kim and Sanders, 2016).

Emergency Response and Action

The geographical impacts and the extent of inundation of the dam break impacts will be dependent on the location and the size of the dam (Duressa, 2018). As revealed by Duressa (2018) the data from the early warning systems are only sent to the local dam officers when only locals are impacted by the dam break and the data will be transmitted to all other locations to allow a region-wide coordinated response in case of a large dam break. Established protocols must be placed to allow dam engineers and local governments to make quick and efficient decisions (Wang and Zhang, 2018). If a dam-related hazard is discovered, dam operators should notify pre-designated emergency first responders in local government, community-level organisations, and the media (Samarajiva, et al., 2006). Disaster management plans must be tailored to the specific characteristics of the dam and its watershed area (Hardjosuwarno, 2014). The author further revealed that these plans must include instructions for on-site personnel on what steps to take to notify supervisors and warning disseminators. Further, these warning systems should play a dominant role while managing safety programmes and supplying information to the public in order to maintain public trust (Samarajiva, et al., 2006).

Local Dissemination

One of the most critical links in an early warning system is the ‘last mile”, which transports alerts and warnings to households in vulnerable towns and villages (Ardeshirtanha and Sharafati, 2020). Following the detection of a dam related hazard, warnings and alerts must be communicated to local authorities (police, local military, fire services, municipality), religious establishments (temples, churches, and mosques), community leaders (such as grama niladhari, farmer organisation leaders), grass-roots organisations (like Sarvodaya) (Samarajiva, et al., 2006). Therefore, the warning can be disseminated to each individual household at risk, allowing people at risk to take the necessary precautions (Zhu, et al., 2021). As revealed by Zhu, et al. (2021), this final component of warning or the instruction for protective measures is required to provide people with the best chance of avoiding serious harm.

Public Education

The general public must be educated on the nature of hazards and their consequences, who and what is at risk, how people will be warned, what the warnings mean, and what actions must be taken (Eckersley, et al., 2017). Warning systems must be tested on regular basis to ensure that they function properly and that the general public understands their purpose and messages (Martin and Rice, 2012). Samarajiva, et al. (2006) asserted that the success of a dam safety programme will be determined in large part by the public's ability to respond suitably to all authority's warnings, alerts, and instructions, both in the event of a dam risks and in the general and everyday use of dams and reservoirs. Finally, safety training should include information on potential risk warning signs (e.g., seepage or overtopping) as well as for instructions on how a local resident can contact the local dam operator and the central dam hazard unit (Eckersley, et al., 2017). As per the identified research gap, it is high time to develop an EWS including the key functional characteristics discussed above to minimise the risks of dam breaks in Sri Lanka. The following section presents the conceptual framework developed based on the literature review.

3.5 CONCEPTUAL FRAMEWORK

Based on the discussion above, a conceptual framework has been developed as shown in Figure 2. The purpose of the conceptual framework is to present how the functional characteristics of Early Warning Systems can support to minimise the causes and impacts of dam breaks.

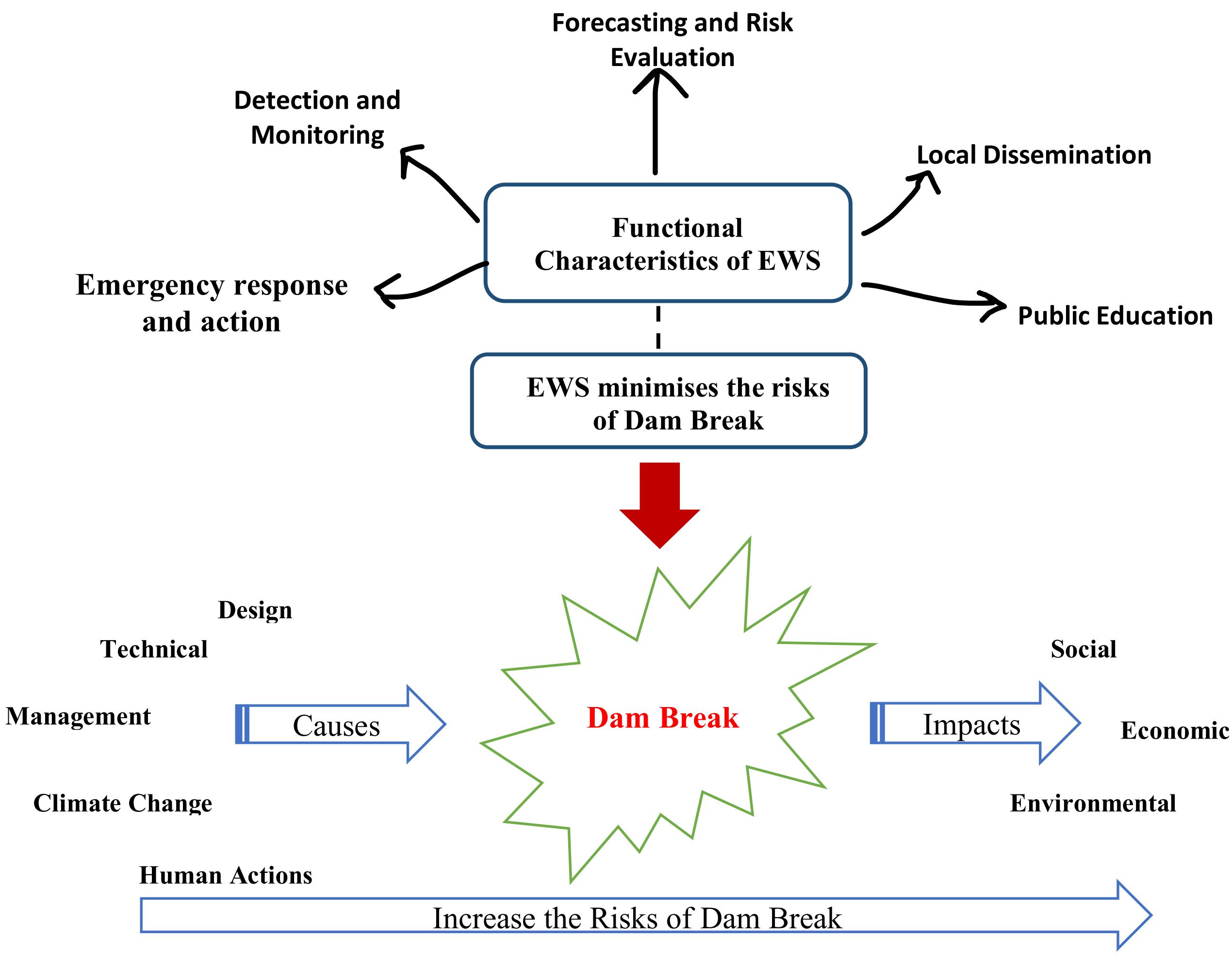

Figure 2: Conceptual framework

As shown in Figure 2, the dams are a very important infrastructure which gives enormous benefits. However, due to the identified causes, the risks of dam break will increase and create very disastrous consequences on social, economic, and environmental aspects. As illustrated in the conceptual framework, the EWS is the most suitable strategy to reduce the risk of dam failures during the construction, operation, and maintenance of the dams. The key functional characteristics of EWS are explored, as illustrated in the conceptual framework. How these functional characteristics will be utilised in the context of EWS for dam breaks in Sri Lanka is the way forward of this study. As the technology has developed and expanded worldwide, it can be used to enhance the characteristics of EWS in one platform (Fan, et al., 2018). Since all the theoretical information gathered on the dam breaks can be incorporated with the technology medium by sharing social, economic, and environmental information, technology will be a supportive platform to handle the different levels of information about the dam breaks by increasing the efficiency and effectiveness of EWS. As such this research will further analyse the utilisation of technological platforms to effectively evaluate and implement the functional characteristics of EWS for dam breaks in Sri Lanka.

Hence this conceptual framework will act as a basic guide to capture primary data in order to contextualise the functional characteristics of EWS to effectively minimise the risks of dam breaks in Sri Lanka.

4. CONCLUSION

Literature synthesis has been developed to summarise the existing knowledge on dams, dam breaks, and the EWS. Moreover, the availability of EWS for the disaster management industries will be a huge support to reducing the risk of dam breaks by enhancing the safety of humans as well as the properties. The conceptual framework has been developed by highlighting the key findings of the study. The causes that can increase the risk of dam breaks were categorised as design, technical, management, climate change, and human actions. The dam break will further create social, economic, and environmental impacts. To minimise such disaster risks due to dam breaks, EWS can be used as a strategy to ensure the safety of the communities affected by dam breaks during the construction, operation, and maintenance of the dams. As such, risk forecasting and evaluation; detection and monitoring; emergency response and action; local dissemination; and public education have been identified as the main functional characteristics of an EWS. EWS will be filtered all information collected through the risk analysis and communicate the warnings for recommended parties in a common language which can be understandable by all vulnerable parties within a lead time period. The conceptual framework will be used to gather primary data to enhance the efficiency of the functional characteristics of EWS in the context of the dam breaks in Sri Lanka. As a way forward, the research will also explore how technological platforms can facilitate to efficiently implement the functional characteristics of EWS for the dam breaks in Sri Lanka.

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