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**F** – literature search

# Application of fuzzy cognitive mapping in the analysis of small earth dam failure

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## Abstract

Small earth dams are most valuable in arid and semi-arid areas where they are used for both domestic and agricultural purposes. These dams however, continue to fail. The causes of such failures are interconnected in the sense that one can trigger the other. Most research into earth dams nevertheless, uses reductionist approaches. Such approaches do not consider the complex interactions between these modes and/or causes. This research used fuzzy cognitive mapping to identify the prominent modes and causes of small earth dam failure in Swaziland and to capture their interactions. A sample of seven earth dam construction experts was purposively selected from five institutions for individual interviews. An individual map was developed from each interview. An aggregated map was thereafter developed by combining seven individual maps. The results indicated that overtopping, piping and sliding were the common modes of earth dam failure. Overtopping was mainly due to siltation whilst animal barrows and tree roots were largely responsible for piping. Sliding was mostly associated construction defects and sudden drawdown. It was concluded that most of the failures were linked to poor management of catchments and that of the dams. It is recommended that future designs and management should increase the level of community participation in order to limit some of the causes associated with land use practices.

**Key words:** *dam failure, fuzzy cognitive mapping, small earth dams, systems thinking*

## INTRODUCTION

Small earth dams are most valuable in arid and semi-arid areas where they are constructed to hold back water for smallholder irrigation, livestock watering and domestic use. These dams are usually constructed for rainwater harvesting or on small rivers to retain flood runoff. Small earth dams respond rapidly to precipitation and runoff hence, they are favoured to harness sporadic, spatial and sometimes temporal rainfall [Senzanje *et al.* 2008]. Small earth dams are mostly operationally efficient. This is because most of these dams are located in close proximity to the point of use, which makes water abstraction relatively inexpensive. In addition, small earth dams are relatively easier to design and much simpler to construct, especially when compared to concrete dams and masonry dams. Nevertheless, engineering literature is filled with numerous accounts of earth dam failure [Huang, Xiong 2017; Imbrogno 2014; Sharma, Kumar 2013]. The main drawback for small earth dams is their susceptibility to failure [Myronidis 2017].

The frequency of failure is much higher in small earth dams compared to that of medium to large dams. This is largely attributed to poor dam design, the quality of construction material and to lack of proper maintenance [Mufute *et al.* 2008; Zhang *et al.* 2009]. There are many modes of dam failure e.g. piping, sliding, overtopping, etc. Although diverse, these modes and their causes are at times interrelated in a complex manner. More often several causes are involved within a particular mode of failure. It is as such difficult to isolate a distinct, single cause for a particular earth dam failure [Delgado-Hernández *et al.* 2014; Kihachu 2016; Zhang *et al.* 2009]. In a study conducted in Zambia, Kolala *et al.* [2015] concluded that a combination of spillway impairment and internal erosion were the source of most earth dam failures. However, FORSTER *et al.* [2000] noted a combination of piping and overtopping as causes of other dams failure. The various modes of dam failure are as such interconnected in the sense that one mode can trigger the other. Most of the studies conducted on dam failure, however, do not comprehensively examine these possible interactions. The cause-and--effect relationships between the different modes of failure are strongly related and cannot therefore be fully represented by reductionist approaches that consider each mechanism independently. Systems thinking approaches are as such important in the diagnosis of earth dam failure as these approaches consider the details of various modes and their interactions.

Over the years the government of Swaziland (GoS) has constructed a number of small earth dams throughout the country. These dams are most valuable especially for rural households and smallholder irrigated agriculture. Earth dams as such, play a vital role in food security. Many of these dams, however, continue to fail [Government of Swaziland 2005]. In recent times the GoS in partnership with the International Fund for Agricultural Development and the European Union have set up various earth dam rehabilitation initiatives in an effort to revive some of the infrastructure [MANYATSI, MHAZO 2014]. In this context, it is important to conduct research on some of the issues that had previously led to the failure of the small earth dams in Swaziland in order to avoid future occurrences and also to ensure reliable water supply and sustainability of livelihoods. Hence, a fuzzy cognitive map of the main causes of small earth dam failure in Swaziland was developed in this study. The objectives of the study were (a) to determine the common modes of small earth dam failure and (b) to determine the major causes of these failures. A systems approach to the diagnosis of earth dam failure, as it will be demonstrated through fuzzy cognitive mapping, is important because it captures the inter-linkages between the various failure modes and causes. This in turn, allows decision-makers to locate high leverage intervention points within the failure system. The research is important given that the lessons learnt could be used for future designs, construction and in rehabilitation works.

## FUZZY COGNITIVE MAPS

Fuzzy cognitive maps are signed digraphs first introduced by KOSKO [1986] to model human perceptions. They are an extension of cognitive mapping that includes fuzzy mapping and neural networks. Instead of using signs only to indicate cause-and-effect (as is the case with cognitive mapping), FCMs also associate a weight with each link. The mapping process involves: (a) the identification of concepts (trends, actions, events, or goals), (b) determination of causal relationships between these concepts and lastly, (c) the determination of the strength of each causal link. Graphically concepts are represented as nodes ($C$) and the causal link between node $C_i$ and $C_j$ as an edge ($W_{ij}$). Edges can be one of three types *viz.* positive ($W_{ij} > 0$), negative ($W_{ij} < 0$) and no relationship whatsoever ($W_{ij} = 0$). A positive causal relationship means that an increase in the value of $C_i$ leads to an increase in $C_j$. A negative relationship indicates that an increase in the value of $C_i$ causes a decrease on the value of $C_j$. Fuzzy cognitive maps as such, are semi-quantitative, participatory tools. This is because the quantification of drivers and links is interpreted in relative terms only. Fuzzy cognitive maps can be drawn from data obtained from interviews and by extraction from written texts (worksheets, pattern notes, and reports) where participants individually or in groups develop a map. The weight of each causal link can be directly expressed as real numbers drawn from the bipolar fuzzy interval (–1…0…1) or through linguistic weights. The linguistic weights are thereafter transformed into fuzzy sets using linguistic modifiers. Fuzzy cognitive mapping wide application is evident in environmental management [VAN VLIET *et al.* 2010], social systems [CARVALHO 2013] and agricultural systems [OZESMI, OZESMI 2004].

Fuzzy cognitive maps are a product of multiple nodes with many interconnections and feedback. Graph theory indices are often used to analyse the structure of FCMs through different indices. The commonly used index for FCMs analysis is degree centrality. Degree centrality refers to the number of ties that a particular node has with other nodes. Nodes with more ties have multiple alternative ways or resources to reach goals. The degree centrality index $C_I$ is calculated as a sum of a concept's in-degree ($id(C_i)$) and out-degree ($od(C_i)$) index (Eq. 1).

$$C_{Ii} = od(C_i) + id(C_i) \tag{1}$$

In-degree centrality represents the total strength of ties directed to a particular concept. Conversely, out-degree refers to the total strength of ties that a concept directs to others. The computation of out-degree index as follows:

$$od(C_i) = \sum_{j=1}^{N} W_{ij} \tag{2}$$

Where: ($od(C_i)$) is the out-degree of variable $C_i$ and $W_{ij}$ represents the weight of ties from $C_i$ directed to other concepts. In-degree centrality index is computed based on Equation 3.

$$id(C_i) = \sum_{j=1}^{N} W_{ji} \tag{3}$$

Where: $id(C_i)$ is the in-degree of variable $C_i$ and $W_{ij}$ represents the weight of ties directed towards $C_i$.

Concepts can be classified into three different types based on centrality *viz.* transmitter, receiver and/or ordinary. Transmitter concepts have a positive out-degree and zero in-degree whilst receiver concepts have zero out-degree and a positive in-degree. Ordinary concepts on the other hand, have both positive in-degree and out-degree.

Fuzzy cognitive mapping was selected for this research based on its cognitive accessibility and the ability to capture system interactions. According to SHONGWE and BEZUIDENHOUT [2019], the use of linguistic weights in the construction of FCMs makes them (FCMs) more accessible to people from a range of background, especially when compared to causal loop diagrams and current reality trees. This is because most people relate easier to discrete linguistic weights than continuous numerical weights [CHEAH *et al.* 2011]. The actual process of constructing FCMs nevertheless, can be demanding especially when large systems with multiple nodes are taken into consideration.

## STUDY METHODS

There are many institutions that construct small earth dams in Swaziland. These include, amongst others, the GoS, parastatals and private institutions. Most of the small earth dams in Swaziland are constructed by government through the Ministry of Agriculture (Land Use Planning Department). The Land Use Planning Department is mainly responsible for the design, construction and rehabilitation of small earth dams and diversion weirs for small-scale irrigation development. The department has three office categories *viz*. design engineers, construction engineers and irrigation officers [Government of Swaziland 2019]. The availability of different experts from the various institutions introduces complexity owing to multiple perspectives. Different individuals possess diverse ways of interpreting even the "same situation". Research into such contexts should therefore, be interpretive in nature. Interpretive research approaches understand reality as defined by the subjective experience of individuals. The study as such, was a survey that targeted several individuals working for different institutions that construct small earth dams in Swaziland. Institutions who participated in the research were promised confidentiality and anonymity.

A sample of seven earth dam construction experts was purposively selected from five institutions for individual interviews (Tab. 1). Purposive sampling is a non-probability sampling technique that is widely used to address issues of transferability in research. This is because specific information is emphasised within a purposive sample rather than generalised, as is the case with most quantitative approaches. Rather than size, sampling was also guided by accessibility and the availability of experts. Hence, in spite of the attempt to have a representative sample, there could be bias in the results as only seven stakeholders were interviewed. The participants in the study had been actively involved with small earth dam construction for a minimum of three consecutive years. To the researchers' knowledge, these individuals were highly involved with issues within the small earth dam industry and as a result, provided representative viewpoints. Table 1 also shows the positions held by the interviewed individuals within their institutions and their responsibilities (in relation to small earth dams). Most of the participants were civil engineers and the responsibilities included planning, dam design, construction and monitoring.

**Table 1.** Profile of interviewed participants

| Institution | Participant position | Responsibility of expert |
|---|---|---|
| A | soil conservation engineer | monitoring |
| A | soil scientist | planning and monitoring |
| A | quantity surveyor | planning and monitoring |
| B | civil engineer | design, construction and monitoring |
| C | civil engineer | design and construction |
| D | civil engineer | design and construction |
| E | civil engineer | design and construction |

Source: own elaboration.

A conceptual fuzzy cognitive map was developed by the researchers and validated by two dam experts. The conceptual model served as a basis for a questionnaire that was used to collect data (concepts and links). To capture the strength of each causal link, the questionnaire utilised a linguistic scale. Linguistic modifiers were prepared beforehand to convert discrete weights into continuous numerical values. The linguistic weights were namely: rarely, occasional, moderate, and a great deal. These expressions were converted into numerical values of 0.25, 0.5, 0.75 and 1.0, respectively [STACH *et al.* 2005].

Data from each questionnaire was used to develop individual maps. In total seven individual maps were generated from the interviews. These individual maps were thereafter added together to develop a single aggregated map. Firstly, each individual map was converted into an adjacency matrix in the form $E = (e_{ij})$, where concept $C_i$ was listed on the vertical axis and $C_j$ on the horizontal. The adjacency matrices were thereafter augmented (in case of deficient concepts) and additively superimposed to generate a group matrix ($E_i$). The group matrix was transformed into an aggregated map ($E_c$) by normalising each of the matrix element by the number of experts who supported it, $k$ (Eq. 4).

$$E_c = \frac{1}{k}\sum_{i=1}^{k} E_i \qquad (4)$$

Combining the different individual maps into a single map allowed for the construction of a bias-free map. This combination is however oblivious of the fact that each individual map represents only a partial view of the system. Out-degree, in-degree and the centrality index for the aggregated map were computed using the FCMapper software [BACCHOFER, WILDENBERG 2010]. The FCMapper was also used to conduct scenario analysis. Data from the interviews that were not directly used to develop the map(s) were summarised and presented tables.

## RESULTS AND DISCUSSION

Total of 94 earth dams were constructed by the five institutions considered for the study between the year 2000 and 2017 (Tab. 2). All of these dams were simple embankments (homogenous). This is in consonance with the survey conducted by the GoS that found homogeneous dams to be the most dominant form of earth dams in Swaziland [Government of Swaziland 2005]. Most of these dams were constructed by institution A (87.2%). Over 18% (15/82) of the dams constructed by institution A had undergone rehabilitation. All the dams constructed by institution B had also undergone rehabilitation. No rehabilitation work had been conducted on dams constructed by institution C, D and E. The non-rehabilitation of the dams constructed by C, D and E does not necessarily mean that their dams were in a good condition. These institutions (C, D and E) were private engineering consultants and their role within the dams was only restricted to design and construction (Tab. 1).

**Table 2.** Status of small earth dams in Swaziland

| Institution | Dams constructed | | Dams rehabilitated | |
|---|---|---|---|---|
| | number | % | number | % |
| A | 82 | 87.2 | 15 | 83.3 |
| B | 3 | 3.2 | 3 | 16.7 |
| C | 3 | 3.2 | 0 | 0 |
| D | 3 | 3.2 | 0 | 0 |
| E | 3 | 3.2 | 0 | 0 |
| Total | 94 | 100 | 18 | 100 |

Source: own study.

The main modes of earth dam failure in Swaziland were overtopping, piping and sliding (Tab. 3). Using a linguistic rating scale of rare to a great deal, overtopping and piping were found to occur on a great deal of times. The occurrence of sliding was rare to occasional. These findings concur with those of ZHANG *et al.* [2007]. A global survey conducted by ZHANG *et al.* [2007] found that most earth dams fail through quality-related modes (42.5%) and overtopping (36.4 %). Quality-related modes as referred to by ZHANG *et al.* [2007] included piping, sliding and failure due to culverts and embedded structures. Fifty eight percent of the quality-related modes were attributed to piping and 18.3% to sliding. Similarly, studies in India [International Commission on Large Dams 2000] and Zambia [KOLALA *et al.* 2015] found overtopping to be the most prevalent mode of small earth dam failure.

**Table 3.** Common modes of small earth dam failure in Swaziland (*n* = 19)

| Mode of failure | Frequency of failure mode occurrence | | | |
|---|---|---|---|---|
| | rare | occasional | moderate | great deal |
| Overtopping | 2 | 2 | 2 | 1 |
| Piping | 1 | 3 | 2 | 1 |
| Sliding | 3 | 2 | - | – |

Source: own study.

Overtopping occurs when water levels surpass the height of a dam's crest, forcing water to spill over. As the water level surpasses the crest, it erodes the dam leading to complete collapse. The major causes of overtopping are insufficient spillway capacity, settlement of the dam foundation and flooding due to extreme rainfall. The aggregated fuzzy cognitive map (Fig. 1) indicates that the main causes of overtopping in Swaziland were siltation (0.85), rainfall (0.71), settlement (0.50) and insufficient spillway capacity (0.39), respectively. Siltation increases the load on a dam wall whilst decreasing the dam's freeboard and subsequently, storage capacity. The reduction in storage consequently leads to overflow into the embankment. Siltation is regarded as one of the greatest risks to small earth dams in Africa, especially in areas where there are no environmental protection practices [MUYAMBO 2000]. A study conducted in Zimbabwe found that siltation was of serious concern in about 80% of all small earth dams [MUFUTE *et al.* 2008].

Siltation could be controlled by proper management of the catchment area. The use of straw bales and sedi-mats is often recommended. Degraded watersheds could also be rehabilitated to reduce the rate at which sediments are delivered into reservoirs. The issue of extreme rainfall can only be considered at the dam's design phase. As can be seen in Figure 1 that insufficient spillway was mostly due to maintenance (0.85), routine maintenance in earth dams is as such critical.

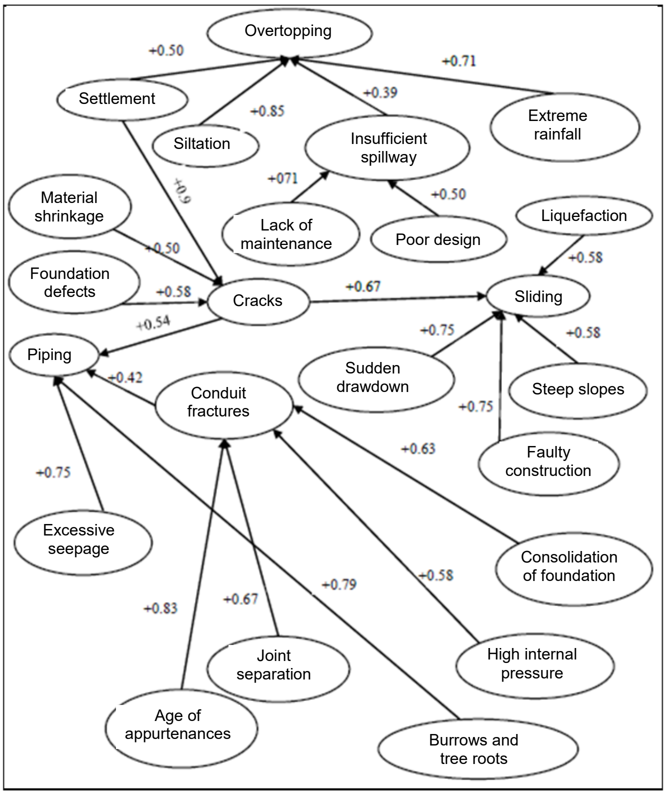

Fig. 1. An aggregated fuzzy cognitive map for the main causes of small earth dam failure in Swaziland; source: own study

All earth dams exhibit some form of seepage but only to a certain degree. Excessive seepage, however, may cause dams to fail. The failure of dams due to seepage occurs in two forms *viz.* sloughing and piping. Failure due to piping occurs through the progressive erosion of leaks that develop under or through an embankment. Other causes of piping include a poor choice of construction material, differential cracks, lack of formal soil compaction, large tree roots in the embankment, and animal burrows [JANSEN 2012]. The main causes of piping in Swaziland (Fig. 1) were perceived to be excessive seepage (0.75) and animal burrows and tree roots (0.79). Rodent activity, tree roots and poor construction are often found to be the common causes of piping in most small earth dams [ROCQUE *et al.* 2001]. Large tree roots and decaying roots provide paths for seepage whilst cracks shorten seepage paths. Most of the cracks found in earth dams are, however, longitudinal [FELL *et al.* 2000]. Longitudinal cracks present no potential seepage path for piping but rather scarps of slide surfaces. Transverse cracks in contrast, create paths for concentrated seepage.

Failure due to sliding occurs when the average stress between any potential sliding surfaces becomes greater than the average strength. An increase in pore-water pressure as such may cause sliding. Sliding also occurs due to steep slopes and faulty construction [EVANS 2006]. The main causes of dam slides in Swaziland (Fig. 1) were sudden drawdown (0.75) and faulty construction (0.75). This supports a previous study by the GoS that found that most earth dam slides in the country were a consequence of insufficient clay and/or compacting material [Government of Swaziland 2016]. A study by BHATTARAI *et al.* [2016] reported that most failures due to sliding occur as a result of drawdown and poor quality material.

As can be seen in Figure 1, there were 23 concepts that characterised small earth dam failure in Swaziland. Figure 2 shows a centrality index graph that also reflects in-degree and out-degree indices. The concepts with the highest degree centrality indices were sliding, cracks and conduit fractures, respectively. According to GOLBECK [2013], the higher the degree centrality index, the more central a node is. Most of the nodes in the map were transmitter concepts (Fig. 2). Transmitter concepts represent forcing functions that cannot be controlled by other concepts. All the receiver nodes had a higher centrality index than the transmitter nodes. This was largely attributed to the high number of ties each concept had than to weight. Furthermore, these concepts were the common modes (except for cracks) of failure from which the map was conceptualised.

Cracks, conduit fractures and insufficient spillway were the only ordinary concepts in the map. These in addition, had the second, third and sixth highest degree centrality index, respectively. Degree centrality index does not however, take the global structure of a map into consideration. As such, a node may be highly connected but not in a position to reach other nodes quickly. Insufficient spillway and conduit fractures, unlike cracks only affected overtopping and piping, respectively. As such, the most central concept in the map (in relation to the three) was cracks. Cracks were directly linked to two of the common failure modes (sliding and piping). In the same vein, the settlement concept was also important as it affected overtopping, sliding and piping (through cracks).

Figure 3 represents results from a scenario simulation for all the concepts in the fuzzy cognitive map. The steady state values were obtained from steady state calculations attained after twenty iterations (using the FCMapper). The concepts with the highest initial values (>0.9), as indicated in Figure 3, were sliding, piping, conduit fractures, overtopping, and cracks, respectively. This suggests that these concepts were the most influential factors in the failure of small earth dams in Swaziland.

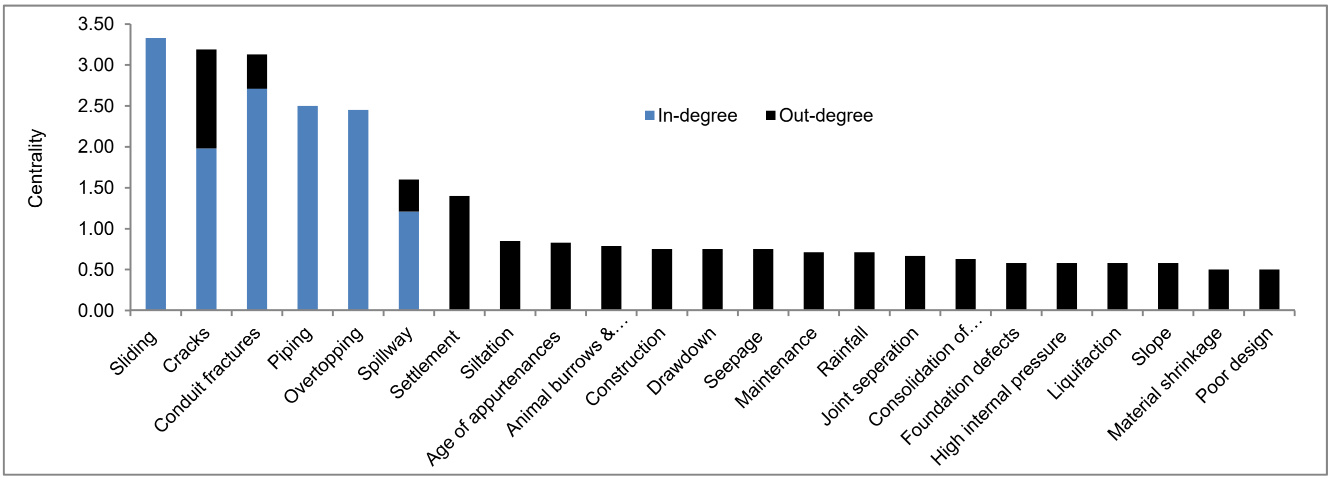

Fig. 2. Representation of the concepts in the aggregated map according to their centrality; source: own study

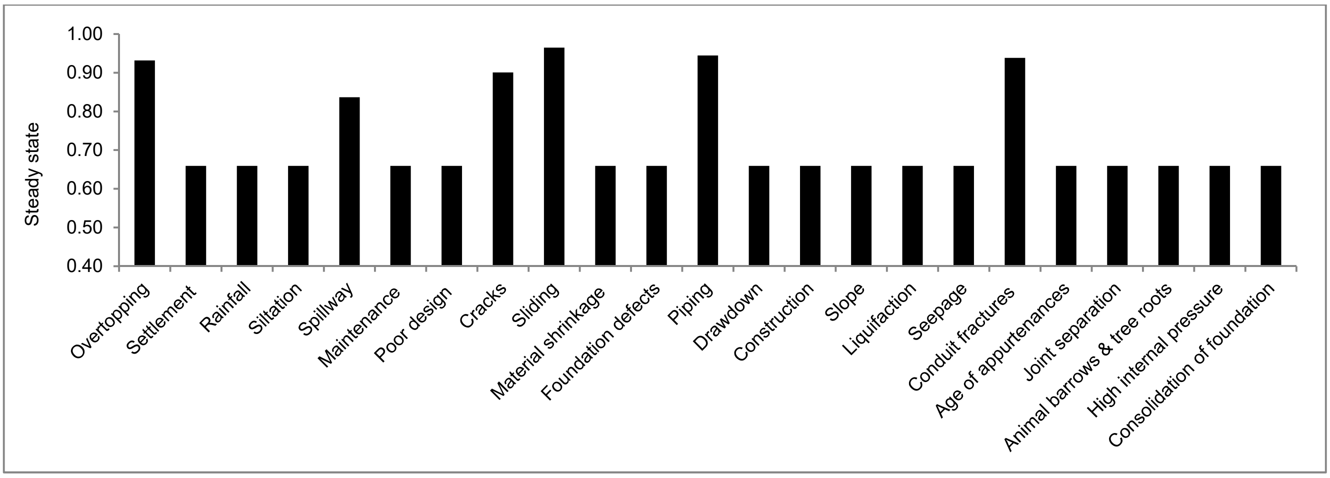

Fig. 3. Steady state values for the different small earth dam concepts; source: own study

Figure 4 shows results from two scenario analyses. In scenario 1 the steady state value of the crack concept was changed to a minimum (0). The steady state value of the settlement concept was also minimised (0) in scenario 2. Minimising cracks resulted in the decline of the piping (0.95–0.91) and sliding (0.97–0.94) concepts only. There was a slightly higher decline in cracks (0.90–0.82) in scenario 2 compared to the decline in overtopping (0.93–0.91). The higher decline can be attributed to the higher weight on the causal link between settlement and cracks. The results in Figure 4 shows the serious influence settlement and cracks have on the occurrence of overtopping, piping and sliding.

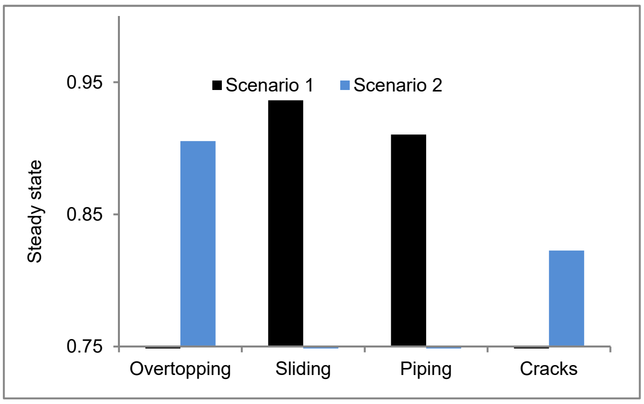

Fig. 4. Scenario analysis for small earth dam failure concepts; source: own study

Even though piping, overtopping and sliding initially had high degree centrality indices (Fig. 2), these concepts were not considered for scenario analysis. That was because the concepts (piping, overtopping and sliding) were receiver concepts. The selection of the cracks concept was because cracks are an ordinary concept that directly linked modes (piping and sliding). Settlement was selected because it links overtopping and cracks.

## CONCLUSIONS

Small earth dams are important especially for rural households and smallholder irrigated agriculture. Many of the constructed dams however, continue to fail and rather unfortunately, research into their failure is dominated by reductionist approaches that consider failure mechanisms independently. A systems thinking approach using fuzzy cognitive maps (FCMs) was used for this study conducted in Swaziland to determine the main modes and causes of small earth dam failure. The research found that overtopping (36.8%), piping (36.8%) and sliding (26.4%) were the common modes of earth dam failure. The prevalent cause of overtopping was siltation whilst the principal cause of piping was seepage. Sliding was mostly associated with sudden drawdown and faulty construction. Scenario analysis results indicated that there was a reduction in the incidence of sliding and piping with a decrease in cracks. Similarly, there was a reduction in the occurrence of overtopping and cracks with a decrease in settlement. It can be concluded from the study that most of the causes of small earth dam failures in Swaziland were linked to quality of construction material and the management of catchments and/or dams. It is therefore recommended that in the future dam design and management should improve community participation in order to sensitise communities about the effects of land use practices on dam life and management. Such designs should also include thorough seepage analysis.

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