The Causes of Dam Failures a Study of Earthen Embankment Dams on the Copperbelt Province of Zambia

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***Abstract*— The prime purpose of this paper is to summarise the study that aimed at establishing the risks and causes of dam failures associated with earthen embankments dams on the Copperbelt province of the Republic of Zambia.**

The paper's methodology consisted of identifying dams with notable failure anomalies and then assessing them through field surveys. Also utilised were satellite and computer technologies namely; Google earth, Global mapper and GIS. Secondary data was involved by usage of annual reports, dam rehabilitation reports, assessment reports and contract documents in capturing of secondary data.

The study revealed that the (43) assessed dams were subjected to a range of anomalies on the risks and cause of failures. The counts for these anomalies were presented into groupings. The first group had anomalies that were considered to be responsible for directly causing the failure of dams and this grouping was also referred to as lethal anomalies. However, in some instances these anomalies were analysed as risks of failures. The grouping lethal anomalies was generally given more attention and their listing and occurrences were as follows; overtopping at (37%) , followed by failures induced by sabotage at (26%) and then internal erosion at (21%), spillway impairments at (11%) and the least being blockage of spillway at (5%).

Second is the grouping for non-lethal anomalies and these were anomalies that were noted to have only posed as risks of failure, but were not directly responsible for failure of dams. These anomalies included; letting trees to grow on embankments and spillway areas, embankment surface erosion, extreme habitation of reservoirs by aquatic weeds and extreme siltation of reservoir.

Amongst the findings is a further probe into the aspect of failures by overtopping. This is because failure by overtopping came out to be a prominent cause of failures of dams in the study area. In this further probe it was revealed that from referral hydrological and hydraulic point of view, the majority (over 65%) of the assessed dams had undersigned spillways.

The conclusion included lack of upholding of past hydrological observation on dam designs, lack of knowledge and non-adherence to guidelines, therefore resulting into ill design practices. Poor maintenance and management was also cited.

Keywords—Dams, Dam failures, Overtopping, Internal erosion, Spillwayimpairment, Sabotage, Satelite technology

I. INTRODUCTION

Today the third world is faced with a lot of challenges with regard to designing and maintenance of infrastructure in the sectors of water resources and environmental engineering. One of the challenges faced under these sectors is that of "Dam Failures" with emphasis on those made of earthen embankments. Emphasis is placed on this type of dam owing to the fact that they are the most common types of dams in the world and reports have shown that the frequency of failure of such dams is about four times greater than that observed for concrete and masonry dams [1].

A dam failure is commonly defined as an incident of structural failure that involve unintended releases or surges of impounded water or incidents that lead to the loss of the dam [4]. In addition literature such as by [10], regards dam failure as the loss of the ability of a particular dam facility to hold water in its reservoir that might be induced by the filing of the reservoir by siltation and probably by vegetation.

In some developed parts of the world, the problem of dam failures has always been of great importance because of their economic and environmental attributes. Therefore, the problem has always given rise to a particular interest among hydraulic engineers in estimating downstream valley that are risk of inundation in instances of dam failures [6].

On the contrary in some third world countries, not much importance has been attached to issues of dam failures despites alarming evidence of such incidents. The Copperbelt

Province in the Republic of Zambia is a typical example of an area in third world region that had experienced the failure of embankment dams and yet the ideal practices in the safe guarding and management of such infrastructure are miles away from being attained. This was partly as a result of lack of data collection and analysis programmes that should have focused at establishing the prime risks and cause of dam failures. This problem is coupled by the inability to customise and domesticate the application of various engineering techniques that have been developed in other parts of the globe.

The justification for carrying out this study is that the Copperbelt Province is the commercial and industrial hub of Zambia. It is well known for its copper mining activities which at the same time drive the national economy. For that reason, dams in this particular area play a pivotal role in sustaining the Copperbelt population as they are utilised in the sectors; of fishing, crop irrigation, animal watering, and irrigation of nursery plants of forest plantation, river crossing and water supply for municipal, training and research services. Despite the pivotal role of these dams and their noted incidents of failures (see table 1), there are no proper records that points out on the fundamental causes and solutions to this problem. Hence the urgency of conducting studies such as this one.

This undertaking also includes preliminary works for developing a database of dams on the Copperbelt Province by compiling important parameters such as; their distribution, year of construction, spillway types and classes the dam fall in with regard to their embankment heights and sizes of reservoirs.

II. METHODOLOGY

The methodology comprised of the following elements:

i. Collection of data on the common risks and causes of dam failures and design features from primary and secondary sources from 43 dams i.e. dams that were noted to have exhibited anomalies on risks of failure or had encountered failure ;

ii. Primary sources included; consultation and interviews with key witnesses and relevant authorities involved in construction, repairs and management of dams

iii. Primary sources also included carrying out of field surveys in order to obtain data on dam design specifications such as Crest levels, Full Supply Levels, River bed Levels/ slopes, freeboards, spillway widths, GPS coordinates, construction materials and subsequently noting spillway types and dam heights (among others) in order to classify the dams.

iv. In addition was capturing of data using advanced earth observation techniques and parameters captured included; catchment area, embankment spans, throwbacks, contour lines and base map;

v. Secondary sources included data from existing assessments, annual, constructions and rehabilitations reports as well as dam design drawings;

vi. Historical information on construction dates and past failure events were amongst the data gathered, mainly through eye witnesses and written reports.

vii. Data collecting and analysis tools included camera, dumpy level, GPS, camera and measuring tape for physical surveys. Application of computer software programmes such as Google earth, Global mapper in generating contours, determination of catchment areas, throwbacks and embankment spans whereas GIS technology was used to develop a base map on drainage, distribution of dams and distinguishing the assessed dams from the rest;

viii. Lastly there was a probe to ascertain the adequacy of the existing spillways for all the assessed dams by computing their discharge capacities and then comparing them with the calculated hydrological parameters peak runoffs of their respective catchment areas;

ix. Statistical test were also engaged when comparing or analysising certain parameters in order to check for any possible associations among variables.

III. RESULTS

The criteria used involved assessing every notable dam that exhibited anomalies on the risks of failure and those that had encountered failures.

First and foremost is table 5.1.1 and 5.1.2 showing head counts of dams that failed and those that only encountered notable risks of failure.

Table 5.1.1 A distinction of dams that had failed from those that had risk of failure

Item	Failed	At Risk	Total
No. of dams	15	28	43
Percentages	35%	65%	100%

Table 5.1.2 A distinction of dams that had failed (plus attempted failures) from those with risk of failure

Item	Failed /attempted failure	At risk	Total
No. of dams	15 +6=21	22	43
Percentages	49%	51%	100%

Table 5.1.1 shows that out of 43 of the assessed dams 15 (35%) had failed whilst 28 (65%) were exposed to noticeable risks of failures. Note that table 5.1.2. Shows distinction of a combination of the 15 dams that failed and 6 dams that attempted to fail adding up to 21 (49%) dams from the rest of the assessed dams. Further note that the 6 dams that have been described as attempted failures consist of dams that had started failing but their failure processes were stopped by prompt interventions without which they could have failed.

A. *Specific risks and causes of dam failures*

In the quest to review and interpret specific information on the findings of the observed counts of anomalies on risks and causes of dam failures, then refer to table 5.2.

Table 5.2: Detailed inventory on risks and causes of dam failure for all of the assessed dams

S/N	Name of dam	Anomalies on risks of failures										Anomalies on causes of failures					Spillway types
		Trees	Spil imp	Ovt	Int ero	Spil block	Surero	Draw down	Sabo-tage	Silt	Aqua Weed	Ovt	Sabo-tage	Int ero	Spil imp	Spil block	
1	Mishikishi	0						0				0					Chute
2	Salvation A.	0		0										0			Culverts (Concrete)
3	MFI (1)	0	0									0					Chute
4	MFI (2)	0											0				Chute
5	Kambowa 1	0			0												Free overfall
6	Kambowa 2	0		0													Culverts (Concrete)
7	MMG	0	0														Free overfall
8	ABM	0	0														Free overfall
9	Fibale		0		0							0					Free overfall
10	GDN	0										0					Chute
11	Makango												0				Chute
12	Kalumbwa	0	0		0												Free overfall
13	St Joseph	0		0													Free overfall
14	Chati	0	0	0													Chute
15	APL 1						0										Free overfall
16	APL 2									0							Chute
17	APL 3										0						Chute
18	Kakosa	0	0														Free overfall
19	Mushishima			0													Culverts (Concrete)
20	ED	0												0	0		Free overfall
21	RV	0	0														Chute
22	Kanjili 1	0							0								Chute
23	Kanjili 2	0										0	0				Chute
24	KFH	0															Free overfall
25	St Mary's	0	0	0		0								0	0		Free overfall
26	Lamba	0	0														Chute
27	BTL1			0													Chute
28	BTL2	0										0					Chute
29	Mwekera	0	0		0												Free overfall
30	Kamfinsa	0	0		0												Free overfall
31	Minkofwa		0			0											Free overfall
32	Chilimulilo	0												0			Free overfall
33	Ibenga	0	0					0									Free overfall
34	RN	0	0	0													Free overfall
35	Dola hill	0	0														Chute
36	Mishishi	0										0				0	Free overfall
37	Dam 14	0		0									0				Chute
38	Dam 16	0				0											Culverts (Steel)
39	Dam 17	0		0									0				Chute
40	JF	0		0	0												Culverts(PVC)
41	Muf Valley						0										Drop Inlet (Shaft)
42	LKV 1	0	0	0	0												Free overfall
43	LKV 2	0		0		0											Chute
Totals		34	17	13	7	4	2	2	1	1	1	7	5	4	2	1	
Percentages		42%	21%	16%	9%	5%	2%	2%	1%	1%	1%	37%	26%	21%	11%	5%	

Abbreviations in table 5.2; *Aqua weed=Reservoirs extreme habitation by weeds, Int ero =Internal erosion, Ovt =Overtopping , Silt= Reservoirs extreme siltation, , Spil block= Spillway blockage, Spil imp= Spillway impairment, , Surero= Surface erosion,*

Legend for table 5.2

0 Anomaly for risk of dam failure
0 Anomaly for attempted dam failure
0 Anomaly for dam failure

Note that the details in table; 5.2 are further redisplayed and summarised in figure 5.2 and 5.3 for further interpretations/ analysis. The said figures separately deals with observed anomalies on risks of failure and those that caused failure respectively. In addition table 5.3 takes a direct head count of dams that were at risk and those that failed.

When interpreting figures 5.1to 5.3 note that information in table 5.2 reviewed that most of the assessed dams were subjected to more than one count of risks or causes of failure. Therefore the reason that the observed counts of the anomalies surpasses the total number of dams assessed.

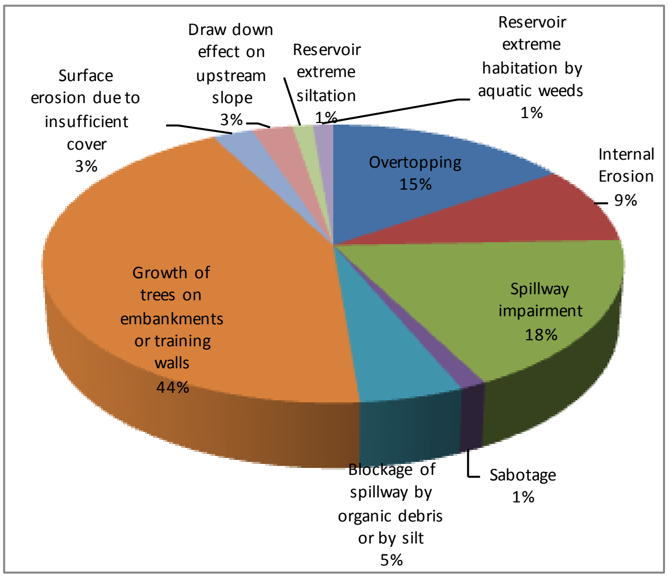


Fig 5.1**:** Observed anomalies responsible for risks of dam failures

The results in table 5.2 and its supplementary figure 5.1 shows that, the anomaly of letting trees grow on the embankment and training walls dominated with 42%. In other words, out of 43 dams, 37 exhibited this anomaly. In fact it was noted that in some instances not only did the trees grow naturally on the embankments and spillway area, but they were actually planted with the notion of reinforcing the areas in question.

Nevertheless, one point worthy taking note of in table; 5.2 is that out of all the noted counts of anomalies, the ones that are known to be lethal and of the greatest concern are those that were responsible for causing failures namely overtopping, internal erosion, spillway impairments, blockage of spillways and human acts.

As a result, by focusing on lethal anomalies it was noted that of the dams at risk; spillway impairments were the most pronounced with 21% each and seconded by overtopping with 16%. Coming third was internal erosion with 9%. Still amongst the lethal anomalies was 5% for blockage of spillway by floating organic debris and the least was Sabotage at 1%.

Other recorded anomalies (non-lethal) included Surface erosion of embankments; Draw down effect on upstream slopes, Extreme siltation and Extreme habitation of aquatic weeds. Note that the referred to, extreme habitation by weeds was to an extent that the entire reservoir was covered by a dense network of aquatic plants known as Water Hyacinth.

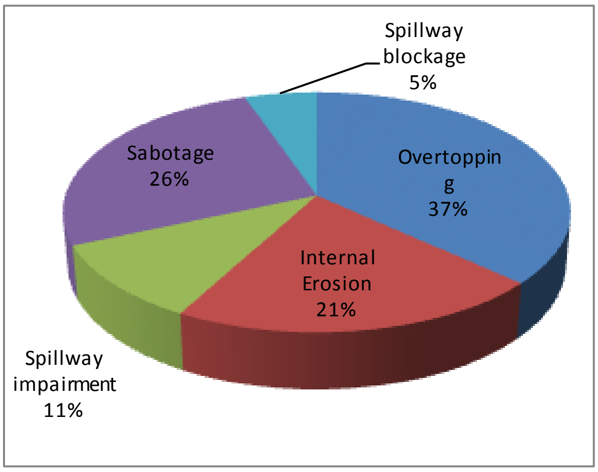


Fig5.2. Observed anomalies responsible of causing dam failures

On the other hand figure 5.2 shows the anomalies that were responsible of the failures. Overtopping was the most pronounced with 37%. This was surprisingly followed by failure due to Sabotage accounting for 26% and then internal erosion with 21%. Others recorded the lethal anomalies that had caused failures were spillway impairment with 11% and the least was Blockage by organic debris or silt with 5%.

A significant point that was drawn from figure 5.2 is that its details aligns themselves to most of the existing literature as those from [6][2][7]and [8], where it has been stated that, "Dam breaching due to overtopping has significantly claimed more embankment dams than any other cause of dam failures.

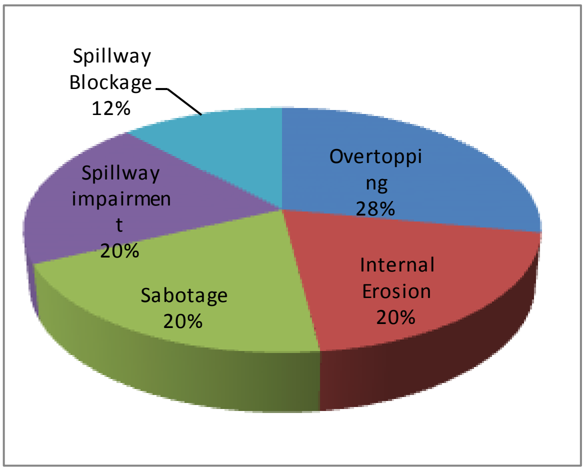


Fig5.3. Observed anomalies responsible of causing dam failures and failure attempts

In the quest to validate the prominence of failure by overtopping, a consideration was established to identify dams that encountered attempted failures and these were basically anomalies that were noted to have had the failure process initiated but the dams were rescued from failures by prompt human action. This group consisted of 6 dams and they were drawn from the 28 dams that were known to have had encountered risks. The 6 dams were then added to the list of 15 dams that had failed to add up a group of 21 dams (49%). This group was deemed as dams that failed and those that attempted failure and the group was separated from the rest as displayed in table 5.1.2.

Analysis of anomalies for the referred to group of 21 dams is displayed in figure 5.3. Which reaffirms that overtopping with (30%) still dominated then followed by equal proportions of spillway impairment with (19%) and then internal erosion with (18%), sabotage with (18%) and spillway blockage with (11%) whilst the list was growth of trees on embankment and training walls with (4%). This outcome also gave a further affirmation of a report by [8], where it has been stated that overtopping has significantly claimed more dams than any single cause of dam failure and accounts for 1/3 of recorded dam failures.

Also note inclusion of growth of trees on embankment and training walls from a group of anomalies that were earlier considered as non-lethal.

It is worth to note that the two (2) recorded counts of anomalies for spillway impairments consisted of failures that occurred along the interface (contact) area of the spillways and earthen embankments, implying that internal erosion was also at play. This combination is as reflected in failure incidents of St Marys and ED dams in table 5.2.

Also to be noted from table 5.2 are the close relationships between incidents of spillway blockages and those of overtopping in that out of a total of 5 incidents of spillway blockages, 4 of them lead to either a risk or failure by overtopping. This indicated that spillway blockages are one of the perquisites of overtopping. .

B. Backgrounds of dams and associating their ages to failure incidents

It was difficulty to point out the background information of most of the identified dams due to lack of historical data. Complete comprehensive data on the ages and methods of construction were not very practical to gather and validate, as certain dams were too old, in that some dates as far as the 1940s. Hence key witnesses to their construction and certain failure events had relocated or were bereaved. Then, some dams were on properties that had changed ownerships and this hindered the efforts of getting clear historical track records. Also most dams were not registered with the relevant authorities to have their background records displayed as per requirement.

Nonetheless, adequate background information (i.e. data on period of construction) was collected from at least 21 dams out the 43 assessed dams. The said information was then subjected to the spearman's correlation statistical test in the quest to establish the nature of correlation between the ages of the dams against the forms of failures events they had encountered as lined up in table 5.3. Based on this enlightenment the statistical test gave a spearman's rank coefficient of 0.8858 indicating strength of correlation whose degree of freedom was 21 and level of significance of less than 0.001. It can therefore be interpreted that there was a very strong correlation between the ages of dams and their vulnerability to failure.

Table 5.3 Failures status for dams with traceable ages

S/N	Name of dam	Period of construction	Failure status
1	Chilimulilo	Pre 1960s	failure
2	Dam 16	Pre 1960s	failure
3	Dam 17	Pre 1960s	failure
4	Makango	Pre 1960s	failure
5	Kambowa 1	Pre 1960s	attempt of failure
6	Dam 14	Pre 1960s	attempt of failure
7	Mwekera	Pre 1960s	attempt of failure
8	Kambowa 2	Pre 1960s	risk of failure
9	Kamfinsa	1960s	attempt of failure
10	St Mary's	1960s	failure
11	ABM	1960s	risk of failure
12	MMG	1970s	risk of failure
13	Kanjili 2	1970s	failure
14	Kanjili 1	1970s	risk of failure
15	RN	1980s	attempt of failure
16	ED	2000s	failure
17	Kalumbwa	2000s	risk of failure
18	GDN	2010s	failure
19	BTL2	2010s	failure
20	BTL1	2010s	risk of failure
21	JF	2010s	risk of failure

C. Clasification of dams and linking their failure incidents to spillway types

Classification of dams reviewed that all the assessed dams had earthen embankment dams and most of them had spillways constructed of erosion protective material namely; concrete and masonry with a few of them having features of steel and timber. The assessed dams were constructed with; Free overfall spillways, Chutes spillways or Culvert Spillways. For details on spillway types of the assessed dams, refer to table 5.2.

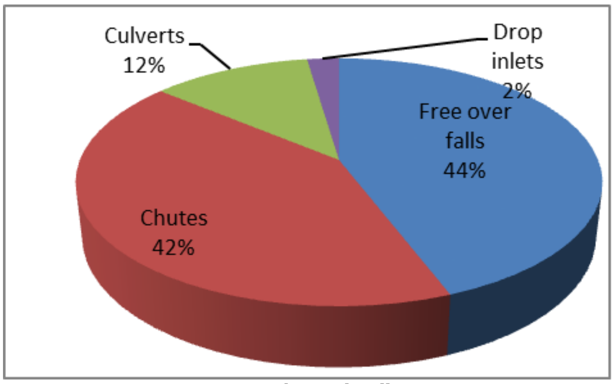


Fig 5.4. Observed spillway types

On the other hand note that the data in figure 5.4 does not seem to back literature from sources such as [3], where it is stated that Chute spillways are the most common types of spillways used on embankment dams, instead Free overfall spillways were observed to be more common at 44% and then followed chute spillways at 42%.

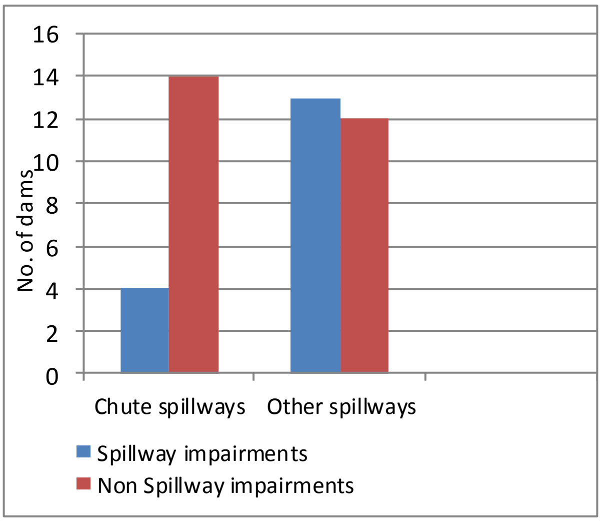


Fig 5.5 Failure resistances of chute spillways vs other spillways

Evaluation of data in figure 5.5 shows that 4 out of 14 dams with chute spillways had encountered spillway impairments whereas 13 out of 32 dams with other spillway types encountered spillway impairments. In other words only 29% of chutes spillways had impairments and 41% of other group of spillway types had impairments, indicating that chutes spillways were less vulnerable to failure.

Furthermore, this data was subjected a Chi square statistical by taking chute spillways as a control sample. However, the value (X2) calculated from the Chi square test was 3.906 indicating that chutes spillways were found to be significantly less vulnerable to failures than the other types of spillways grouped together at the level of significance of 0.05.

Classifications of dams also revealed that all the assessed dams belonged to the class for “Small dams” i.e. they all had dam walls heights that were less than 8m except for one (Muf Valley dam) which had a dam wall height that was over 14m and thus was classified as a “Large dam”.

Another line of classification that is based on reservoir size reaffirms that all the dams assessed had reservoir capacities that were below 1 000 000m3 except for Muf Valley dam which had a capacity that between 3 000 000 m^3 - 20 000 000 m^3 a range for the class of “Large dams.” For details on criteria used in this particular classification refer to table 5.3.

Table 5.3: Classification of dams based on the Capacities and Height

Size	Capacity (m^3)	Height (m)
Small	Below 1 000 000	Below 8
Medium	1 000 000 – 3 000 000	8- 15
Large	3 000 000 - 20 000 000	15- 30
Major	Above 20 000 000	Above 30

Source; [11]

Refer to figure 5.6 for a base map showing the dams that were assessed and other (identified) on the Copperbelt Province. Their general distribution is that they are concentrated in the immediate outskirts of the urban centres of the province.

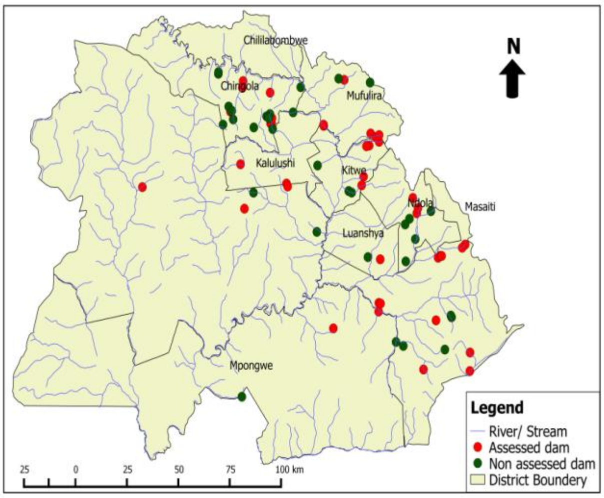


Fig 5.6 Distribution of dams on the Copperbelt Province

D. Summery of a further probe into failure of dams by overttoping

One of the fundamental outcomes of the study was that most lethal and prominent cause of dam failures was overtopping. It is in this regard that a further probe into the issue of failures by overtopping was embarked on. This was done by ascertaining the shortcomings in design features of dams that could have been responsible for the prominence of overtopping. The activities conducted in this segment of the study included establishing the capacities of spillways (i.e. by considering the spillway widths, freeboard, spillway types, and channel slopes). These features were then compared with existing hydrological parameters that are associated with every dam that was assessed under the study. The said hydrological parameters were basically the peak runoffs of the dams. The hydrological parameters for catchment areas that were established from primary data were captured using Google earth/Global mapper satellite images and then fused into existing regional models as provided for in [7]. The framework to this concept is as displayed in figure 5.7.

.Note that specific and localized peak runoff models (i.e. for Copperbelt) are yet to be established and hence the reason a regional model was applied (i.e. a model meant for Southern Africa of which Copperbelt falls under).

a) Comparison and analysis of spillway capacities with peak runoffs.

It is well underlined that the basic principle in designing of dams is to make sure that the spillway has the capacity to contain peak runoffs associated with the catchment in which a particular dam is built. It against this principle that the tabulation and analysis of information in figure 5.8 was founded upon.

Information in figure 5.8 depicts that, the majority of the dam had spillways that could not meet the basic hydrological requirement for the kind of catchment area they had been built in. Results show that under the lower bound, 65% of the dams could not meet required specifications whilst 67% and 70% were figures for mid and upper bounds respectively. Nevertheless, note that 7% of the dams in each bound had parameters that were not fully determined due to complexities in either their spillway designs or due to the fact that they operate whilst submerge.

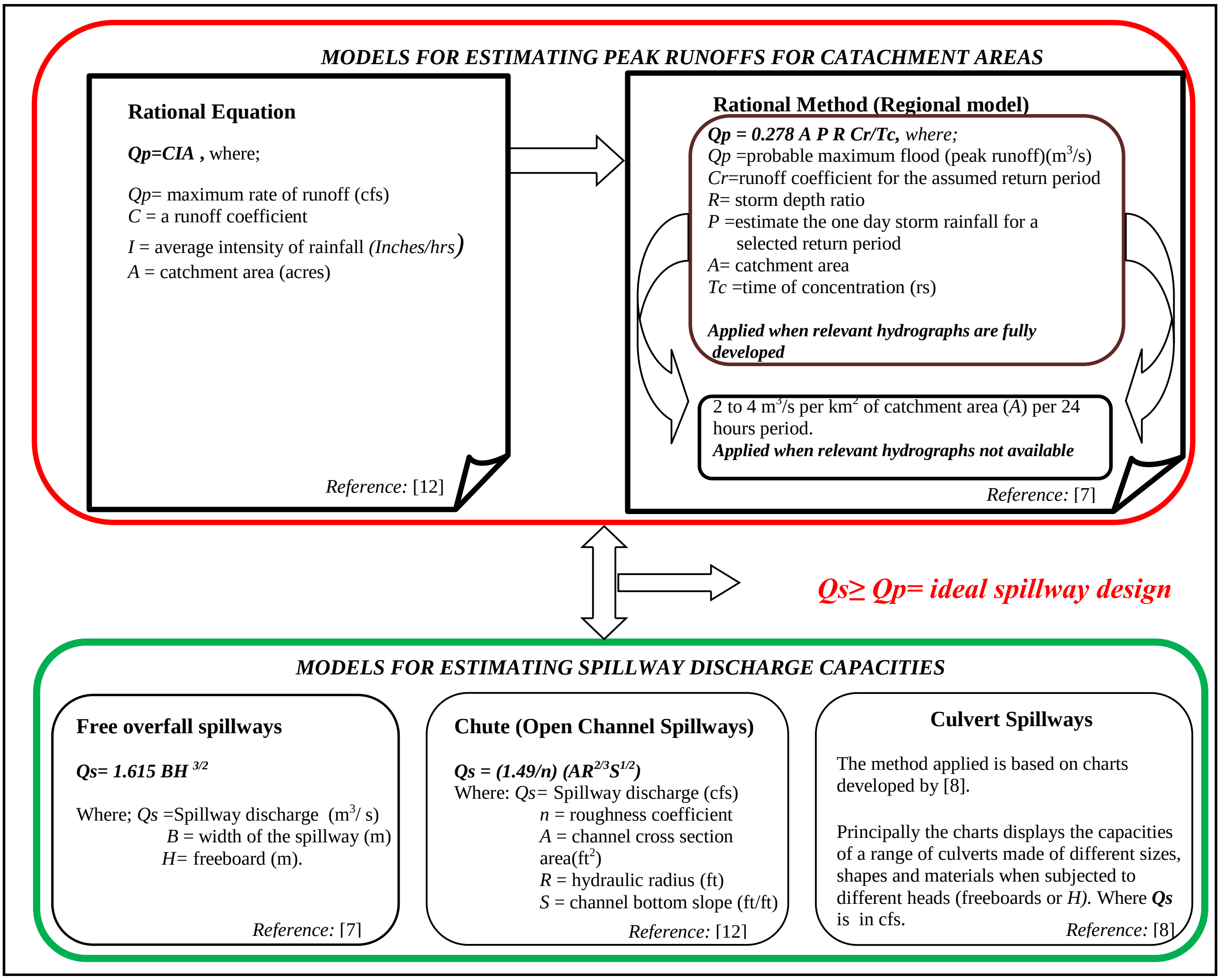
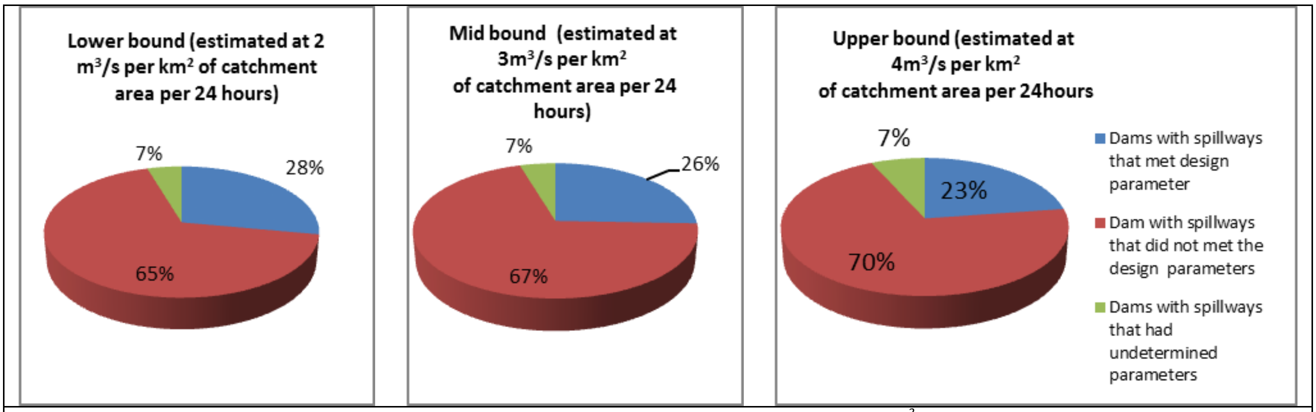


Fig 5.7: Theoretical framework for checking the adequacy of spillway discharge capacities (Qs) against peak runoffs (Qp)



According to FAO [7], the model for determining the peak runoffs has bounds ranging from 2 to 4 m^3/s per km2 of catchment area per 24 hrs. Therefore, for this reason that the runoffs were computed using separate bounds namely 2,3 and 4 m^3/s per km2 as presented by the 3 pie charts.

Fig 5.8: A comparisons of existing spillway design capacities with peak runoffs

IV. CONCLUSION

In view of aim of the study it can be concluded that the causes of dam failures included overtopping, internal erosion, sabotage, spillway impairments and blockage of spillways by silt or biological aquatic debris. The listed causes were deemed as the lethal forms of risks and causes of dam failures for the study area. Failure by overtopping exhibited prominence and then followed by equal proportions of internal erosion and sabotage.

As for the noted risks of failure, a range was recorded. These included growth of trees on embankments and spillway area, overtopping, spillway impairment, internal erosion, spillway blockages, surface erosion due to insufficient coverage by erosion resistant material on embankments, draw down effect on upstream slopes, extreme siltation and reservoir invasion by aquatic weeds.

From the study's overall point of view, failure due to overtopping came out to be more of a threat amongst the causes of dam failures more especially amongst the lethal ones as it accounted to more than a third of the incidents of failure.

A point not to be overlooked is that of letting trees to over grow on embankments and spillway. This came out as the most common anomaly though not considered as a lethal factor.

Surprisingly, spillway impairment was very prominent amongst the dams that encountered risk as it tallied above well-known phenomena of overtopping and internal erosion respectively. This implied that earthen made embankments were found to be less vulnerable than their respective spillway features that were made mostly of concrete and masonry.

One factor worth mentioning is that overtopping was more dominant among the dams that failed and spillway impairment was more dominant among dams that encountered risks. It can therefore be carefully stated that when conducting a physical assessment of dams on the Copperbelt, one would develop an impression that spillway impairment (and in most cases combined with internal erosion in the interface areas of the spillways and embankment) of being the most challenging aspect of failures and yet what actually claims most of the failure of dams is overtopping. This impression is propelled by the fact that failures by past evidences of overtopping tend to be concealed more especially if a dam had been reconstructed unlike in the cases of spillway impairment whose evidences remain visible as they remained unattended to more especially on dams that were at risk.

Another surprising outcome was failures induced by detrimental human acts in form of sabotage. These were ranked second from overtopping among the lethal of causes of dam failures outranking well known causes of failures such as internal erosion. This phenomenon was not common in most of the literature.

It was also concluded that the assessed dams had different backgrounds in that some dated as far as the 1940 whilst others were a few years old. Most of the dams that encountered failure were later on rehabilitated. It was however difficulty to gather sufficient information on the historical backgrounds of all the dams due to lack of records with the relevant authorities and dam operators. Nevertheless, adequate data on the periods of construction was obtained from at least 21 out of 43 dams and this was used validate statistically that there was a correlation between the ages of the dam and their vulnerability to failure.

The classifications of dams indicated that 42 dams were "Small dams", whereas one (1) dam was a "Large dam". It was also noted that a greater number of dams had Free overfill spillways, followed by those with Chute spillways and then those with culvert spillways, coming last was one dam with a Drop inlet spillway. This order of prominence was contrary to the most existing literature under which it has been stated that chute spillways have been known to be the most widely used among earthen embankment dams. In addition chute spillways were found to be significantly less vulnerable to causes of failures than a grouping of other spillways.

All in all the prominence of overtopping led into a further probing were it was revealed that trends of serious hydrological and hydraulic anomalies were noted with regard to the dam designs. The inconsistencies were noted to prevail among the relationship between the sizes of catchment areas and the spillway specifications.

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