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Estimation of possible Flooding Risks for Enhancement in Flood Resilience in River Valleys

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ABSTRACT

Flood is one of the major natural hazards which could cause great disaster. In order to enhance the flood resilience, the proper estimation of flood risks mainly possible loss of life is very much important. Catastrophic flooding could occur downstream of dams in case of dam failure and the possible damages i.e. loss of life & property damage could also be quite significant. The conventional flood resilient measures are not sustainable for long-term flood risk management in developed as well as in developing countries. This study emphasizes the enhancement in flood resilience based on realistic assessment of flooding risks specially in case of dam failure flooding.

As case study, the Jhelum river valley downstream of Mangla dam (329 km long) in Pakistan has been considered. Based on official data, thorough investigation has been carried out for the evaluation of possible flooding risks in the Jhelum river valley downstream of Mangla dam. The results have also been generalized for other river valleys in the world. The results of this research would be useful for the enhancement in flood resilience through risk reduction measures in river valleys downstream of dams not only in Pakistan but also in other parts of the world.

KEYWORDS
Jhelum river Valley, Flooding Risks, dam failure Flooding, Flood Resilience

INTRODUCTION

Floods are always considered to be one of the major hazards which could cause great disaster. The impact of high flooding on people and property could also be very significant. Especially possible extreme flooding due to dam failure poses extra risks to people and property in river valleys downstream of the dams. In order to minimize the flood damages on long-term basis, enhancement in existing flood resilient measures is essentially required in river valleys. For this purpose, proper and realistic assessment of possible flooding risks due to dam break flooding is needed. Dam failures are severe threats to life and property and are now being recorded and documented more thoroughly than in the past. Life and property loss statistics justify the need for dam owners to better understand the risks of failure and the hazards to the public posed by dams. Dam safety is a very essential part of reservoir management. In the past, reservoir managers have not always given adequate attention to dam safety with respect to the people living downstream. Moreover, the precise consideration of dam failure risks has not been practiced by the dam engineering profession. For many aging dams, proper risk assessment for dam collapse and damage analysis downstream of the dam due to flood wave propagation was not carried out at the time of dam planning. [6], [10], [12]

This study emphasizes the importance of flood risk assessment for the enhancement in flood resilient measures in river valleys. In this context, the possible impacts of dam break flooding in river valleys on the life of people have been focused. Risk assessment can provide valuable information on the risk reduction characteristics and potential benefits of structural and non-structural risk reduction options. Due to extreme flooding, the most severe damage is the loss of life which does not have any substitute [1], [12]. In this research, estimation of possible life loss and subsequent risks due to dam failure flooding has been done in a river valley downstream of a dam.
As a case study, the Jhelum river valley downstream of Mangla dam (329 km long) in Pakistan has been considered. Based on official data, thorough investigation has been carried out for the evaluation of possible flooding risks in the Jhelum river valley downstream of Mangla dam. The results have also been generalized for other river valleys in the world. The results of this research would be useful for the enhancement in flood resilience through risk reduction measures in river valleys downstream of dams not only in Pakistan but also in other parts of the world.

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A) Jhelum River Valley

The Jhelum river valley downstream of Mangla dam is about 329 km long up to the upstream of Trimmu barrage with various hydraulic structures. The main hydraulic structures are Jhelum bridges, Rasul barrage, Malikwal bridge and Khushab bridge (Fig. 1). There are five tributaries between Mangla dam and Rasul barrage, Suketar nallah, Bandar kas, Jabba kas, Kahan river and Bunha river (Fig. 1).

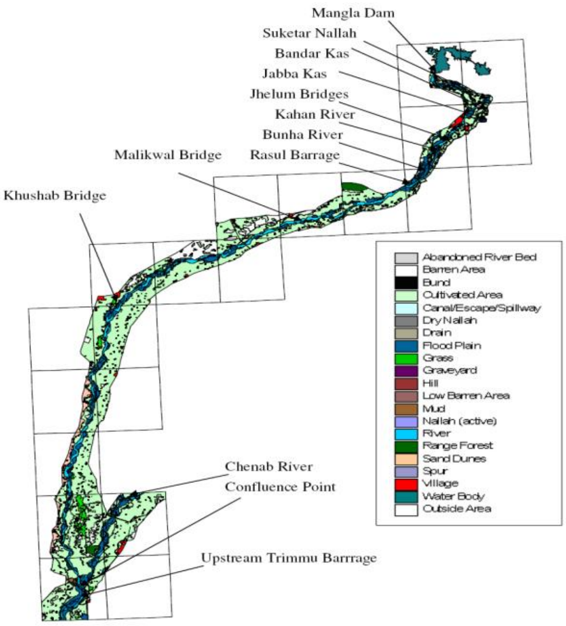

Fig. 1. Jhelum river valley downstream of Mangla dam

Moreover, Fig. 1 illustrates also the confluence point of the Jhelum river and Chenab river. Available data of the downstream valley include mainly the river cross-sections, data of hydraulic structures, location of houses along the flood plains and population data (98-census).

According to 98-census data [38], there are more than one million people at risk of flooding downstream of Mangla dam along the project reach. Most of the population along the project reach is rural and people are engaged in agriculture. The Mangla dam supplies electric power to downstream areas and also irrigates the downstream fields of agriculture. The project area also covers some urban populated areas along the Jhelum river valley like Jhelum city, Pind Dadan Khan, Malikwal, Bhera, Khushab, Jouharabad, Sahiwal etc

B) Mangla Dam

With a height of about 125 m (above riverbed) after the recent raising of about 9.15 m, Mangla dam is one of the largest earth and rock-fill dams in the world [36]. The crest length of the main dam is about 2,561 m [35]. The original catchment area of the reservoir is about 33,360 km^2 and the water surface area (at conservation level) is about 253 km^2 [34]. In this study, Mangla dam has been analyzed with raised conditions. Fig. 2 shows the top view of Mangla dam.

Fig. 2. Top view of Mangla dam (by Google earth)

MODELING IN MIKE 11

According the available GIS and other official data one dimensional modeling for unsteady flow conditions has been carried out by using the model tool MIKE 11.

There are about 82 available cross-sections for the investigated part of Jhelum river valley. The river valley is very broad and shallow with a gentle longitudinal average slope of about 0.0004. For all modeling scenarios, the upstream and downstream boundary conditions are an outflow hydrograph at Mangla dam and respectively the water levels upstream of Trimmu barrage as shown in Fig. 1. According to data availability different hydraulic structures have been defined at the respective downstream locations. Moreover, the contributions of five tributaries between Mangla dam and Rasul barrage have also been added as inflow boundaries.

For calibration of the model, the 1997 flood (peak Q downstream of Mangla dam: 12,798 m^3/s) in the Jhelum river has been taken into consideration. While the model has been validated with the past highest flood of 1992 (peak Q downstream of Mangla dam: 26,293 m^3/s).

A) Theory of Flood Routing in MIKE 11

For unsteady flow simulations the computations depend on hydrodynamic flow conditions. One dimensional flood routing in MIKE 11 is based on an implicit finite difference scheme developed by [2]. MIKE 11 is capable of using kinematic, diffusive or dynamic and vertically integrated equations of conservation of continuity and momentum (the 'de Saint Venant' equations), as required by the user. The basic equations are derived considering the conservation of mass and conservation of momentum. The resulting equations are mentioned as (Eq. 1) and (Eq. 2) [24].

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \qquad (1)$$

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$$\frac{\partial Q}{\partial t}+\frac{\partial\left[\alpha\frac{Q^2}{A}\right]}{\partial x}+gA\frac{\partial h}{\partial x}+\frac{gQ|Q|}{C^2AR}=0 \qquad (2)$$

Where
Q = discharge (m^3/s)
A = flow area (m^2)
q = lateral inflow (m^3/s)
h = stage above datum (m)
C = chezy resistance coefficient ($m^{1/2}/s$)
R = hydraulic or resistance radius (m)
α = momentum distribution coefficient

The transformation of the de Saint Venant equations to a set of implicit finite difference equations is performed in a computational grid consisting of alternating '*Q*- points and *h*-points', points where the discharge (*Q*) and water level (*h*) are computed at each time step as shown in Fig. 3.

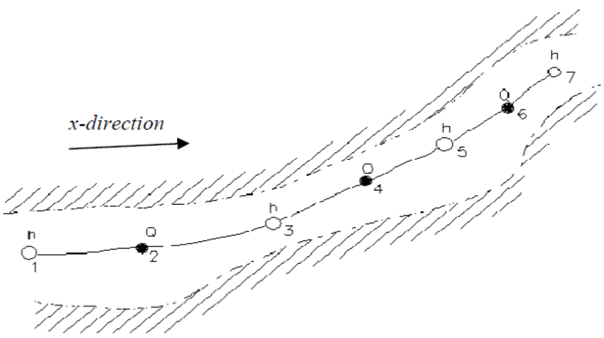

Fig. 3. Channel section with computational grid [24]

The computational grid is generated automatically by the model on the basis of the user requirements. The *Q*-points are always placed midway between neighboring *h*-points, while the distance between *h*-points may differ. As a rule, the discharge will be defined as positive in the positive *x*-direction (increasing chainage). The adopted numerical scheme is a 6-point Abbott-scheme which is an implicit finite difference scheme.

B) Dam Break Flood Routing

An erosion based overtopping failure has been analyzed by using MIKE 11 dam break module. The time to failure is related to the full development of the breach with respect to erosion after the initiation of dam failure. The breach parameters for different breach cases have been estimated by using various available relations based on case studies [11], [16], [17], [18], [20], [27], [28], [29], [30], [31]. The estimated breach heights for breach cases are about; 41 m, 62 m and 84 m.

In MIKE 11, an erosion based breach development is modeled only by using the energy equation. The initial and the final breach shape must be specified. During the development of the breach the trapezoid increases in size and changes the shape to a linear way as shown in Fig. 4. [24]

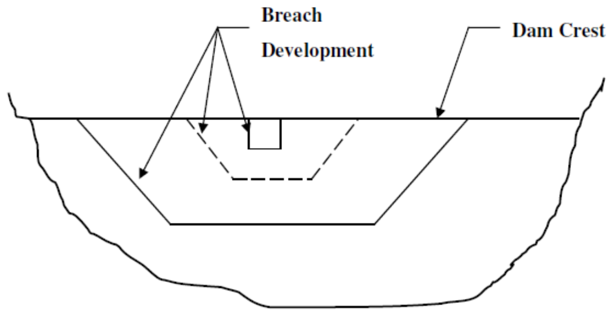

Fig. 4. Linear development of the breach [24]

In large reservoirs, the peak discharge occurs when the breach reaches its maximum depth and width [32], [33], [37].

According to the breach parameters for different cases and dam break setup, simulations were run for three failure cases in order to determine the outflow hydrographs after failure. Fig. 5 shows the computed outflow hydrograph for dam failure cases. The maximum outflow for the worst case of failure is more than 300,000 m^3/s which could be the highest possible discharge after the failure of Mangla dam [14].

For dam break flood routing, the computed failure outflow hydrographs (Fig. 5) have been considered for the unsteady flow simulations.

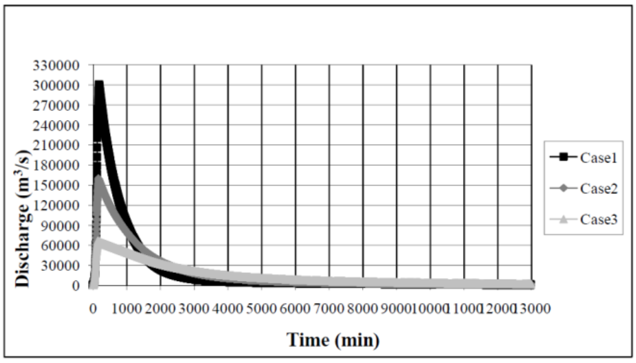

Fig. 5. Outflow hydrograph from dam break simulations

Depending on the available data, the maximum contribution of tributaries was considered for all scenarios. The necessary extrapolation of the cross-sections with respect to increase of the water levels was also done for different flooding scenarios. The results of maximum discharge after dam break flood routing are shown in Fig. 6.

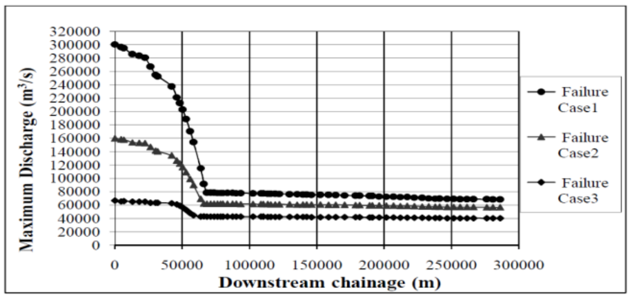

Fig. 6. Maximum discharges in Jhelum river valley after dam break flood routing

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In all scenarios the maximum discharge decreases along the reach due to retention of upstream hydrograph with respect to the shape of cross-sections. The random increase in the discharge in the upstream part of the reach is due to the contribution of the tributaries at different locations.
The results of maximum water levels after dam break flood routing downstream of Mangla dam are shown in Fig. 7.

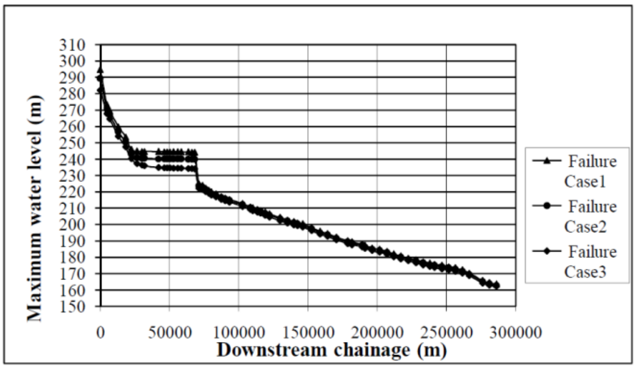

Fig. 7. Maximum water levels in Jhelum river valley after dam break flood routing

In all cases, the water levels upstream of Rasul barrage (located at chainage: 69540 m) are higher than the water levels downstream of Rasul barrage due to possible impoundment upstream of Rasul barrage.

EVALUATION OF FLOODING RISKS

Due to extreme flooding, loss of life (*LOL*) is the most severe damage which does not have any substitute. In this study the estimation of possible loss of life has been done by using an improved and elaborate method developed by the main author [12]. The suggested *LOL* estimation method has been developed by considering thoroughly the weaknesses and useful ideas in different available methods. The generalized form of the method is as follows by (Eq. 3): [12]

$$LOL_i = PAR_i \times FAT_{BASE} \times F_{sv} \times F_{age} \times F_{mt} \times F_{st} \times F_h \times F_{war} \times F_{ev} \quad (3)$$

Where

LOL_i = Loss of life at a particular location ´´i`` downstream of the dam

PAR_i = Population at risk at a particular location ´´i`` downstream of the dam

FAT_{BASE} = Base Fatality rate of 0.15 from [19] for the worst case of medium severity. An average value of 1.0 for all other factors with average conditions is assumed. The other factors could differ from 1.0 depending on the specific available information. These factors have been defined after a qualitative plausibility analysis according to the related information available in the literature [12]. Further details of this method can be found in [12].

F_{sv} : Flood severity factor based on flood severity indication

F_{age} : Age risk factor depending on different age groups in PAR

F_{mt} : Material risk factor

F_{st} : Storey risk factor

F_h : Health risk factor

F_{war} : Warning factor depending on the initiation of warning and flood travel time

F_{ev}: Ease of evacuation factor

According to the available census data (1998) and maps [38], population at risk (*PAR*) has been estimated at the locations downstream of Mangla dam. Depending on the extent of flooding and available location of houses on the GIS map, the estimated *PAR* has been approximately related to the 92- flood (peak Q: 26,293 m^3/s) [12]. The estimated *PAR* is about 1178,038 including 63% rural and 37% urban [38]. No extra information about the location of houses in the flood plains is available for more extreme flooding scenarios. Obviously the population at risk (*PAR*) will be more for higher flooding scenarios.

For scenarios of higher flooding like dam failure flooding, *PAR* has been increased quantitatively at each downstream location with respect to the increase in flooded area. All other factors for *LOL* computation due to dam failure have been estimated by following the procedure suggested by the *LOL* estimation method.

A) Risk Determination

The residual risks downstream of Mangla dam have been determined for different dam failure cases. By definition, risk is the combination of the probability of occurrence and possible consequences (damages). It can be categorized in two ways [3], [4], [5], [9], [21], [23]:

- Individual risk
- Societal risk

A,A) Individual Risk

Individual risk is the frequency at which an individual may be expected to sustain a given level of harm (loss of life in this case) from the occurrence of specific hazards. It is computed by averaging the probable risk of life loss over the population at risk (*PAR*) in a particular area due to a specific event. The annual individual risk can be calculated by (Eq. 4) [3], [21], [23].

Individual risk/year = (Total *LOL*/Total *PAR*)* Annual probability of occurrence (4)

In this case, the individual risk per year has been computed for different dam failure cases with respect to the overall annual failure probability of *2.63 E-3* [12] and estimated *LOL* for different failure cases considering the worst case of warning initiation of 30 minutes after the failure. Fig. 8 shows the computed individual risk per year for the considered failure cases of Mangla dam.

According to the recent guidelines of Australian National *Committee on Large Dams (ANCOLD) the limit of* individual tolerable risk for existing dams is 1 in 10,000/year (ANCOLD) [3], [9]. ANCOLD guidelines consider the ALARP principle (as low as reasonably practicable) which emphasizes the further reduction of residual risks [7], [8].

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As shown in Fig. 8, the individual risk per year for the worst case of dam failure is exceeding the maximum limit of ANCOLD and it can be considered to be intolerable or unacceptable for Mangla dam. For the other two cases of dam failure the annual individual risk is tolerable as it is within the limits (1.0 E-4).

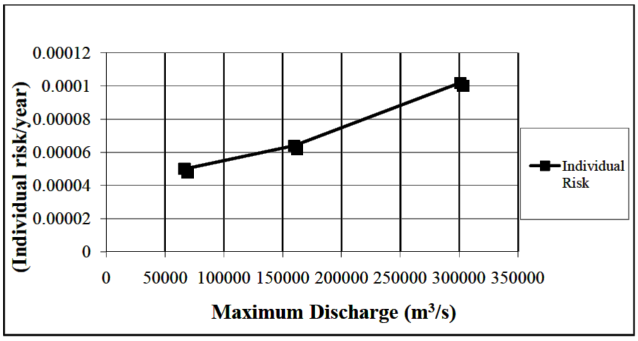

Fig. 8. Individual risk for different dam failure cases

A,B) Societal Risk

Societal risk is the relationship between the failure probability and the number of people suffering from a given level of harm (loss of life) in a given population due to specific hazards. It is determined by the F-N chart, where F is the cumulative frequency of events per year (failure probability of dam) and N is the number of fatalities due to dam failure [3], [9], [21].

In this research, the overall failure probability of Mangla dam (*2.63 E-3*) [12] has been considered for the determination of the societal risk by the F-N chart. Fig. 9 shows the F-N chart for societal risk according to recent guidelines of societal tolerable risk by [3] for existing dams.

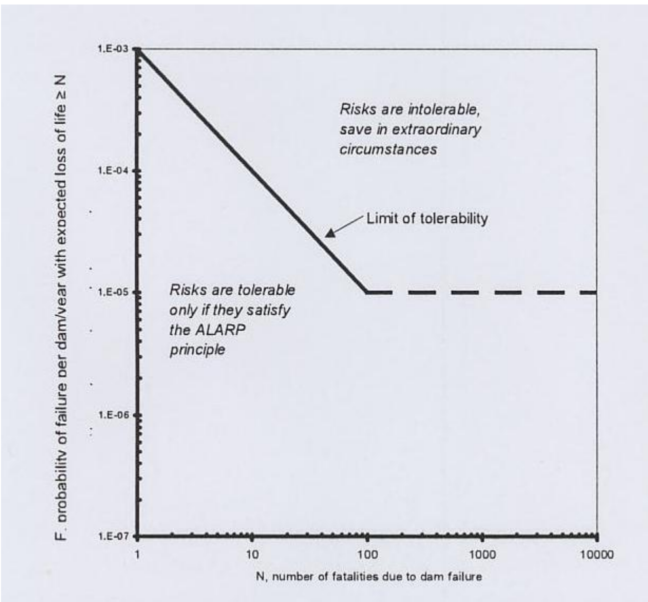

Fig. 9. Societal risk guideline for existing dams [3]

The dark black line shows the limit of tolerability. Risks are tolerable only if they satisfy the ALARP principle, 'reducing risks as low as reasonably practicable' (ALARP). ALARP is the main consideration in fulfilling the requirements for tolerability of risks under common law legal systems [7], [8], [9].

The overall failure probability is beyond the probability limit given in F-N chart. Moreover, the total loss of life (number of fatalities) in all dam failure cases is also very high [12], [13]. Actually the dam was built with the safe design principles available in the past in order to fulfill the risk safety requirements in future. But now due to more advancement in research, the risk safety standards have become more severe for dams with respect to extreme events. According to the current standards, the societal risk for Mangla dam is not in the acceptable limits due to high probability of failure and loss of life in all failure cases. It is strongly recommended that the existing flood resilient measures for Mangla dam should be improved and new measures should also be introduced to minimize the possible residual risks (individual and societal) due to dam failure.

GENERALIZATION OF RESULTS

For different valley shapes downstream of the dams, the loss of life due to dam failure flooding will be different. In order to generalize the flooding risks estimated for Jhelum river valley for other river valleys in the world, the impact of downstream valley shapes on loss of life and associated risks has been analyzed. For this purpose, different changes in the valley shape downstream of Mangla dam have been suggested.

A) Suggested Changes in the Valley Shape

Following changes in Jhelum river valley have been suggested for the sake of generalizing hydrodynamics and *LOL*-results for other valley shapes downstream of the dams.

- Changes in valley slope
- Changes in valley width

Both parameters are very important in a river valley. They influence the flooding quite significantly.

A,A) Suggested Changes in Valley Slope

The Jhelum river valley is very broad and shallow with a mean slope of 0.0004. According to Fig. 10, this mean slope comes into the category of 'regime' with slope<0.001 [22]. For such very broad and shallow rivers, valley is usually not so steep.

In order to analyze the effect of valley slope on possible loss of life due to extreme flooding downstream of the dam, different valley shapes have been produced with the following suggested valley slopes. These valley slopes have been maintained the same through the whole reach (between the consecutive cross-sections) for different valley shapes.

Investigated Valley Slopes: *0.0004, 0.0007, 0.0009, 0.001, 0.0015*

Different slope values have been considered up to 0.001 starting from the mean value of 0.0004. Additionally, a higher slope of 0.0015 has also been considered in order to

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have an example of the pool-riffle category (0.02<S>0.001) as in Fig. 10. All other parameters have been kept the same for these valley shapes.

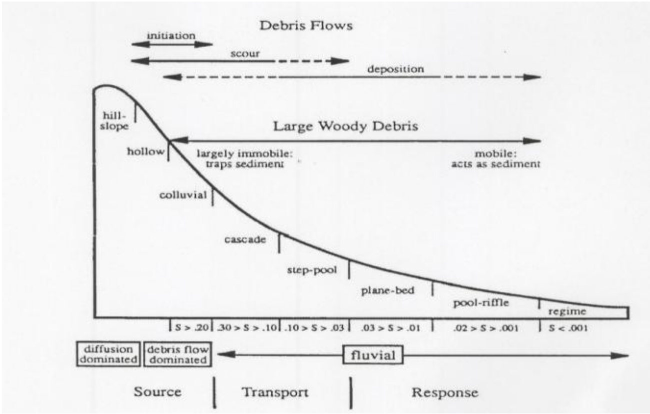

Fig. 10. Idealized stream showing the general distribution of channel types [22]

A,B) Suggested Changes in Valley Width

Different changes in the width of valley have been suggested. The changes in valley width have been considered in terms of entrenchment ratio.

By definition, the entrenchment ratio is the ratio of the width of flood-prone area to bank full surface width of the channel. The flood prone width is defined as the width measured at an elevation that is twice the maximum bank full water depth. This flood prone elevation has also been related to a frequent flood (50 years or less return period) by field observations [25], [26]. The computation of entrenchment ratio is illustrated in Fig. 11.

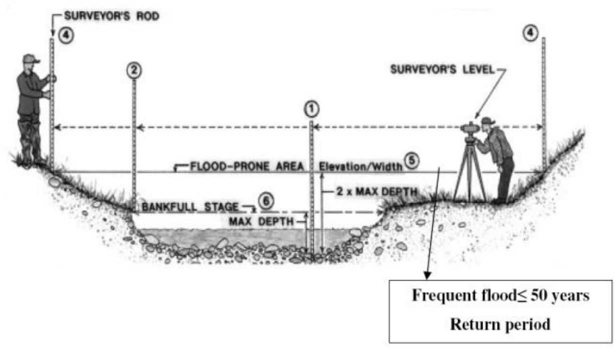

Fig. 11: Computation of entrenchment ratio [26]

In this study, the available definition of flood prone elevation with respect to a frequent flood (50 years or less return period) has been considered for computation of entrenchment ratio. The highest flood in the past (92-flood) in Jhelum river downstream of Mangla dam had return period of 35 years [12] and it was a rare event. So depending on available data, different valley shapes have been produced with the following suggested entrenchment ratios using the computed results of 97-flood of 8 years return period in order to analyze their impact on possible loss of life due to severe flooding.

Investigated Valley Widths (entrenchment ratios): *1.4*, *1.8*, *2.2*, *2.6*

For different valley shapes the entrenchment ratios have been kept the same for all downstream cross-sections. The bank full width has not been changed. Only the flood prone width of cross-sections has been changed accordingly to have respective entrenchment ratios for different valley shapes.

B) Loss of Life Estimation For Different Valley Shapes

Loss of life (*LOL*) has been estimated by using the flood routing results of different flooding scenarios with different changes in the downstream valley shape. In all cases of *LOL* estimation the worst case of warning initiation (30 minutes after failure) has been considered. In the following sections, the results of *LOL* estimation have been discussed for different scenarios of valley shapes.

B,A) LOL Results for Different Valley Slopes

LOL estimation has been done for suggested valley slopes by using the results of dam break flood routing. The population at risk (*PAR*) has estimated with respect to the flooded areas for different flooding scenarios of valley slopes. Fig. 12 shows the total *PAR* downstream of Mangla dam for different valley slopes. It is obvious that *PAR* decreases with the increase in valley slope. This is due to the decrease in the area of influence downstream of the dam.

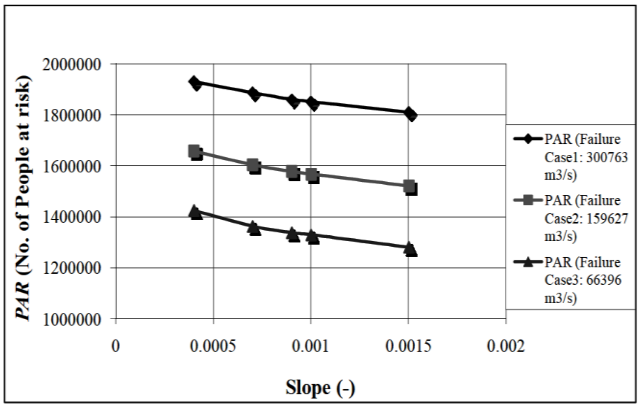

Fig. 12. People at Risk due to dam break flooding for different valley slopes

The percentage of total loss of life in Jhelum river valley due to dam break flooding has been computed with respect to the total *PAR* for different scenarios of valley slopes as shown in Fig. 13.

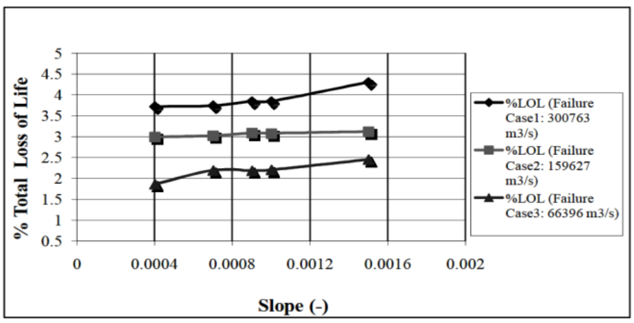

Fig.13. Impact of valley slopes on % Total Loss of Life

The percentage of total loss of life increases with the increase in valley slope and vice versa. In other words, the steeper the valley the higher the percentage of possible loss of life. The maximum value is about 4.3% for the failure case1 with the slope of 0.0015. This increase in percentage of total *LOL* is due to the increase in overall flood severity and decrease in warning time (reduction in flood travel time due to fast flooding) with the increase in downstream valley slope.

B,B) LOL Results for Different Valley Widths

Loss of life estimation has been done for different scenarios of the suggested valley widths (in terms of entrenchment ratio) by using the results of dam break flood routing.

Fig. 14 shows the computed *PAR* for different flooding scenarios with the suggested entrenchment ratios.

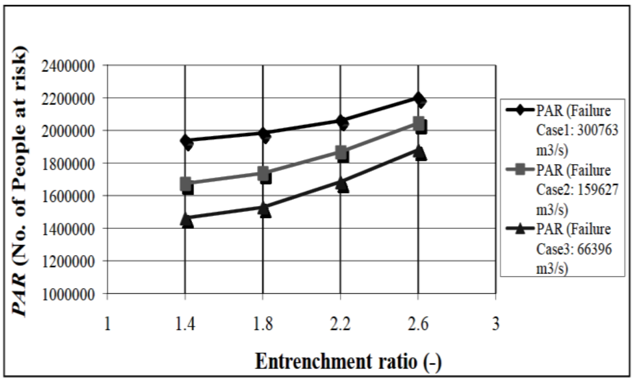

Fig. 14. People at Risk due to dam break flooding for different valley widths (entrenchment ratio)

The number of people at risk (*PAR*) increases with the increase in the entrenchment ratio. This is due to increase in the area of influence (flooded area) with the increase in valley width (entrenchment ratio). In order to analyze the impact of valley width on loss of life, the percentage of total loss of life for different scenarios has been computed as shown in Fig. 15.

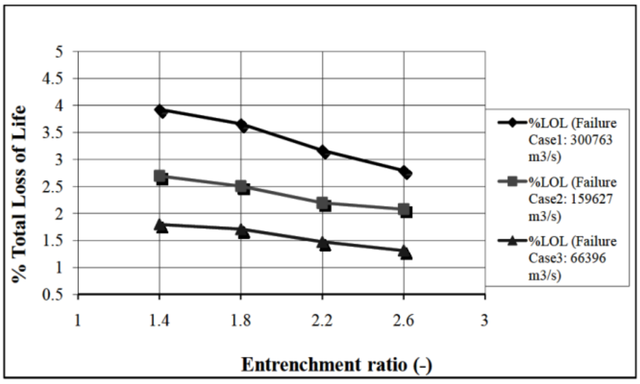

Fig. 15. Impact of valley widths on %Total Loss of Life

The percentage of total loss of life decreases with the increase in the entrenchment ratio of the valley and vice versa. The broader the valley the lower the percentage of loss of life. The maximum percentage of total loss of life is close to 4% for the failure case1 having an entrenchment ratio of 1.4 (most confined). The decrease in percentage of total LOL with the increase in valley width (entrenchment ratio) is because of the decrease in overall flood severity and increase in warning time (increase in flood travel time).

C) Risk Determination for Different Valley Shapes

The residual risks have also been determined for different scenarios of valley shapes by using the results of possible loss of life due to dam break flooding. The estimated overall failure probability of Mangla dam (*2.63 E-3*) [12] has been considered for the computation of individual risk.

C,A) Individual Risk for Different Valley Slopes

By using the *LOL* results of different scenarios with dam failure, the annual individual risk has been calculated as shown in Fig. 16.

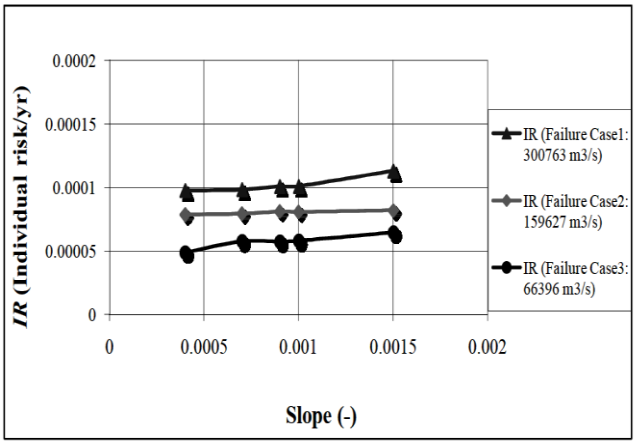

Fig. 16. Impact of valley slopes on individual risk

It is quite clear from the results that the individual risk per year increases with the increase in valley slope. For the worst case of dam failure with valley slopes up to 0.001, the individual risk per year is very close to the tolerable limit of 1.0 E-4 by [3], [9]. Moreover, for the slope of 0.0015 (steepest considered) in the worst case of dam failure, the individual risk crosses the ANCOLD limit. Collectively, it can be said that the steeper the valley the higher the individual risk and vice versa. This increase in individual risk per year is due to the increase in overall flood severity and decrease in warning time (reduction in flood travel time due to fast flooding) with the increase in downstream valley slope.

C,B) Individual Risk for Different Valley Widths

In order to analyze the impact of changes in valley width on individual risk, the individual risk per year has been computed for different scenarios of valley widths (entrenchment ratio). Different flooding scenarios with dam failure have been considered. Fig. 17 shows the individual risk per year for different dam break flooding scenarios with different valley widths.

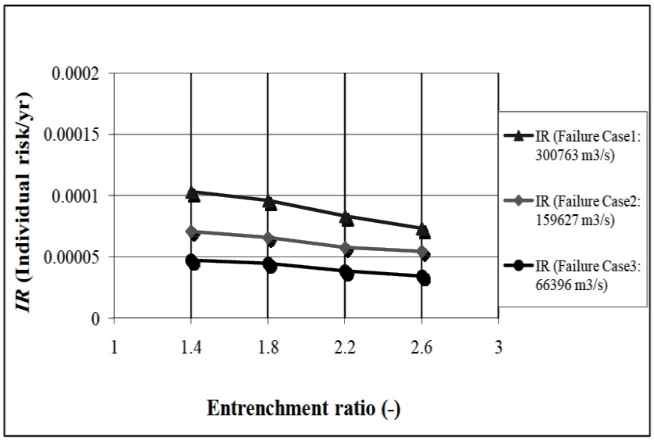

Fig. 17. Impact of valley widths on individual risk

The individual risk decreases with the increase in valley width (in terms of entrenchment ratio). In the worst case of dam failure, the individual risk is equal to the tolerable limit of 1.0 E-4 given by [3] for the entrenchment ratio of 1.4 (most confined). The broader the valley the lower the individual risk and vice versa. The decrease in individual risk with the increase in valley width (entrenchment ratio) is because of the decrease in overall flood severity and increase in warning time (increase in flood travel time).

C,C) Societal Risk for Different Valley Shapes

For dam failure cases, the societal risk has been analyzed with respect to the overall failure probability of Mangla dam (*2.63 E-3*) [12] and respective loss of life in different scenarios of changes in valley shape. The estimated loss of life in all flooding scenarios of suggested changes in valley shape is quite higher than 10,000 [3], [9], [21].

The overall failure probability is also very high and it is out of the range of F-N chart (Fig. 9) [3], [9]. So for dam failure cases with different changes in valley shape (slope and width), the societal risk can be considered to be impermissible. It can be concluded that the societal risk downstream of very big dams like Mangla dam with different valley shapes remains unacceptable for different dam break flooding scenarios. It strongly justifies the need of improving the existing structural and non-structural risk reduction measures and also planning new useful measures in order to minimize the residual risks downstream of big dams.

CONCLUSIONS & RECOMMENDATIONS

This study describes an updated procedure for the estimation of possible loss of life and subsequent residual risks downstream of dams due to catastrophic dam failure flooding. The proper evaluation of flooding risks is very important for enhancement in flood resilient measures in river valleys in order to minimize the possible damages mainly loss of life. The flood damages in river valleys could be more severe in case of failure of big dams like Mangla dam because of large water storage.

The individual and societal risks for Mangla dam have been determined using the estimates of possible loss of life in Jhelum river valley due to dam failure flooding. Individual risk for the worst case of dam failure is higher than the limit of individual tolerable risk (1 in 10,000) for existing dams as suggested by ANCOLD. Further, the societal risk for all dam failure scenarios is also unacceptable according to F-N chart by ANCOLD (detail in section 3). The results have been generalized for other river valleys in the world with respect to the valley slope and valley width.

The individual risk increases with the increase in valley slope and it decreases with the increase in valley width. The individual risk exceeds the tolerable limit of 1.0 E-4 by ANCOLD in the worst case of dam failure for the steepest considered slope of 0.0015. The individual risk is almost equal to the tolerable limit of 1.0 E-4 by ANCOLD in the worst case of dam failure for the most confined case of valley width with the entrenchment ratio of 1.4.

The societal risk for different dam failure flooding scenarios with different valley shapes also remains unacceptable according to F-N chart by ANCOLD.

The estimated residual risks downstream of Mangla dam in case of possible dam failure would be useful for the enhancement in flood resilience in the Jhelum river valley by improving the existing risk reduction measures (structural and non-structural).

Structural measures include repair of existing levees and dykes, construction of new levees and dykes and dam raising or possible reduction in maximum operating level of the reservoir (if required to avoid possible overtopping) etc. The non-structural measures could be e.g. improvement and introduction of new techniques in warning efficiency, emergency evacuation and safe operating procedures. The people living near the flood plains should also be relocated to safe places. Moreover, the awareness in people at risk about the possible flood severity should also be enhanced.

The evaluation of possible residual risks due to dam failure for different river valley shapes provides very useful guidelines for concerned authorities to plan and implement the suitable risk reduction measures with respect to the particular river valley shape downstream of dams.

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