



Seepage assessment of Hattian Bala landslide dam using hydrological data

Fawad S. Niazi

Graduate Research Assistant, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA

Tayyeb Akram

Dean, National Institute of Transportation (National University of Sciences and Technology), Islamabad, Pakistan

Sajjad Haider

Faculty Member, National Institute of Transportation (National University of Sciences and Technology), Islamabad, Pakistan

ABSTRACT

On Oct. 8, 2005, debris from an earthquake triggered landslide blocked two tributaries of Jhelum River at their confluence, near Muzaffarabad, Azad Kashmir, creating two lakes. Spillways construction reduced the volume of water in the smaller lake. However, the larger lake kept filling till Apr. 2007, when its surface elevation reached the spillway level. Inundation upstream of this natural dam can cause substantial downstream damage in case of failure. This paper presents the results of a study aimed at evaluating the inflow of water into the dam body through seepage from the larger lake by utilizing hydrological data. Desired results could not be obtained due to data inadequacies; yet, a practical method was developed which can be applied to the study of similar cases.

RÉSUMÉ

Le séisme du 8 octobre 2005 au nord de Muzaffarabad, Azad Kashmir a provoqué de nombreux glissements de terrain, bloquant ainsi deux affluents de la rivière Jhelum. Suite à cet événement, deux réservoirs ont été artificiellement créés. Des évacuateurs de crue ont été construits afin de réduire le volume d'eau dans le plus petit réservoir. Cependant, le second réservoir a continué à se remplir jusqu'en avril 2007. Une brèche dans le barrage pourrait occasionner d'importants dégâts en aval. Cet article présente les résultats d'une étude hydrologique visant à évaluer l'infiltration d'eau à travers barrage. Même si des inexactitudes sur les données expérimentales n'ont pas permis d'obtenir les résultats désirés, une méthode pratique a été développée, afin de l'utiliser sur des cas semblables.

1 INTRODUCTION

Landslide dams are complex geomorphologic features which occur frequently in hilly areas and cause stream impoundments. Although they form rapidly, their life span is generally limited. This temporal disruption of channels by landslide dams can pose substantial hazard. Accounts of catastrophic outburst floods from naturally dammed reservoirs causing loss of lives, housing and infrastructure have been given from many regions of the world (Korup 2002). Generally, such dams break within the first year or stabilize with time (Schneider 2006). According to Schuster (1993), 55% of 187 investigated examples worldwide failed within one week of their formation, whereas, 89% failed after one year.

The factors controlling failure of landslide dams are known to be overtopping, breaching, slope failure and seepage. Possibility of failure through seepage induced piping/internal erosion and high confined pore pressures in foundations appears to be the most probable phenomena owing to the heterogeneous nature of the material composing most of the landslide dams (Korup 2002 and Engemoen 2000). The study of the seepage process through an earth dam, thus, provides a basis for understanding the erosion process that can possibly take place in case of landslide dams.

Hattian Bala Landslide Dam is one example of such cases from the recent times. On Oct. 8, 2005, a M7.6

earthquake triggered innumerable landslides in the affected hilly areas including a major landslide near Hattian Bala Town, Muzaffarabad, Azad Kashmir. With a debris volume of around 85 million m³, it blocked two tributaries of the Jhelum River at their confluence, namely Karli and Tang water channels, resulting into two lakes (see Figures 1 and 2). Debris from this landslide moved downhill at very high velocity and completely wiped off Laudiabad village burying hundreds of people along with their houses and belongings. Besides the geologic materials, it also brought with it and masked the vegetation growth that existed on the original ridge/slope. As observed during the site visits and comparison of the pre- and post-event topographic maps of the area, it can be conjectured that major portion of the debris accumulated in Karli channel and rushed up the intervening ridge between the Karli and Tang channels. Due to the high momentum and enormous volume of the debris material, it did not stop at the intervening ridge, but also spilled over into the Tang channel. As observed at the site, the debris blocking the Tang channel as well as its portion at toe of the dam are mainly composed of coarse-grained material (including boulders) with a relatively low proportion of fines.

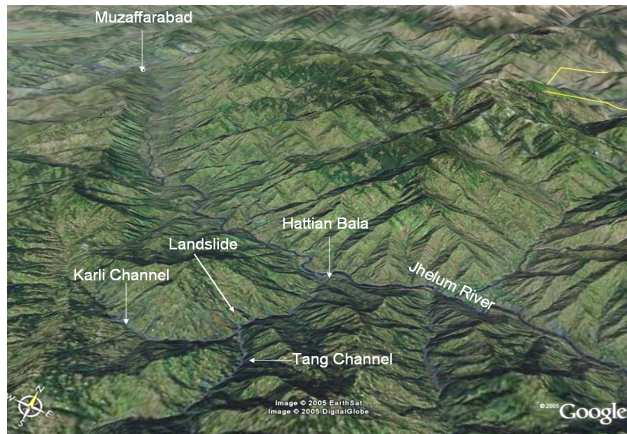


Figure 1. 3-D view of Hattian Bala landslide area (Google Earth 2005)

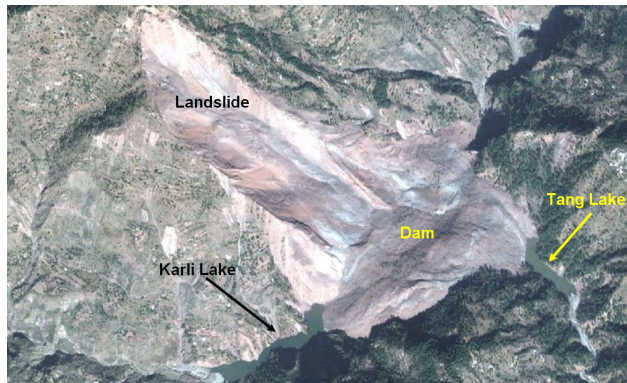


Figure 2. Satellite imagery of Hattian Bala landslide and dam (Denlinger and O'Connell 2006)

To assess the possibility of downstream damage due to failure of this natural embankment/dam, several studies were undertaken and the evolution of the situation was controlled by various national and international agencies. Preventive measures were also undertaken in the form of construction of spillways (see Figures 3, 4 and 5) along the lowest crest elevations on the natural embankment for both the lakes (following approximately the pre-event alignment). Subsequently, the potential hazard of Tang Lake significantly reduced, owing to the washing out of fines and the subsequent steady state seepage conditions, thereby reducing its volume. As far as Karli Lake is concerned, the water surface elevation kept rising continuously till Apr. 2007, when it reached its capacity by impounding about 50 million m^3 of water (NESPAC and GSP 2006) and started overtopping through the spillway (see Figure 5). The filling curve of Karli Lake is shown in Figure 6. The inundation associated with the Karli channel landslide dam failure still endangers a substantial downstream population, particularly the population located in the vicinity of Hattian Bala Town.

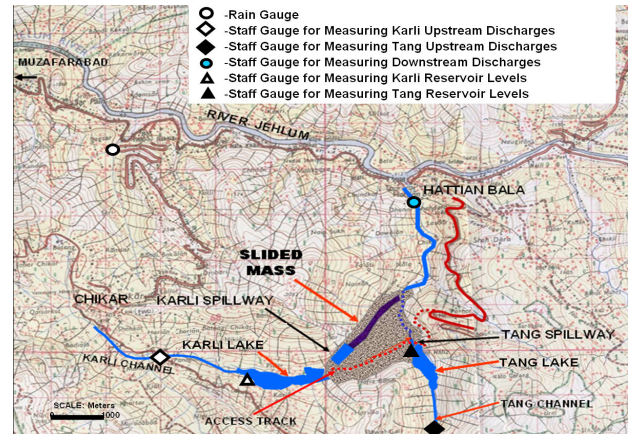


Figure 3. Map indicating mitigation works and monitoring mechanisms (Abeer 2006)



Figure 4. A pictorial view of open cut spillway at the landslide toe in front of Karli Lake (facing westwards)

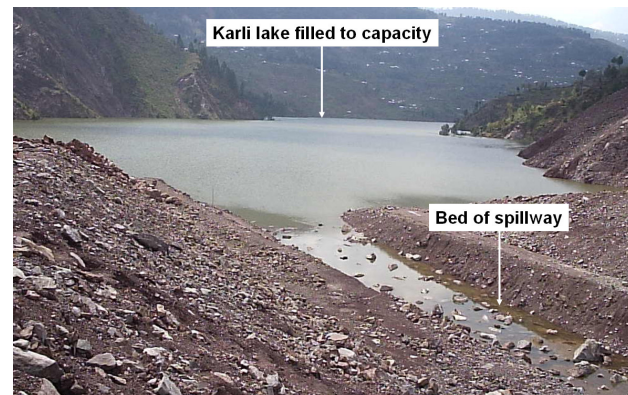


Figure 5. A pictorial view of Karli Lake filled to capacity

A study was conducted to evaluate ingress of water into the dam body through seepage from Karli Lake by utilizing the available hydrological and topographical data, so as to assist in subsequent stability analyses and hazard potential assessment of the dam.

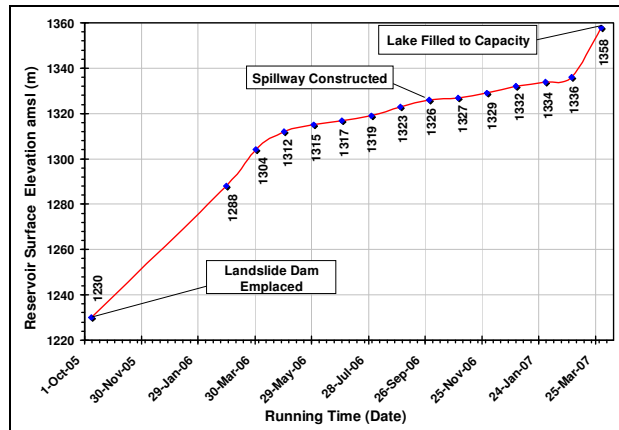


Figure 6. Filling curve of Karli Lake

2 OBJECTIVES

Objectives of this study were defined as follow:

- To assess the possibility of seepage from Karli Lake by comparing daily upstream inflows from both channels with the downstream discharges.
- To estimate the loss of water into the dam body from Karli Lake by comparing the actual daily increase in volume in the Karli Lake with the daily upstream inflow volume of Karli channel.
- To estimate the seepage volume by combining the upstream inflow volume and comparing it with the downstream discharge volume.

3 MONITORING MECHANISMS AND AVAILABLE DATA

A monitoring system installed by the Surface Water Hydrology Sub-Division, WAPDA (Water and Power Development Authority), Pakistan, enabled availability of hydrological data/records, which were utilized for this analysis. Details of this monitoring mechanism are given in Figure 3. These records include (WAPDA 2006):

- Daily inflow of Karli channel measured approximately 5 km upstream of the dam body.
- Daily inflow of Tang channel measured approximately 1.5 km upstream of the dam body.
- Daily downstream discharge measured approximately 2.5 km downstream of the dam body.
- Karli Lake daily surface elevations measured approximately 1.2 km upstream of the dam body.
- Tang Lake daily surface elevations measured approximately 150 m upstream of the dam body.
- Daily precipitation record measured using rain gauge installed at a site approximately 6.5 km North-West of the landslide dam. Precipitation records covered a period from Mar. 28, 2006 to Dec. 31, 2006 with data missing for few intermediate days (data available for 248 days).

The daily inflow/discharge and elevation records covered a period from Feb. 11, 2006 to Dec. 31, 2006, with data missing for few intermediate days (data available for 285 days). Besides, the following additional information/data was also utilized for this study:

- Plan areas and cumulative volumes of Karli and Tang Lakes at selected elevations shown in Table 1 and Figures 7 and 8, calculated using contour map of the Area (see Figure 9).
- Key data of catchment areas for both the channels given in Table 2.

4 LIMITATIONS OF THE DATA

Despite the availability of extensive data, this study had to deal with a number of limitations to arrive at some viable conclusions. These include the following:

- The downstream discharge measurements had been done at a location approximately 2.5 km downstream of the dam body, rather than at the foot/toe of the dam. The additional contribution to this downstream discharge by various water sources, like channels and springs, has not been accounted for, since no data on their specific numbers and yields was available. Yet, it is known from various field visits that there are number of channels and springs contributing to the downstream flow.
- The discharge data of the springs and small water channels in the catchment areas of Karli and Tang channels was not available for the purpose of incorporating into the analysis. Besides the springs identified in their study by NESPAK and GSP (2006), there are innumerable smaller channels (perennial as well as non-perennial) contributing to the total inflow into both the lakes. These channels were observed during the site visits as well as in the topographical maps of the area. However, the discharge data for these channels was not available at the time of the analysis.
- Precipitation introduces new inflows of water which are un-gauged (e.g., non-perennial stream channels, runoff from catchments etc.). Hence, the interpretation became difficult.
- The plan/surface areas for both lakes were available for 'selected elevations (contours)' only (see Table 1), whereas water levels in the lakes had been fluctuating in fractions of a meter on a daily basis. The surface areas at actual elevations (corresponding to daily changes in the levels) between those selected contours were, therefore, calculated by approximation through interpolations, rather than precise measurements.
- Pertinent data like the daily temperatures for the assessment of evaporation losses and the groundwater levels were not available.

Table 1. Elevations and corresponding plan areas/capacity data for Karli and Tang Lakes (NESPAK and GSP 2006)

Karli Lake	Tang Lake
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Elevation amsl (m)	Plan Area (m ²)	Volume b/w Contours (m ³)	Cumulative Volume (m ³)	Elevation amsl (m)	Plan Area (m ²)	Volume b/w Contours (m ³)	Cumulative Volume (m ³)
1,230	-	-	-	1,190	-	-	-
1,267	160,658	1,726,858	1,726,858	1,202	606,43	431,715	431,715
1,280	232,815	2,435,523	4,162,381	1,210	704,24	507,415	939,130
1,300	381,038	6,077,983	10,240,364	1,220	103,830	865,885	1,805,015
1,320	561,085	9,363,349	19,603,713	1,230	141,159	1,220,177	3,025,192
1,340	796,750	13,509,659	33,113,372	1,234	161,325	604,520	3,629,712
1,360	1,040,789	18,321,133	51,434,505	-	-	-	-

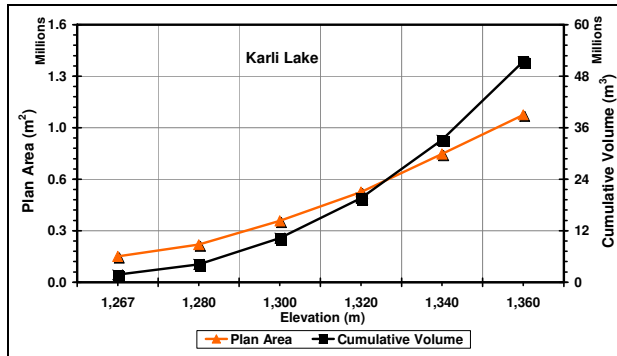


Figure 7. Plan Areas/Volume vs. Elevation (Karli Lake)

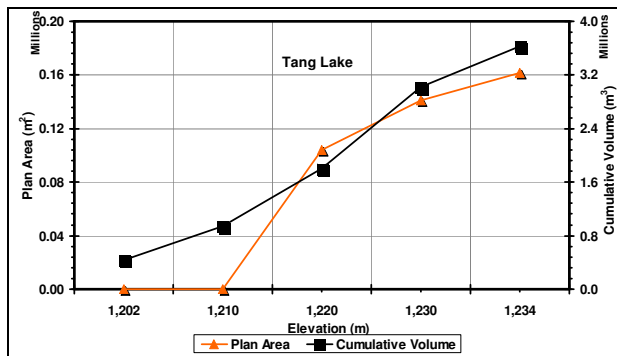


Figure 8. Plan Areas/Volume vs. Elevation (Tang Lake)

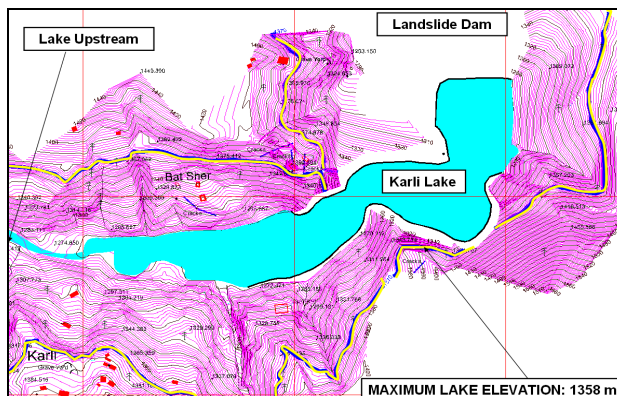


Figure 9. Contour map of Karli Lake area (Abeer 2006)

Table 2. Key data of catchment areas of Karli and Tang channels (NESPAK and GSP 2006, and Hoydal et al. 2006)

Channel	Area (km ²)	Length (km)	No of Springs
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Karli	45	13	232
Tang	30	8	102

5 METHODOLOGY

Specifics of the methodology adopted for each of the following comparisons are given below:

5.1 Comparison of Daily Discharges

- Daily lakes' surface elevations were plotted to observe the tendencies of increase or decrease with upstream discharges. Separate charts were prepared for each month.
- Daily upstream and downstream discharges, and daily precipitation data were plotted to study the tendency of fluctuations in discharges with precipitation. Separate charts were prepared for each month to identify the trend(s).

5.2 Comparison of Daily Volumes Increase in Karli Lake

- Surface areas of water corresponding to the daily rise in surface elevation in Karli Lake were calculated using the contour map made by Survey of Pakistan, plan areas calculated according to NESPAK and GSP (2006) and the Grapher computer program.
- Daily increases in volume of water in Karli Lake were estimated by taking the product of the daily water rise and the average surface area at respective elevations calculated above.
- The volume calculated with the above procedure was compared with the volume calculated from daily inflow discharge.

5.3 Estimation of Seepage Volume

Seepage volume can only be found in case $Q_{vol. dis.} > Q_{vol. cont.}$, where $Q_{vol. dis.}$ is the upstream inflow volume, and $Q_{vol. cont.}$ is the volume between contours (actual volume).

To calculate seepage volume in other cases where $Q_{vol. cont.} > Q_{vol. dis.}$ or $Q_{vol. cont.} = Q_{vol. dis.}$, we need to calculate the un-gauged flow.

Therefore, inflow – outflow + un-gauged flow = change in storage.

$Q_{in} - Q_{out} + Q_i = \text{Change in storage, or}$

$Q_{in} + Q_i - \text{Change in storage} = Q_{out}$

$$Q_{in} + Q_i - \Delta h \cdot A_{ave.} / \Delta t = Q_{out} \quad [1]$$

Q_{in} is upstream inflow discharge, Q_i is un-gauged flow (rainfall on the surface area of lake + runoff from catchments), $\Delta h / \Delta t$ is the change in height of water in lake with time, $A_{ave.}$ = Average plan area with respect to $\Delta h / \Delta t$, and Q_{out} = potential seepage discharge.

5.3.1 Dry Period

For dry period, equation [1] becomes:

$$Q_{in} - \Delta h \cdot A_{ave.} / \Delta t = Q_{out} \quad [2]$$

Our measuring interval was 24 hours; so by converting equation [2] from rate of volume to volume basis, we get:

$$Q_{in} \cdot \Delta t - \Delta h \cdot A_{ave.} = Q_{out} \cdot \Delta t \quad [3]$$

$Q_{out} \cdot \Delta t$ is the potential seepage volume. When $Q_{out} \cdot \Delta t = 0$, this implies that $Q_{in} \cdot \Delta t = \Delta h \cdot A_{ave.}$. In other word, inflow wholly goes into storage plus evaporation, hence there is no water for seepage. When $Q_{out} \cdot \Delta t > 0$, this implies that water is available for seepage. If $Q_{out} \cdot \Delta t < 0$, this implies anomalous results, which can perhaps be explained by the contribution of springs flow that persists even during dry weather.

5.3.2 Rainy Days

For converting rate of volume to volume basis, equation [1] becomes:

$$(Q_{in} + Q_i) \cdot \Delta t - \Delta h \cdot A_{ave.} = Q_{out} \cdot \Delta t \quad [4]$$

Omitting evaporation effects during rainy days (due to atmospheric moisture), equation [4] holds good. If $Q_{out} \cdot \Delta t = 0$, this implies that $(Q_{in} + Q_i) \cdot \Delta t = \Delta h \cdot A_{ave.}$. In other word, inflow wholly goes into storage, hence no water for seepage. If $Q_{out} \cdot \Delta t > 0$, this implies that seepage volume is being underestimated by amount $Q_i \cdot \Delta t$. If $Q_{out} \cdot \Delta t < 0$, this implies that storage is more than inflow. Q_i leads to increase in storage.

This possible analysis was discarded owing to large number of unknown variables during the rainy days.

5.3.3 Adopted Analysis Approach

To calculate $Q_{out} \cdot \Delta t$, analysis was performed on the basis of dry period data for the days having positive potential seepage volume (Apr., May, Sept. and Oct.; total 92 dry days for which data was available). Following calculations were made and the results are presented in the subsequent sections.

- Seepage volume for both channels for 92 days.
- Sum of upstream inflow discharges for both channels for 92 days.
- Sum of downstream discharges for both channels for 92 days.
- Seepage volume expressed as percentage of upstream inflow discharge.
- Seepage volume expressed as percentage of downstream discharge.
- Seepage volume trapped within the dam body.

6 OBSERVATIONS AND RESULTS

Based on the methodology adopted for this study, the results/observations are as follows:

6.1 Comparison of Daily Discharges

A sample set of the graphical representation of the daily lakes' levels, upstream inflows as well as downstream discharges, and precipitation for the month of Oct. 2006 is shown in Figures 10 and 11. The same was applied to the entire study period spanning from Feb. to Dec. 2006. The results/observations are enlisted below:

- The water surface elevation in Karli Lake constantly rose throughout the period under consideration [from 1282.44 m amsl (above mean sea level) on Feb. 11, 2006 to 1333.59 m on Dec. 31, 2006].
- The water surface elevation in Tang Lake fluctuated between 1215.71 and 1223.10 m amsl with changes in upstream discharges and periodic rainfall during the period under consideration.
- The net downstream discharge for almost entire period under consideration (95.44%) was more than the upstream inflow of Tang channel, except for the dates characterized by heavy rainfall (34 mm to 63 mm).
- The upstream discharges of the two channels and the downstream discharge for the period under consideration fluctuated between following limits:
 Karli upstream: 2.897 – 0.257 m³/s
 Tang upstream: 2.806 – 0.213 m³/s
 Downstream: 2.870 – 0.370 m³/s
- There was a trend of increase in upstream discharge of both channels as well as downstream discharge commensurate with periodic rainfall except for a limited period (5.26%), where the data showed erratic trends of either similar or considerably higher values of upstream discharges as compared to downstream discharges. These erratic trends were observed during rainy days. In all such cases the downstream discharges during the following days were relatively higher than the normal trend.

- Sum of the upstream discharges from both the channels was distinctly higher (1.47 times on the average) than the net downstream discharge over the entire period under consideration (as per the available data).
- During dry spells (Apr., May, Sept. and Oct.), the upstream discharges of both channels showed a decreasing trend.

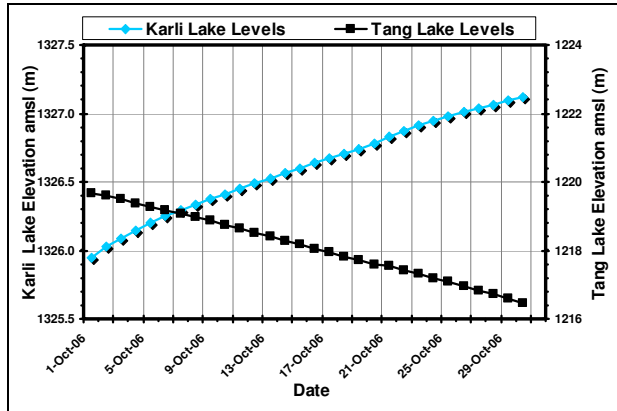


Figure 10. Daily surface elevations of Karli and Tang Lakes: Oct. 2006

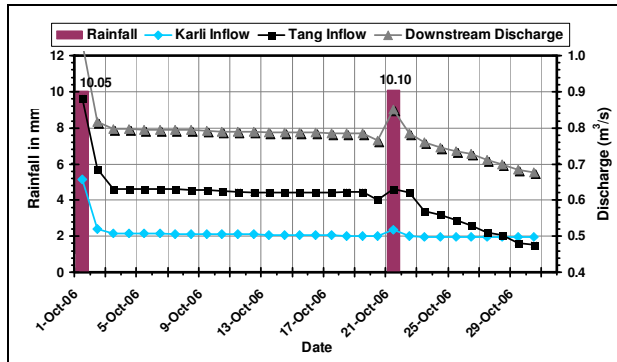


Figure 11. Daily discharges and rainfall: Oct. 2006

6.2 Comparison of Daily Volumes Increase in Karli Lake

The polynomial fit of the data for Karli Lake is presented in Figure 12. The equation used for calculating plan areas corresponding to daily increase in elevations is given below:

$$Y = 1235.3 + 0.00023 \cdot X - 1.82 \cdot 10^{-10} \cdot (X^2) + 7.71 \cdot 10^{-17} \cdot (X^3) - 3.134 \cdot 10^{-24} \cdot (X^4) \quad [5]$$

The plan areas thus calculated were used to find the actual daily increase in volume of Karli Lake. The results/observations are enlisted below:

- The daily increase in actual volume was generally (with the exception for the month of Jul. 2006)

more than the volume calculated from upstream discharge for rainy days and few of the following days for the entire period under consideration.

- During dry months (Apr., May, Sept. and Oct.) the trend was opposite, i.e. greater volume calculated from daily discharge than the volume calculated from rise in surface elevation method.

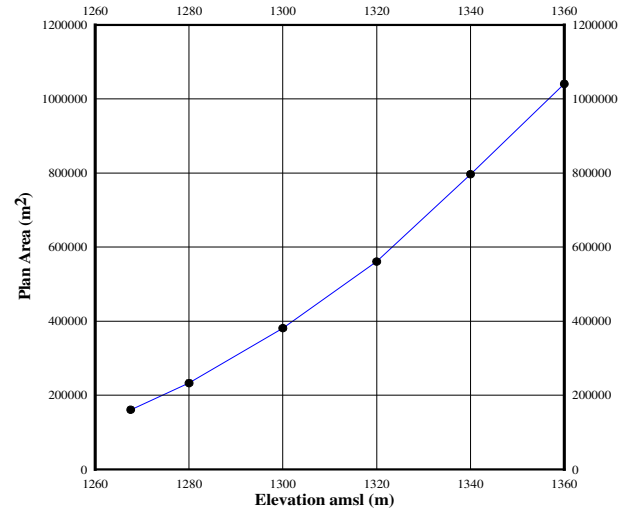


Figure 12. Plan areas vs. surface elevations for Karli Lake

6.3 Estimation of Seepage Volume

This analysis required additional polynomial fitting for the similar data of Tang Lake. The plot thus obtained is presented in Figure 13. The equation used for calculating plan areas corresponding to daily change in elevations is given below:

$$Y = 1190.003 - 2.932 \cdot 10^{-6} \cdot X + 5.23 \cdot 10^{-9} \cdot (X^2) - 2.273 \cdot 10^{-14} \cdot (X^3) \quad [6]$$

The plan areas thus calculated were used to find the actual daily change in volume of Tang Lake. Results of this analysis indicated that a substantial quantity of potential seepage volume was being accumulated inside the dam body. Specific calculations yielded the following results:

- Seepage volume for 92 days = 7.3 million m³
- Sum of upstream discharges for 92 days = 10.8 million m³.
- Sum of downstream discharges for 92 days = 7.8 million m³.
- Seepage volume expressed as percentage of upstream discharge = 67.57%.
- Seepage volume expressed as percentage of downstream discharge = 93.39%.
- Seepage volume trapped within the dam body = - 0.5 million m³.

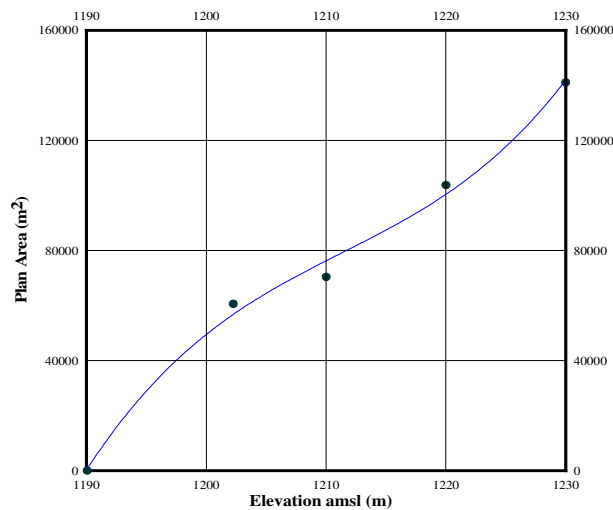


Figure 13. Plan areas vs. surface elevations for Tang Lake

7 CONCLUSIONS AND RECOMMENDATIONS

Based on the analyses conducted during the course of this study, following conclusions are drawn:

- It is probably relevant to base the analysis on dry period data.
- The downstream discharge being greater than the upstream discharge of Tang channel alone and the sum of upstream discharges being more than the net downstream discharge ($Q_{in} > Q_{out}$) creates two possibilities.
- Either, the seepage of water from Karli Lake through the dam body was contribution to the downstream seepage discharge of Tang Lake, or, there was a substantial contribution by additional un-gauged hydrological features (channels and springs) along the downstream stretch between the dam and measurement gauge installed 2.5 km downstream.
- There is a loss of water from Karli Lake into the dam body through infiltration/seepage owing to large upstream face, volume and proportionally large pore spaces available within the unconsolidated natural dam.
- There is a loss of water by infiltration/seepage along the perimeter of Karli Lake surface with water touching fresh and relatively dryer edges with daily rise in elevation.
- There is a limited loss of water from the surface of lake due to evaporation during the hotter months (May – Oct.).
- The specific amount of water possibly infiltrating into the dam body cannot be approximated owing the number of unknown and un-gauged variables stated in the foregoing.
- The negative value of seepage volume contained in pore spaces can be attributed to the contribution to downstream discharge by additional water channels as indicated earlier. More realistic results

could have been obtained, had the daily downstream discharge been measured precisely at the toe of this dam.

- The hydrological data based analysis failed to determine the part of seepage volume being trapped in the dam body due to limited data available.
- As Karli Lake has remained filled to its capacity since Apr. 2007 and water from the lake has been overtopping through the spillway for quite some time, the hydrogeological immaturity of the dam is inching towards a steady state. A continuous system of monitoring and analyzing the upstream and downstream discharges coupled with all relevant variable factors is likely to bring about a realistic assessment of the seepage scales and extents from Karli Lake. It will ultimately help in assessing the seepage induced internal erosion and thus the stability of the dam in times to come.

Based on the conclusions drawn from this analysis, the following actions are recommended for future studies:

- Upstream and downstream discharges need to be monitored to determine the amount of seepage volume trapped inside/passing through the dam body.
- The downstream discharge should be measured immediately next to the downstream toe of the dam.
- Contribution of springs and seasonal water channels along the Karli Lake, daily precipitation and evaporation losses should also be measured/monitored.
- Evaporation effect should be incorporated for the hot/dry days, as suggested in this study, by obtaining daily temperatures of the area for the period understudy.
- Monitoring wells should be installed at selected locations in the dam body to physically ascertain the seepage trends and relate those to inflow/outflow tendencies.

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