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Embankment Dam Spillway Adequacy Evaluation under Probable Maximum Flood the Case of Tendaho Dam, Ethiopia

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Abstract:
Embankment dams constructed in flood prone areas have high probability of overtopping if their spillway is not designed to pass the maximum flood. Checking adequacy of spillway helps to pre plan mitigation measures if there would be failure. This study evaluates adequacy of embankment dam spillway to pass PMF using HEC-HMS model taking Tendaho embankment dam constructed on lower Awash River in Ethiopia as case study. The spillway of the dam was constructed in flood susceptible area to pass 10,000 years' flood. The model was calibrated and validated using twenty-four rainfall stations in the catchment and nine years observed flow data at tendaho station. The result of the study indicates that there would be overtopping of the dam under PMF with 20cm and hence inadequacy of Tendaho embankment dam spillway to pass PMF.

Keywords: *Tendaho, spillway adequacy, HEC-HMS, PMF*

1. Introduction

Embankment dams are highly susceptible to failure basically due to their non rigidity. Among the causes of failure for embankment dam overtopping and piping takes the major position. For dams constructed in flood prone areas the possibility of overtopping failure is very high if spillway of the dam is not adequate to pass the maximum flood.

Tendaho dam is embankment dam constructed on lower Awash River in Ethiopia to irrigate 60,000-hectare land. The height of the dam is 44m with $1.86*10^6$ m^3 reservoir capacity. The spillway of this dam was designed to pass 10,000-year flood.

During winter season Awash River basin is highest flood susceptible basin among Ethiopian basins. Considering flood susceptibility in mind this paper evaluates the adequacy of Tendaho dam spillway to pass PMF with the help of HEC-HMS model.

Evaluation of spillway adequacy is necessary for constructed dam to preplan mitigation measures if there would be failure in future.

When the life loss is likely as a result of dam failure PMF is considered as a design flood. According to WMO (1986) pmp which helps for calculating PMF is the largest depth of precipitation for a given duration that is physically possible over a particular area and geographical location at a certain time of the year.

And the methods used for determining PMP are: Storm model approach based on realistic meteorological processes, maximization and transposition of actual storms, Use of generalized depth-area-duration data and Statistical analyses of extreme rainfalls. WMO (1986) suggested Statistical procedures for estimating PMP wherever sufficient precipitation data are available or where other meteorological data, such as dew point and wind records, are lacking. Hershfield (1961, 1965) developed statistical approach to estimate PMP.

Probable maximum flood is a flood from a given catchment with zero probability of exceedance and or it is an upper limit flood resulting from severe combination of critical hydrologic and meteorological conditions. There are two basic approaches which help us to determine PMF. The first method is deterministic approach and the second one is probabilistic approach. In the first method rainfall – runoff models are used and the second approach relies on flood or rainfall with specified return period.

A number of models have been developed to determine PMF from pmp. As example in United States, the hydraulic Engineering Center (HEC-1) and HEC- hydrologic modeling system (HEC-HMS) models are widely used by the corps of engineers, and the flood hydrograph and runoff (FHAR) used by USBR for computing flood hydrograph. These models use unit hydrograph concept, which represent rainfall- runoff as a linear system. In this study HEC-HMS in concert with Arc GIS was used to determine PMF and to evaluate spillway adequacy.

2. Project Location and Catchment Description

Awash River basin is one of eleven Ethiopia river basins which rises from southern edge of Ethiopian highland, 150km west of the capital Addis Ababa at altitude of 3,000m above sea level and terminate at Lake Abe, on boarder with Djibouti, at altitude of about

250m. The basin has a drainage area of 112,211km^2 and the total length of the river is some 1,200km. Drainage area up to Tendaho dam location is about 60,405km^2 (see Figure 1).

Tendaho dam is largest embankment dam constructed on lower Awash River in Ethiopia. The dam is mainly constructed to irrigate 50,000 hectares of land to enable cultivation of sugarcane for Tendaho sugar factory and 10,000hectares of land for residents. The dam has reservoir capacity of 1.86*10^6 m^3 and height of 44m. The spillway of the dam is designed to pass 10,000-year flood.

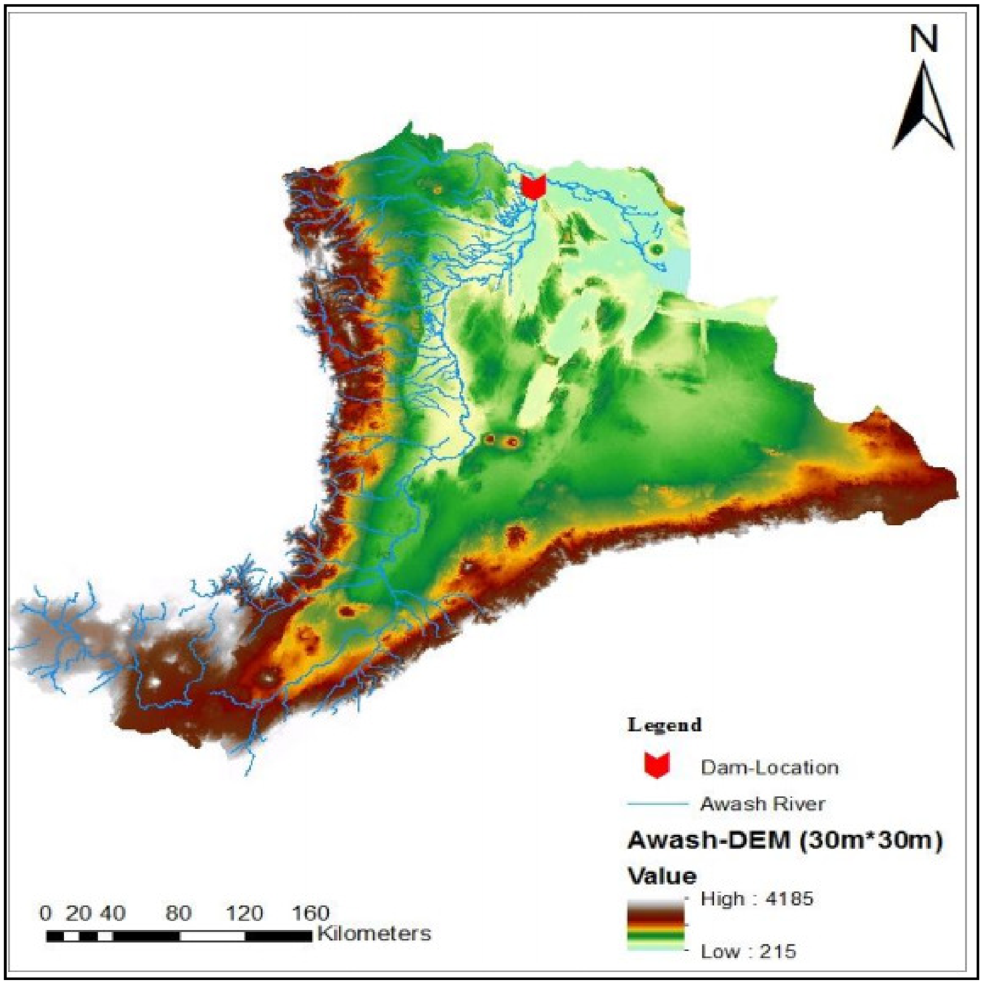

Figure 1: Tendaho Dam Location and River Awash

3. Methodology

Methodology used for the study is presented with conceptual frame work shown in Figure 1.

3.1. Data Used

3.1.1. Meteorological Data

Meteorological data for selected rain gauge stations were collected from national meteorology agency. Twenty-four stations with twenty-nine years' daily rainfall data (from 1985 to 2013) were collected. To select twenty-four stations first the basin was categorized in to four sub catchments (i.e. Upland sub catchment, Upper valley sub catchment, western and middle valley sub catchment and lower valley sub catchment) depending on location. After categorizing in to sub catchment availability of rainfall data for the stations in each sub catchment was checked. Following this six rain gauge stations were selected from each sub catchment.

To fill missed rainfall data first normal annual rainfall of all stations were determined. After determining normal annual rainfall, three stations closer to station having missed data was selected. Then, the normal annual rainfall of missed station was compared with normal annual rainfall of the selected neighboring stations. For the stations with normal annual rainfall of neighboring three stations within ten percent of normal annual rainfall of station with missed data arithmetic mean method were used. For the stations with normal annual rainfall of neighboring three stations higher or lower than ten percent of normal annual rainfall of station with missed data normal ratio method were used.

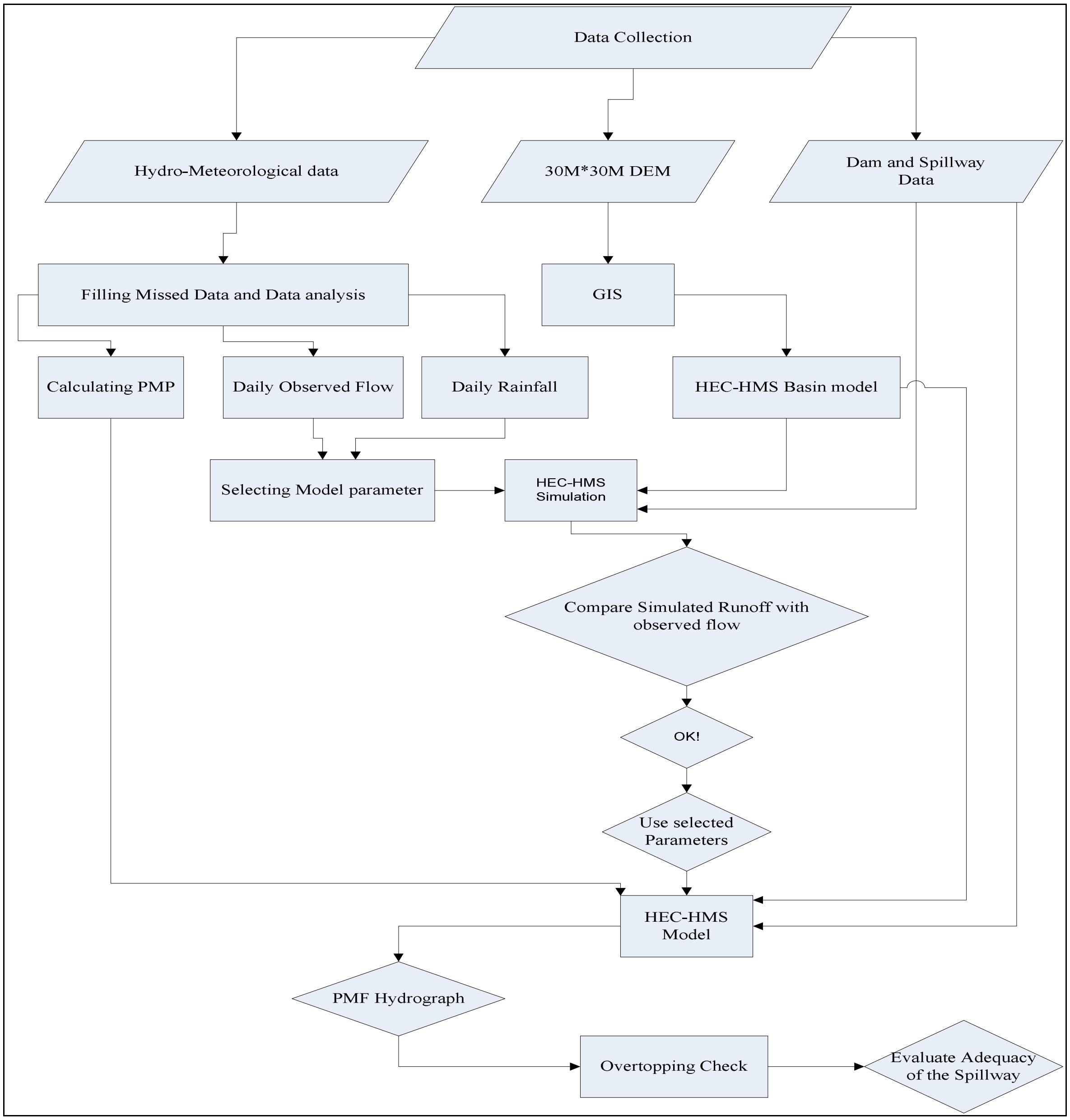

Figure 2: Conceptual Framework of followed methodologies

After filling missed rainfall data, consistence and homogeneity of recorded rainfall data was checked. To test consistency of rainfall data double mass curve technique was used and applied for each sub catchment (See Figure 2 to 5). As observed from figure there is no clear shift or change in slope for all stations, hence the rainfall data at all stations are consistence. To test homogeneity Mann-Kendall rank statistics was used to check existence of trend in data series. The ratio of Mann-Kendall rank statistics, τ to standard deviation, σ of data series is determined for all stations. For no trend in the data series, the value of τ/σ lies within the limits of ±1.96 at the 5% level of significance (Rakhecha, P. R., and V. P. Singh, 2009). (See Table 1).

Station name	τ/σ	Station name	τ/σ	Station name	τ/σ
AA Bole	-1.163	Melkasa	1.838	Aliyu amba	-1.647
Modjo	0.300	Metahara	-1.501	Gewane	0.413
Bantu Liben	-0.948	Nuraera	-0.313	Dessie	-0.563
Boneya	-1.422	Awara melka	-0.904	Mile	-1.753
Ginchi	-1.050	Majete	-0.675	Adaitu	-0.132
Ejersa Lele	0.563	Shola gebeya	-1.185	Bati	-0.863
Koka dam	0.225	Jara	1.913	Combolcha	0.338
Nazeret	-0.863	Kara kore	-1.541	Mersa	-1.163

Table 1: Homogeneity test by Mann- Kendall rank statistics

As it can be observed from Table 1 for all stations the value of τ/σ lies within the limit of ±1.96. Thus, there is no trend and the data are homogeneous.

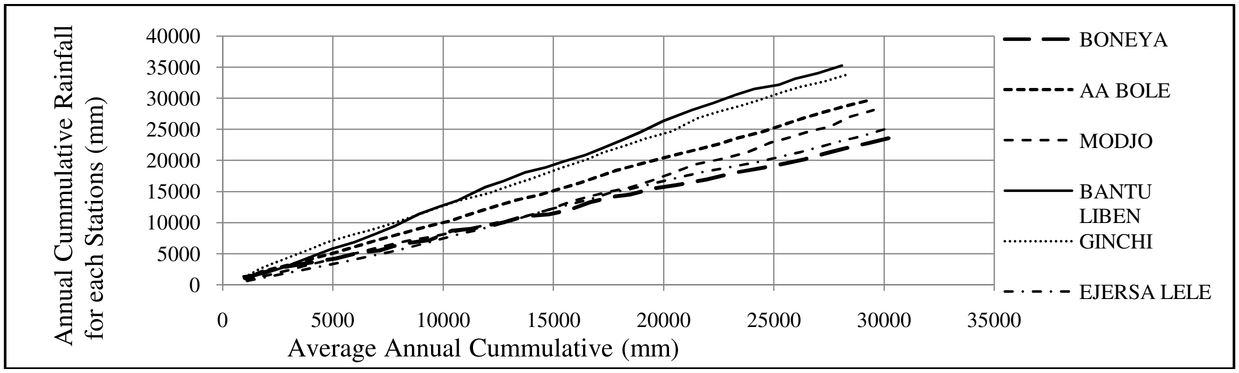

Figure 3: Double mass curve for upland sub catchment

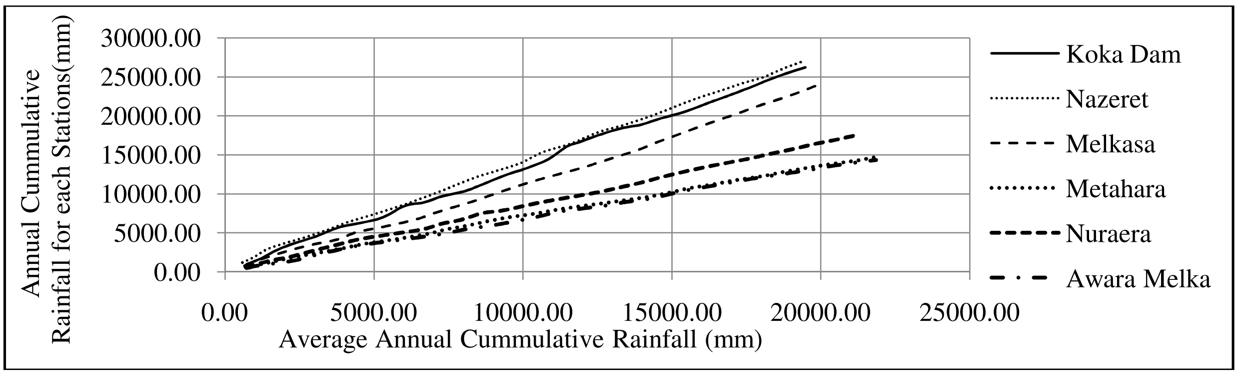

Figure 4: Double mass curve for upper valley sub catchment

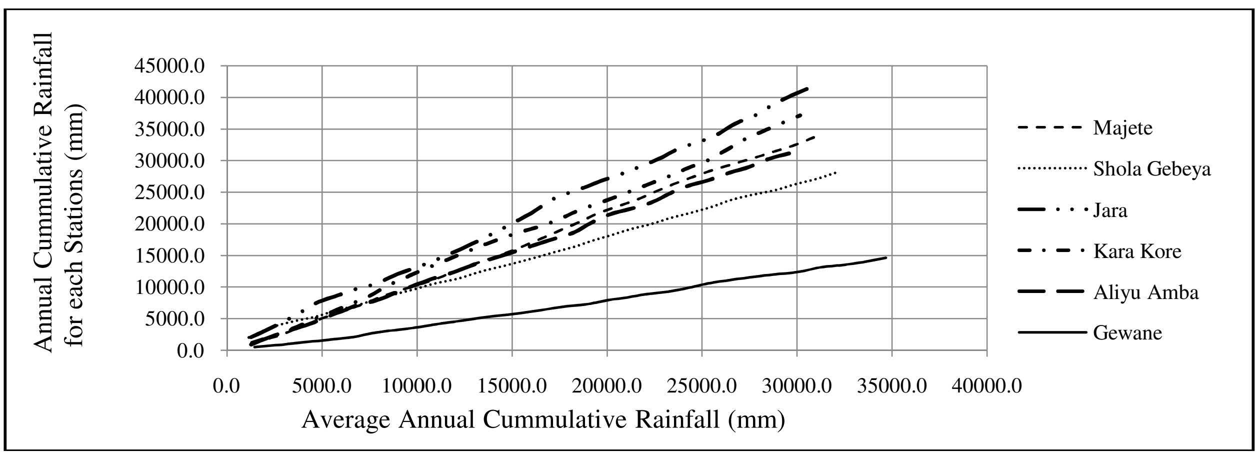

Figure 5: Double mass curve for west and middle valley sub catchment

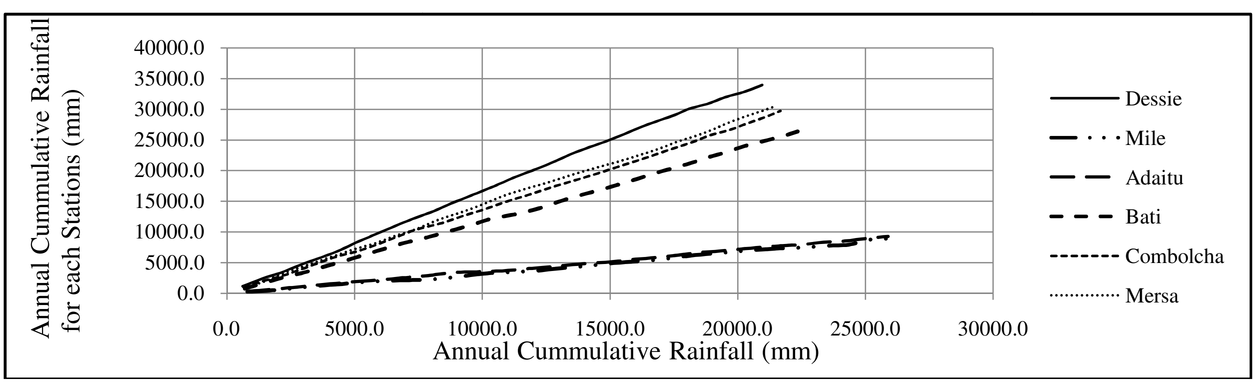

Figure 6: Double mass curve for lower valley sub catchment

3.1.2. Flow Data

Flow data from Tendaho station (from 1984 to 1993) was used for this research. The main purpose of flow data here is to calibrate and validate the HEC-HMS model. Since rainfall data starts from 1985 flow data from 1985 to 1993 were used. In this case five years' flow data (1985 to 1989) were used for model calibration and four years' flow data (1990 to 1993) were used for validation of HEC-HMS model.

Independence and stationarity, and outlier test of flow data was checked. Independence and stationarity was checked using Wold-Wolfowitz (1943) (W-W) test. Using W-W test the following results were obtained:

R= 2101748.91

$\bar{R}$= 2027613.302

Var (R) = 1531854724

$$U = \frac{(2101748.91 - 2027613.302)}{(1531854724)^{1/2}} = 1.894$$

The test value U is less than the critical value at 5% significance level $U_{0.025}$ = 1.96. Thus, we can accept the hypothesis of independence and stationarity. The flow data are concluded to be independent and stationary at the 5% significance level.

Grubbs and Beck (1972) test (G-B) were used to detect outliers. Using this test the highest threshold value, X_H and the lowest threshold value, X_L are calculated to be 822.104 and 229.33 respectively. The largest recorded value was 594.7 which does not exceed the threshold value, X_H. Thus there are no high outliers in the sample. The smallest recorded value was 231.4 and is not less than X_L, thus there are no low outliers in the sample.

3.2. Estimation of PMP

Statistical techniques were used to estimate PMP because, the data, mainly annual maximum daily rainfall, required for estimation of probable maximum flood are available. The general procedures followed were:

- Maximum annual daily rainfall for twenty-nine years for twenty-four stations was extracted from daily rainfall data.
- Using maximum annual rainfall data probable maximum precipitation was determined for each station by Hershfield (1965) formula.

After calculating PMP for each station average depth of PMP over an area was calculated by using Thiessen polygon. GIS gives area enclosed by polygon surrounding each rainfall stations. Figure 7 shows Theissen polygon with rainfall station and Table 2 presents PMP for each rainfall stations with area enclosed by their polygon.

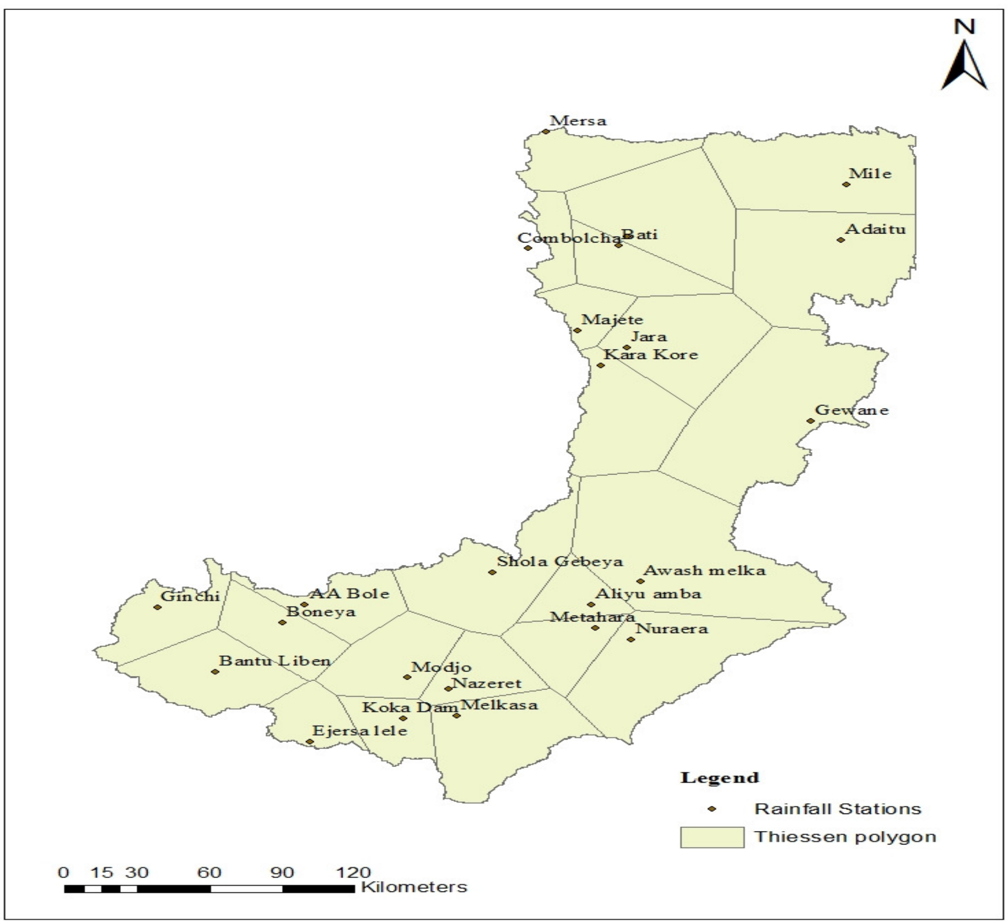

Figure 7: Theissen Polygon with rainfall Station

Name of the station	PMP	Polygon Area (Km^2)
AA Bole	243.90	1549.18
Modjo	367.56	2028.58
Bantu Liben	302.92	2366.92
Boneya	448.77	1637.09
Ginchi	305.02	1739.37
Ejersa lele	397.63	1111.34
Koka dam	423.03	1225.75
Nazeret	1169.73	1460.09
Melkasa	283.81	3002.06
Metahara	210.01	1431.85
Nuraera	352.98	3817.74
Awara Melka	466.87	6441.95
Majete	364.63	903.74
Shola Gebeya	306.21	3299.28
Jara	403.09	3141.34
Kara Kore	336.5	2686.63
Aliyu Amba	567.84	1041.54
Gewane	415.37	5553.68
Dessie	310.27	3560.73
Mile	362.14	3924.42
Adaitu	204.18	4409.93
Bati	522.15	1555.38
Combolcha	221.69	852.84
Mersa	434.67	1666.9

Table 2: PMP of rainfall stations

Using Values of Table 2 above the following formula were used to calculate average depth of Probable maximum precipitation over an area.

$$\left[\overline{\mathrm{PMP}} = \frac{\mathrm{A_1} * \mathrm{PMP_1} + \mathrm{A_2} * \mathrm{PMP_2} + \cdots + \mathrm{A_n} * \mathrm{PMP_n}}{\mathrm{A_{total}}}\right]$$

Where, $\left[\overline{\mathrm{PMP}} = \frac{\mathrm{A_1} * \mathrm{PMP_1} + \mathrm{A_2} * \mathrm{PMP_2} + \cdots + \mathrm{A_n} * \mathrm{PMP_n}}{\mathrm{A_{total}}}\right]$ = Areal PMP

PMP_1, PMP_2, PMP_n are probable maximum precipitation at station 1, 2, and n respectively

A_1, A_2, A_n are Thiessen polygon areas of station 1, 2, and n respectively.

The average depth of probable maximum precipitation calculated was 378.133mm. Hershfield formula for PMP is valid only for area less than $25Km^2$. For areas greater than $25Km^2$ area reduction factor must be applied. For Ethiopia area reduction factor is not calculated. For large watershed, > 1000 Km^2, area reduction factor lower than 0.6 have been used in East Africa (Watkins and Fiddes, 1984). For this study 0.6 is used as a reduction factor. Using this, the average depth of probable maximum precipitation calculated was 226.88mm.

3.2.1. Rainfall Hyetograph and Storm Frequency Determination

Determination of PMF and spillway adequacy check using HEC-HMS model needs frequency storm. Since, hourly data is not available for this study nested bell shaped or alternate block method was used to generate rainfall hyetograph. Figure 8 shows generated rainfall hyetograph for PMP.

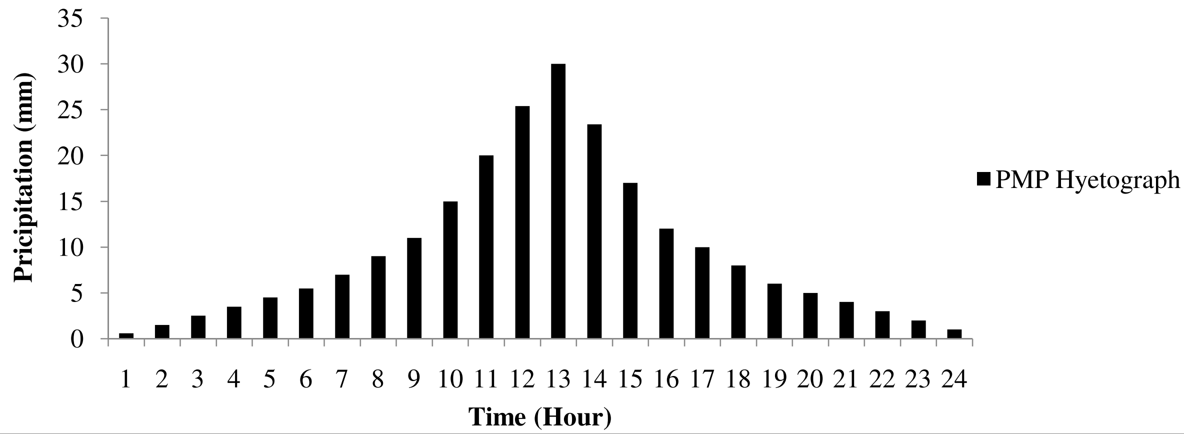

Figure 8: Rainfall Hyetograph for PMP

After generating rainfall hyetograph 24 hours' storm frequency was determined. Figure 9 shows 24 hours plotted frequency curve.

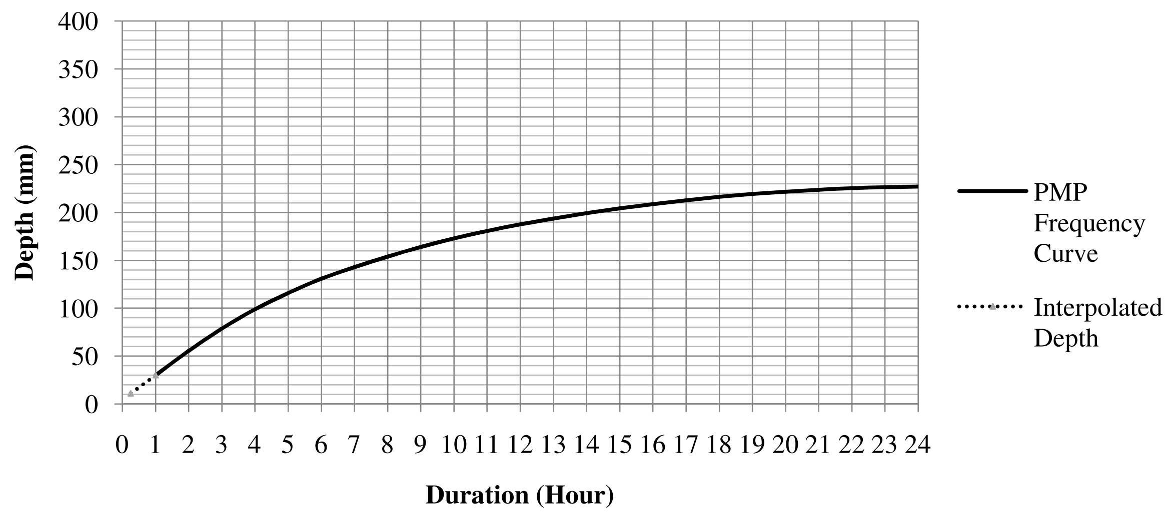

Figure 9: 24 hour Storm frequency curve

3.2.2. Determination of Daily Areal Precipitation

Daily areal precipitation was developed for the whole catchment using Thiessen polygon shown in figure 7. Here, the need to develop daily areal precipitation is for calibration of the HEC-HMS model. Only Nine years' daily flow data is available at Tendaho station for calibration and validation of HEC-HMS model. Hence, daily areal precipitation is developed only for nine years (from1985 to1993).

3.2.3. HEC-HMS Basin Model Component Development

The basin model is developed by importing the basin map from GIS. On imported basin maps sub basins, junctions and reservoir is set. There are twenty-five sub basins in the catchment. After setting these sub basins, sub basin parameters are filled. The parameters filled are: sub basins area, loss method, transform method and base flow method. For this study, initial and constant loss method, Snyder unit hydrograph transform method and recession base flow method are used. The area for each sub basin is extracted from GIS map.

For initial and constant loss case it is assumed that the catchment is likely saturated when extreme event occurs, and thus set the initial loss equal to 0.00mm. The constant loss is the parameter to be calibrated. In transform method standard lag and peaking coefficient are also calibrated parameter. The basin model component with junction and sub basin is shown in Figure 10.

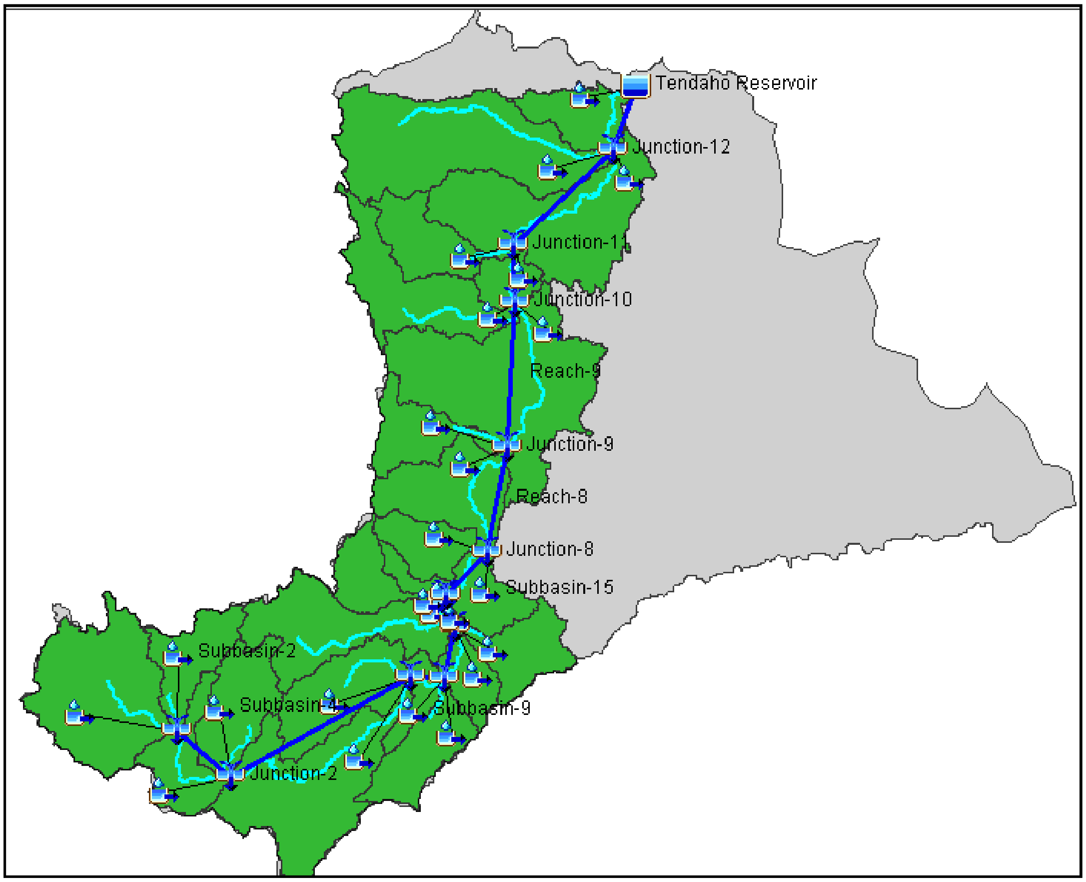

Figure 10: Basin model component

3.2.3.1. HEC-HMS Meteorological Model Component Development
Meteorological model component was developed using 24 hours' frequency storm with 15-minute intensity duration. Table 3 shows the frequency storm used for PMP.

Duration (hr)	**0.25**	**1**	**2**	**3**	**6**	**12**	**24**
Depth (mm)	11	30	55.4	78.8	130.8	187.8	226.88

Table 3: Frequency Storm used for PMP

3.2.4. HEC-HMS Control Specification Model Component Development
In control specification starting and end day and the time interval is set. For this study 24 hours' duration, equal with storm duration, with 15-minute time interval was used.

3.2.5. Paired Data Model Component Development
To develop paired data model component elevation storage data of Tendaho reservoir was used.

3.3. HEC-HMS Model Calibration and Validation
For the current study only nine years' daily flow data (from1985 to 1993) is available. From these data five years' daily flow data (1985 to 1989) was used for calibration and four years' daily flow data (1990 to 1993) was used for validation. Daily areal rainfall of the same period with daily flow data was used for calibration and model validation. HEC-DSSVUE was used to import areal precipitation and daily flow data to HEC-HMS model. Using these data (observed hydro-meteorological data) three parameters (constant loss of initial and constant loss method, peaking coefficient, C_P and basin coefficient, C_t of Snyder unit hydrograph transform method) were calibrated.
For this study, the model performance in simulating observed flow has been evaluated during calibration and validation through using Nash and Sutcliffe efficiency criteria (NSE), coefficient of determination (R^2), Percent difference /Relative Volume Error (D) and through graphical inspection of simulated and observed hydrographs.
Optimized value of the parameters and their performance indices during calibration and validation is reported in Table 4 and hydrograph comparison for calibration and validation is expressed in Figure 11 and 12.

	Calibrated parameter		
	Constant rate (mm/hr) loss	C_t of the basin lag	C_p, peaking coefficient
Optimized value	0.7	2.505	0.1
Performance indices	Calibration	Validation	
NSE	0.839	0.874	
R^2	0.873	0.913	
D (%)	8.245	9.367	

Table 3: Optimized value of the parameters and their performance indices during calibration and validation

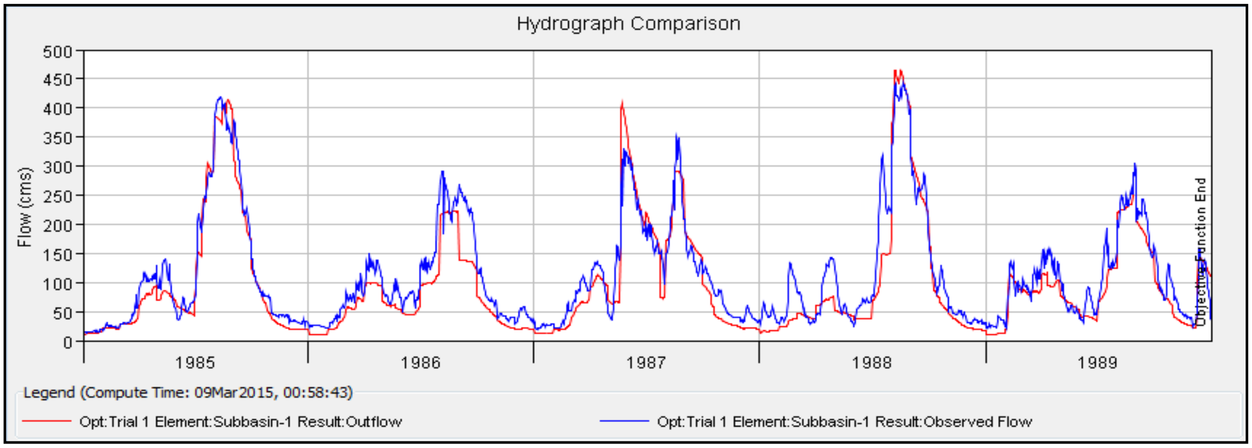

Figure 11: Hydrograph comparison for calibration

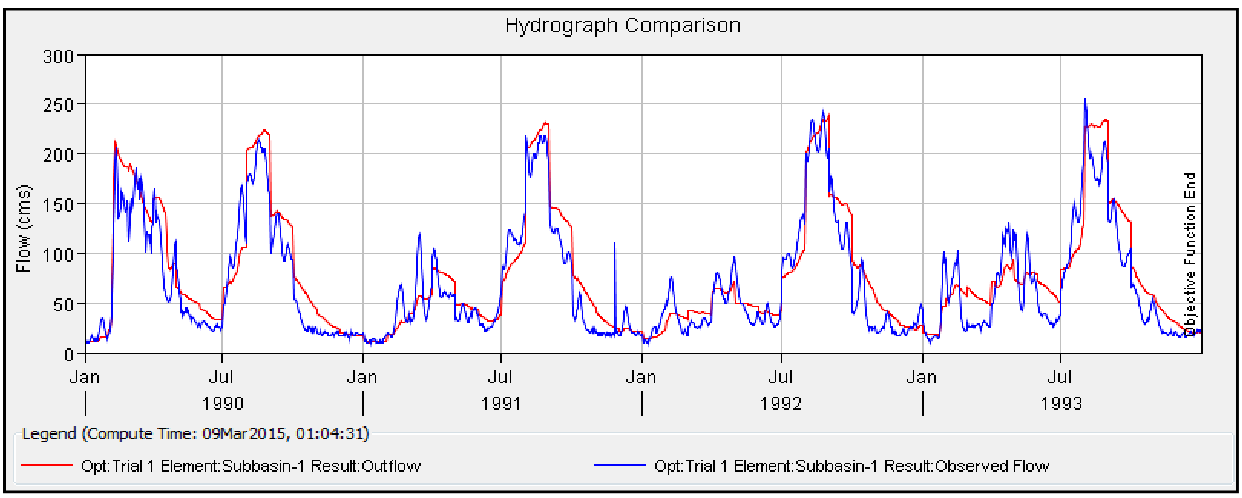

Figure 12: Hydrograph comparison for Validation

After calibrating and validating the model, using optimized values the model was simulated. The simulation result showed that maximum water surface elevation of 412.2m in the reservoir (see Figure 13). As the top of the dam is at 412m, this means that the dam would be overtopped by the event. Overtopping of the dam indicates that inadequacy of Tendaho dam spillway to pass PMP. The simulated peak storage was 2569484.6 (1000m^3). (See Figure 14 for HEC-HMS general summary).

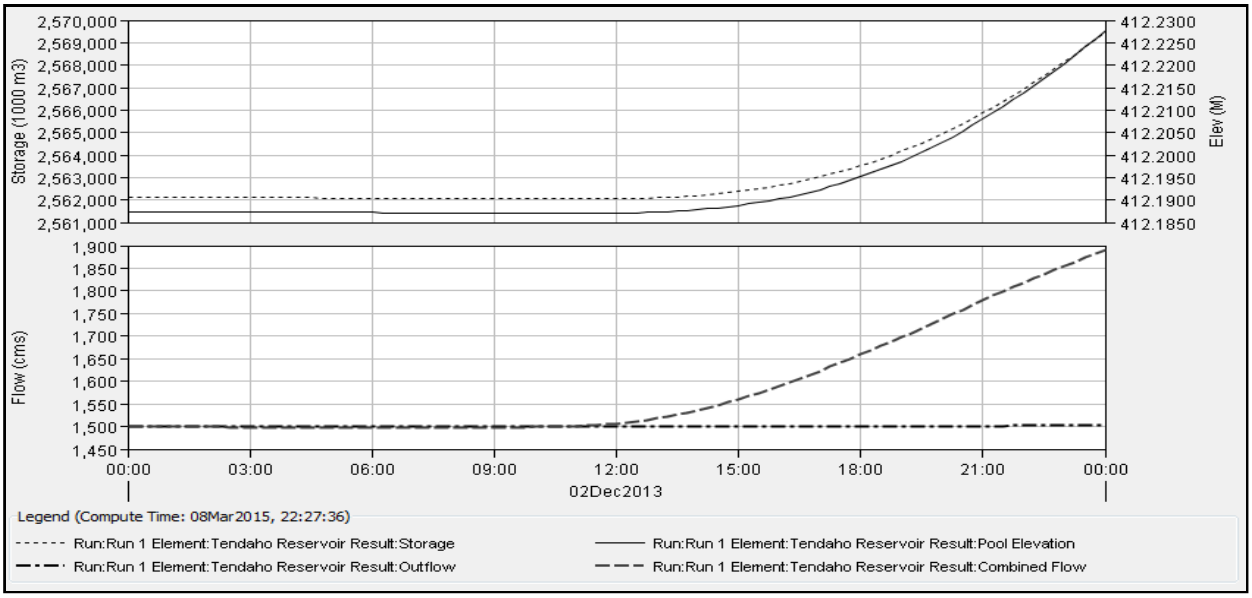

Figure 13: Elevation-storage change with time for Tendaho reservoir under PMP storm event

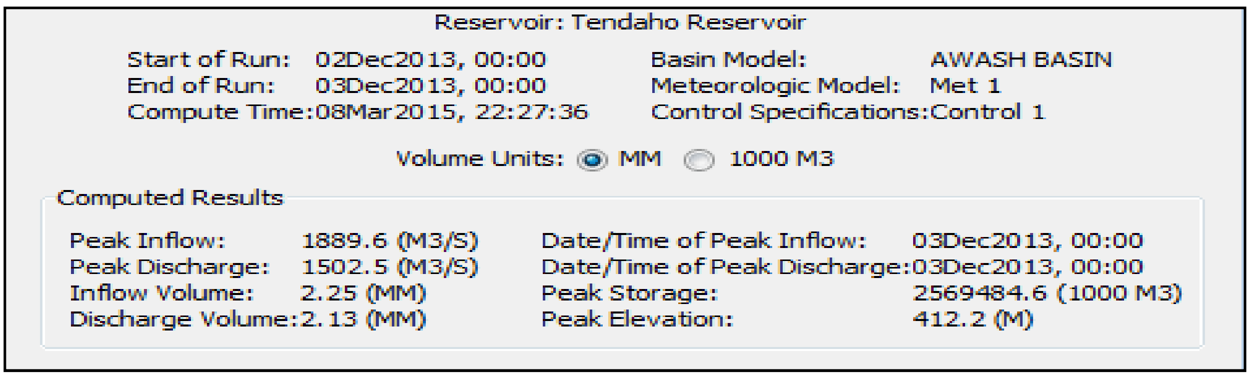

Figure 14: HEC-HMS general summary

4. Conclusion

In this study Tendaho embankment dam spillway adequacy was evaluated under probable maximum flood using HEC-HMS model in concert with ARC-GIS. Tendaho dam catchment was first classified in to four sub basin and from each sub basin six rainfall stations were selected. Using Hershfield (1965) statistical formula PMP was determined for each rainfall stations. After calculating PMP for each station average depth of PMP over an area was calculated by using Thiessen polygon. Tendaho station flow data was used for calibration and validation of HEC-HMS model. Accordingly, five years' flow data, from 1985-1989 was used for model calibration and four years' flow data, from 1990-1993 was used for validation of calibrated parameters. With optimized values of calibrated parameters, the model was simulated under pmp and Peak elevation of 412.2m was observed. As elevation of top of the dam is 412m there would be overtopping of the dam and hence, spillway is inadequate.

5. References

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