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Dam Breach Analysis Using HEC-RAS and HEC-GeoRAS: The Case of Kesem Kebena Dam

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Abstract

Ethiopia has been booming with active construction of dams within the past few decades for different infrastructural needs, but has never experienced demolition or failure of dams in its history; hence little attention is being given to possible breach scenarios of dams and the resulting floodings. This paper makes analysis of the possible breach of kesem dam and the resulting flood inundation. In this study, the dam has been checked for both overtopping and piping failure modes using one dimensional river analysis model called HEC-RAS. Empirical equations were used to predict dam breach parameters of the two failure modes for use in this model. PMF inflow with a peak 9237.77 m^3/s is used as an input to the reservoir to check if overtopping failure was possible. The spill way has proven to have adequate capacity for the flood due to the PMF. Therefore, breaching of the embankment was not possible. Piping failure was also simulated in HEC-RAS and the resulting breach due to piping failure, was analyzed and flood hydrograph was obtained at different cross sections along the river. These are flood hydrographs at 20 km, 40 km and 60 km at the downstream. The resulting flood plain was also mapped using HEC-GeoRas to show the extent of flooding.

Keywords

Dam Breach Analysis, Flood Mapping, HEC-RAS, HEC-GeoRAS

1. Introduction

While dams provide the ability to control the flow of fresh water and function to simplify our lives in many ways, they also pose an inherent and inevitable threat to the environment and to public safety. Since the creation of the first dams, dams have been failing due to unpredictable environmental conditions, poor engineering, or improper management. Unfortunately, when dams fail they often do so catastrophically because of the large amount of potential energy involved.

Dams are complex structures subjected to several forces that can cause failure, these forces are active over the entire life of the dam, and failures of dames controlled or uncontrolled is inevitable. Many efforts have been made to reduce the potential hazard of dams as well as to provide emergency action plans for the event of a dam failure. Dam breach analysis can provide basic information about flood events that can be beneficial in dam engineering, emergency action planning, and floodplain management.

Different organizations and researchers have contributed their findings in the analysis of dam break and its consequence. They have derived regression equations based on data from historical dam failure events that are used in predicting the breach geometry. This includes Macdonald and Langridge Monopolies and Froehlich empirical relations. Development of analytical models using the principle of hydraulics and sediment transport; are also useful in simulating the breach process and downstream flooding.

Kesem dam and irrigation project is located 225 km E of Addis Ababa, Ethiopia and 40 km NW of Metehara town. The Kesem river catchment covers about 3000 km^2 area and extends from an altitude of almost 3600 m down to 860 m a.m.s.l. The project involves 90 m high rock earth fill dam to impound half a billion-cubic meter of water to irrigate 20,000 hectares of land for sugar cane plantation [1]. Since small towns and sugarcane plantations are present downstream of the dam, dam breach analysis should be done as a precaution for reasons that may result due to dam failure.

In Ethiopia, a contrary vigorously engaged in the development of dams, such per event analysis is not being carried out as part of the project by designers or researchers. However, dam breach modelling needs to be customary design procedure to identify the possible causes of dam failure, simulate the breaching process so that design parameters can be reviewed. And in the event of failure map the area that will be flooded to demarcate prone areas while planning the downstream area for various infrastructures, alert concerned bodies to a precaution on dam safety plans and formulate a hazard management system. Therefore, in our current case of Kesem Dam breach analysis a scenario is selected and outflow hydrograph from the breach is routed which results in a flood inundated map on the downstream side of the dam.

2. Materials and Method

The methodology adopted in this study includes, data collection, organization and analysis of data using modeling software.

DATA USED

DEM: Dam breach analysis involves routing the outflow hydrograph from the breached dam throughout downstream of the river from the dam up to the downstream boundary, this will require elevation data of the reservoir and elevation data of the cross section of the river including the flood plain. Digital Elevation Model (DEM) of 30 × 30 is used as a source of elevation data for this study.

LULC: Once a dam breach takes place, the original river cross section on the downstream as well as a large area of flood plain of the river on the left and right side will be inundated and will act as a channel to convey the flood wave as it travels to the downstream. The land use and land cover will define the channel characteristics of the flood plain during flooding. Therefore, the estimation of Manning's channel roughness coefficient is based on land use land cover map of the flood plain on the downstream.

PRECIPTATION: the breaching event is considered during an extreme flood (probable maximum flood/PMF) event entering the reservoir, that results from extreme precipitation scenario obtained from frequency analysis of historical records of precipitation.

SOFTWERE: HEC-RAS and HEC-GoeRAS are used in conjunction for hydraulic modeling.

2.1. Dam Breach Parameter

The estimation of possible breach dimensions and development time is also necessary in any assessment of dam safety since breach parameters will directly and substantially affect the estimate of the flow, inundated areas and warning time at the downstream locations [2].

The available breach parameter and peak breach flow estimation techniques can be classified into three categories, as follows: Comparative analysis, Regression-based methods based on data collected from actual dam failures, and Physically-based simulation models [3]. **Table 1** shows the Regression-based methods of detailed dam breach parameter estimations using Mac Donald and Langirdge-Monopolis and Froehlich's equations.

Agency guidelines are generally in the form of suggested ranges [4] or conservative upper bound estimates. Therefore, they do not appear to be intended for obtaining accurate breach flow estimates. The physically-based embankment dam breach models, such as BREACH [5] and BEED [6] rely on bed-load type

Table 1. MacDonald and Langridge-Monopolis (1984) and Froehlich (2008) empirical equations.

Breach Parameters	MacDonald and Langridge-Monopolis (1984)	Froehlich (2008)
Volume Eroded V_{er} (m^3)	$V_{er} = 0.0261(V_{out} \times h_w)^{0.769}$ (earth fill) $V_{er} = 0.00348(V_{out} \times h_w)^{0.852}$ (rock fill)	
Breach Width B (m)	$B_b = \dfrac{V_{er} - H_b^2\left(CZ_b + \dfrac{H_b Z_b C_3}{3}\right)}{H_b\left(C + \dfrac{H_b Z_3}{2}\right)}$	$B_{avg} = 0.27 K_o V_w^{0.32} H_b^{0.04}$ $K_o = 1.0$ for piping $K_o = 1.3$ for overtopping
Breach Side Slope (H:V)	0.5:1	0.7:1 piping 1.0:1 overtopping

erosion formulas, which may be appropriate for some stages of the breach process, but are not consistent with the mechanics of much of the breaching process as observed in the field or laboratory (Wahl 1988). Therefore, in practice, most widely used methods for predicting breach parameters are based on regression analyses of data collected from dam failures [3].

In this study, the MacDonald and Langridge-Monopolis (1984) and Froehlich (2008) empirical formulas, which are developed from regression analysis of data collected from various dam failure experiences, are used to estimate the Dam breach parameters of Kesem Dam.

2.2. Hydraulic Model Development

2.2.1. HEC-GeoRAS Modeling

HEC-GeoRAS is a set of ArcGIS tool specifically designed to process geospatial data to be used with the Hydrologic Engineering Center's River Analysis System (HEC-RAS) software. The extension allows users to create an HEC-RAS import file containing geometric data from an existing digital elevation model (DEM) [7].

Essential data required to work with HEC-GeoRAS are terrain data (Digital Elevation Model DEM) and land use information. The geometry file for HEC-RAS contains information on cross-sections, hydraulic structures, river banks and other physical attributes of river channels. The pre-processing using HEC-GeoRAS involves creating these attributes in GIS, and then exporting them to the HEC-RAS geometry file. In HEC-GeoRAS, each attribute is stored in a separate feature class called RAS Layer [7]. These RAS layers are added to the map document with a pre-assigned semiology. Since these layers are empty they are populated by digitizing each layer.

The Stream Centerline layer is used to identify the connectivity of the river system. It is created in the downstream direction and is used to assign river stations to the cross sections, bridges, and other structures to order of computational nodes in the HEC-RAS model. The Cross-Sectional Cut Lines layer is the principal data constructed using HEC-GeoRAS. Cut lines are digitized across the floodplain area to capture the profile of the land surface. Cross sections should be digitized perpendicular to the path of flow in the channel and overbank areas to be consistent with one-dimensional flow characteristics. A summary of RAS Layers and their use in building a hydraulic model is provided in **Table 2**, whereas their geometrical orientation is shown in **Figure 1**.

The final task before exporting the GIS data to HEC-RAS geometry file is assigning Manning's n value to individual cross-sections. HEC-GeoRAS accomplishes this by using a land use feature class with Manning's "n" value stored for different land use types. **Figure 2** shows cross section cutline of Kesem River and their corresponding land use.

2.2.2. HEC-RAS Modeling

HEC-RAS is a one-dimensional river hydraulics model used for steady-flow and

Table 2. Summary of HEC-GeoRAS layers and corresponding output for HEC-RAS.

RAS layers	Description
Stream Centerline	Used to identify the connectivity of the river network and assign river stations to computation points.
Cross-Sectional Cut Lines	Used to extract elevation transects from the DEM at specified locations and other cross-sectional properties.
Bank Lines	Used in conjunction with the cut lines to identify the main channel from overbank areas.
Flow Path Centerlines	Used to identify the center of mass of flowin the main channel and overbanks to compute the downstream reach lengths between cross sections.
Land Use	Used to assign flow roughness factors (Manning's *n* values) to the cross sections.
Inline Structures	Used to extract the weir profile from the DEM for inline structures (dams).

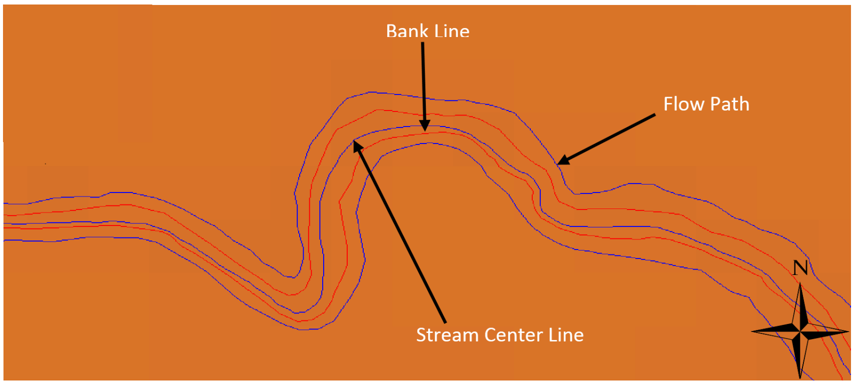

Figure 1. Stream Centerline, Bank Lines and Flow Path layers digitized in HEC-GeoRAS tool.

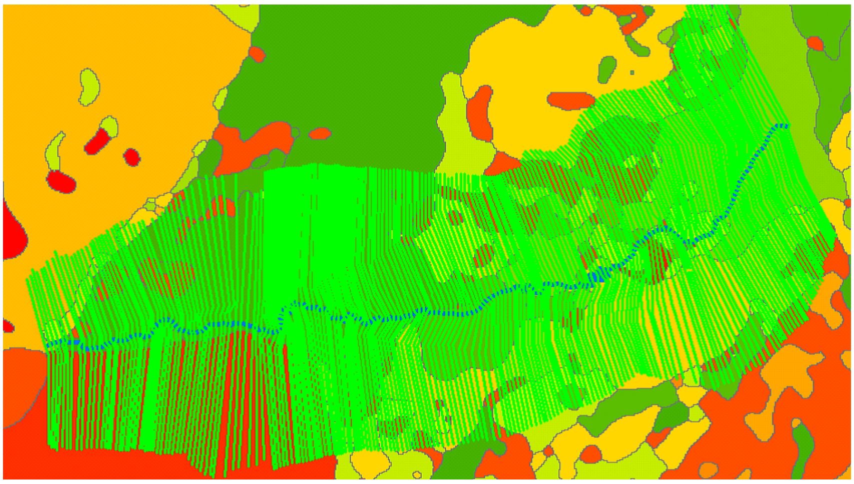

Figure 2. Cross section cut lines of Kesem River and land use layer of the study area.

unsteady-flow water surface profile computations through a network of open channels [8]. Because HEC-RAS solves the full Saint-Venant equations, it is well suited for computing the flood wave propagation resulting from a dam failure scenario [9].

1) Dam Profile

A dam is modeled in HEC-RAS as an inline structure. An inline structure is represented with a weir profile (that includes the spillway). An inline structure can be directly added to HEC-RAS or it can be imported from ARCGIS together with other geometric data. In this study, the inline stricture is imported from ARCGIS.

Inline structure data are entered in HEC-RAS. This data includes a weir/Embankment profile, and any gated spillways that may be modeled [8]. In this study only weir and Embankment profile are entered since the spillway is not gated. **Figure 3** shows profile of Kesem dam as an in-line structure in HEC-RAC.

2) Dam Breach Data

To model dam failure in HEC-RAS Dam Breach parameters (breach shape and formation time) estimated using different empirical formulas and failure mode are entered in HEC-RAS. Since HEC-RAS supports both over toping and piping failure mode, breach parameters estimated for each failure mode is used for dam failure modeling in HEC-RAS. Data entry of breach information for Kesem dam in HEC-RAS is shown in **Figure 4**.

Channel Cross Section data

Cross sections are one of the key inputs to HEC-RAS. Cross sections are digitized in ArcGIS using the HEC-GeoRAS tool and are imported into HEC-RAS along with other geometric data. Cross section cut lines are used to extract elevation data from the terrain to create cross sectional profile across the channel flow [10]. The intersection of cut lines with HEC-GeoRAS layers such as centerline and flow path lines are used to compute HEC-RAS attributes such as bank station (locations that separate channel from flood plain), downstream reach length (distance between cross sections) and Mannings (n) [10]. Cross sections provide useful information such as elevation across the flood plain, station points and Mannings roughness coefficient which are then used for Dam Breach analysis in HEC-RAS. In this study, cross section cut lines are digitized every 200 m along

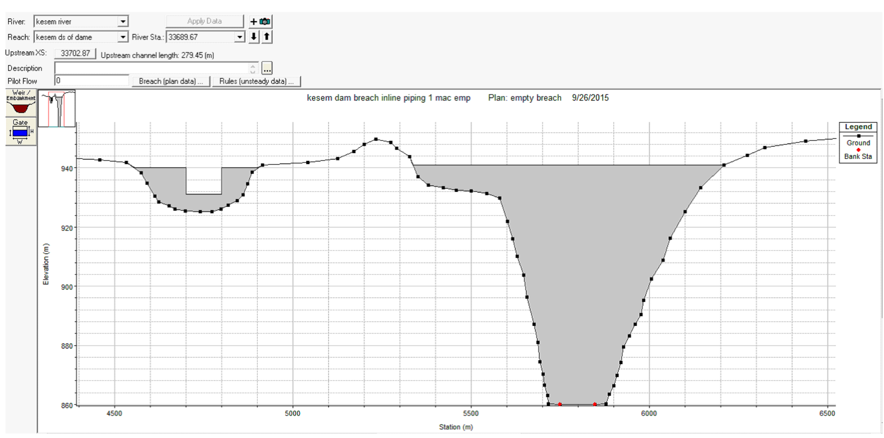

Figure 3. Cross sectional profile of Kesem dam in HEC-RAS.

Figure 4. Dam breach data of Kesem dam in HEC-RAS.

downstream of the river from the dam up to the downstream boundary 60 km from the dam. **Figure 5** shows cross section cutline across Kesem River and other geometric data in HEC-RAS.

3) Unsteady flow analysis

Flood is a typical example of unsteady flow since the stage of the flow changes instantaneously as the flood wave passes by [11]. In this study HEC-RAS is used to simulate unsteady flow throughout the downstream of Kesem River from Kesem dam up to the downstream boundary 60 km from the dam. Once all of the geometric data are entered in to HEC-RAS, required unsteady flow data must be entered to undertake the unsteady flood simulation. Unsteady flow data includes boundary conditions at all of the external boundaries of the system, as well as any desired internal locations, and set the initial flow and storage area condition at the beginning of the simulation. Generally unsteady flow data required are boundary condition and initial condition.

There are different types of boundary conditions some of them are Flow Hydrograph, Stage Hydrograph, Stage and Flow hydrograph, Rating Curve, Normal Depth, Lateral Inflow hydrograph etc. Unsteady flow data used as a boundary condition in this study are PMF Inflow Hydrograph (**Appendix 1**) and Normal depth. The PMF Inflow Hydrograph is used as an upstream boundary condition. Inflow Hydrograph boundary condition of Kesem River and its plot are shown on **Figure 6**. Normal depth is used as a downstream boundary condition. Normal depth can only be used as a downstream boundary condition for an open-ended reach. To use normal depth, it is required to enter a fraction slope for the reach in the vicinity of the boundary. The slope of the water surface is often a good estimate of the friction slope [8].

In addition to the boundary condition, initial condition should be established at the beginning of the unsteady flow simulation. Initial condition consists of flow and stage information at each of the cross sections, as well as elevations for any storage areas defined in the system [8]. Once all the geometric and unsteady flow data have been entered, unsteady flow calculations can be performed.

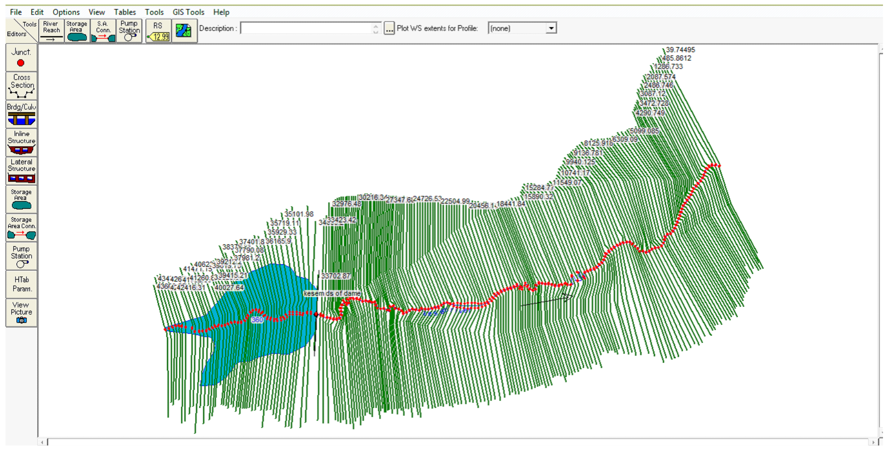

Figure 5. Cross section cutline across Kesem River.

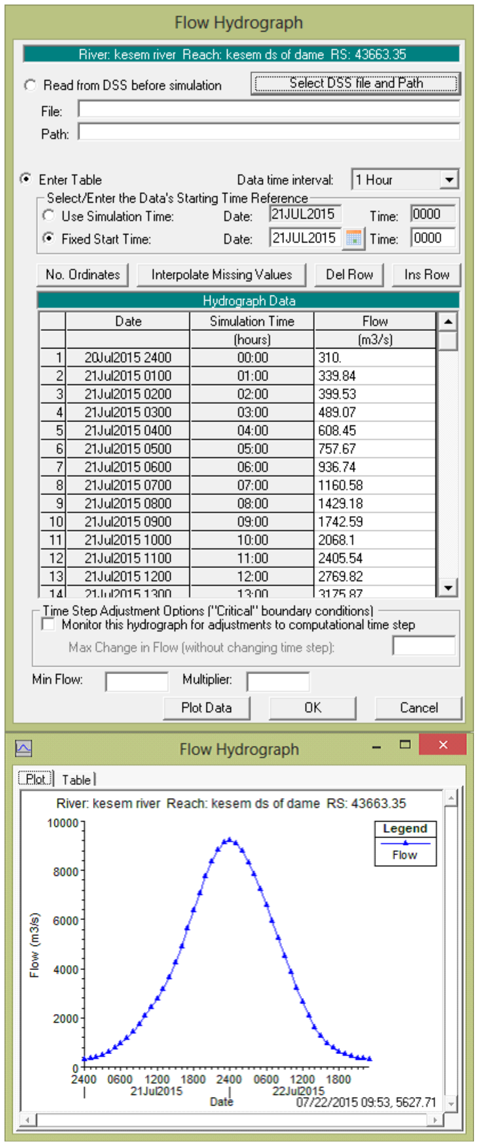

Figure 6. PMF Inflow Hydrograph of Kesem River as an upstream boundary condition in HEC-RAS.

2.3. Flood Plain Mapping

The unsteady flow analysis in HEC-RAS results in water surface elevation at locations from upstream boundary to downstream boundary. This result is used for flood Floodplain mapping which is accomplished in HEC-GeoRAS. The geo-referenced cross sections are imported to HEC-GeoRas and water surface elevations attached to the cross sections are used to create a continuous water surface. The water surface is then compared with the terrain model and the floodplain is identified where the water surface is higher than the terrain. HEC-GeoRAS produces inundation maps for flood extent and depth.

2.4. Model Protocol

As it is shown on the chart Figure 7, the first step in dam breach analysis is selection of dam failure Scenario (overtopping, piping, earthquake, land slide etc.). For the selected failure scenario dam breach parameters are determined using the MacDonald and Langridge-Monopolis (1984) and Froehlich (2008) Empirical relationships. On the other hand, HEC-GeoRAS on ArcGIS platform is used to extract river cross section coordinate data at various points along the river by

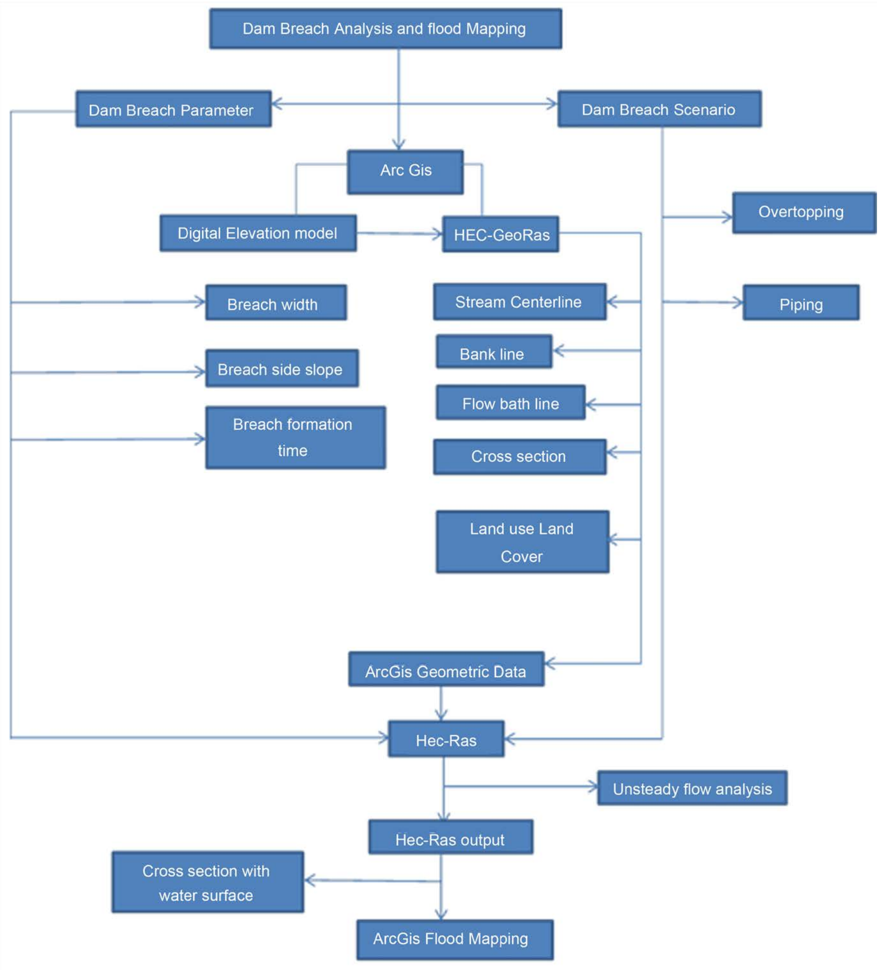

Figure 7. Summary of the methodology of Dam Breach Analysis.

making use of the digital elevation model of the anticipated flood plain. This extracted coordinates are used to generate geometrical cross sections of river at various points along the river. The cross-sectional data obtained is used for unsteady flow analysis in HEC-RAS. After unsteady flow analysis, the output from HEC-RAS which contains water surface elevations at individual cross-sectional points attached to them; is imported into ArcGIS and is used to prepare a flood map.

3. Results and Discussion

Estimating the dam breach parameters is one of the most important things that have to be done before dam breach analysis is simulated. Both MacDonald and Langridge-Monopolis (1984) and Froehlich (2008) are used to estimate breach parameters. The modes of failure for this dam are assumed to be overtopping and piping type of failure.

Breach parameters are estimated for both overtopping and piping and are used as an input for HEC-RAS. These are dam breach parameters breach width, breach side slope and breach formation time which are used as a geometric data during unsteady flow analysis. Results of dam breach parameter calculations for overtopping and piping failure mode for both MacDonald and Langridge-Monopolis (1984) and Froehlich (2008) methods are as follows.

Overtopping: Froehlich (2008):

Average breach width,

$$B_{avg} = 0.27 K_o V_w^{0.32} H_b^{0.04}$$

$$B_{avg} = 215.14 \text{ m}$$

Breach formation time,

$$t_f = 63.2\sqrt{\frac{V_W}{gH_b^2}} = 1.982 \text{ hrs}$$

Overtopping: MacDonald and Langridge-Monopolis (1984)

Volume of material eroded from the dam embankment,

$$V_{eroded} = 0.00348\left(V_{out} * H_w\right)^{0.852}$$

$$V_{eroded} = 3664595.25 \text{ m}^3$$

Bottom Width of the breach,

$$B_b = \frac{V_{er} - H_b^2\left(CZ_b + \frac{H_b Z_b C_3}{3}\right)}{H_b\left(C + \frac{H_b Z_3}{2}\right)}$$

$$B_b = 356.13 \text{ m}$$

Breach formation time

$$t_f = 0.0178\left(V_{eroded}\right)^{0.364}$$

$$t_f = 4.36 \text{ hrs}$$

Piping: Froehlich (2008):

Average breach width,

$$B_{avg} = 0.27 K_o V_w^{0.32} H_b^{0.04}$$

$$B_{avg} = 192.93 \text{ m}$$

Breach formation time,

$$t_f = 63.2 V_w * g H_b^2$$

$$t_f = 1.535 \text{ hrs}$$

Piping: MacDonald and Langridge-Monopolis (1984)

Volume of material eroded from the dam embankment,

$$V_{eroded} = 0.00348 \left(V_{out} * H_w\right)^{0.852}$$

$$V_{eroded} = 2536087.89 \text{ m}^3$$

Bottom Width of the breach

$$B_b = \frac{V_{er} - H_b^2 \left(CZ_b + \frac{H_b Z_b C_3}{3}\right)}{H_b \left(C + \frac{H_b Z_3}{2}\right)}$$

$$B_b = 148.7 \text{ m}$$

Breach formation time

$$t_f = 0.0178 \left(V_{eroded}\right)^{0.364}$$

$$t_f = 3.81 \text{ hrs}$$

Summary of dam breach parameters using Macdonald and Langridge-Monopolis and Froehlich's method is presented in Table 3 for Kesem-Kebena Dam.

Breach parameter from one of the methods is selected Based on the results from unsteady flow analysis, envelop curve and peak outflow regression equations.

Table 3. Summary of estimated breach parameters.

Table Overtopping		
Dam breach parameters	**Froehlich (2008)**	**Macdonald and Langridge-Monopolis (1984)**
Breach bottom width	215.14 m	356.13 m
Breach side slope	1.0:1	0.5:1
Breach formation time	1.982 hrs	4.36 hrs
	Piping	
Breach bottom width	136.95 m	148.7 m
Breach side slope	0.7:1	0.5:1
Breach formation time	1.535 hrs	3.81 hrs

3.1. Unsteady Flow Analysis

Unsteady flow analysis is the basic part of dam breach analysis where PMF flood hydrograph entering in to the reservoir is routed as it passes through the reservoir to the crest of the dam or the breach section. Further routing is also done as the flood wave travels to the downstream boundary section of the river. Area elevation curve has been developed and used for reservoir routing (Appendix 2), whereas channel geometry obtained from Hec-GeoRas was used for channel routing. After entering initial conditions and boundary conditions for the farthest upstream and downstream cross sections in to HEC-RAS; unsteady flow simulation can be initiated. In the unsteady flow analysis of this study; PMF inflow hydrograph of Kesem River and normal depth of the farthest downstream vicinity are used as a boundary condition whereas, initial flow and elevation for the storage area are used as initial conditions.

Unsteady flow analysis of overtopping

Unsteady flow simulation of overtopping failure in HEC-RAS requires PMF inflow hydrograph as an upstream boundary condition. Overtopping failure occurs when the flood due to the PMF inflow passes over the embankment.

Flood resulting from the PMF of Kesem River did not overtop the dam during unsteady flow simulation. The PMF raised the reservoir water surface elevation only to 939 m which is 2 m below the dam crest. Figure 8 shows the maximum water surface elevation on the dam profile during unsteady flow simulation.

3.2. Unsteady Flow Analysis of Piping

Unsteady flow analysis due to piping of Kesem dam in HEC-RAS is done after entering the necessary data for the simulation to begin. Dam breach parameters and boundary conditions in this case are the necessary data that are used as an

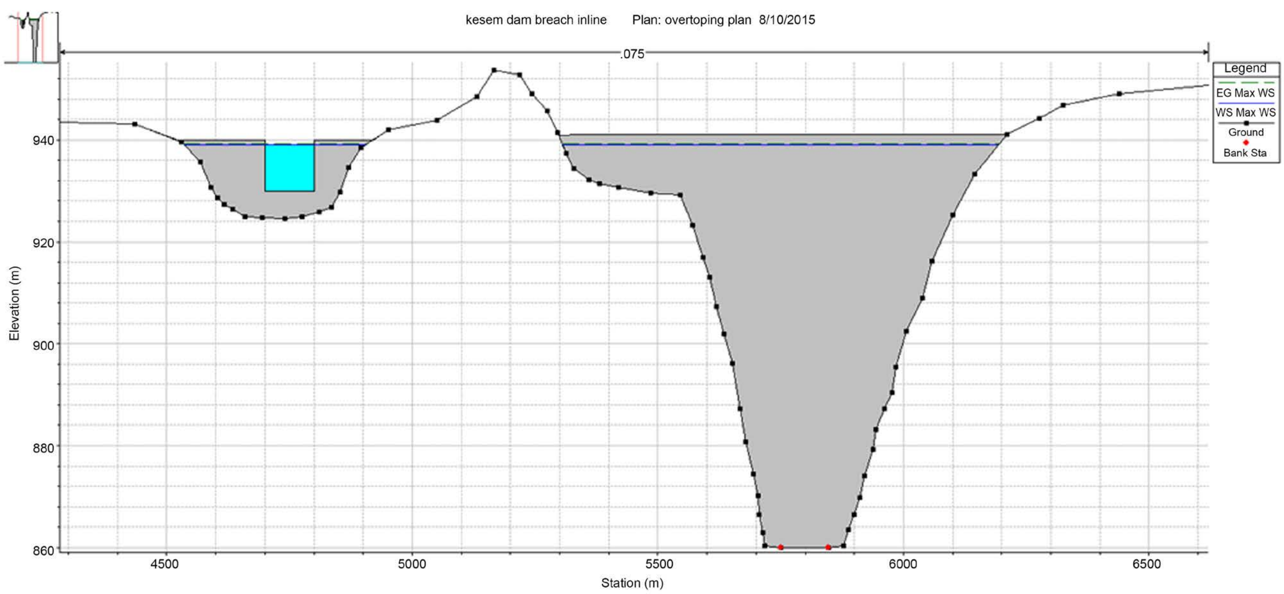

Figure 8. Kesem Dam with maximum water surface.

input in to HEC-RAS. For comparison two empirical formulas MacDonald and Langridge-Monopolis (1984) and Froehlich (2008) are used to estimate breach parameters. Unsteady flow analysis of piping in HEC-RAS is done for both methods.

The starting water surface elevation for piping is taken at the crest of the spillway, since the spill way is only used during flood events. Figure 9 shows water surface elevation before piping begins.

Using breach parameters from Froehlich (2008) and MacDonald and Langridge-Monopolis (1984) for unsteady flow analysis in HEC-RAS out flow hydrograph from the breached dam and hydrograph at every cross section are obtained after the unsteady flow simulation. Figure 10 and Figure 11 shows hydrographs at the inline structure and at 20 km, 40 km and 60 km from the dam for both Froehlich (2008) and MacDonald and Langridge-Monopolis (1984) respectively.

Both Froehlich (2008) and MacDonald and Langridge-Monopolis (1984) have their own importance, Froehlich (2008) differentiate between piping and overtopping and MacDonald and Langridge-Monopolis (1984) differentiate between earth fill dam and rock fill dam. Breach parameters from both equations are more or less similar but breach formation time which is one of the parameters is 1.535 hrs for Froehlich (2008) and 3.81 hrs for MacDonald and Langridge-Monopolis (1984). This makes the magnitude of the pick outflow diminish and the out flow flood to take longer time to pass through the breach in case of MacDonald and Langridge-Monopolis (1984). Figure 12 shows the difference between breach out flow hydrographs using Froehlich (2008) and MacDonald and Langridge-Monopolis (1984).

After unsteady flow analysis due to piping is simulated in HEC-RAS, The result can show the breach on the inline structure and water surface profile of Kesem

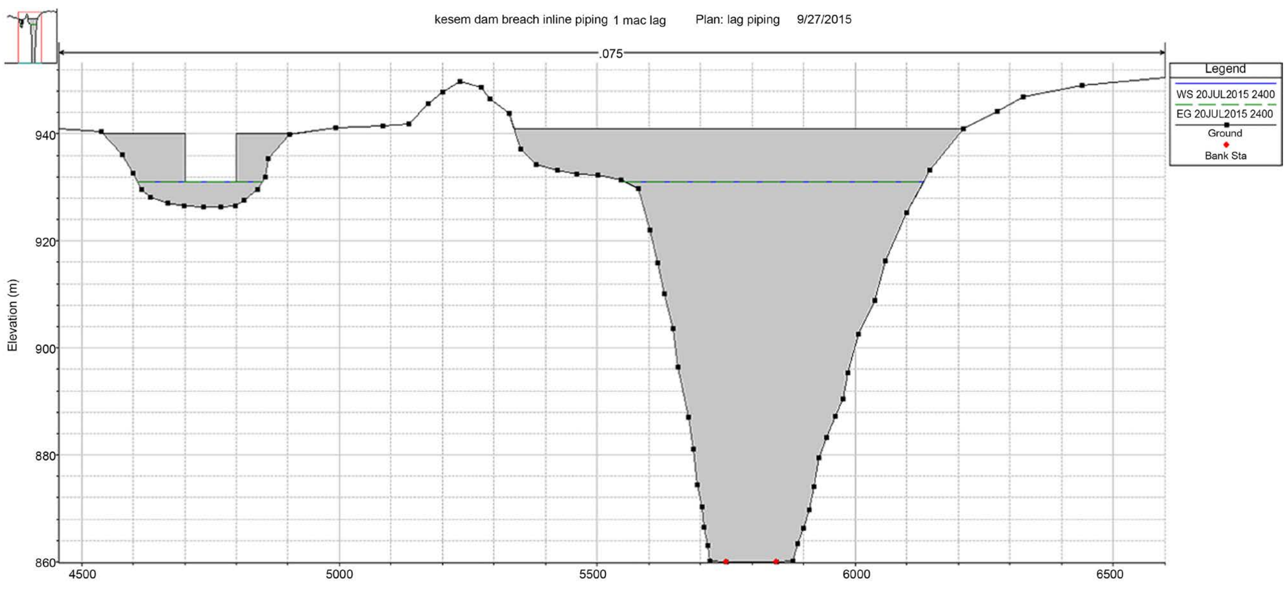

Figure 9. Kesem dam profile with water surface profile at the spillway crust level.

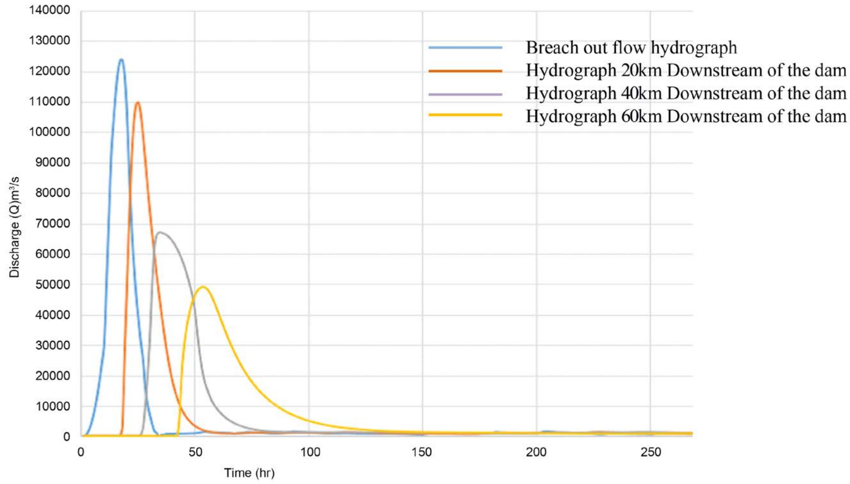

Figure 10. Hydrographs after unsteady flow analysis using Froehlich (2008).

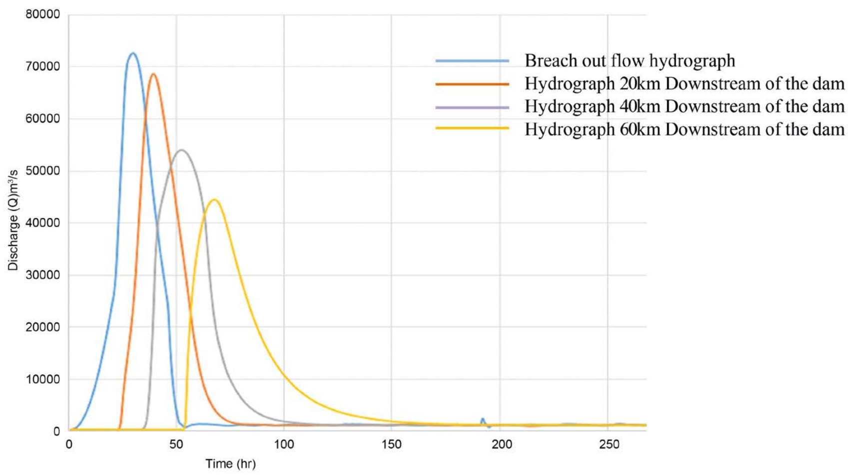

Figure 11. Hydrographs after unsteady flow analysis using MacDonald and Langridge-Monopolis (1984).

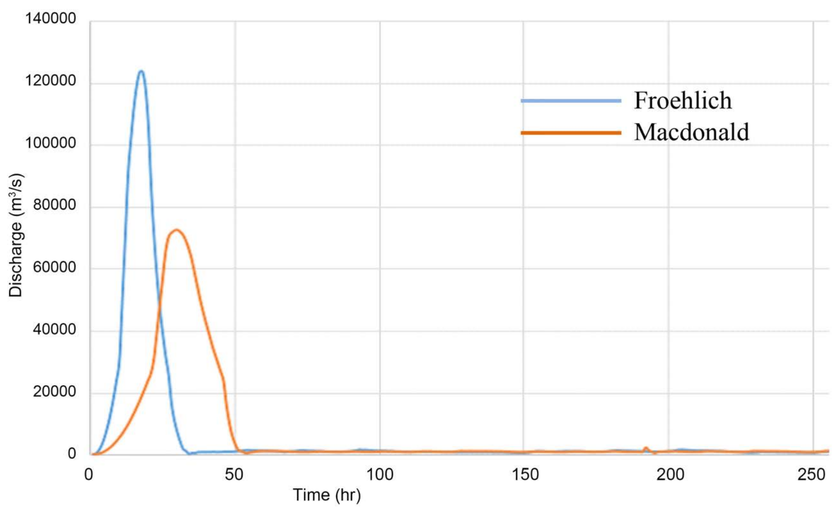

Figure 12. Breach out flow hydrograph of Froehlich (2008) and MacDonald and Langridge-Monopolis (1984).

River. Figure 13 and Figure 14 shows breach on Kesem dam and water surface profile of Kesem River.

3.3. Peak Flow Equations and Envelop Curve

The computed peak outflow from the HEC-RAS model for both Froehlich (2008) (Q_p = 123,685.8 m^3/s) and MacDonald and Langridge Monopolis (1984) (Q_p = 72,670.8 m^3/s) are compered to Peak outflow regression equations as a test for reasonableness. Several researchers have developed equations from historical dam failure data. The equations developed are only used for comparison purpose.

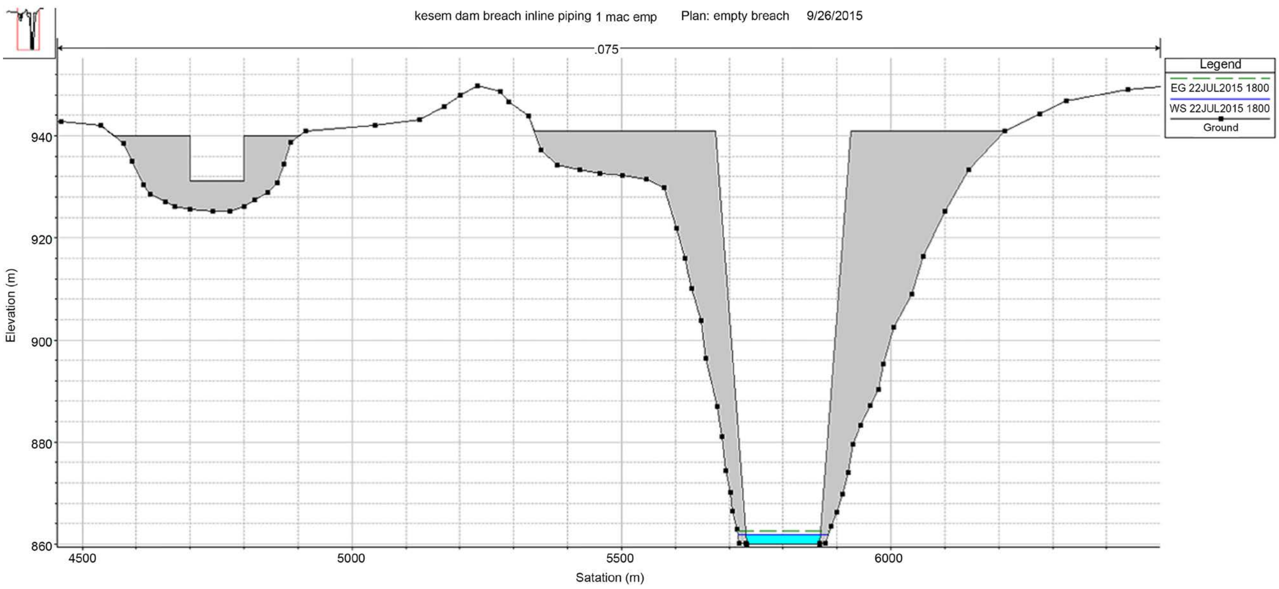

Figure 13. Kesem dam profile after the breach.

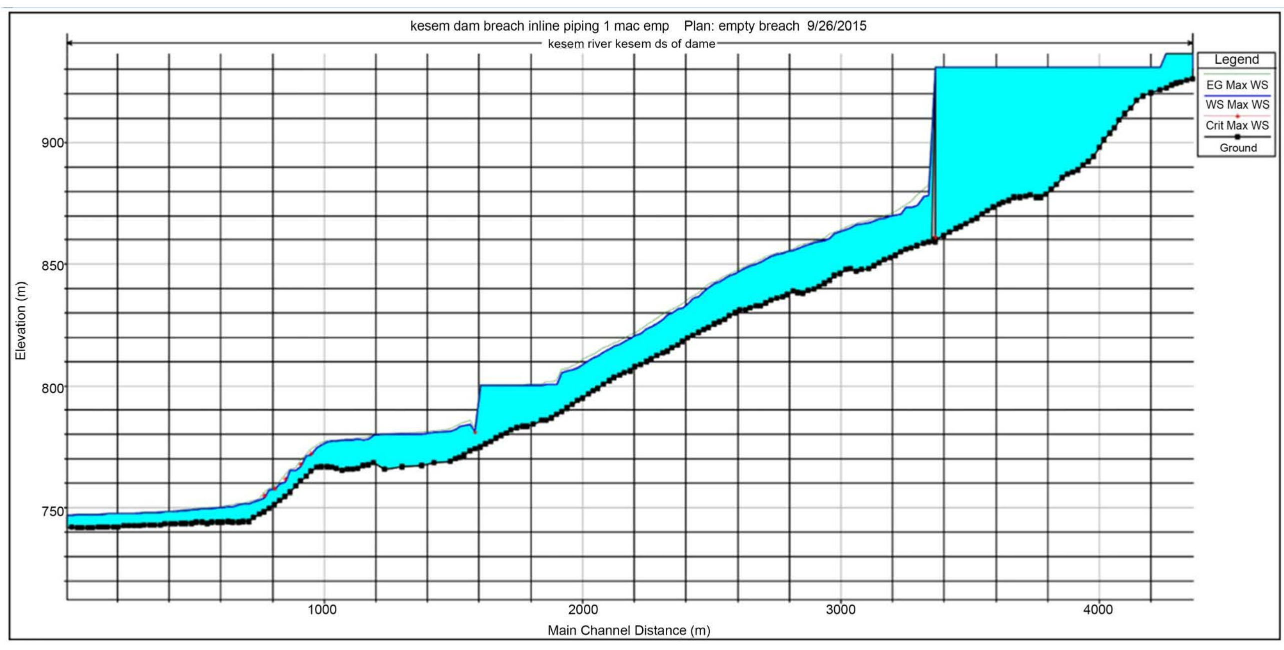

Figure 14. Water surface profile of Kesem River.

Shown below is peak outflow equations and there resulting peak outflow for Kesem dam breach.

- USBR (1982): $Q = 19.1\left(h_w\right)^{1.85} = 49483\ \text{m}^3$

  h_w—Depth of water above the breach invert at time of breach (70 m)
- MacDonald and Langridge Monopolis (1984):

  $Q = 3.85\left(V_w h_w\right)^{0.411} = 81618.04\ \text{m}^3$

  V_w—volume of water above the breach invert (480 Mm^3)
- Soil conservation service (SCS, 1981): $Q = 16.6\left(h_w\right)^{1.85} = 43007.03\ \text{m}^3$
- Hagen (1982): $Q = 0.54\left(Sh_d\right)^{0.5} = 106477.265\ \text{m}^3$

  S—Reservoir storage for water surface elevation at breach time (480 M^3)

  h_d—height of the dam (81 m)
- Singh and Snorrason (1984): $Q = 13.4\left(h_d\right)^{1.89} = 54217.794\ \text{m}^3$
- Costa (1985): $Q = 1.122\left(S\right)^{0.57} = 99609.41\ \text{m}^3$

Peak outflow obtained from the HEC-RAS model using breach parameters from Macdonald and Langridge Monopolis (1984) is closer to peak outflow from regression equations when compared to peak outflow Obtained from the model using breach parameters from Froehlich (2008). Peak outflow from the model using breach parameters from Macdonald and Langridge Monopolis (1984) have an average error of 0.3 when compared with results from peak outflow regression equations whereas peak outflow from the model using breach parameters from Froehlich (2008) have an average error of 0.4 when compared with results from peak outflow regression equations.

Froehlich (2008) Q_p—4,271,521.367 cfs (120,000 m^3/s).

Macdonald and Langridge Monopolis (1984) Q_p—2,272,026.669 cfs (74,000 m^3/s).

Hydraulic Depth 230 ft.

In addition to the peak flow equations, the model peak outflow can also be compared to envelop curve of historical failure. Figure 15 shows the envelop curve and where peak outflows from the model lay on the envelop curve; while using breach parameters from both Macdonald and Langridge Monopolis (1984) and Froehlich (2008).

Peak outflow obtained from the HEC-RAS model using breach parameters from Macdonald and Langridge Monopolis (1984) lays in the envelop curve but peak outflow obtained from HEC-RAS using breach parameters from Froehlich (2008) lays outside of the curve. This shows that breach parameters obtained from Macdonald and Langridge Monopolis (1984) is more conservative than breach parameters obtained from Froehlich (2008) therefore it is selected for analysis. Breach outflow hydrograph has been presented in Appendix 3.

3.4. Flood Mapping

Flood mapping is the final step in dam breach analysis. In this study, the HEC-GeoRAS tool in GIS performs the flood mapping process in GIS. The flood map shows the maximum water surface and up to where this maximum water

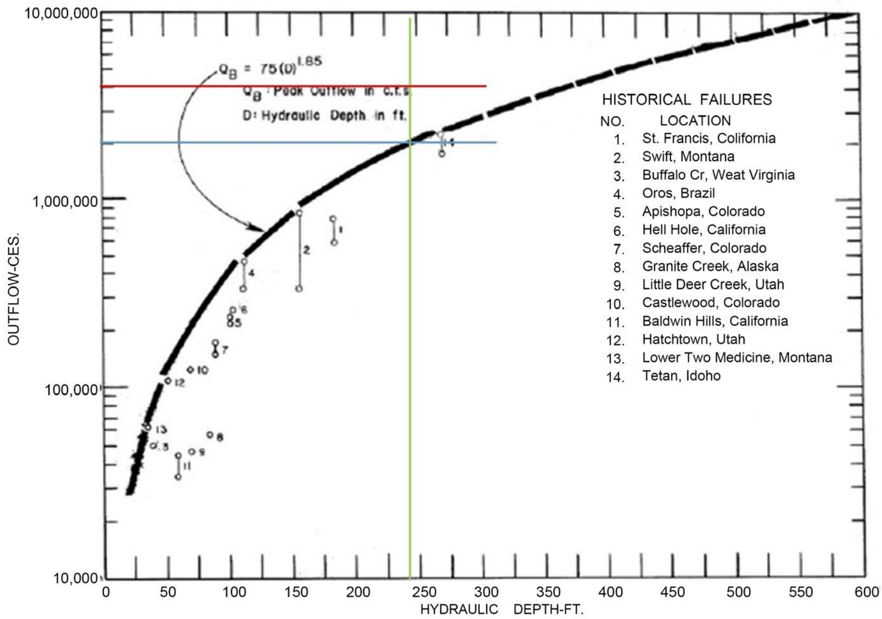

Figure 15. Peak outflow envelop curve of Historical dam failures.

surface extends on the flood plain. The flood map is created on a type of DEM called TIN which is derived from a raster DEM. Once the flood map is created it can be shown on the TIN itself or on an aerial map of the study area. Since peak outflow from HEC-RAS using breach parameters from Macdonald and Langridge Monopolis (1984) is more accurate when compared with results of peak outflow regression equations and lays inside the envelop curve, water surface elevations obtained using breach parameters from Macdonald and Langridge Monopolis (1984) are used for the mapping process. Figure 16 shows map of the flood due to piping of Kesem Dam on a TIN and Figure 17 shows map of flood due to piping of Kesem dam on an aerial map.

The flood map covers 183 km^2 of land which is under water. The map shows different water surface elevations, differentiating them with color.

As seen from the flood map that is overlain on areal map of the study area Sabure Town and Alibete village are affected by the flood.

The water surface profile can also be displayed on the XYZ perspective plot in HEC-RAS. Figure 18 shows the XYZ perspective plot for unsteady flow analysis of Kesem River.

4. Conclusions and Recommendation

4.1. Conclusions

Dam breach is modeled after selecting a failure scenario. Failure scenarios selected for this study are overtopping and piping, because most historical dam failures are due to those types of failure scenario. In this study, Kesem dam can safely pass the PMF inflow of Kesem River without overtopping the embankment; this is because the dam has adequate spillway capacity and free board.

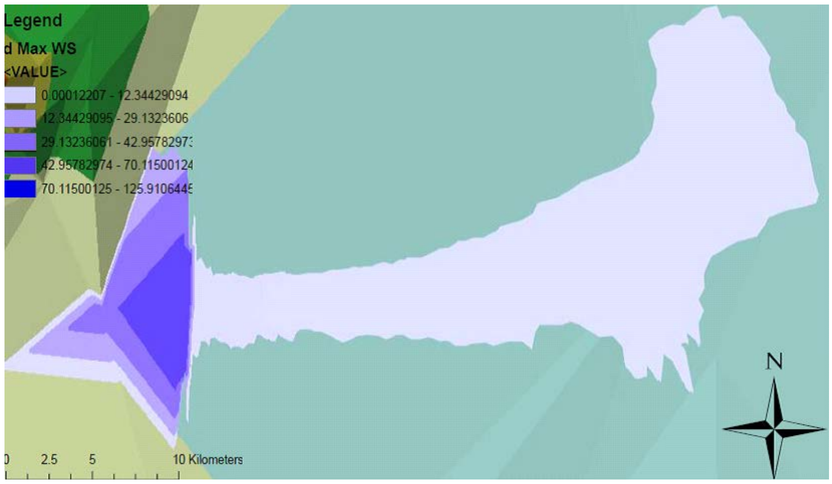

Figure 16. Flood map on a TIN derived from DEM.

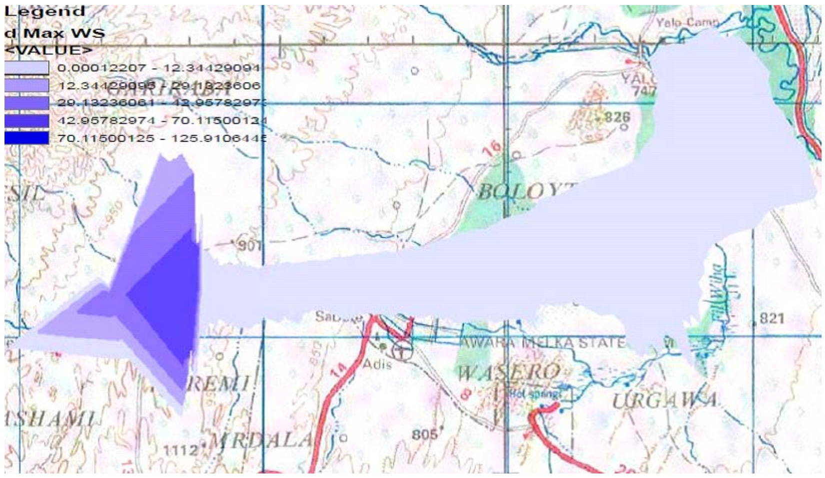

Figure 17. Flood map on an aerial map of the study area.

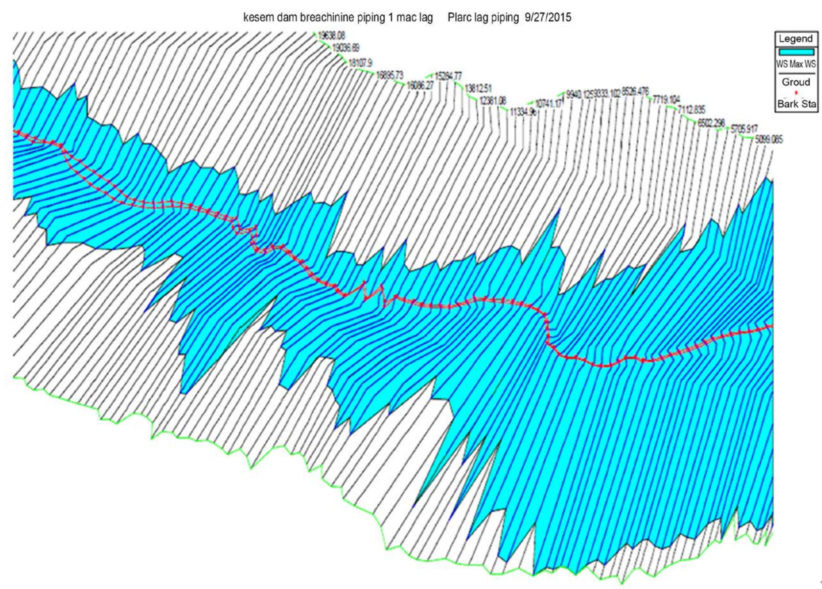

Figure 18. Perspective plot of water surface profile in HEC-RAS.

Empirical formulas are used to predict the breach parameters of Kesem dam. Froehlich (2008) and MacDonald and Langridge-Monopolis (1984) are used to estimate the breach parameter, where in turn the breach parameters are used for unsteady flow calculations in HEC-RAS. When peak outflow obtained with this empirical equations were compared to peak outflow empirical equations and peak out flow envelop curve from historical dam failure, MacDonald and Langridge-Monopolis (1984) was found to be more conservative and reliable as can be seen in the result. Peak outflow obtained using MacDonald and Langridge-Monopolis (1984) have an error of 0.3 when compared to peak outflow equations and lays inside the peak outflow envelop curve. Peak outflow obtained using Froehlich (2008) have an error of 0.4 when compared to peak outflow empirical equations from historical failure and lays outside the peak outflow envelop curve. Hence, Peak outflow using MacDonald and Langridge-Monopolis (1984) was chosen for unsteady flow analysis in HEC-RAS and Inundation Mapping in ArcGIS.

From the plotted flood map on ARCGIS TIN and aerial map, it can be seen that the flood affects 18,300 hectares of area. The XYZ plot also shows the extent of the water surface on the cross sections. The XYZ perspective plot in HEC-RAS and the flood map on ARCGIS are somewhat different, this is because HEC-RAS only sees elevation deferens on the cross sections not in between the cross sections but it is a different case for ARCGIS it can see elevation difference everywhere depending on the quality of DEM. From the map, it can be concluded the flood from the dam breach covers Sabure town, Alibete village and irrigation farms.

4.2. Recommendation

Although there are number of dams for hydropower, irrigation and water supply in Ethiopia, dam breach analysis has been given very little and/or no attention in the country. But it is very essential towards mitigating loss of life and property due to the flood from the dam breach. In the future, more studies on dam breach analysis will need be done in this country. Possible infrastructural developments in the towns affected by flooding during the event of dam breach, needs to account for possible emergency conditions. This may include adequate water ways for construction of bridges. Emergency drills might also need to be prepared for these conditions by the concerned flood management and mitigation offices.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix 1

PMF inflow hydrograph of the entire catchment

Direct surface runoff Hydrograph	Base Flow	PMF Hydrograph
(m^3/s)	(m^3/s)	(m^3/s)
0	310	310
29.8448	310	339.8448
89.5344	310	399.5344
179.0688	310	489.0688
298.448	310	608.448
447.672	310	757.672
626.7408	310	936.7408
850.5768	310	1160.5768
1119.18	310	1429.18
1432.5872	310	1742.5872
1758.1016	310	2068.1016
2095.5392	310	2405.5392
2459.8224	310	2769.8224
2865.8736	310	3175.8736
3343.5376	310	3653.5376
3922.6776	310	4232.6776
4594.4064	310	4904.4064
5328.7872	310	5638.7872
6066.1488	310	6376.1488
6767.7592	310	7077.7592
7433.5448	310	7743.5448
8024.792	310	8334.792
8502.7136	310	8812.7136
8819.6352	310	9129.6352
8927.772	310	9237.772
8791.1704	310	9101.1704
8457.284	310	8767.284
8021.5168	310	8331.5168
7508.0464	310	7818.0464
6916.9464	310	7226.9464
6272.008	310	6582.008
5606.0936	310	5916.0936
4919.2952	310	5229.2952
4211.576	310	4521.576

Continued

3539.516	310	3849.516
2903.2992	310	3213.2992
2311.8864	310	2621.8864
1774.2384	310	2084.2384
1308.2768	310	1618.2768
931.9232	310	1241.9232
654.1384	310	964.1384
457.0008	310	767.0008
304.6672	310	614.6672
188.1768	310	498.1768
107.5296	310	417.5296
53.7648	310	363.7648
17.9216	310	327.9216
0	310	310

Appendix 2

Elevation, area and capacity relationship of Kesem Reservoir

Elevation	Original Area	Original Capacity
(m)	(km^2)	(MCM)
930	28.66	480
928	26.38	410
926	24.5	365
924	21.29	324
922	19	285
920	16.5	248
918	13.86	216
916	12.7	190
914	11.29	165
912	10.1	143
910	9.45	124.7
909	8.9	113.6
908	8.34	103
906	7.76	89
904	6.73	74.68
902	5.68	61.8
900	5.1	52
898	4.18	40.4

Continued

896	3.78	35.72
894	2.98	27.26
892	2.29	20.67
890	2	17.8
888	1.62	13.3
886	1.38	11.56
884	1.06	8.51
882	0.84	6.13
880	0.68	5.1
878	0.5	3.6
876	0.42	3.07
874	0.32	2.4
872	0.28	2
870	0.22	1.7
868	0.18	1.4
866	0.14	0.9
864	0.09	0.5
862	0.05	0.2
860	0	0

Appendix 3

Breach outflow hydrograph using Dam breach parameters from Macdonald and Langridge-Monopolis

River: kesem river Reach: kesem ds of dame RS: 33702.87			
		Stage	Flow
	Date	INST-VAL	INST-VAL
		METERS	M3/S
1	20 Jul 2015 2400	931.11	310.38
2	21 Jul 2015 0005	931.1	374.29
3	21 Jul 2015 0010	931.1	578.74
4	21 Jul 2015 0015	930.96	869.59
5	21 Jul 2015 0020	930.94	1356.96
6	21 Jul 2015 0025	930.91	1976.62
7	21 Jul 2015 0030	930.8	2710.48
8	21 Jul 2015 0035	930.72	3596.91
9	21 Jul 2015 0040	930.63	4621.29
10	21 Jul 2015 0045	930.51	5775.41

Continued

11	21 Jul 2015 0050	930.37	7062.89
12	21 Jul 2015 0055	930.22	8489.24
13	21 Jul 2015 0100	930.05	10052.16
14	21 Jul 2015 0105	929.84	11761.06
15	21 Jul 2015 0110	929.62	13597.78
16	21 Jul 2015 0115	929.38	15555.28
17	21 Jul 2015 0120	929.11	17626.51
18	21 Jul 2015 0125	928.79	19799.97
19	21 Jul 2015 0130	928.43	22069.26
20	21 Jul 2015 0135	928.03	24426.03
21	21 Jul 2015 0140	927.56	26855.79
22	21 Jul 2015 0145	926.94	31987.12
23	21 Jul 2015 0150	926.15	40679.11
24	21 Jul 2015 0155	925.18	49383.71
25	21 Jul 2015 0200	923.94	58048.04
26	21 Jul 2015 0205	922.39	66360.09
27	21 Jul 2015 0210	920.77	70518.41
28	21 Jul 2015 0215	919	71827.07
29	21 Jul 2015 0220	917.05	72507.2
30	21 Jul 2015 0225	914.98	72670.8
31	21 Jul 2015 0230	912.69	72060.66
32	21 Jul 2015 0235	910.31	70956.92
33	21 Jul 2015 0240	907.7	69005.88
34	21 Jul 2015 0245	904.94	66326.91
35	21 Jul 2015 0250	902.12	63007.54
36	21 Jul 2015 0255	898.97	58404.44
37	21 Jul 2015 0300	895.99	54035
38	21 Jul 2015 0305	893.06	49642.19
39	21 Jul 2015 0310	890.35	45789.22
40	21 Jul 2015 0315	887.76	42212.87
41	21 Jul 2015 0320	885.31	38952.82
42	21 Jul 2015 0325	882.79	35372.93
43	21 Jul 2015 0330	880.47	32440.87
44	21 Jul 2015 0335	878.17	29578.76
45	21 Jul 2015 0340	875.86	26768.61
46	21 Jul 2015 0345	873.4	23476.48
47	21 Jul 2015 0350	869.89	15720.35
48	21 Jul 2015 0355	867.88	10014.62

Continued

49	21 Jul 2015 0400	866.07	6045.1
50	21 Jul 2015 0405	864.64	3535.43
51	21 Jul 2015 0410	863.21	1721.92
52	21 Jul 2015 0415	862.64	1327.31
53	21 Jul 2015 0420	862.09	898.59
54	21 Jul 2015 0425	861.67	694.05
55	21 Jul 2015 0430	861.89	886.06
56	21 Jul 2015 0435	862.09	1047.58
57	21 Jul 2015 0440	862.3	1205.06
58	21 Jul 2015 0445	862.39	1251.99
59	21 Jul 2015 0450	862.47	1306.7
60	21 Jul 2015 0455	862.53	1359.26
61	21 Jul 2015 0500	862.52	1356.58
62	21 Jul 2015 0505	862.51	1332.41
63	21 Jul 2015 0510	862.53	1352.1
64	21 Jul 2015 0515	862.52	1347.25
65	21 Jul 2015 0520	862.48	1308.87
66	21 Jul 2015 0525	862.46	1287.09
67	21 Jul 2015 0530	862.43	1261.57
68	21 Jul 2015 0535	862.38	1220.29
69	21 Jul 2015 0540	862.34	1184.29
70	21 Jul 2015 0545	862.3	1153.84
71	21 Jul 2015 0550	862.24	1105.64
72	21 Jul 2015 0555	862.2	1070.1
73	21 Jul 2015 0600	862.15	1031.57
74	21 Jul 2015 0605	862.13	1028.98
75	21 Jul 2015 0610	862.14	1043.06
76	21 Jul 2015 0615	862.18	1070.46
77	21 Jul 2015 0620	862.23	1109.82
78	21 Jul 2015 0625	862.28	1152.61
79	21 Jul 2015 0630	862.33	1200.05
80	21 Jul 2015 0635	862.32	1169.85
81	21 Jul 2015 0640	862.33	1180.37
82	21 Jul 2015 0645	862.28	1145.93
83	21 Jul 2015 0650	862.24	1107.26
84	21 Jul 2015 0655	862.21	1083.91
85	21 Jul 2015 0700	862.17	1056.29
86	21 Jul 2015 0705	862.16	1048.39

Continued

87	21 Jul 2015 0710	862.18	1063.81
88	21 Jul 2015 0715	862.21	1093.6
89	21 Jul 2015 0720	862.26	1135.72
90	21 Jul 2015 0725	862.32	1184.81
91	21 Jul 2015 0730	862.38	1237.38
92	21 Jul 2015 0735	862.33	1186.78
93	21 Jul 2015 0740	862.31	1159.45
94	21 Jul 2015 0745	862.28	1138.83
95	21 Jul 2015 0750	862.21	1081.49
96	21 Jul 2015 0755	862.19	1065.51
97	21 Jul 2015 0800	862.22	1098.28
98	21 Jul 2015 0805	862.24	1125.08
99	21 Jul 2015 0810	862.27	1154.2
100	21 Jul 2015 0815	862.32	1189.79
101	21 Jul 2015 0820	862.36	1203.24
102	21 Jul 2015 0825	862.39	1239.8
103	21 Jul 2015 0830	862.34	1189.02
104	21 Jul 2015 0835	862.34	1185.65
105	21 Jul 2015 0840	862.32	1180.21
106	21 Jul 2015 0845	862.26	1115.59
107	21 Jul 2015 0850	862.25	1116.69
108	21 Jul 2015 0855	862.2	1077.62
109	21 Jul 2015 0900	862.16	1045.45
110	21 Jul 2015 0905	862.16	1047.28
111	21 Jul 2015 0910	862.17	1062.06
112	21 Jul 2015 0915	862.2	1091.1
113	21 Jul 2015 0920	862.26	1135.14
114	21 Jul 2015 0925	862.33	1193.92
115	21 Jul 2015 0930	862.41	1262.85
116	21 Jul 2015 0935	862.4	1239.02
117	21 Jul 2015 0940	862.39	1234.2
118	21 Jul 2015 0945	862.38	1228.04
119	21 Jul 2015 0950	862.33	1179.25
120	21 Jul 2015 0955	862.32	1168.09
121	21 Jul 2015 1000	862.28	1142.63
122	21 Jul 2015 1005	862.23	1090.23
123	21 Jul 2015 1010	862.2	1074.96
124	21 Jul 2015 1015	862.21	1087.06

Continued

125	21 Jul 2015 1020	862.25	1124.84
126	21 Jul 2015 1025	862.31	1179.77
127	21 Jul 2015 1030	862.39	1257.12
128	21 Jul 2015 1035	862.5	1343.31
129	21 Jul 2015 1040	862.49	1329.45
130	21 Jul 2015 1045	862.48	1303.25
131	21 Jul 2015 1050	862.51	1332.42
132	21 Jul 2015 1055	862.5	1334.69
133	21 Jul 2015 1100	862.48	1303.78
134	21 Jul 2015 1105	862.48	1308.06
135	21 Jul 2015 1110	862.48	1314.37
136	21 Jul 2015 1115	862.46	1292.16
137	21 Jul 2015 1120	862.45	1280.61
138	21 Jul 2015 1125	862.45	1283.41
139	21 Jul 2015 1130	862.43	1264.07
140	21 Jul 2015 1135	862.41	1244.88
141	21 Jul 2015 1140	862.4	1240.62
142	21 Jul 2015 1145	862.37	1214.39
143	21 Jul 2015 1150	862.34	1188.82
144	21 Jul 2015 1155	862.31	1169.88
145	21 Jul 2015 1200	862.27	1129.77
146	21 Jul 2015 1205	862.23	1100.87
147	21 Jul 2015 1210	862.19	1064.1
148	21 Jul 2015 1215	862.14	1029.75
149	21 Jul 2015 1220	862.13	1027.37
150	21 Jul 2015 1225	862.15	1043.77
151	21 Jul 2015 1230	862.19	1076.16
152	21 Jul 2015 1235	862.24	1122.85
153	21 Jul 2015 1240	862.3	1175.61
154	21 Jul 2015 1245	862.37	1235.23
155	21 Jul 2015 1250	862.35	1196.42
156	21 Jul 2015 1255	862.35	1200.81
157	21 Jul 2015 1300	862.32	1179.43
158	21 Jul 2015 1305	862.27	1123.38
159	21 Jul 2015 1310	862.25	1119.95
160	21 Jul 2015 1315	862.21	1076.61
161	21 Jul 2015 1320	862.17	1047.88
162	21 Jul 2015 1325	862.15	1046.01

Continued

163	21 Jul 2015 1330	862.13	1028.99
164	21 Jul 2015 1335	862.15	1044.51
165	21 Jul 2015 1340	862.21	1091.86
166	21 Jul 2015 1345	862.27	1148.86
167	21 Jul 2015 1350	862.34	1209.6
168	21 Jul 2015 1355	862.38	1226.66
169	21 Jul 2015 1400	862.36	1210.76
170	21 Jul 2015 1405	862.33	1177.06
171	21 Jul 2015 1410	862.31	1166.62
172	21 Jul 2015 1415	862.26	1127.03
173	21 Jul 2015 1420	862.23	1093.34
174	21 Jul 2015 1425	862.18	1062.21
175	21 Jul 2015 1430	862.17	1058.16
176	21 Jul 2015 1435	862.18	1067.52
177	21 Jul 2015 1440	862.22	1099.26
178	21 Jul 2015 1445	862.27	1148.97
179	21 Jul 2015 1450	862.35	1213.32
180	21 Jul 2015 1455	862.45	1299.9
181	21 Jul 2015 1500	862.42	1268.58
182	21 Jul 2015 1505	862.39	1226.67
183	21 Jul 2015 1510	862.37	1214.51
184	21 Jul 2015 1515	862.3	1150.46
185	21 Jul 2015 1520	862.25	1108.2
186	21 Jul 2015 1525	862.2	1075.34
187	21 Jul 2015 1530	862.19	1073.29
188	21 Jul 2015 1535	862.2	1080.63
189	21 Jul 2015 1540	862.22	1096.19
190	21 Jul 2015 1545	862.24	1112.64
191	21 Jul 2015 1550	862.25	1123.59
192	21 Jul 2015 1555	863.37	2381.78
193	21 Jul 2015 1600	862.82	1589
194	21 Jul 2015 1605	862.31	1099.21
195	21 Jul 2015 1610	861.8	728
196	21 Jul 2015 1615	862.05	1012.11
197	21 Jul 2015 1620	862.28	1194.19
198	21 Jul 2015 1625	862.31	1177.16
199	21 Jul 2015 1630	862.38	1226.16
200	21 Jul 2015 1635	862.41	1263.36

Continued

201	21 Jul 2015 1640	862.38	1224.19
202	21 Jul 2015 1645	862.38	1217.55
203	21 Jul 2015 1650	862.37	1223.18
204	21 Jul 2015 1655	862.32	1170.33
205	21 Jul 2015 1700	862.31	1161.47
206	21 Jul 2015 1705	862.27	1139.17
207	21 Jul 2015 1710	862.22	1086.68
208	21 Jul 2015 1715	862.19	1072.51
209	21 Jul 2015 1720	862.2	1081.97
210	21 Jul 2015 1725	862.23	1109.48
211	21 Jul 2015 1730	862.28	1156.86
212	21 Jul 2015 1735	862.35	1218.86
213	21 Jul 2015 1740	862.44	1294.82
214	21 Jul 2015 1745	862.43	1274.2
215	21 Jul 2015 1750	862.43	1262.98
216	21 Jul 2015 1755	862.43	1273.18
217	21 Jul 2015 1800	862.41	1248.9
218	21 Jul 2015 1805	862.38	1218.84
219	21 Jul 2015 1810	862.37	1213.7
220	21 Jul 2015 1815	862.33	1179.16
221	21 Jul 2015 1820	862.29	1147.73
222	21 Jul 2015 1825	862.26	1127.75
223	21 Jul 2015 1830	862.21	1076.81
224	21 Jul 2015 1835	862.17	1053.97
225	21 Jul 2015 1840	862.18	1066.78
226	21 Jul 2015 1845	862.22	1098.79
227	21 Jul 2015 1850	862.28	1155.3
228	21 Jul 2015 1855	862.36	1224.7
229	21 Jul 2015 1900	862.47	1322.62
230	21 Jul 2015 1905	862.5	1320.88
231	21 Jul 2015 1910	862.53	1354.27
232	21 Jul 2015 1915	862.53	1351.68
233	21 Jul 2015 1920	862.49	1319.85
234	21 Jul 2015 1925	862.48	1309.08
235	21 Jul 2015 1930	862.48	1313.05
236	21 Jul 2015 1935	862.46	1290.38
237	21 Jul 2015 1940	862.44	1272.48
238	21 Jul 2015 1945	862.43	1270.89

Continued

239	21 Jul 2015 1950	862.41	1249.49
240	21 Jul 2015 1955	862.38	1224.21
241	21 Jul 2015 2000	862.37	1213.65
242	21 Jul 2015 2005	862.33	1184.37
243	21 Jul 2015 2010	862.3	1154.22
244	21 Jul 2015 2015	862.27	1129.64
245	21 Jul 2015 2020	862.22	1086.4
246	21 Jul 2015 2025	862.18	1055.84
247	21 Jul 2015 2030	862.11	1005.7
248	21 Jul 2015 2035	862.09	997.52
249	21 Jul 2015 2040	862.1	1013.46