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AN INTEGRATED APPROACH TO SIMULATE FLOODING DUE TO RIVER DIKE BREACH

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This paper presents an integrated approach that enables the simultaneous modeling of dike breaching process and flood propagation. The dike breaching process is modelled with a simple breach model implemented into a 2-dimensional hydrodynamic flood model – Telemac2D. Telemac2D models the propagation of the arising flood into the hinterland. The breach model generalizes dike breaching process in two general stages. In the first stage, dike breaching is predominantly vertical with limited lateral breach growth; and in the second stage breach grows only laterally. The breach model requires breach location, breach duration, and length and axis of dike affected by the breach as input parameters. Breach starts at the center of the dike length affected by the breach and can be initiated in three different ways: at a given time, based on water level on the dike or based on water level at a given point. The first stage takes one tenth of the total time required for the entire breach and has a breach width equal to one tenth of the final breach width. The approach is exemplarily applied to model the year 1996 Awash River dike breach flood at Wonji, Ethiopia, a historic dike breach flood that destroyed the sugar plantation and offices of Wonji Shoa Sugar Factory. The water depth calculated with the numerical model is in good agreement with the water level mark left on buildings as witnessed by people present at the place after the disaster, including the dike foreman.

INTRODUCTION

River flood plains are natural spaces for flood waters when rivers flow over banks. However, many river flood plains are reclaimed by humans for purposes such as urban expansion, agriculture, infrastructure and industrialization. Dikes provide a great task of protecting these developments from flooding during high river flows. Nonetheless, dikes never guarantee absolute protection against floods and flood disasters emanating from dike breaching are in the news once in a while. Failure of a dike results in devastating damage as witnessed in many cases around the world. The June 2013 Elbe flood in Germany is a recent memory of how dangerous dike breaches could be.

Extreme precipitation events are likely to increase in the future which is attributed to anthropogenic factors [1]. Days-long heavy rainfall causes extreme flood in rivers. The fact that there is less space for the flood and there is increased probability of occurrence of extreme flood events will substantially increase the probability of flooding due to dike breaching. With increasing proportion of world population living in flood plains [2], the risks of flooding will also increase accordingly. This calls for the evaluation of the risks behind our dikes. Modelling tools have long been recognized as valuable tools for this task. Based on model results, measures can be put in place to alleviate the risk of flooding.

The modelling tools for assessing dike breach floods should be able to model the dike breaching process as well as propagation of the flood into the hinterland as exactly as possible and preferably simultaneously. Flood propagation modelling is a well-established discipline and many flood modelling packages are available in both the public and commercial domains. Even notorious cases of high Froud number flows such as dam-break flows can be modeled at satisfactory level. Dike breach models – models that model the erosion processes during dike breaching or estimate flow hydrograph through a dike breach, on the other hand, are generally limited in availability, capacity and functionality [3]. Even worse, dike breach models that are integrated into flood models and are suitable for river dikes are rare and limited [3]. This paper describes a simple breach model integrated into the hydrodynamic flood model – Telemac2D. The potential of the approach is demonstrated by applying it to a real river dike breach flood.

REVIEW OF RIVER DIKE BREACH MODELING

Many embankment breach models were developed over the years for which an extensive summary can be found in [4]. The models range from simple empirical equations derived from historical embankment failures to complex ones that solve coupled system of shallow water equations, Exner's equations, and sediment transport formula, which Broich [5] called Bed Evolution Equations (BEE). The objective of the simpler approaches is mostly to determine the peak flow and/or the flow hydrograph through the breach for a later routing with flood routing models; whereas the BEE-based models focus on the determination of the dike erosion processes in a coupled manner with 1D, 2D or 3D free surface flow equations in which the flood through the breach is routed with the flow model [5].

The approaches used to determine flow hydrograph through river dike breaches rely on simplification of the flow and erosion processes of the dike. Quite a number of such approaches are reported. Kamrath *et al.* [6] derived an analytical equation similar to weir formula to calculate flow through a river dike breach as function of breach parameters such as velocity, flow depth and geometric characteristics. They assumed that breach occurs along a straight river reach, breach cross-section is rectangular, dike breaches to the ground level of the flood plain, and the breach width remains constant. Paquier and Beraud [7] determined discharge hydrograph through a levee breach with Manning's equation by using the water level in the river channel and a critical flow depth at the toe of the dike. Meyer-Peter and Müller equation is used to estimate erosion volume at each time step. The breach cross-section is assumed to be trapezoidal except at the beginning of piping failure mode in which case it is circular. Liu and Wu [8] used an overflow type equation that relates breach outflow with the breach width, water level in the channel and flood plain, failure duration, and final breach level to determine flow through levee breach.

The more complex approaches model dike breaching according to physical principles by employing BEE. Several attempts to model river dike breaches in this manner are reported. Lin *et al.* [9] presented an approach for modelling dike breach that integrates shallow water equations, sediment transport, bed deformation, and breach expansion equations. Dike breaching is modelled with non-equilibrium sediment transport equations and riverbed deformation equations and lateral erosion of the dike is modelled with Osmans's riverbank-expansion equation given for cohesive soils. Fäh [10] presented modelling of levee breaching using sediment transport equations for bed and suspended load coupled with the shallow water equations. He found that the model results are sensitive to input parameters that determine the dike lateral erosion process. Wu *et al.* [11] modelled non-cohesive embankment breaching using non-equilibrium total load sediment transport equation and slope avalanching coupled with the shallow water equations. The application of the approach to test case showed that the model results are sensitive to input parameters. Sabbagh-Yazdi and Jamshidi [12] presented a hydrodynamic model for gradual embankment breaching. The model uses the flow equation adapted for steep slopes coupled with suspended sediment transport and bed evolution. They applied the approach to a test case and found encouraging results; nonetheless, they point out that embankment breaching type flows need to be modelled with 3D models for better results.

From the application point of view, none of the breach models may be considered better than the others. One would expect the physically-based models to do very well over the other models since they are derived from the physical principles of erosion, deposition and water flow. That is not the case though, because of the limitation of the applicability of BEEs, which are derived for uniform flow conditions, to supercritical flows typical of dike breach and their limitation in modelling lateral embankment erosion [3].

DESCRIPTION OF THE CURRENT APPROACH

The approach presented here integrates the modelling of the dike breaching process with the routing of the flood into the flood plain. This is accomplished by implementing the dike breaching processes within the hydrodynamic model – Telemac2D. The current dike breach implementation in Telemac2D is an extension of an already existing dike breach module.

Modeling of dike breaching process

Breaching of river dikes can result due to either overtopping when the water level is over the dike level or piping in case of long duration floods. Pertaining to their thin and small height nature of river dikes, for both overtopping and piping modes of failure, the breach formation process can be generalized into two stages [13]. The first stage constitutes breach initiation, creation of initial breach channel and the vertical erosion of the dike. In the second stage, the breach channel grows laterally.

A simple dike breaching model based on these stages is given. It works as follows. Breaching is initiated at given location along the axis of the dike, which can be done in three ways – at a given time, based on the water level on the dike, or based on the water level at a given location. The evolution of the breach is determined by breach duration, final breach width, and final breach level. Once the breach is initiated, in the first stage, it grows vertically at faster rate and erodes to the desired final level (in general the ground level) within tenth of the duration needed for the entire breach. The breach also grows laterally at this stage but at similar rate as in the following stage. In the second stage, the breach continues to widen laterally until final breach width is attained. The final breach width is defined through the definition of points on which breaching appears with the use of the nodes of the finite elements of Telemac2D.

The hydrodynamic flood model - Telemac2D

Telemac2D is a 2-dimensional hydrodynamic model developed at Studies and Research Division of Electricité de France. It solves the shallow water equations using the finite element or the finite volume method using unstructured triangular elements. It has several numerical options, which make it suitable to choose the appropriate one for the flow conditions at hand. It has schemes proved to be suitable for flows with high Froude number i.e. supercritical flows – typical of dike breach (dam break) flows. For the detail numerical aspects of Telemac2D, refer to [14].

APPLICATION OF THE APPROACH TO THE YEAR 1996 AWASH RIVER DIKE BREACH FLOOD AT WONJI, ETHIOPIA

The study area

The study area is located in central Ethiopia about hundred kilometers south of the capital Addis Ababa near the town of Adama (see Figure 1). Most part of the area belongs to Wonji Shoa Sugar Factory (WSSF). It is on the flood plains of Awash River about ten kilometers downstream of Koka Hydropower Dam. Awash River is one of Ethiopia's twelve river basins and it is the most developed and utilized river in the country compared to the other river basins. Koka Hydropower Dam and the irrigation schemes of WSSF's sugar plantation are the very first large scale developments on Awash River.

The year 1996 Wonji flood

The flow of Awash River at Wonji is dependent on the water released from the reservoir of Koka Dam. The reservoir has lost much of its capacity to sedimentation due to sediment load arising from erosion in the upstream catchment. The substantial decrease in the capacity of the reservoir due to sedimentation means that the maximum water level of the reservoir is easily attained. When the water level in Koka Reservoir reaches maximum level, flood gates of the dam are opened. Opening of flood gates causes high flood risk to the downstream irrigation schemes and settlements such as Wonji.

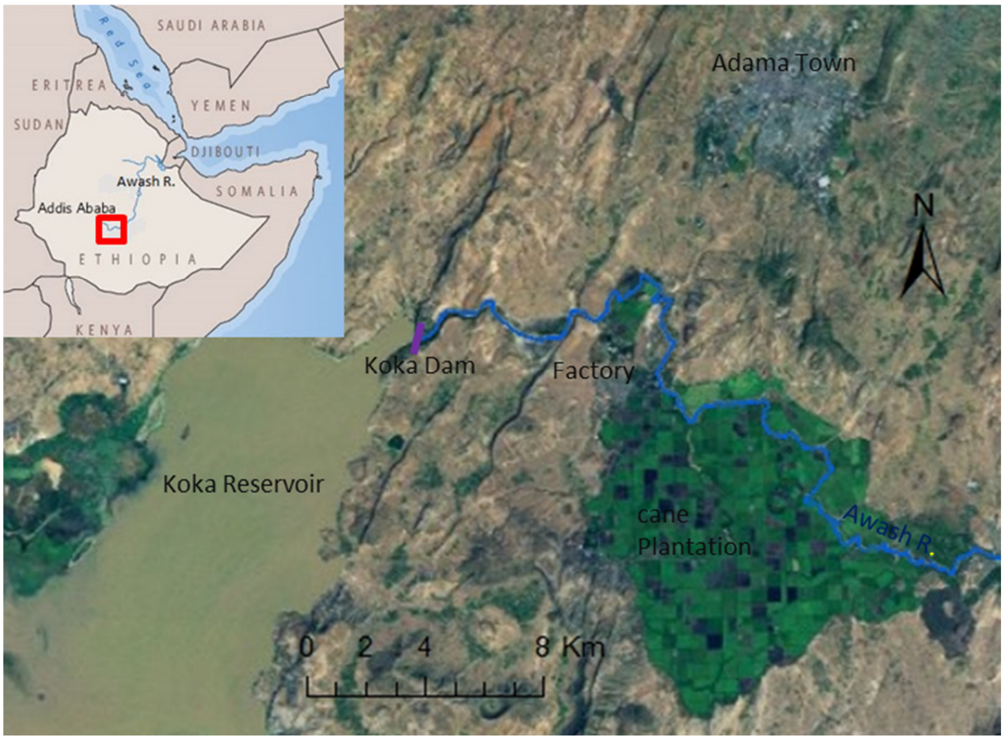

Figure 1. Location map of WSSF and its sugar cane plantation

In August 1996, heavy rains poured for days in the catchment upstream of Koka Dam which filled the reservoir to its maximum capacity. The water level was continually rising and to avert catastrophic dam failure, flood gates were opened. This caused widespread flooding between Wonji and Metehara [15]. The dikes at WSSF breached and the sugar factory, residential houses, offices and sugar cane plantation were flooded, causing unprecedented damage to WSSF. Flood damage included flooding of about 400 hectares of sugar cane plantation, displacement of about 40,000 people, inundation of buildings and factory machinery [16].

Data and information regarding the 1996 Wonji flood

Data collection is not a priority during disasters. Thus, very limited data and information can be found for the 1996 Wonji flood. The single reliable data relevant to this study is the flow measurement at Awash River gauging station just downstream of Koka Dam, some kilometers upstream of Wonji. Daily flow records are available at this gauging station. Awash River flow records are missing for the Wonji gauging station during the flood time, understandably due to inaccessibility.

No information is available as to the depth and extent of the flood in the plain. However, according to eye witnesses, who returned to the area after the flood, the flood level marks left on walls of buildings reaches the level of window beams. That is approximately between 0.8 and 1.0 m above the ground level.

Also, unreported are number and location of breaches, breach time, and breach duration. Although Associated Press [17] reported dike breaches at three locations, only one prominent breach occurred according to the dike foreman, the location of which is shown in figure (2). According to Associated Press [17], the dike breach occurred on 24 Aug 1996 but the exact time is not given. No information is available regarding the duration of the breach. The dike foreman suggested the dike breaching processes might have taken about an hour.

Model set up

Telemac2D model for the study area is set up with the help of Kalypso1D2D. Kalypso1D2d is an open source hydrodynamic model building module that can be used to set up, run and analyze results of 2D or coupled 1D/2D hydrodynamic models based on unstructured mesh. It is originally developed for RMA10 and it is recently extended for Telemac2D. Further information on Kalypso1D2D can be obtained from [18].

The model boundaries for the current study area are set as follows. Upstream model limit is selected at location where there is constricted topography just upstream of the flood plain, the downstream model limit is at a weir, and the other model boundaries are based on elevation of the ground level as shown in Figure 2.

The boundary condition at the upstream liquid boundary is Awash River flow measurements at Koka Dam gauging station. And the boundary condition at the downstream liquid boundary, that is the boundary at the weir, is water level-discharge relationships derived for flow over broad-crested weir. The additional boundary condition is the dike breach condition at the specified location in Figure 2. Dike breaching is set to start on 24 Aug 1996 at 12:00 am. The breach would take an hour and is about 100 m wide.

Modelling results and discussion

The evolution of the breach is shown in figure 3. The evolution depends on the breach model and the dike breach boundary conditions given above. The evolution of the breach could not be compared with real information as there is none.

The numerical results of flood inundation depth on 27 Aug 1996 is shown in figure 2. This inundation area is in agreement with the UNDP/DHA inspection team who witnessed extensive flooding of the sugar plantation on this date [19]. Nevertheless, no information is available to validate the model results.

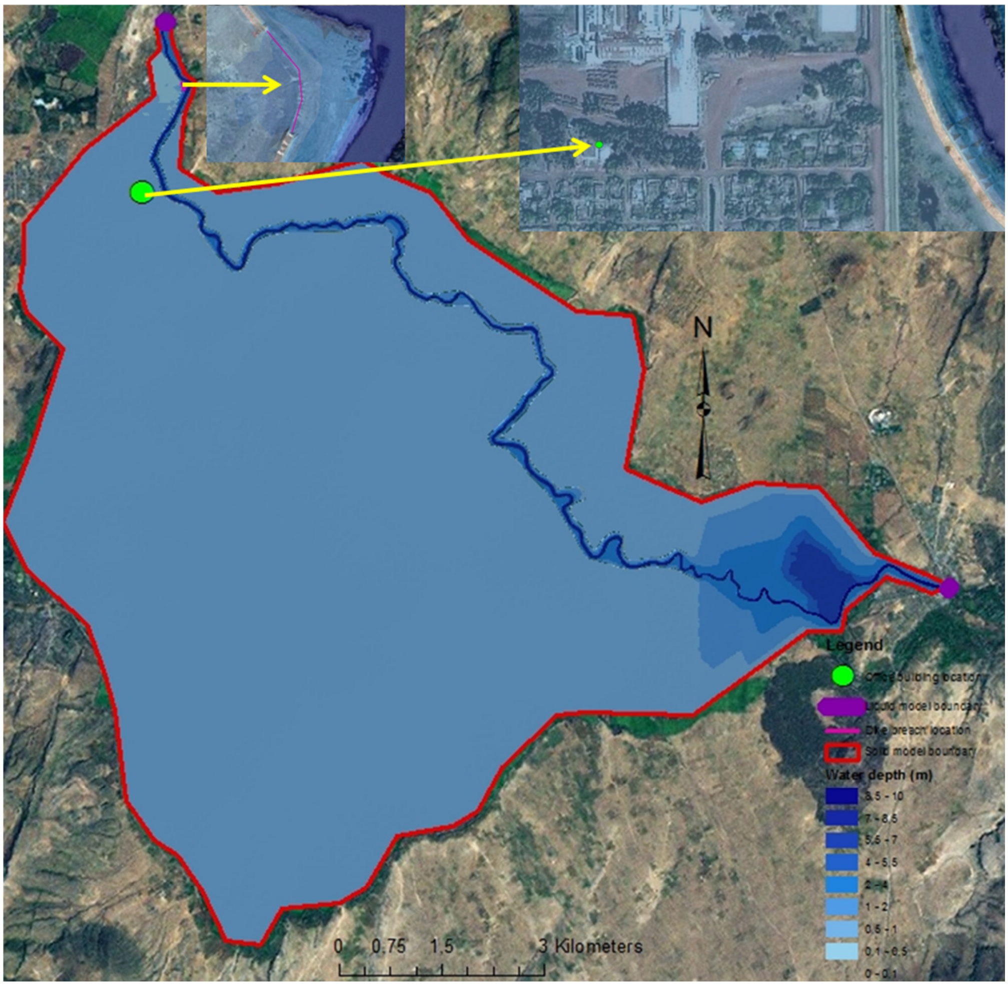

Figure 2. Model boundary, location of dike breach and an office building, and inundation depth on 27 Aug 1996 at 12:00 pm

Figure 3. Dike breach evolution simulated with Telemac2D

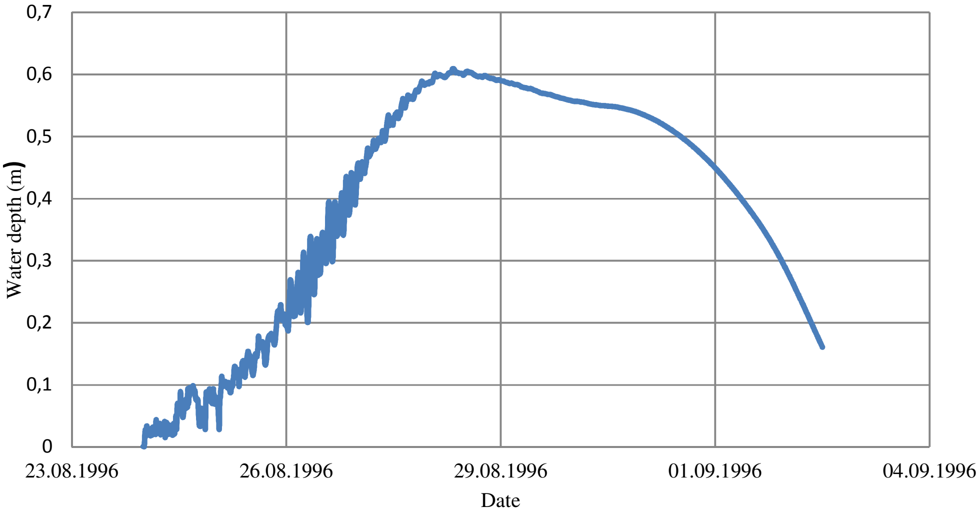

Figure 4. Simulated water depth over time at a location of an office building

Figure 4 shows the water depth over time at a location of an office building, shown in Figure 2. The maximum depth is about 0.6 m. This value is less than the water level marks left by the flood on buildings. The difference could arise from factors which are not known precisely such as breach time and breach duration, in addition to numerical errors of the model. The simulation result shows a rising water depth on 27 Aug 1996 which is in line with the witness of UNDP/DHA inspection team [19].

CONCLUSION

The model results show that the presented approach can be utilized reliably to model flood propagation arising from river dike breaching. Precautions, however, has to be taken in the choice of breach parameters. In the presented case, good judgments for parameters are taken with the help of the information from the dike foreman. Nevertheless, sensitivity of the breach parameter needs to be analyzed.

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REFERENCES

[1] Seneviratne S.I., Nicholls N., Easterling D., Goodess C.M., Kanae S., Kossin J., Luo Y., Marengo J., McInnes K., Rahimi M., Reichstein M., Sorteberg A., Vera C. and Zhang X., "Changes in climate extremes and their impacts on the natural physical environment", In " Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation" [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)],

A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press (2012), pp 109-230.

[2] *NASA Earth Observatory, "Two Billion Vulnerable to Floods by 2050; Number Expected to Double or More in Two Generations", (2004), Retrieved 19 March 2014, from http://earthobservatory.nasa.gov/Newsroom/view.php?id=24957*

[3] *ASCE/EWRI, "Earthen Embankment Breaching", Journal of Hydraulic Engineering, Vol. 137, No. 12 (2011), pp 1549–1564.*

[4] *Morris M. W., Kortenhaus A. and Visser P. J., "Modelling Breach Initiation and Growth", (2009), Retrieved from http://www.floodsite.net/html/publications2.asp*

[5] *Broich K., "Sediment transport in breach formation process", Proc. of 4th IMPACT Workshop, UCL Louvain-la-Neuve, (2003), Retrieved from http://www.impact-project.net/publications/wp2_pub5.pdf*

[6] *Kamrath P., Disse M., Hamme M. and Köngeter J., "Assessment of Discharge through a Dike Breach and Simulation of Flood Wave Propagation", Natural Hazards, Vol. 38, No. 1-2 (2006), pp 63–78.*

[7] *Paquier A. and Beraud C., "Validating a simplified model for flood hazard downstream levees", In River flow 2010: proceedings of the International Conference on Fluvial Hydraulics, Bundesanstalt für Wasserbau, (2010).*

[8] *Liu W.-C. and Wu C.-Y., "Flash flood routing modeling for levee-breaks and overbank flows due to typhoon events in a complicated river system", Natural Hazards, Vol. 58, No. 3 (2011), pp 1057–1076.*

[9] *Lin L., Jinren N. and Rogers B. B. D., "Simulation of dike-break processes in the Yellow River", Science in China (Series E), Vol. 45, No. 6 (2002), pp 606–619.*

[10] *Faeh R., "Numerical Modeling of Breach Erosion of River Embankments", Journal of Hydraulic Engineering, Vol. 133, No. 9 (2007), pp 1000–1009.*

[11] *Wu W., Marsooli R. and He Z., "Depth-Averaged Two-Dimensional Model of Unsteady Flow and Sediment Transport due to Noncohesive Embankment Break/Breaching", Journal of Hydraulic Engineering, Vol. 138, No. 6 (2012), pp 503–516.*

[12] *Sabbagh-Yazdi S.-R. and Jamshidi M., "Depth-Averaged Hydrodynamic Model for Gradual Breaching of Embankment Dams Attributable to Overtopping Considering Suspended Sediment Transport", Journal of Hydraulic Engineering, Vol. 139, No. 6 (2013), pp 580–592.*

[13] *Fujita, Y., & Tamura, T. (1987). ENLARGEMENT OF BREACHES IN FLOOD LEVEES ON ALLUVIAL PLAINS. Natural Disaster Science, 9(1), 37–60.*

[14] *UNDP/DHA, " Ethiopia - Floods Information Report No. 3", (1996), Retrieved from http://reliefweb.int/report/ethiopia/ethiopia-floods-information-report-no-3*

[15] *Hervouet J.-M., "Hydrodynamics of free surface flows: modelling with the finite element method", John Wiley & Sons Ltd, (2007).*

[16] *UNDP/DHA, "Ethiopia - Floods Information Report No. 4", (1996), Retrieved from http://reliefweb.int/report/ethiopia/ethiopia-floods-information-report-no-4*

[17] *Associated Press, "20,000 Ethiopians Evacuated", (1996), Retrieved from http://reliefweb.int/report/ethiopia/20000-ethiopians-evacuated*

[18] *Björnsen Beratende Ingenieure GmbH, "Kalypso 1D/2D", (2014), Kalypso: List of products. Retrieved from http://kalypso.bjoernsen.de/index.php?id=334&L=1*

[19] *Ahrens J. D., "Koka Dam - River Awash Floods, Report of the Joint UN Assessment Team", (1996), Retrieved from http://www.africa.upenn.edu/eue_web/Awash29aug.htm*