# Failure of the Mtera-Kidatu Reservoir System in the Early 1990s

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## ABSTRACT:

*Four possible causes for the failure of the Mtera-Kidatu Reservoir System within the Rufiji River Basin in Tanzania in the early 1990s were investigated. These were sudden decrease in inflows, sudden increase in losses, sudden increase in hydropower generation, and unnecessary spills; or a combination of these, and it was found out that unaccounted for and unnecessary spillage was the main cause. This paper proposes that consideration of the flows that are generated within the intervening catchment (i.e. catchment between Mtera and Kidatu) and the operational policy that maximum power is produced at Kidatu most of the time must be the core in the management of the reservoir system. If this was the case in the past then the Mtera Reservoir should not have gone dry in the 1991-1994 period. The validity of this assertion was tested with the TALSIM 2.0 model and an efficiency of 95% was achieved, indicating a very good correlation with the investigative techniques employed in this study.*

*Keywords*: Mtera-Kidatu Reservoir System; Operational Policy; Reservoir Management; Rufiji River Basin; Tanzania

## INTRODUCTION

Electricity generation and its distribution play a major role in a country's development, and in this technological era where electricity is classified as an engine of supporting economic growth, maximum attention has to be paid to its generation and efficient operation if the country is to enjoy the comfort and benefits it brings. This has to be done in an integrated manner (Yawson *et al*., 2003) and in an efficient management way.

This paper investigated the failure of the Mtera-Kidatu Reservoir System in 1991 and 1992 when water levels in the Mtera Reservoir went very close to its dead storage level. The reservoir system comprises two reservoirs - the Mtera Reservoir and the Kidatu Reservoir, with the former being upstream of the latter. The system is mainly for hydropower production and the failure of the system can be said to be occurring when the levels in the reservoirs get below the mid-way of the full supply level and the dead storage level, especially with the Mtera Reservoir. This is because Mtera Reservoir serves, basically, as storage for maximum power generation at the Kidatu Dam.

The estimation of inflows into the reservoirs had been modelled on a daily time-step using records/data prior to the impoundment of the river. Therefore, one can say with a high level of confidence how much water enters the reservoirs on a day-to-day basis. Land use change can also adversely affect the accuracy of the inflows' estimates using these models, but this is not the case of the Great Ruaha River Basin, since there had not been any major or significant land use change. Estimation of loss of water from the reservoirs was also carried out to ascertain whether the amount of water lost through evaporation, and due to seepage and percolation is much higher than what was assumed at the design stage.

Finally, TALSIM 2.0 – 'Simulation von Talsperren (Systemen)' (Froehlich, 2001) – model that had been applied in several places including reservoir systems in certain parts of Africa was applied to this system and it did confirm the assertion of unaccounted for or unnecessary spillage from the reservoirs.

## THE STUDY AREA

The Mtera-Kidatu Reservoir System is located in the Rufiji River Basin in Tanzania as shown in Figure 1. The basin is the biggest river basin, covering an area of about 20% of the mainland Tanzania (Danida/World Bank, 1945). It is over 180,000 km$^2$. The Mtera Reservoir is larger than the Kidatu Reservoir with a surface area of 620 km$^2$ at its full capacity. It is 8.5 m deep ranging from 690.0 m to 698.5 m above mean sea level. Corresponding values for the Kidatu Reservoir are a surface area of 9.5 km$^2$ at full capacity and a depth of 17 m ranging from 433 m to 450 m above mean sea level. The storage capacity of Mtera Reservoir is 125 million cubic metres and that is roughly 25 times larger than the Kidatu Reservoir. The installed capacity at Mtera is 80 MW of power whereas at Kidatu it is 200 MW. There are 2 turbines at Mtera and 4 turbines at Kidatu (Yawson *et al.*, 2003). This information is summarised in Table 1. The Kidatu Dam is located approximately 170 km downstream of the Mtera Dam.

**Table 1: Summary of Mtera-Kidatu Reservoir System's Details**

| Parameter | Mtera Reservoir | Kidatu Reservoir |
|---|---|---|
| Live Storage (MCM) | 3,200 | 125 |
| Spillway Capacity (m$^3$/s) | 4,000 | 6,000 |
| Generating Capacity (MW) | 80 | 200 |
| Turbine Discharge Capacity (m$^3$/s) | 96 | 140 |
| Full Supply Level (m.a.s.l.) | +698.5 | +450.0 |
| Dead Storage Level (m.a.s.l.) | +690.0 | +433.0 |
| Catchment Area (km$^2$) | 67,884 | 80,040 |

Kidatu Dam/Reservoir was constructed in 1976 and the Mtera one was constructed in Mid-1980.

The three main rivers contributing to the Mtera Reservoir are the Great Ruaha River, the Little Ruaha River and the Kisigo River. The Great Ruaha River at Msembe Ferry (1ka59) provides about 56% of the runoff into the reservoir. The Little Ruaha River at Mawande (1ka31), which joins the Great Ruaha River downstream of Msembe Ferry, provides an additional 18%, whilst the Kisigo River (i.e. 1ka42, joining it further downstream) is about 26% (Danida/World Bank, 1995).

There are several tributaries between Mtera and Kidatu Reservoirs that also contribute to the inflows at Kidatu. The ones considered in this paper are flows from the Lukosi River at Mtandika (1ka37a) and the Yovi River (1ka38), and of course the contribution of rainfall within the intervening catchment (i.e. between Mtera and Kidatu) in addition to the flows from Mtera.

Prior to 1988, hydropower was only generated at Kidatu. In 1988, an additional turbine was installed at Mtera to increase the generating capacity of the reservoir system, but this is unlikely to be the cause of persistent low water levels in the Mtera Reservoir in the early 1990s. Although, Kidatu is a much smaller reservoir, its function is, largely, to maintain sufficient head for power generation. Hence, power is mainly generated at Kidatu and water is mainly stored at Mtera.

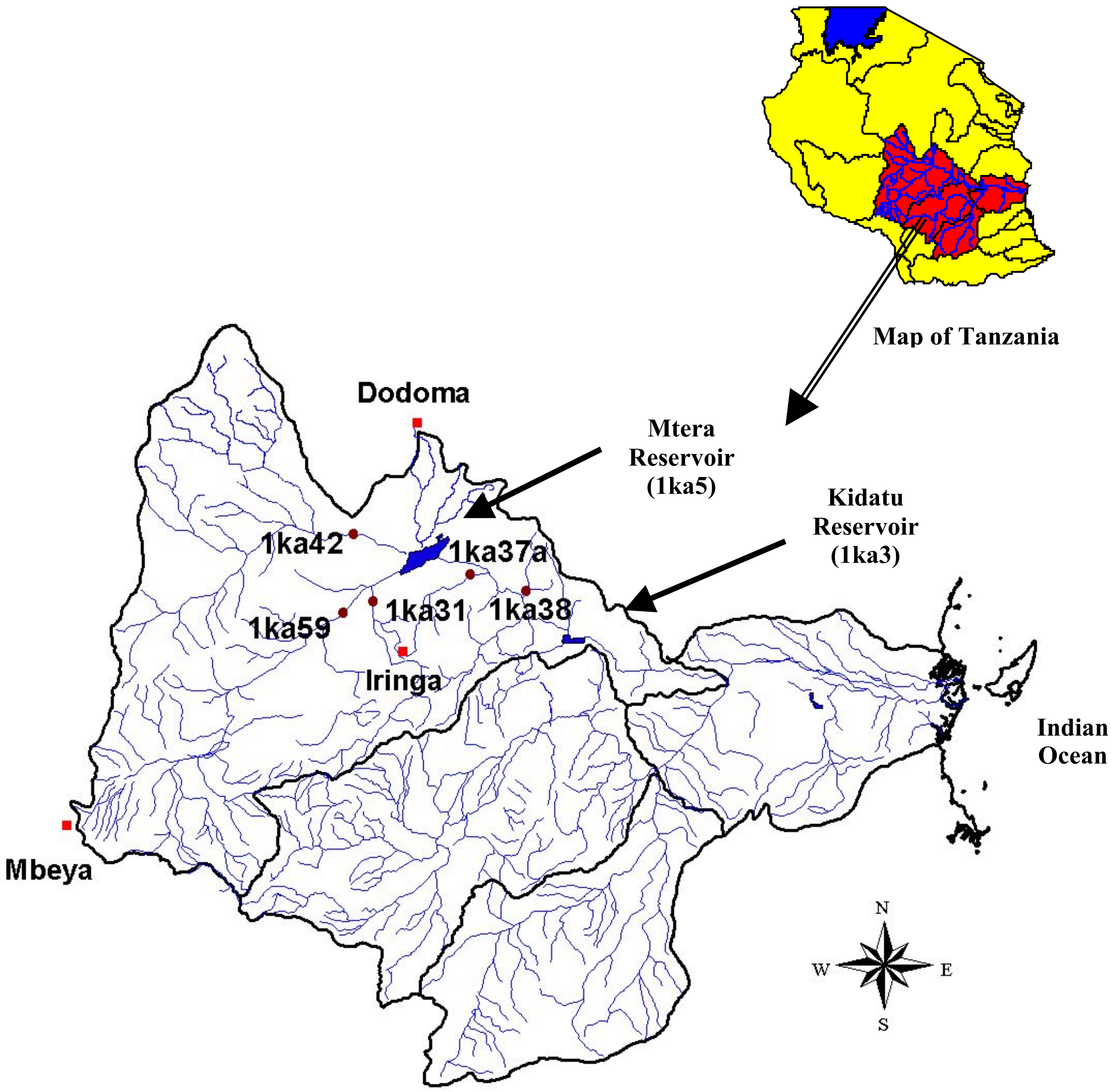



**Figure 1: Location of the Mtera-Kidatu Reservoir System within the Rufiji River Basin in Tanzania**

## METHODS FOR INVESTIGATING THE FAILURE

The investigation of the possible or likely cause(s) of the failure of the Mtera-Kidatu Reservoir System in 1991 and 1992 was done along the following lines:

- Sudden decrease in inflows,
- Sudden increase in losses,
- Sudden increase in generated power, and
- Unnecessary spills.

Any one of the above or a combination of them could have caused the failure of the Mtera Reservoir to recover to its full conditions in 1991 and in 1992. The failure of the reservoir in 1994 and beyond was, in fact, caused by the phenomenon that started in 1991 and persisted through 1992. If the reservoir had gone to the full capacity or nearly full conditions in 1991 and in 1992 then the reservoir would not have failed in 1994, for instance.

### Inflows

It is possible to simulate flow conditions in a river by using mathematical/hydrological models (Dooge, 1973; Singh, 1995). One such model, Simple Linear Model (SLM), was used to relate the flow at Great Ruaha River at Mtera (1ka5) with the flows from Little Ruaha River at Mawande (1ka31), Kisigo River (1ka42) and Great Ruaha River at Msembe Ferry (1ka59). The same SLM was used to relate the flow at Great Ruaha River at Kidatu (1ka3) with the flows from Lukosi River at Mtandika (1ka37a), Yovi River (1ka38), 1ka5 and the average rainfall within the intervening catchment.

The SLM is a multiple regression model where the dependent variable is the runoff at the outlet of the catchment/basin and the independent variables are rainfall and/or upstream flow values (Kachroo, 1992; Kachroo and Liang, 1992; Liang and Nash, 1988; Liang *et al*., 1992; WHO, 1992). The model results in estimating flows at both 1ka3 and 1ka5 are presented in Table 2, using the Nash and Sutcliffe efficiency criterion (Nash and Sutcliffe, 1970).

**Table 2: SLM efficiency results in estimating flows for the Great Ruaha River at Mtera (1ka5) and at Kidatu (1ka3)**

| Name of Catchment | | Calibration Period | SLM efficiency (in %) during calibration | Verification Period | SLM efficiency (in %) during verification | Catchment Area ($km^2$) |
|---|---|---|---|---|---|---|
| Output | Inputs | | | | | |
| 1ka5 | -1ka31<br>-1ka42<br>-1ka59 | 1957-1975 | 93.87 | 1976-1979 | 72.21 | 67,884 |
| 1ka3 | -1ka5<br>-1ka37a<br>-1ka38<br>-Intervening catchment areal rainfall | 1958-1969 | 91.83 | 1970-1975 | 89.18 | 80,040 |

Since Mtera Reservoir was impounded in 1980, the model was calibrated for pre-impoundment period of 1957 to 1975. The data of 19 years was used for the calibration of the model and the remaining 4 years, 1976 to 1979, was used for the verification of the model.

The model registered an efficiency of above 93% during calibration and an efficiency of above 72% during verification, indicating a good performance (WREP, 2003).

Similarly, for the Kidatu Reservoir, river flow data at Kidatu (1ka3) was consistently available from 1954 to 1975; prior to impoundment of the reservoir. Observed flows at three flow stations; 1ka5, 1ka37a and 1ka38 combining with the average rainfall over the intervening catchment was used to estimate flows at 1ka3. The SLM was calibrated over a period of 12 years from 1958 to 1969. The model verification was done from 1970 to 1975 (6 years). Good model efficiencies were obtained, with an efficiency of above 91% during calibration and 89% during the verification period. Again, signifying a good model to use for flow estimates at Kidatu (WREP, 2003).

**Losses**

Main losses that occur in reservoirs are evaporation followed by losses due to seepage or groundwater percolation and in some cases direct pumping. However, there is no evidence of direct pumping from the Mtera Reservoir, and it is hardly likely that losses due to percolation increased suddenly at the end of 1990, i.e., after the reservoir had been in operation for nearly seven years. It is also very unlikely that losses due to evaporation increased suddenly at the end of 1990 (much higher than what was assumed at the design stage).

But for the completeness of investigation, annual and expected seasonal losses due to evaporation, computed using empirical model, are compared with the combined losses due to evaporation and percolation calculated by the water balance of the reservoir. It is assumed that the losses due to percolation and seepage are small compared to the losses due to evaporation. As a result, it is expected that the losses calculated by water balance should be comparable in magnitude to the evaporation losses estimated by the empirical model.

**Hydropower generation**

It is a well-known fact that there was a decrease in the hydropower generation at Mtera-Kidatu Reservoir System in 1991 and 1992. However, for the sake of completeness of the investigation, a comparison is made between the turbine discharges from Mtera and Kidatu in 1991 and 1992 with releases made in previous years.

Prior to installation of a turbine at Mtera water was spilled from Mtera to feed Kidatu. After the installation of the turbine all the water that was necessary to be released is not spilled but a part of it is passed through the turbine to generate additional power. The amount of water that passes through the turbine at Mtera would have been spilled anyway to feed the Kidatu Reservoir. Therefore, installation of a turbine at Mtera Reservoir is not likely to have any adverse effect on decrease in water levels at Mtera.

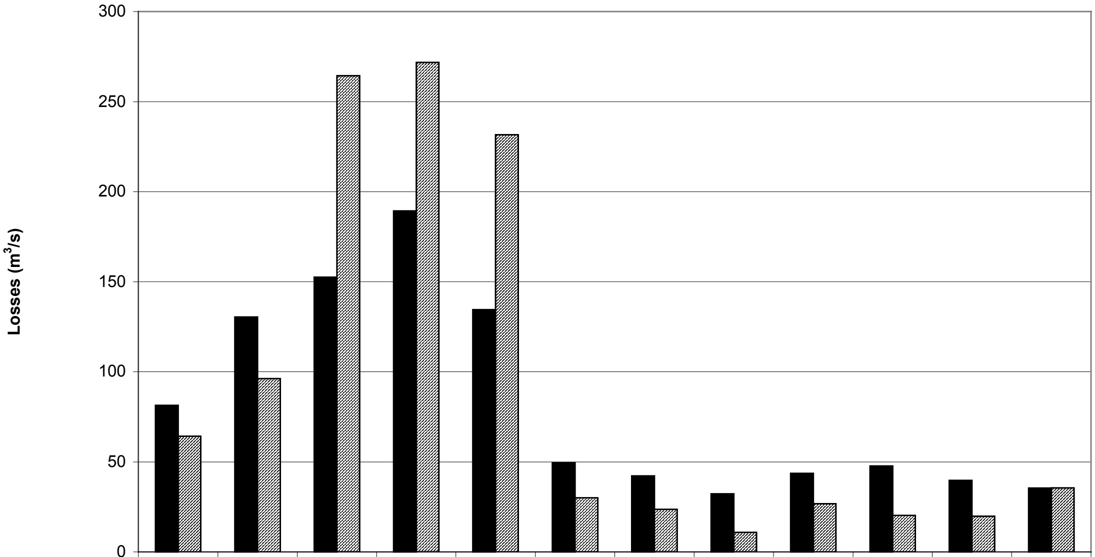
**Unnecessary Spills**

Investigation of whether the amount of water that was spilled from the Mtera Dam was more than what was necessary to feed the Kidatu Dam was done in the following way. Searching for clues from the records of spill from the Mtera and the Kidatu Reservoirs by comparing the total outflow from the Mtera and from the Kidatu and by comparing the observed losses from the Mtera Reservoir with losses estimated from the reservoirs using models (WREP, 1999).

## RESULTS OF THE INVESTIGATION

Open water potential evaporation and its lake evaporation equivalent from the reservoir system using data of daily duration, from 1972 to 1994, were calculated using an empirical model (Morton *et al*., 1985). Comparison of expected monthly losses, based on the model estimates, and those based on the water balance of the Mtera Reservoir revealed that the latter were much higher for the months of January to May. For the remaining months, the water balance losses compared satisfactorily with the model estimated values.

Mean monthly losses for the period 1984 to 1990, and for 1991 and 1992 (Figure 2), shows that the expected monthly losses calculated during the draw down period of the reservoir (i.e. from June to November) are comparable in magnitude with the estimates of evaporation from the Mtera Reservoir. But for the months of January to May (i.e. during the filling up period of the reservoir) the calculated losses are much higher. There is no obvious reason as to why this should be the case unless, of course, there is (1) an error in the estimated inflow data, or (2) an error in the recorded reservoir levels, or (3) an error in the recorded outflow (WREP, 1999).




| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1984 -1990 | 81 | 130 | 152 | 189 | 135 | 49 | 42 | 32 | 44 | 48 | 40 | 35 |
| 1991&1992 | 64 | 96 | 264 | 272 | 232 | 30 | 24 | 11 | 27 | 20 | 20 | 36 |

Month

**Figure 2: Mean Monthly Model Losses from the Mtera Reservoir**

Figure 3 shows a comparison of the observed and estimated monthly flows at 1ka5 by the SLM for the 16 years prior to the start of construction of Mtera Reservoir in 1980. From the estimated annual flows from 1983 to 1993 (Table 3), inflows in 1991 and in 1992 were not exceptionally low. They were in the same order of magnitude as in previous years. It is interesting to note that the average observed flow at 1ka5 prior to the construction of the reservoir was equal to 118 $m^3/s$. This must have been the value for which the Mtera Reservoir was designed. During the operation period, from 1983 to 1994, the estimated inflow in the reservoir has always been higher than 118 $m^3/s$.

**Table 3: Estimated Annual Flow into Mtera Reservoir from 1983 to 1993 (in $m^3/s$)**

| Model | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SLM | 213 | 174 | 187 | 169 | 238 | 148 | 240 | 248 | 175 | 146 | 184 | 193 |

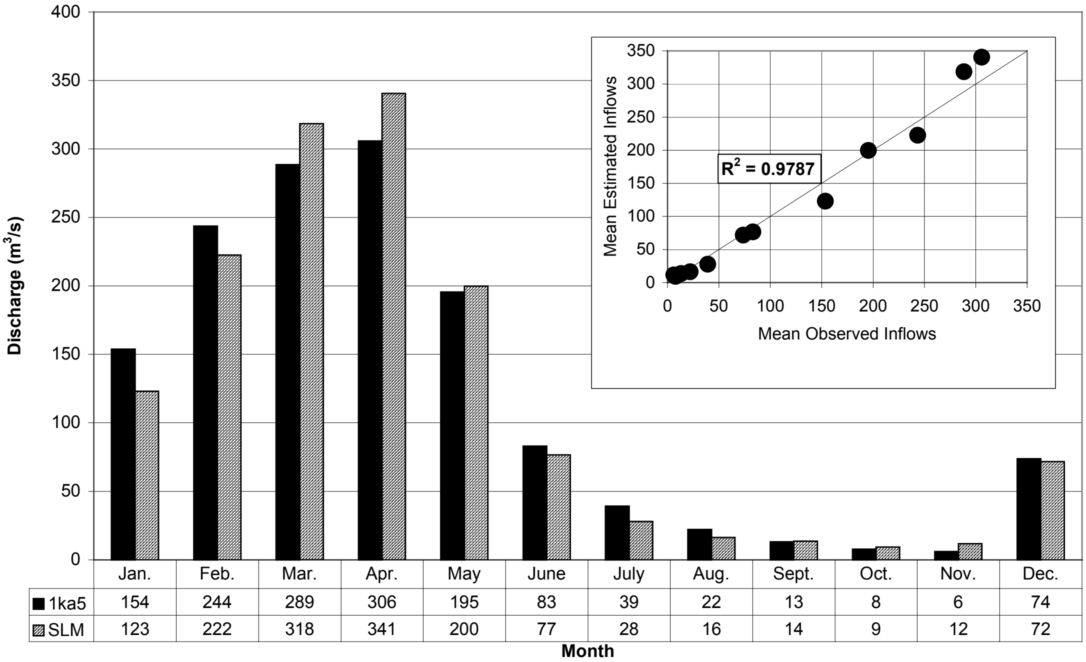



**Figure 3: Comparison of Observed and Estimated Mean Monthly Flows at Mtera (1ka5) using SLM**

This analysis, therefore, rules out decrease in the inflows to the reservoir in 1991 and 1992. To support this conclusion, observed rainfall data in the region had been analysed for decreasing trend. The average annual rainfall prior to 1991 was 855 mm/year compared to 1,022 mm in 1991 and 922 mm in 1992. Statistically, there is no obvious increasing or decreasing trend in the amount of annual rainfall within the catchment.

In addition, there was no sudden increase or any significant increase in the machine discharges at Kidatu Reservoir in 1991 and 1992. The values for these two years are comparable with the previous years. Therefore, increased activity of hydropower development at Kidatu Reservoir was definitely not the cause for the failure of the system. For the recorded spills from the Kidatu Reservoir in 1991 and in 1992, the spill volumes were 621 $Mm^3$ and 353 $Mm^3$, respectively. This is a substantial amount of water and comprises about 30% of the volume from the Mtera Reservoir. It is very difficult to believe that these spills were allowed to happen when the Mtera Reservoir was not full and was struggling to raise its water level to its historical average values.

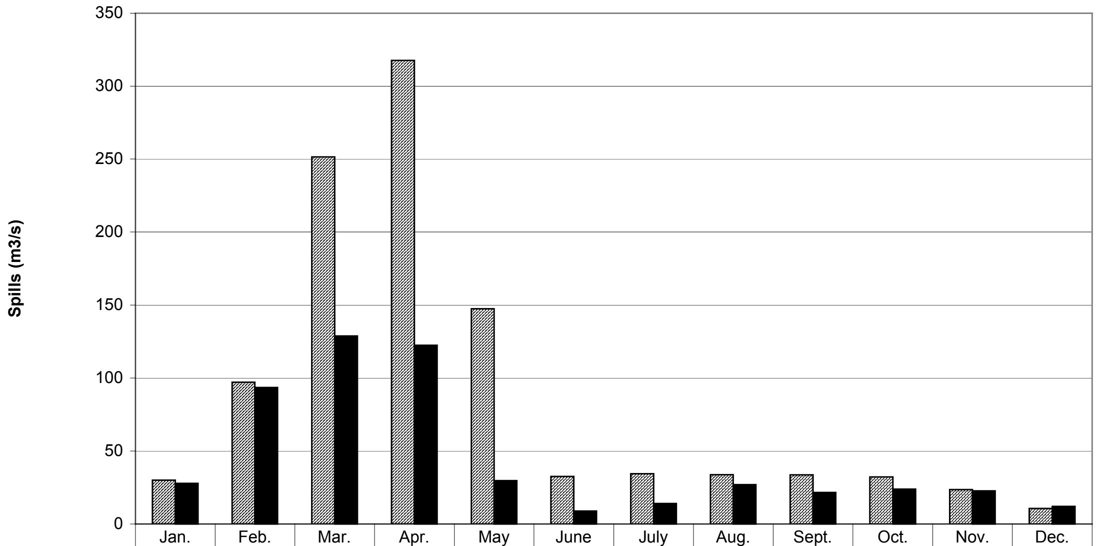
Comparing the total water released (machine discharge plus spill) from the Kidatu Reservoir as well as from the Mtera Reservoir, one would have expected the two quantities to be relatively equal to each other when compared over a period of time if there were no significant contribution from the intervening catchment. However, the available records did not reveal that. Average outflow from Kidatu (101 $Mm^3$) is higher than that of Mtera (65 $Mm^3$). Analysis of spills revealed that most of the spills occurred during the refilling phase of the reservoir (i.e. during the months January to June). Since this is generally the period during which the discrepancy between the observed and the model estimated losses was noted it could be concluded that the actual amount of water that was released form the Mtera Reservoir as spill must have been much higher than what was recorded.

Analysis of the estimated inflows between January and June showed that in 1989 and in 1991 the amount of inflow into the reservoir was more or less the same, 294.3 $m^3/s$ and 247.1 $m^3/s$, respectively, for 1989 and 1991 with the value in 1989 being slightly higher than that of 1991. The total recorded discharge was also similar. It was 89.3 $m^3/s$ in 1989 and 67.3 $m^3/s$ in 1991. Yet in 1989 the water level rose by 3.5 m between January and June whereas in 1991 it rose by only 1 m. Clearly, water was lost through spill in 1991 that was not recorded.

Similarly, the estimated inflow for 1992 between January and June was equal to 219.3 $m^3/s$. In 1990, the reservoir level rose by about 2 m but in 1992 the rise was about 1 m. What is fascinating is that while Mtera Reservoir was struggling to get refilled in 1991 and 1992 the Kidatu Reservoir recorded large amounts of spill – enough to bring the Mtera to its full condition. The average water released from the Mtera Reservoir (61 $m^3/s$ per year) is about two-thirds of the water released from the Kidatu Reservoir (93 $m^3/s$ per year). All these values indicate that a large amount of unrecorded water might have been spilled from the Mtera Reservoir for no reason. If this was not the case, then Kidatu Dam was not generating power as required and Mtera Dam was made to produce at full capacity.

The system's operation was simulated on a ten-day interval and the simulated water levels compare with the recorded reservoir water level at Mtera. The results show that there was a good agreement between the estimated and recorded water levels for the years 1983 up to 1990, but the estimated water levels were much higher than the recorded water levels for the period 1991 and 1992. This simulation analysis confirmed the conclusion drawn from the analysis that the recorded outflows from the Mtera Reservoir are incorrect and if the system was operated efficiently then it should have filled up in 1991 and every other year thereafter.

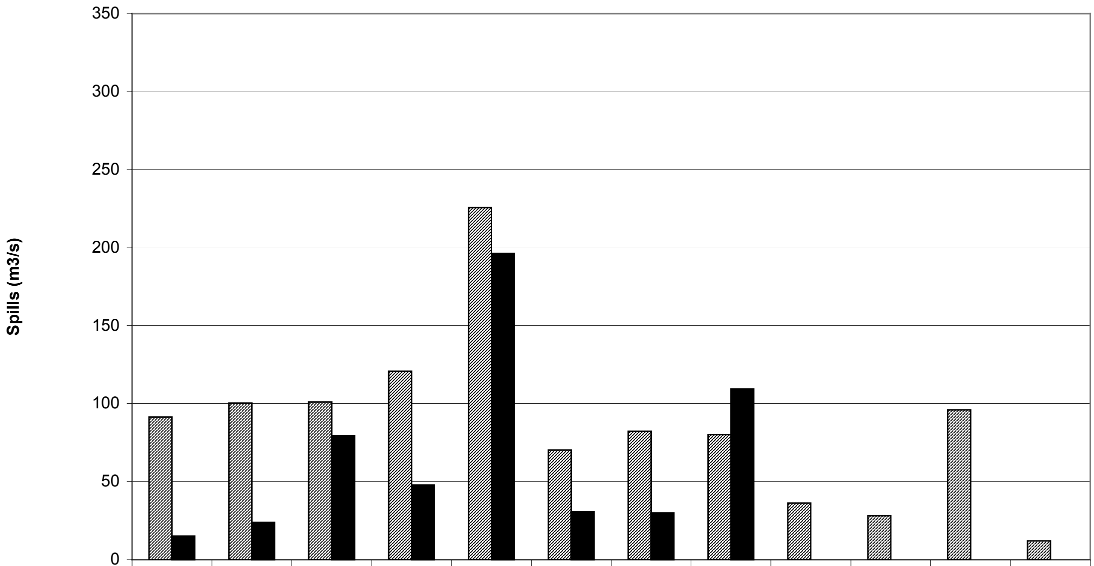
In fact, it was observed during the simulation analysis that there should have been more spills for both Mtera and Kidatu Reservoirs compared to the historical spills. The mean monthly and yearly spills at the Mtera Reservoir are shown in Figures 4 and 5, respectively.




| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean Est. | 29.9 | 97.1 | 251.6 | 317.7 | 147.4 | 32.5 | 34.4 | 33.8 | 33.7 | 32.3 | 23.6 | 10.6 |
| Mean Obs. | 27.9 | 93.6 | 128.9 | 122.5 | 29.8 | 8.9 | 14.1 | 27.0 | 21.7 | 24.0 | 22.7 | 12.0 |

Month

**Figure 4: Plot of Mean Monthly Simulated versus Historical Spills from the Mtera Reservoir**




| Year | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Est. Spills | 91.4 | 100.4 | 101.1 | 120.7 | 225.7 | 70.3 | 82.3 | 80.1 | 36.4 | 28.1 | 96.0 | 12.0 |
| Obs. Spills | 15.2 | 23.9 | 79.4 | 47.9 | 196.3 | 30.7 | 30.0 | 109.4 | 0.0 | 0.0 | 0.0 | 0.0 |

**Figure 5: Plot of Annual Simulated versus Historical Spills from the Mtera Reservoir**

## VERIFICATION OF THE RESULTS USING TALSIM 2.0 MODEL

The results of the investigation discussed above were verified using TALSIM 2.0 model, a reservoir simulation model developed by the Institute for Hydrualics and Water Resourses Engineering, Section for Hydrology and Water Management of the Technical University of Darmstadt, Germany (Froehlich, 2001).

Observed data of inflows, rainfall, releases and spills from 1983 to 1990 were used to calibrate the model. By comparing the computed water levels with the observed water levels, the unknown factors of the model (such as the characteristics of the spillway) are calibrated. The calibration procedure is by trial and error. Once the model had been calibrated using the time period from 1983 to 1990, a continuation of the simulation from 1991 to 1993 determined which factors were the likely causes of the dramatic drop in water levels that occurred during that period.

From 1983 to 1990, the model was able to represent the annual rise and fall of the water levels quite well. In 1991 and 1992, although inflow into the reservoir is relatively low, the model predicts that reservoir levels should remain at a relatively high level, while the observed water levels drop significantly. The failure of the reservoir system, i.e. the dropping of water levels in Mtera Reservoir, started from 1991 onwards. In the simulation as well as the modelling, however, the water levels remained at a high level even after 1991. The only option that seems to justify the difference of the observed and the simulated levels is that the recorded discharges do not represent what was actually released from the reservoir from 1991 to 1993. In other words, there is likelihood that large amounts of water were discharged from Mtera Reservoir during 1991, 1992 – and maybe 1993 – without being (fully) recorded.

It is also a possibility that the discharge from the intervening catchment, which is about 12,000 km$^2$ and contributes between 15% and 40% of the inflow into Kidatu Reservoir each year, was and/or is not being computed or accounted for correctly in the normal operation of the system.

Figure 6 shows the closeness of the water levels produced by the TALSIM 2.0 model and results from the investigated techniques employed in this study with an efficiency of almost 95%, indicating a very good correlation.

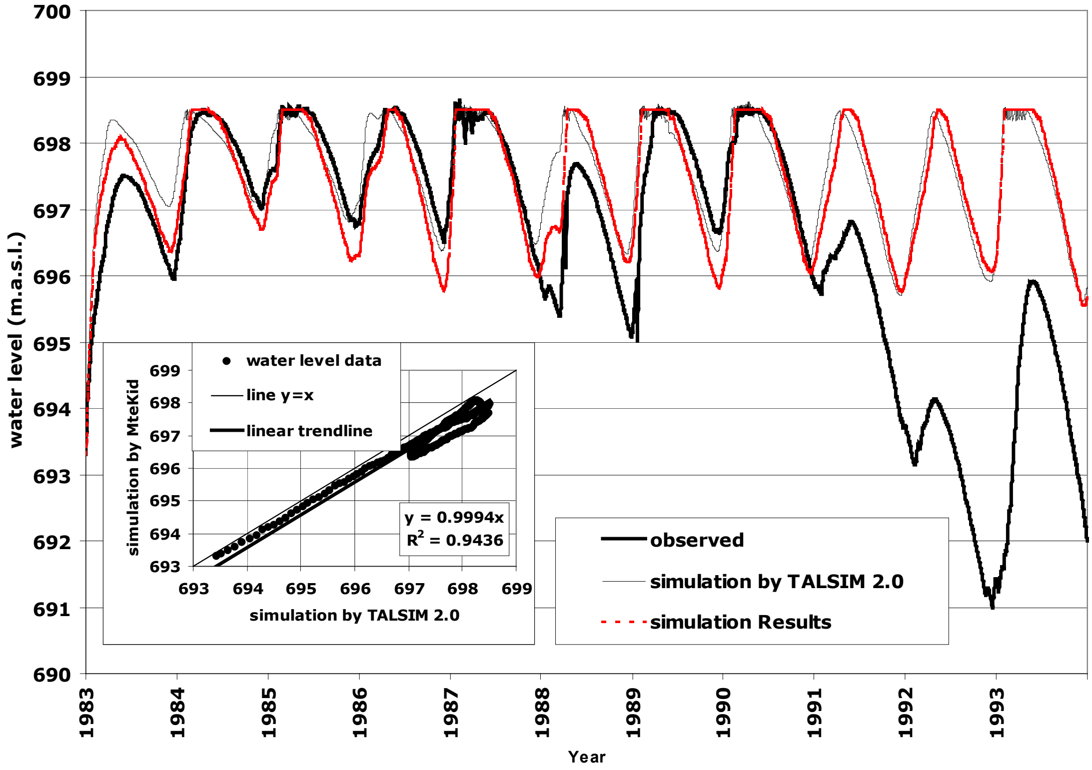



**Figure 6: Verification of the Investigation using TALSIM 2.0 model**

A possible way the two results would have failed was by changing the operation rule such as making Kidatu Dam to run below full capacity levels and maximising power generation at Mtera Dam instead. This can easily happen if some of the turbines at Kidatu are not functioning, and that would not have produced efficiently for the reservoir system in terms of overall power generation.

## CONCLUSION AND RECOMMENDATION

Possible causes for the failure of the Mtera-Kidatu Reservoir System had been investigated in this paper and it had been concluded that unaccounted for and/or unnecessary spillage at the Mtera Dam is the most likely cause of the system's failure. The other possible causes considered were sudden decrease in inflows, sudden increase in losses and sudden increase in hydropower generation. There is enough evidence that a large amount of unrecorded water might have been spilled from the Mtera Reservoir.

Simulation of reservoir operation based on maintaining historical machine discharges at Mtera and Kidatu Reservoirs indicated that much higher reservoir water levels should have been attained in 1991 and 1992 than what was attained and that would have averted the subsequent failure of the reservoir system in 1994. Clearly, there was a serious problem with the reservoir operation policy of the Mtera-Kidatu Reservoir System during this period 1991-1992 that this study investigated.

It is recommended from this study that the operation of the system should be done taking into account the flows generated by the intervening catchment with respect to the amount that can actually be used by the turbines at Kidatu before releases are made at Mtera. The conclusion drawn from this investigative study was strongly supported with the application of TALSIM 2.0 model, which have been applied extensively in other reservoir systems.

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