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Short communication

WATER BALANCE EVALUATION, LEAKAGE RATE AND TOTAL WATER LOSS OF KOKA RESERVOIR, ETHIOPIA: COMMENTS ON PREVIOUS STUDIES AND NEW DETERMINATIONS

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ABSTRACT: Water balance evaluation of Koka Reservoir was attempted by different authors, and different leakage rates were estimated. However, the water balance equation that the previous authors used does not take into account ground water inflow into the reservoir. Koka Reservoir is known to receive groundwater inflow from the north, west and south shores and from the reservoir floor, and loses water by leakage at the northeast reservoir bank and where it abuts on the Koka Dam. Hence, previous estimated leakage rates and total reservoir water loss are incorrect. An appropriate water balance equation is proposed for Koka Reservoir, and subsurface outflow (leakage rate) of 485 mm^3/year and total reservoir water loss of 546 mm^3/year are determined. The new determinations are recommended to be used for Awash River simulation model.

Key words/phrases: Ethiopia, Koka Reservoir water loss, leakage rate, subsurface inflow, water balance

INTRODUCTION

Koka Dam was built on Awash River, Ethiopia, in 1960 for hydropower and irrigation purposes. It is located at 8°24'N latitude and 39°05'E longitude (Fig. 1). The dam is a concrete gravity type, with a height of 23.8m, crest length of 438.8m and a reservoir area and capacity of 236 km^2 and 1850 mm^3, respectively.

The foundation rock mass beneath the Koka Dam was initially treated by curtain grouting during construction, and no serious leakage problem beneath the dam was reported. However, leakage from Koka Reservoir has been reported since the completion of the dam.

Previous reservoir water balance evaluations have given leakage rates of 90-435 mm^3/year (FAO, 1965; Ital Consult, 1970; Meacham, 1972 cited in Gibb, 1975; Halcrow, 1989). According to these studies, vertical leakage occurs through the whole reservoir floor sediments. Subsequent studies have shown that leakage occurs through volcanic rock masses at the northeast (right) bank of the reservoir and abut on the Koka Dam and that the reservoir receives ground water inflow from the north, west and south directions, and through its floor (Sileshi Mamo, 1995; 1999; Sileshi Mamo and Yokota, 1998a; 1998b) (See Figure 1).

The purpose of this study is to evaluate previous water balance studies and determine appropriate leakage rate and total water loss of Koka Reservoir.

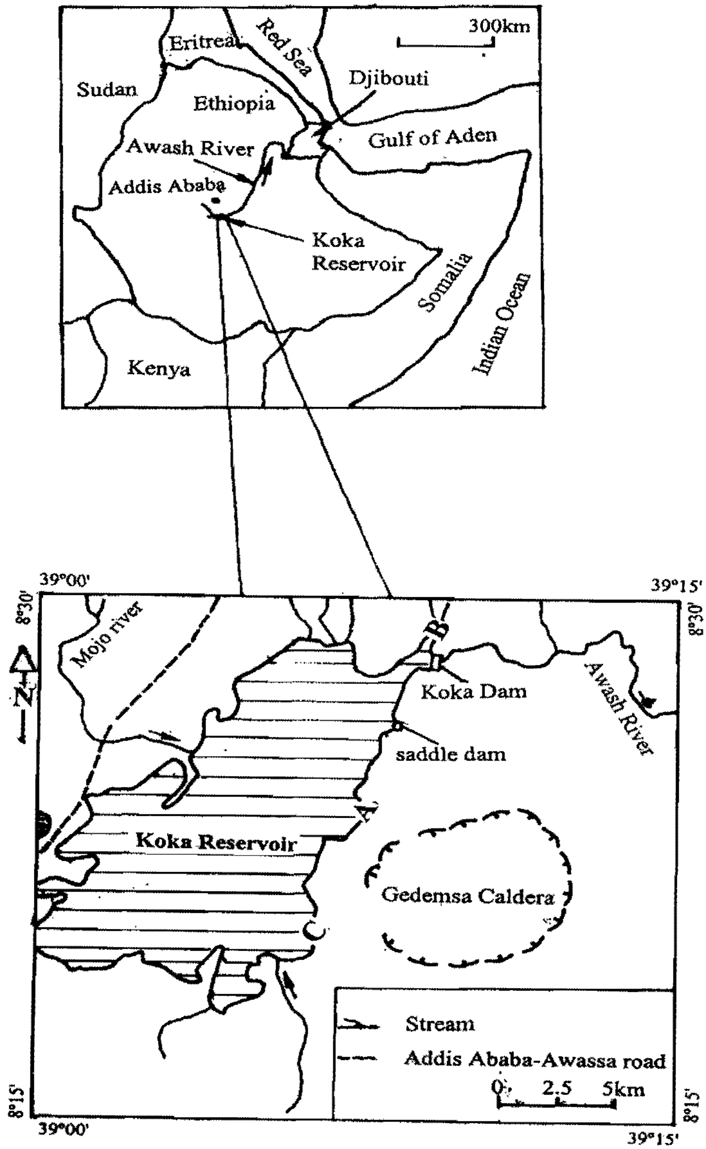

Fig. 1. Location map of Koka Reservoir showing leakage sites (between A and Koka Dam, and Koka Dam and B).

PREVIOUS STUDIES

A number of consulting companies studied the water balance of Koka Reservoir and estimated the following leakage rates:

FAO (1965) = 400 mm^3/year
Ital Consult (1970) = 435 mm^3/year
Meacham (1972) cited in Gibb (1975) = 90 mm^3/year
Halcrow (1989) = 173 mm^3/year

Meacham (1972), as reported in Gibb (1975), estimated leakage rate by comparing surface flow at Koka Dam using pre Koka Dam data and post Koka Dam reservoir out flows adjusted for storage and evaporation. Flow rates were calculated using the Addis Ababa rainfall data.

For wet season flows, June to October, Meacham (1972) found that the post Koka Dam flows were on average 80 mm^3 higher than pre Koka Dam flows. Considering a direct rainfall on the reservoir of 130 mm^3, leakage loss of 50 mm^3 was calculated for this period.

During the period between November and May, Meacham (1972) found that the pre Koka Dam and post Koka Dam adjusted flows were the same, which suggests that leakage loss was balanced by the direct rainfall on the reservoir, which is 40 mm^3. The average annual leakage loss was therefore reported to be 90 mm^3/year. However, Meacham's (1972) report is not available to the author so as to give further comments on this method of estimating leakage rate, and the period used in this computation is unknown. Nevertheless, this approach of evaluation does not consider ground water contribution to Koka Reservoir storage, and therefore the estimated leakage rate is not accurate.

FAO (1965), Ital Consult (1970) and Halcrow (1989) used the following water balance formula to estimate leakage rates.

Leakage = Surface inflow + Area (Precipitation - Evaporation)
- Surface outflow - Change in reservoir storage .... (1)

Direct abstraction rate from Koka Reservoir for local public and livestock uses cannot be known, and was not considered in the above water balance evaluation. However, in comparison to other parameters, it is small to affect the change in reservoir storage.

FAO (1965) evaluated water balance on annual basis, and estimated leakage rates of 435 mm^3/year and 405 mm^3/year for the years 1962-63 and 1963-64, respectively. However, FAO (1965) used short (2 years) period data, and did not consider monthly variations in water balance components. Pan evaporation data was used in water balance evaluation.

Ital Consult (1970) did water balance evaluation on annual basis for the period between 1963 and 1969 (7 years). They estimated annual leakage rates, which range between 227 mm^3/year and 784 mm^3/year, with a mean of 439 mm^3. Pan evaporation data was used in this water balance evaluation.

Applying Gumbel's law of statistical distribution or law of large numbers, Ital Consult (1970) estimated surface inflow to Koka Reservoir at frequencies of 50%, 80% and 95%. From Gumbel graph of probabilities, reservoir levels were read at the same frequencies with the calculated inflows of the hydrological years, that is, at 50%, 80% and 95%. Using these reservoir levels, leakage rates of 435, 350 and 300 mm^3/year were read, respectively at frequencies of 50%, 80% and 95%, from the graph of annual leakage rates versus annual average reservoir levels. Ital Consult (1970) recommended annual leakage loss of 435 mm^3, which was obtained at frequency of 50%, for water balance studies.

However, the reason why Ital Consult (1970) chose this value and disregarded the others is not clear. Furthermore, because evaluation was done on annual basis, it does not take into account the monthly variation of parameters.

Halcrow (1989) evaluated water balance on monthly basis, and has estimated mean monthly leakage rates for the period between 1968 and 1987. Mean monthly leakage rates have also been estimated for the same period excluding 1971 and 1974, and 1971, 1974 and 1975 data, which give anomalously high leakage rates (See Table 1).

Halcrow (1989) interpreted the latter to represent the reservoir leakage rates, and reported a mean annual leakage rate of 173 mm^3, which is the algebraic sum of mean monthly positive and negative computed values.

The present study shows that high leakage loss is not seen for all months of 1971, 1974 and 1975, and in all of the other years. Hence, those data estimated for the period between 1968 and 1987 are. best representative than the others, (Table 1).

In Halcrow (1989) monthly Koka Reservoir level, which was read at the staff gauge, was converted to areas and storage volumes using elevation/area/storage curves of the reservoir. NEDECO's 1969 and 1981 curves have been used for 1968–78 and 1979–83 data, respectively. Halcrow's 1989 curve was used for the years between 1983 and 1987.

Table 1. Mean monthly leakage data in mm³ (Halcrow, 1989)*.

Month	1968-87	1968-87 excluding 1971 and 1974	1968-87 excluding 1971, 1974 and 1975
January	-31.4	-37.3	4.3
February	-4.4	-7.8	-8.5
March	3.2	-0.9	0.6
April	-1.3	-3.2	-3.2
May	7.9	8.6	8.6
June	-8.9	-21.1	-25.1
July	199.5	188.5	177.7
August	216.6	205.7	218.1
September	-130.1	-149.5	-147.1
October	-36.8	-32.5	-23.1
November	-35.0	-44.8	-37.8
December	58.2	19.3	9.2
Net sum	237.5	125.0	172.5

* Leakage estimation was done for each year and mean monthly data calculated for the given periods.

Evaporation from Koka Reservoir was derived from potential evapotranspiration rate. Pan evaporation data at Koka gave low open water surface evaporation, and therefore was not used in water balance evaluation.

Rainfall data for the period 1961 to 1979 for the nearby Wonji station, which is located at 8°27'N latitude and 39°14E longitude, were used. The period mean derived from 1961 to 1979 data was used in the water balance study for the period 1979 to 1987 because of intermittent records.

Surface water inflow into the Koka includes flow at Melka Hombole station on Awash River, which is located at 8°23'N latitude and 38°47'E longitude, and flow at Mojo station on Mojo stream that is located at 8°36'N latitude and 39°05'E longitude, and local ungauged runoff from the surrounding area of the reservoir. Outflow from the reservoir was taken from flow recorded at Koka gauge station, immediately down stream of the Koka Dam. Hydrometeorological data are given in Table 2.

The water balance formula (equation 1) that FAO (1965), Ital Consult (1970) and Halcrow (1989) used to estimate leakage rates does not consider ground water inflow into the reservoir. The author believes that this water balance formula is not appropriate to estimate leakage rates for cases such as Koka Reservoir where ground water inflow is an important component of the reservoir water. Therefore, previously determined leakage rates and total reservoir water losses are not realistic. New and more accurate values are determined based on a more appropriate water balance equation for Koka Reservoir.

Table 2. Hydrometeorlogical data (Halcrow, 1989).

Month	Precipitation avg. 1961-79 (mm)	Evaporation avg. 1968-87 (mm³)	Surface inflow avg. 1968-87 (mm³)	Surface outflow avg. 1968-87 (mm³)	Storage* avg. 1968-87 (mm³)	Reservoir area avg. 1968-87 (km²)
January	12.62	22.7	16.1	89.6	982.7	152.5
February	27.43	22.8	17.4	77.8	908.3	151.0
March	45.23	26.2	25.2	86.1	824.0	149.4
April	54.02	27.1	32.3	88.1	749.2	147.6
May	61.22	27.5	31.0	91.7	661.0	144.8
June	78.39	27.2	54.6	91.1	616.7	141.9
July	206.08	25.4	309.3	100.5	629.2	142.6
August	197.27	26.4	699.1	146.1	968.1	152.8
September	99.35	28.4	366.1	179.8	1272.4	164.1
October	29.76	27.7	48.9	107.0	1228.1	162.1
November	7.16	24.4	27.3	85.1	1182.2	159.7
December	7.27	22.3	14.1	92.3	1024.6	154.0
Annual	825.8	308.1	1641.4	1235.2		

*** Initial Koka Reservoir storage value in December 1967 was 831 mm³.**

PRESENT WORK AND DISCUSSION

The topographic, geological and hydrogeological setting around Koka Reservoir suggests that the reservoir receives ground water discharge from the north, west and south shores and from its floor. Leakage occurs through the northeast (right) bank of the reservoir (between A and Koka Dam in Fig. 1) and abut on the Koka Dam (between Koka Dam and B in Fig. 1) (Sileshi Mamo, 1995; 1999; Sileshi Mamo and Yokota, 1998a; 1998b).

Tritium radioisotope data of ground water from wells and springs around the reservoir and from the reservoir water have also revealed that old regional pre-atomic bomb period ground waters, at places intermixed with post bomb local ground waters, discharge at the mentioned (north, west and south) shores and on the reservoir floor (Sileshi Mamo, 1999). High tritium values and their spatial variation around the northeast (right) bank and abut on Koka Dam, in comparison to the other areas without reservoir water influence, have shown leakage under flow to this area through the mentioned reservoir banks (between A and Koka Dam, and Koka Dam and B in Figure 1).

Ground waters are highly enriched in stable isotopes (^2H and ^{18}O) close to the northeast (right) bank, and the enrichment decreases away from the reservoir. This suggests mixing of highly enriched reservoir water with less enriched ground water. Mixing rates decrease away from the reservoir, which indicate leakage under-flow through the northeast (right) bank (between A and Koka Dam in Figure 1). Hydrochemistry data have also shown mixing of reservoir water with ground water in the mentioned area that suggests leakage through the northeast (right) bank (Sileshi Mamo, 1995; 1999; Sileshi Mamo and Yokota, 1998a; 1998b).

The reservoir bank between C and A in Figure 1 is watertight, as it is constituted by very low permeable formations such as highly indurated pumice deposit and massive rhyolite, and the foundation of Koka Dam itself (Sileshi Mamo, 1995; 1999; Sileshi Mamo and Yokota, 1998a; 1998b).

Therefore, the Koka Reservoir may be characterized as a through-flow type, which receives groundwater inflow from north, west and south shores and from its floor and that loses water by leakage through the northeast (right) bank and abut on Koka Dam.

Hence a more appropriate water balance formula for Koka Reservoir, which considers ground water input, is the following (see also Figure 2).

$$Go = Gi + Si + A(P - E) - So - \Delta V \qquad (2)$$

where, Go = leakage rate; Gi = Subsurface inflow; Si = Surface inflow; P = Precipitation; E = Evaporation; So = Surface outflow; A = Reservoir area; and ΔV = Change in reservoir storage, which is a difference between storage at the end of current month or year and storage at the end of preceding month or year.

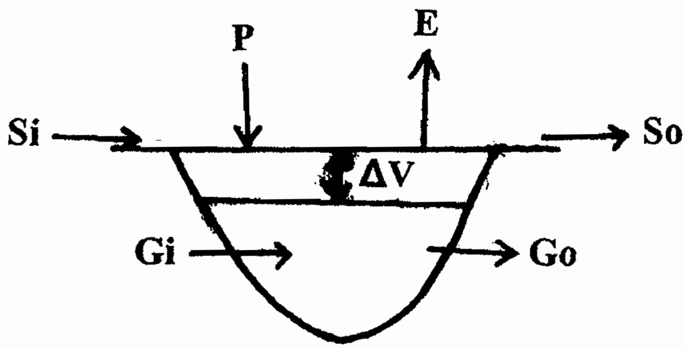

Fig. 2. Water balance components of Koka Reservoir. (P, precipitation; E, evaporation; Si, surface inflow; So, surface outflow; Gi, subsurface (ground water) inflow; Go, subsurface outflow (leakage); ΔV, changes in reservoir storage.)

Equation 2 can be rewritten as follows:

$$\Delta G = Si + A(P - E) - So - \Delta V \quad \text{......} (3)$$

where, ΔG = Go - Gi, and other symbols represent the same parameters mentioned in equation 2.

This formula (equation 3) is identical to equation 1 that FAO (1965), Ital Consult (1970) and Halcrow (1989) used for water balance evaluation, except that the parameter on the left side of equation 1 is leakage rate while that in equation 3 is ΔG value. This implies that the previous data computed using equation 1, which were reported to be leakage rates by FAO (1965), Ital Consult (1970) and Halcrow (1989), represent the difference between leakage rate and subsurface (ground water) inflow (ΔG) in equation 3.

It is found that the water balance evaluation by Halcrow (1989) on monthly basis is a better determination than the other two as it considers seasonal variation. Besides, the evaluation was done for a longer period (20 years), which gives reliable mean monthly ΔG values.

Therefore, mean monthly ΔG values, which are estimated by Halcrow (1989) for the period 1968–87 (Table 1), are used here to estimate leakage rate and total water loss of Koka Reservoir. Positive ΔG values show leakage rate greater than ground water inflow and negative values show leakage rate less than ground water inflow. ΔG values vary from month to month according to the proportion of leakage rate and ground water inflow in a particular month.

Mean annual leakage rate is equal to the sum of ground water inflow and the sum of monthly ΔG values (238 mm^3). Ground water inflow rate into Koka Reservoir is unknown. The sum of mean monthly positive ΔG values (485.4 mm^3/year) gives the minimum leakage rate for Koka Reservoir.

Halcrow (1989) estimated monthly total reservoir water loss using equation 4 below. Data for the period 1968-87, excluding 1971, 74 and 75 were used in this calculation.

Monthly total reservoir water loss
= K times Monthly evaporation rate ...... (4)

where, K is leakage factor given by

K = leakage + evaporation/ evaporation (annual data).

Halcrow (1989) wrongly used 173 mm^3 as annual leakage rate to calculate the leakage factor. This value is a mean annual ΔG value for the period 1968-87, excluding 1971, 74 and 75 data. Furthermore, Halcrow's (1989) approach gave positive total reservoir water loss for all months (Table 3).

Table 3. Total water loss from Koka Reservoir, in mm^3.

Month	ΔG	Evaporation (E)	TRWL*a Halcrow (1989)	TRWL*b this work
January	-31.4	22.7	35.5	-8.7
February	-4.4	22.8	35.66	18.4
March	3.2	26.2	41.26	29.4
April	-1.3	27.1	42.97	25.8
May	7.9	27.5	43.75	35.4
June	-8.9	27.2	43.75	18.3
July	199.5	25.4	40.33	224.9
August	216.6	26.4	40.95	243.0
September	-130.1	28.4	43.91	-101.7
October	-36.8	27.7	42.82	-9.1
November	-35.0	24.4	37.06	-10.6
December	58.2	22.3	34.57	80.5
Annual sum	237.5	308.1	482.53	545.6

*a Total reservoir water loss = K.E; where, E = evaporation (monthly data in mm^3), K = leakage + evaporation/evaporation (annual data).
*b Total reservoir water loss = ΔG + E, monthly data in mm^3; where E = evaporation, ΔG = leakage rate – subsurface inflow.

The monthly total reservoir water loss, which is a net reservoir water loss by leakage and evaporation, should instead be estimated from algebraic sum of mean monthly ΔG values and monthly evaporation rates as given in equation 5 below:

$$\text{Monthly total reservoir water loss} = \Delta G + \text{evaporation rate} \quad \text{............ (5)}$$

In the present work, mean monthly data for the period between 1968 and 1987 are used to calculate monthly total reservoir water loss.

The results obtained using this approach are shown in Table 3 above and compared with those given by Halcrow (1989). ΔG values give net reservoir water losses or gains due to subsurface outflow (leakage) and subsurface (ground water) inflow. Accordingly, estimated monthly Koka Reservoir water losses show negative and positive values as given in Table 3. Negative values indicate that the reservoir has received net gain of water from ground water inflow. This method of estimating the total reservoir water loss considers all factors, and the method could be recommended to be applied for Awash River simulation model.

The annual total reservoir water loss is calculated as the algebraic sum of monthly reservoir water losses, which is 545.6 mm^3/year.

CONCLUSIONS

It is shown that previous estimates of leakage rates and total Koka Reservoir water loss are not realistic. A more appropriate and reliable approach has been followed to calculate subsurface outflow (leakage rate) and total reservoir water loss taking ground water input into consideration. This method of estimating leakage rate and total water loss may also be adapted to other reservoirs and lakes that have subsurface inflow and outflow.

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REFERENCES

1. Gibb, A. (1975). Feasibility study of the lower Awash Valley, part 1, annex 2, climate and hydrology, unpublished report, London.
2. Halcrow (1989). Master plan for the development of surface water resources in the Awash basin, Vol. 4, Climate and Hydrology, unpublished report by Hlcrow Campany (England), Addis Ababa, Ethiopia.
3. Ital Consult (1970). Meky River diversion scheme, Vol. 2, hydrology, unpublished report, Rome.
4. Sileshi Mamo (1995). Research study on the Koka Dam Reservoir leakage paths, unpublished report, Addis Ababa, Ethiopia. Submitted to the Ethiopian Science and Technology Commission.
5. Sileshi Mamo and Yokota, S. (1998a). Estimation of Koka Reservoir leakage paths by hydrogeological and isotope techniques. **In**: *Proceedings, Eighth International Congress of the International Association for Engineering Geology and the Environment*, pp. 2409–2416, (Moore, D. and Hunger, O., eds). A.A. Balkema/Rotterdam/Brookfield.
6. Sileshi Mamo and Yokota, S. (1998b). Leakage path of Koka Reservoir in Ethiopian rift valley and its estimation using hydrogeological techniques. In: *Proceedings, Annual Congress of Chugoku-Shikoku Branch of Japanese Society of Engineering Geology*, pp. 35-40. Shikoku, Japan.
7. Sileshi Mamo (1999). Tracing of leakage path of Koka Reservoir based on geological, hydrogeological and isotopes studies. Unpublished M.Sc. thesis, Shimane University, Japan.
8. FAO (1965). Survey of the Awash River basin, vol. III, climate and hydrology, unpublished report, Food and Agriculture Organization, Rome.