Rainfall influence on water gain and loss from Middle Letaba Dam in Luvuvhu-Letaba Water Management Area, South Africa

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Abstract

The objective of the study was to investigate the influence of rainfall received by the Middle Letaba Dam on its water gain and loss. Relevant data was obtained from Department of Water Affairs. Rainfall increase was followed by increases in: inflow from the source river (with lag of one month), potential evaporation, normal flow, and dam storage volume (with lag of two months). Abstractions from dam were not influenced by rainfall as these were controlled by dam operation rules. The lags for increases of inflow and storage volume possibly resulted from spatial variation of rainfall and occurrence of small dams in the catchment upstream of the dam. The analysis reveals that the dam cannot be maintained at full storage volume from only rainfall, but will need transfers from other catchments.

Keywords: Rainfall, inflow, evaporation, abstraction, outflow, storage volume

1. Introduction

Water demand already exceeds supply in many parts of the world, and more areas are expected to experience this imbalance in the near future. Water is required for domestic, industrial, agricultural, recreational and environmental uses. Demand for water for these uses is rapidly increasing due to increasing population and growing awareness of environmental, health and recreational issues (Vairavamoorthy *et al.,* 2008). Water storage has become important, and man enhances the storage by constructing dams to impound water (Keller *et al.*, 2000; Muller, 2000). According to Keller *et al.* (2000), storage of water in dams involves the capturing of water when and where its economic value is low - or as in the case of floods, even negative and reallocating it to times and places when and where its economic value is high. Dams support economic, social and cultural activities and the functioning of ecosystems (Saiko and Zonn, 2000; Mostert, 2008) through their water supplies for household, industrial, irrigation and ecological requirements (Katambara and Ndiritu, 2009). As revealed by Inocencio *et al.* (2003), construction of dams is an obvious response to the problem of water scarcity.

Dams are often classified as small or large. Small dams are those with embankment volumes generally less than 0.75 million m^3 (BOR, 1987; ICOLD, 1998). These dams are operationally efficient and often closer to the point of use. However, their high surface area to volume ratio leads to high evaporation loss averaging 50 percent of the impoundment (Gleick, 1993; Sakthivadivel *et al.,* 1997). Large dams have embankment volumes of 1 million m^3 or more (ICOLD, 1998). The aggregate design storage capacity of the world's largest dam is about 6 000 km^3 (LeCornu, 1998) while total annual withdrawal is 3 800 km^3 (Gleick, 1998).

The ability of a dam to supply water for different uses is dependant on its water gain and loss and these are influenced by the amount of rainfall it receives. The water gains are inputs (rainfall and inflows) while the losses are outputs (evaporation, abstractions, and outflows), and these result in changes in storage (ORMCP, undated).
The purpose of this study was to investigate the influence of rainfall received over the surface area of the dam on water gain and loss and on water storage volume of the Middle Letaba Dam in the Luvuvhu-Letaba Water Management Area (WMA) of South Africa. The gain components investigated were the rainfall itself and inflow from the source river while the loss components were potential evaporation from the dam and outflow (inclusive of domestic and industry supplies, irrigation and normal flows). The study was necessary to gain understanding of why the dam level is often low while communities targeted for water supply from the dam live in persistent shortage of the resource.

2. Methodology

2.1 Dam location and physical characteristics

The Middle Letaba Dam is on the Middle Letaba River which is part of the Letaba catchment of the Luvuvhu-Letaba WMA. The catchment is located in a semi-arid region in the north-eastern part of South Africa. The western part of the catchment is mountainous with an altitude higher than 2 000m above mean sea level, and that decreases gradually towards the eastern part to slightly below 450m above mean sea level. The Middle Letaba River originates from the mountainous region and flows towards the lower eastern part of the catchment (Tshikolomo *et al.,* 2009; Katambara and Ndiritu, 2009).

The dam is located within the South African Quaternary Catchment (QC) number B82D with an area of 632km^2 while its total catchment area is 1 806km^2 (Midgley *et al.,* 1994). Specifically, the dam is located at 30˚24΄4.68΄΄E and 23˚16΄16.967΄΄S. Smaller dams such as Rietspruit, Lorna Dawn and Duiwelskloof Dam occur in the same catchment upstream of the Middle Letaba Dam. The location of the Middle Letaba Dam is shown in Fig. 1.
At full supply, the dam has a surface area of 1 926ha and a head of 18m with the lowest outlet at -0.520m. The gross full supply capacity is 184 210 000m^3 while the net supply capacity is 171 930 000m^3 (DWAF, 2004a), making the Middle Letaba the largest dam in the WMA when full supply capacity is considered.

2.2 Sampling procedure

The Middle Letaba Dam was purposively sampled for the study because of its water storage volume that was persistently low making water use communities to experience continued shortage of the resource. Leedy and Ormrod (2010) described purposive sampling as the selection of study units for a particular purpose. The purpose of selecting the Middle Letaba Dam was to investigate the influence of the rainfall received over the surface area of the dam on its water gain and loss components and to subsequently identify the causes of persistent low storage volume. As a result of the low water storage volume, the dam completely failed to supply water during July 1994 to February 1995 (DWAF, 2004b). Domestic demand in this period was met by pumping water from dead storage into the outlet tower. The dam continues to fail to supply water to the targeted communities of Giyani Municipality, making it arguably the most water stressed municipality in the Limpopo Province of South Africa.

2.3 Data collection and analysis

The data for rainfall and related water gain and loss components of the Middle Letaba Dam was obtained from the Department of Water Affairs. The department collected the data at the dam site over a period of 20 years from 1990 to 2009 (DWAF, undated).

The data was organized using spread sheet to perform relevant calculations and to draw graphs to illustrate relationships between rainfall and the water gain and loss components. This method of data analysis was in accordance with Leedy and Ormrod (2010) who indicated that electronic spreadsheets can quickly and easily organize the data and make simple calculations once the data is entered into the sheets.

3. Results and discussion

3.1 Rainfall received over the surface area of the dam

Rainfall is the fundamental driving force and pulsar input behind most hydrological processes (Schulze, 1995) and is in fact a major source of water for a dam (Nath and Bolte, 1998). According to Kongo and Jewitt (2006), the hydrological response of a dam can generally be defined as its reaction to rainfall. The mean monthly rainfall received over the surface area of the Middle Letaba Dam is presented in Figure 2.

According to Fig. 2, the rainfall received over the surface area of the dam was high for summer months with 76mm recorded for November, 87mm for December, and 115mm for January. High rainfalls were also received during February (119mm) and March (70mm) with lesser amounts received in the rest of the months. The least rainfalls occurred in June (2mm). The rainfall increased through spring from September (25mm) to October (37mm), and continued to increase in the summer months. The dam received high rainfall in summer with higher falls coming later during the early to mid-autumn. This pattern of rainfall is similar to the general trend in the WMA. It would be expected for the dam to gain more water from direct rainfall during the higher rainfall months.

3.2 The influence of rainfall on inflow from source river

The rainfall received over the surface area of the dam would likely also occur in some parts of the catchment and this would be expected to influence inflow from the source river. This inflow, often referred to as streamflow, consists of the above-dam runoff from the catchment where the dam is located and the runoffs from all upstream catchments. Runoff was defined as the water yield from a given catchment and consists of stormflow, baseflow and seepage (Schulze, 1995; Fargo, 2002; Webb, 2005). The magnitudes of stormflow and baseflow after a rainfall event are influenced by the condition of the land surface. Land with more vegetative cover promotes baseflow while that with lesser vegetative cover promotes stormflow (Chandler, 2006; Heck *et al.,* 2006) and this could have some effect on the amount of inflow at a given time. Land use in the catchment upstream of the Middle Letaba Dam is characterized by irrigated crop farming where tomato is the major crop. The irrigated area varies during the cropping season from 2 100ha to 3 700ha with irrigation water pumped directly from the river (DWAF, 2004b). This type of land use results in lesser vegetative cover which promotes storm flow. The monthly inflows from the source river were calculated based on dam surface area to determine the extent to which the inflows would affect the level of the dam. The influence of monthly rainfall on inflows to the Middle Letaba Dam is shown in Fig. 3.

Although rainfall started to increase in September (25mm), inflow remained low at 114mm. It was only when rainfall continued to increase in October (37mm) that the inflow from the source river increased from 114 to 271mm, showing a time lag of inflow response to rainfall increase. As rainfall continued to increase through November to February, inflow increased up to March. While the peak of rainfall was recorded in February (119mm), that of inflow only occurred in March (8 764mm), presenting a time lag of one month from the highest rainfall received over the surface area of the dam to maximum inflow from the source river. As revealed in Fig. 3, occurrence (or increase) of rainfall received over the surface area of the Middle Letaba Dam was accompanied by an increase of inflow from the source river with a time lag of one month. With the catchment area upstream of the dam often under irrigated cropping with sparse cover, land use patterns may not adequately explain the one month time lag from peak rainfall to peak inflow. The time lag could have resulted from a number of factors, and these include spatial distribution of rain gauges and the occurrence of small dams in the catchment upstream of the Middle Letaba Dam (Fig. 1). The occurrence of other dams in the catchment upstream of the Middle Letaba Dam supports Katambara *et al.* (2009) who revealed that there are many farm dams in the Letaba River system. The time lag from peak rainfall to peak inflow is probably a result of the need for filling time for these upstream dams before the runoff may flow over to the downstream Middle Letaba Dam. The time lag may also be a result of spatial variation of rainfall upstream of the dam.

3.3 Rainfall influence on evaporation from the dam surface

The term evaporation includes potential and actual evaporation where the former is defined as the evaporative demand of the atmosphere and occurs when there is unlimited supply of water while the latter reflects the actual amount of water evaporated from the soil and includes situations of limited supply of the resource (De Silva, 1999). The evaporation from dam surface reflects a situation of unlimited supply and is therefore regarded as potential evaporation. The estimates of the amount and rate of potential evaporation are required in water resource management for a variety of purposes such as the design of dams, catchment water balance studies and municipal and industrial water supply (Mengistu and Savage, 2010).

An investigation of the influence of rainfall on potential evaporation from the dam is important for better understanding the hydrology of the dam. The rainfall and potential evaporation from the Middle Letaba Dam is presented in Fig. 4. Maximum and minimum monthly temperatures are also plotted to assess the extent to which they influence the potential evaporation.

Fig. 4 reveals that evaporation from the surface area of the Middle Letaba Dam was higher than rainfall for the twelve months of the year and this could be reason for levels of the dam to be often low and for its failure to supply water during July 1994 to February 1995 (DWAF, 2004b). The evaporation from the dam surface increased with rainfall and was accordingly higher during summer compared to winter months. The evaporation could not have been influenced by changes in the surface area of the dam due to changes in rainfall as the evaporation was based on the existing dam surface area and expressed mm/month. It may therefore be concluded that rainfall had no influence on the evaporation from the Middle Letaba Dam.

As shown in Fig. 4, the temperatures (both maximum and minimum) at the dam changed with months of the year with higher temperature recorded in the summer compared to winter months. Higher temperatures were associated with higher potential evaporation. The higher temperatures resulted in more energy being available to evaporate the water and hence the changes in potential evaporation across the months were caused by temperature changes.

3.4 The influence of rainfall on outflow from the dam

Outflow from the Middle Letaba Dam includes supplies to households and industry, irrigation and normal flow. The water supplied to households and industry is for primary consumption and is regarded as a priority. The water supplied for household is used for domestic and productive activities while that for industry is used for processing activities. In order to understand the uses of household and industrial water supplies, it is important to consider the population and economic activities (Johnson, 2001; Kojiri, 2008). A total of 2 400ha has been developed for irrigation from the Middle Letaba Dam. The irrigation water demand to serve this area is estimated at 21 million m^3/a. As a result of water shortages and the increased use of the resource for household purposes, the area irrigated is estimated at 1 300ha with a mean annual field edge requirement of 10.3 million m^3/a (DWAF, 2004b). With the continued increase of water demanded for household use, the amount of the resource available for irrigation and hence the area covered could currently be much lesser.

Normal flow also comprises an important part of outflow. Most streams contain, in legal terms, 'public' water, and therefore downstream riparian and other users have a right to a certain amount of water that would likely have been available as streamflow, had the dam not been constructed. As a result, a compulsory release of water from the dam called 'normal flow' has to be discharged downstream (Schulze, 1995). A portion of the normal flow is used to satisfy the requirements for the ecology. The relationship between monthly rainfall and outflow from the Middle Letaba Dam is presented in Figure 5.

Abstractions for household and industry and for irrigation were almost constant throughout the year (Fig. 5). According to Nyabeze *et al.* (2007), the operating rules of the Middle Letaba Dam indicate that 100% of the water demand for household and industry and for irrigation would be supplied when the dam is full. When the reservoir is 30-50% full, 70% of the water requirements for household and industry would be supplied while 35% of water demand for irrigation would be supplied. The fact that the abstractions for the use sectors were constant throughout the year suggests that rainfall did not result in adequate rise in dam level to allow for increase in water supply as guided by the operating rules. Contrary to the other components of outflow, normal flow seemed to have been influenced by rainfall. While the rainfall increased from September to December, normal flow remained constant at 1 mm/month. With continued increase in rainfall in January, normal flow picked up to 4 mm, but this was followed by a drop back to 1 mm in February, a month in which the highest rainfall was recorded. The highest amount of normal flow occurred in March with a mean of 676 mm recorded. This flow was exceptionally high and resulted from the floods in the years 2000 and 2001.

3.5 Rainfall and dam water storage volume

The dam water storage volume reflects the quantity of water stored in a dam at a particular time. The dam storage volume is a product of the interactions of water gain with water loss components. If water gain components bring more water to the dam with water loss components remaining constant, the dam storage volume will increase and *vice versa*. Rainfall is an important water gain component which has a positive influence on the other gain component of inflow and different influences on loss components.

An investigation of the relationship between the rainfall and dam storage volume is therefore necessary for proper planning of water supply and use issues. The relationship between rainfall and dam storage volume of the Middle Letaba Dam is presented in Fig. 6. The dam storage volume was presented as dam level (in mm/month) based on the dam surface area of 1926 ha. Fig.6 seems to be showing an inverse relationship between rainfall and dam storage volume. As the rainfall increased from September to December, dam storage volume decreased. This trend discontinued in January to February in which case a positive relationship occurred, i.e. dam storage volume increased with an increase in rainfall. The inverse relationship generally recurred from March through to the winter months. Increases in rainfall during September to December were accompanied by decreases in dam storage volume. As rainfall continued to increase in January (115mm), dam storage volume also increased (3 280mm). As rainfall increased to its peak in February (119 mm), further increased dam storage volume was recorded (3 494mm), with larger storage volume registered in March (4 104mm) when rainfall actually started to drop. As the rainfall dropped sharply in April (30mm), dam storage volume increased slightly to a peak of 4 184mm. With the rainfall remaining low through winter months, dam storage volume gradually decreased. The peak storage volume of 4 184 mm represents 80.6 million m^3 which is far less than the 184,210,000m^3 design storage capacity of the dam, an assertion of the view that the dam levels are persistently low.

The peak of rainfall was recorded in February, that of inflow was in March and the highest dam storage volume was in April (Fig. 6). The results reveal a time lag of two months from the peak of rainfall to that of dam storage volume. Again the time lag could have resulted from factors such as the spatial distribution of rain gauges, spatial variation of rainfall and the occurrence of small dams in the catchment upstream of the Middle Letaba Dam.

The apparent inverse relationship between rainfall and dam storage volume should be a result of the two months time lag between the two factors of the hydrology of the dam. Fig. 7 presents the correlation between rainfall with a 2-month lag and water storage volume of the Middle Letaba Dam. A strong correlation (R^2=0.8086) occurred between rainfall lagged by two months and dam storage volume. This result shows that occurrence of rainfall had a strong influence on dam storage volume although this influence would usually be evident after two months from the rainfall event when the rainfall itself had stopped (or decreased). Consequently, the slope of the graph is negative, suggesting an inverse relationship in which occurrence of rainfall would lead to a decrease in dam storage volume and *vice versa*.

The peak water storage volume of 80.6 million m^3 compared to dam design storage capacity of 184,210,000m^3 suggest that the dam can never be filled from rainfall, but will require transfer of water from other catchments to fill up. Such transfer could be done from the new Nandoni dam in the nearby Luvuvhu River Catchment. The transfer of water to the Middle Letaba Dam will result in improved supply of the resource to the communities planned to be supplied from this dam. Increased water supply to the communities will result in improved provision for the households and for sectors such as agriculture and small industries that are very important for the economic development of this area.

4. Conclusions

The rainfall received over the surface area of the Middle Letaba Dam was high in summer and low in winter months with the peak in February (119mm) and the least in June (2mm). The rainfall had a positive influence on inflow from the source river with a time lag of one month from the peak of rainfall to that of inflow. Although there seemed to be a positive relationship between rainfall received over the dam surface area and the potential evaporation from the dam, the two hydrological factors had no influence over each other. The potential evaporation was rather influenced by the temperatures at the dam site. The rainfall influenced normal flow as a component of outflow and such influences were only evident during years of large rainfalls (floods). Abstractions for household and industry and for irrigation were not influenced by rainfall and this was because these components of outflow are controlled under strict operation rules of the dam. Dam storage volume also increased with increasing rainfall with a time lag of two months from peak rainfall to maximum storage volume. There was a strong correlation (R^2=0.8086) between rainfall lagged by two months and dam storage volume. The time lag between rainfall and inflow from the source river and that between rainfall and storage volume were probably a result of the spatial distribution of rain gauges, spatial variation of rainfall and the occurrence of small dams within the catchment upstream of the dam. The dam storage volumes were very low compared to dam design capacity suggesting that the dam cannot be maintained at a desirable full level from only the rainfall (including inflow), but will need to be filled through transfers from other catchments. Transfers of water to the dam will result in improved supplies for household consumption and for important sectors for economic development of the area.

5. References

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6. Figures

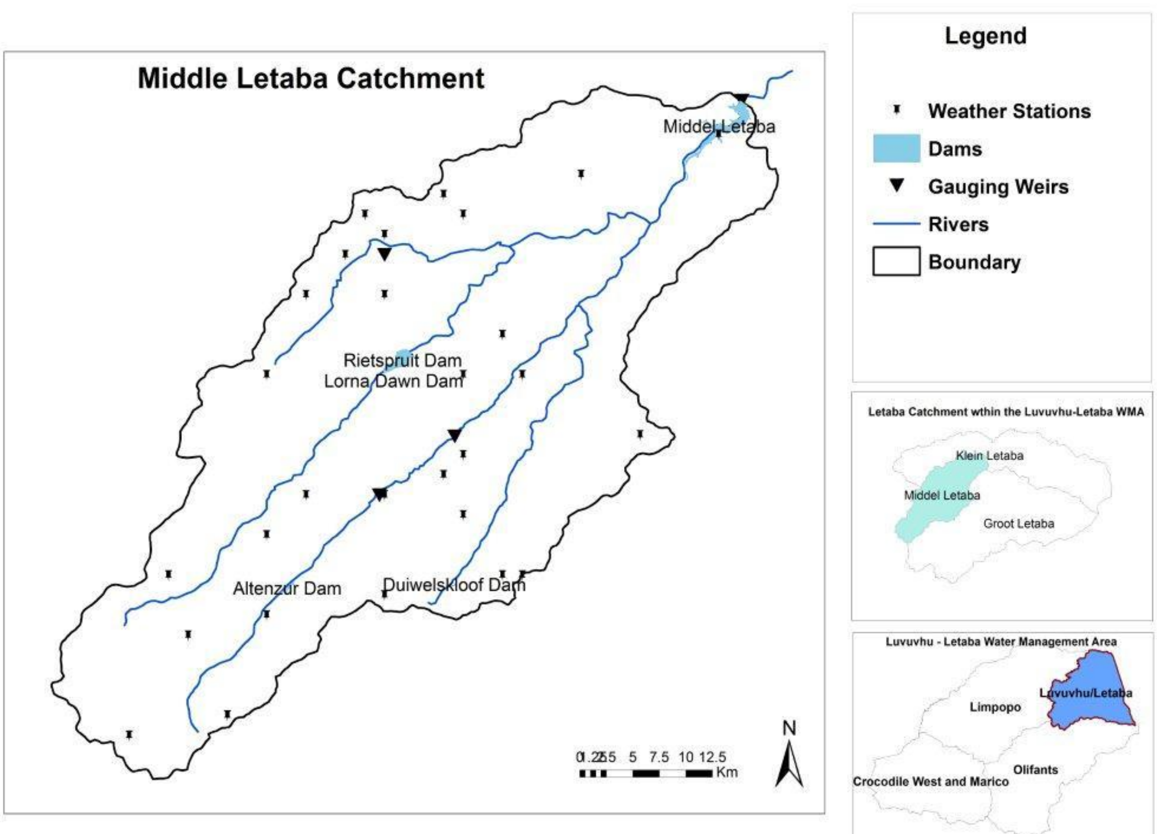


Fig. 1 Location of the Middle Letaba Dam in the Letaba catchment within the Luvuvhu-Letaba WMA

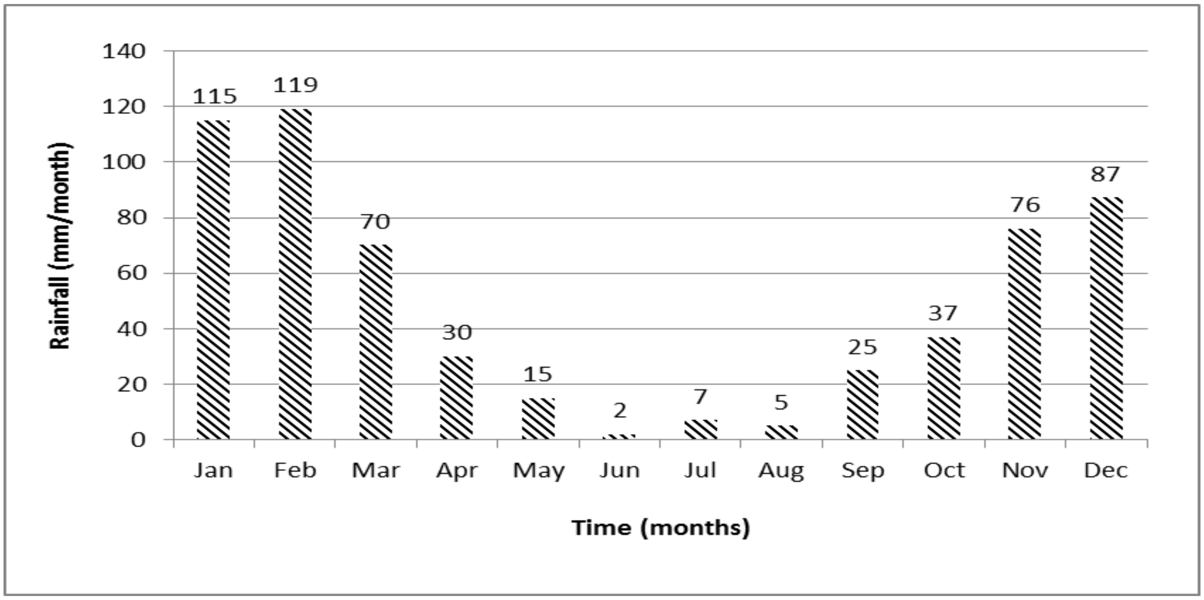


Fig. 2 Mean monthly rainfall received over the surface area of the Middle Letaba Dam during 1990- 2009 (DWAF, undated).

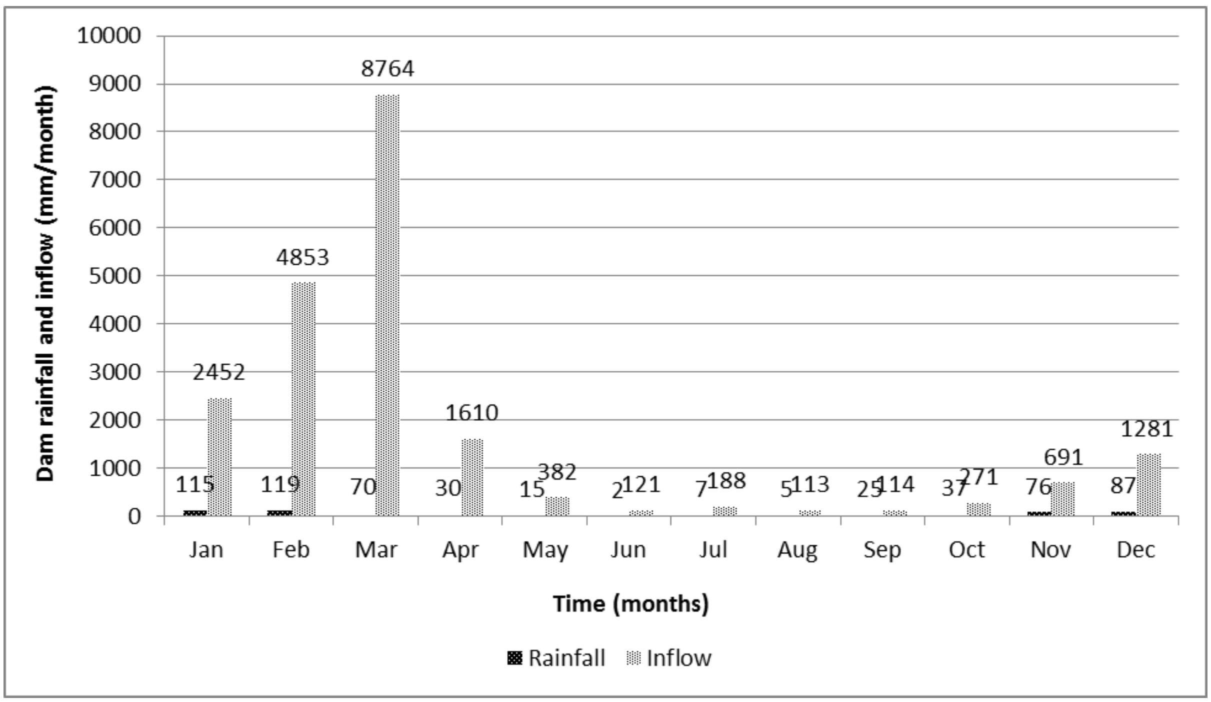
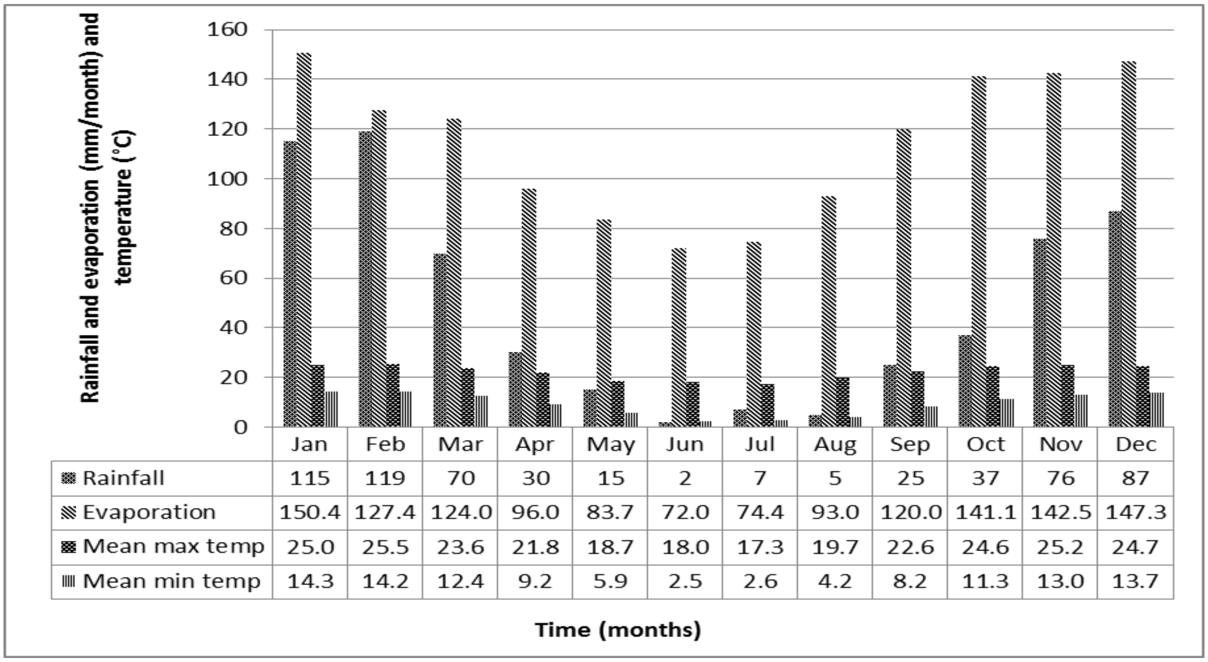
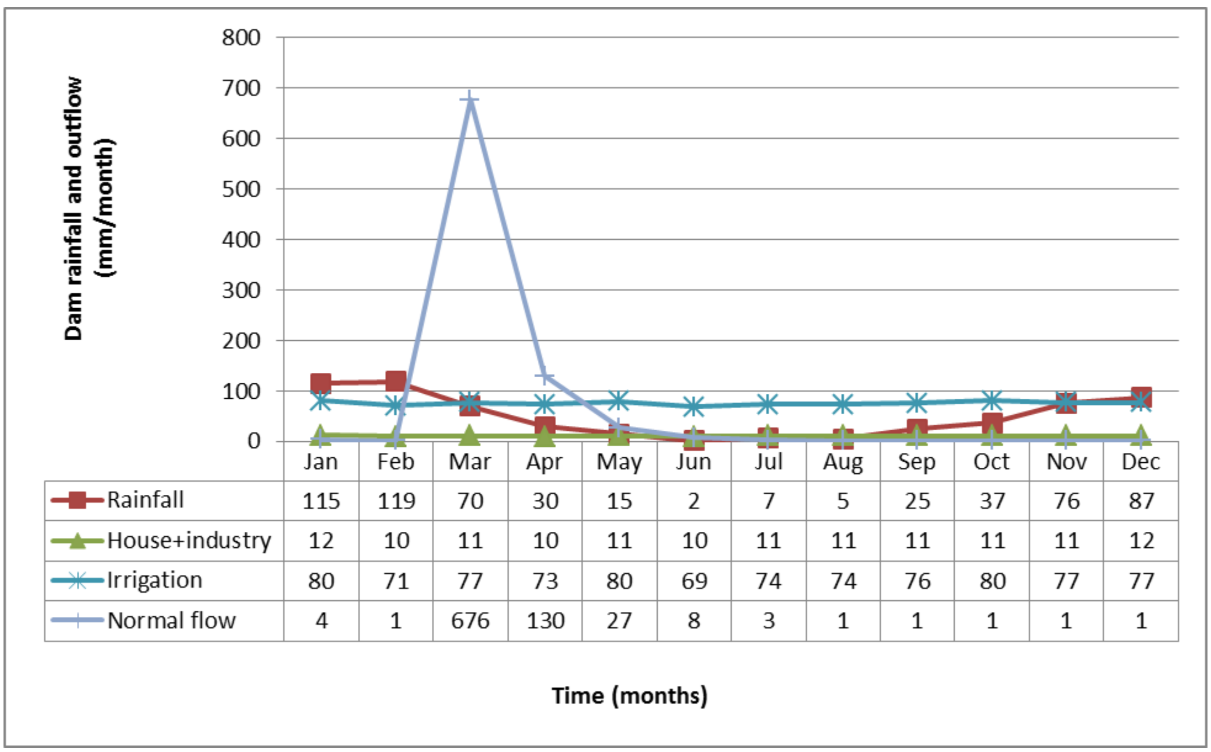


Fig. 3 Mean monthly rainfall and inflow to the Middle Letaba Dam during 1990 – 2009 (DWAF, undated).



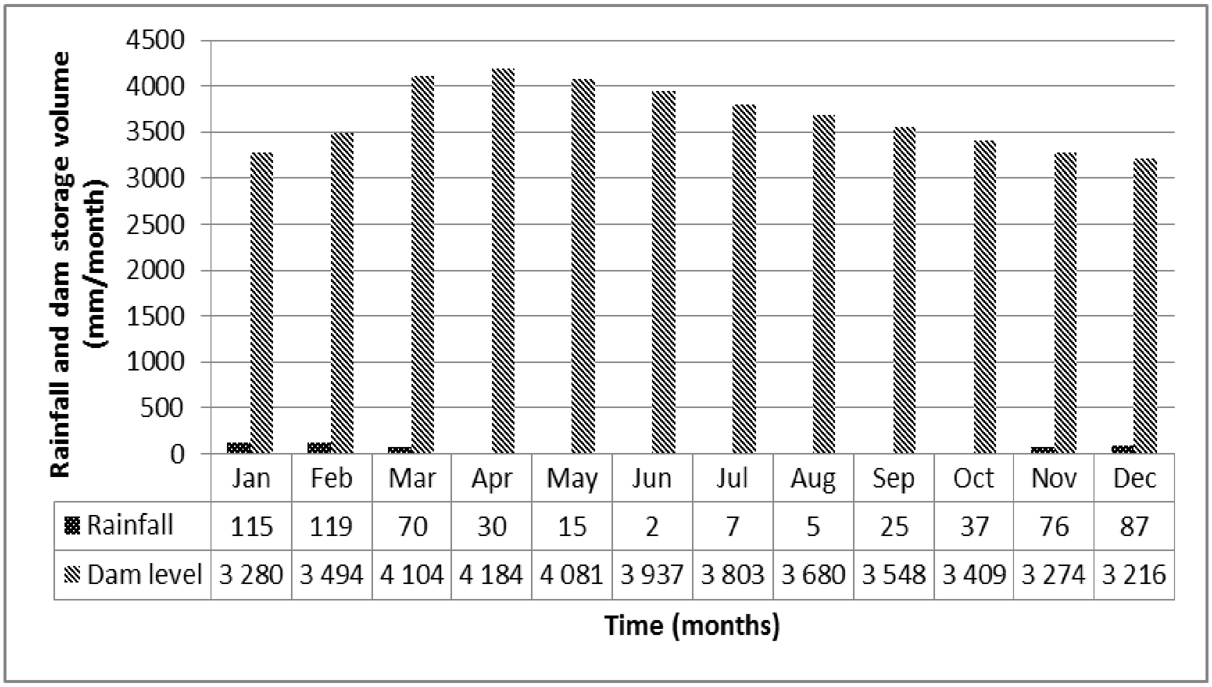
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	115	119	70	30	15	2	7	5	25	37	76	87
Evaporation	150.4	127.4	124.0	96.0	83.7	72.0	74.4	93.0	120.0	141.1	142.5	147.3
Mean max temp	25.0	25.5	23.6	21.8	18.7	18.0	17.3	19.7	22.6	24.6	25.2	24.7
Mean min temp	14.3	14.2	12.4	9.2	5.9	2.5	2.6	4.2	8.2	11.3	13.0	13.7

Fig. 4 Mean monthly rainfall and evaporation from the Middle Letaba Dam during 1990 – 2009 (DWAF, undated).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	115	119	70	30	15	2	7	5	25	37	76	87
House+industry	12	10	11	10	11	10	11	11	11	11	11	12
Irrigation	80	71	77	73	80	69	74	74	76	80	77	77
Normal flow	4	1	676	130	27	8	3	1	1	1	1	1

Figure 5. Mean monthly rainfall and outflows from the Middle Letaba Dam during 1990-2009 (DWAF, undated).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	115	119	70	30	15	2	7	5	25	37	76	87
Dam level	3 280	3 494	4 104	4 184	4 081	3 937	3 803	3 680	3 548	3 409	3 274	3 216

Fig. 6 Mean monthly rainfall and dam storage volume of Middle Letaba Dam during 1990-2009 (DWAF, undated).

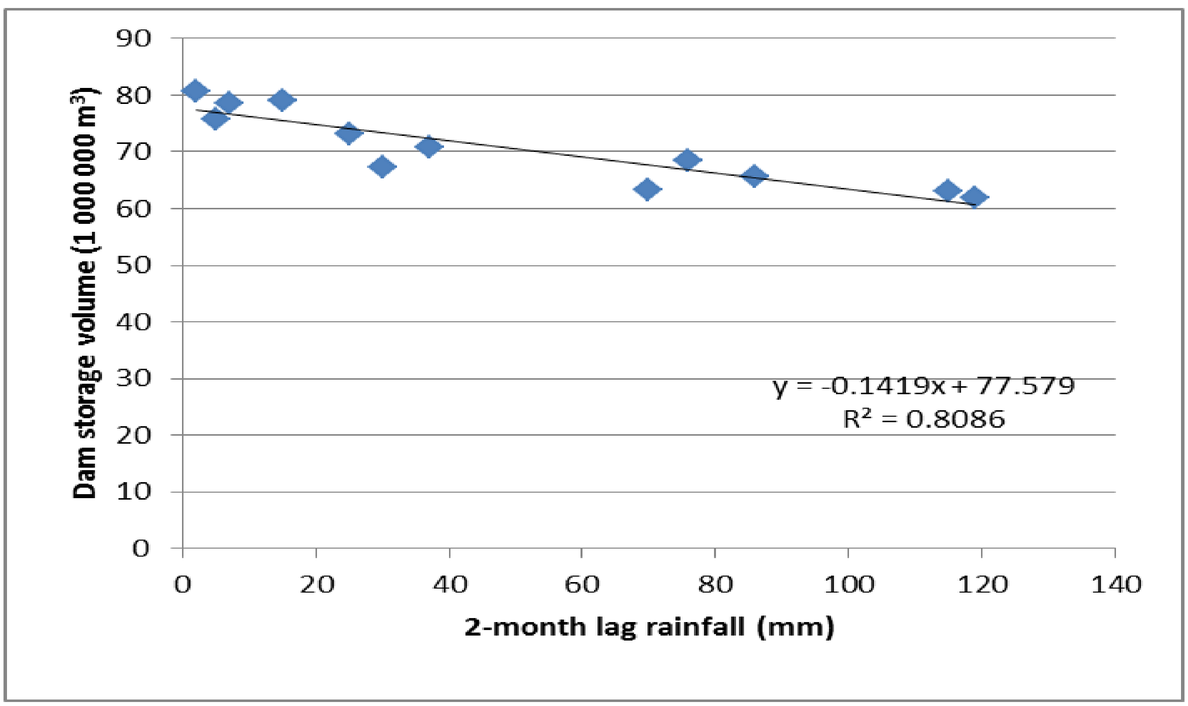


Fig. 7 Correlation between mean monthly rainfall with a 2-month lag and dam storage volume of Middle Letaba Dam during 1990-2009