Maqalika Reservoir

Utilisation and sustainability of Maqalika Reservoir as a source of potable water supply for Maseru in Lesotho

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Maseru is the capital of Lesotho and is the country's main centre for commerce and industry. The study area is located on the north-eastern outskirts of the Maseru urban area. The catchment occupies an area of 44km^2, with a length of approximately 13km and channel slope of 0.4km/km. The Maqalika Reservoir was built in 1983 to meet the water demand for Maseru until 1995, and its storage capacity was 3.7mm^3. The storage is gradually decreasing as sediment, carried by the natural catchment run-off, accumulates in the reservoir. Moreover, water pumped into the reservoir from the Caledon River (which is heavily sedimented) has its own contribution of silt. This paper attempts to find the volume occupied by accumulated sedimentation in the reservoir. For the determination of sedimentation through pumping, hydrological data was generated using two stations upstream, and results were used in Basson and Rooseboom trap efficiency mathematical equations, which yielded 6 789m^3. The impact of sediment through catchment run-off, was calculated by applying map methodology, established by Rooseboom (1992), which yielded 4 598 * 10^{6}m^3.

Introduction

Erosion and sedimentation cause both environmental and economic impacts. Both are important, but it is often only the economic impact that spurs a jurisdiction to take action. Environmental impacts are harder to see. They tend to build slowly and not produce dramatic results for many years, when it may be too late to correct the problem (Goldman et al. 1986).

Sedimentation generally limits the lifespan of a reservoir. The replacement of lost storage capacity is a worldwide problem and the need therefore exists to limit construction of reservoirs as much as possible (Basson and Rooseboom, 1999).

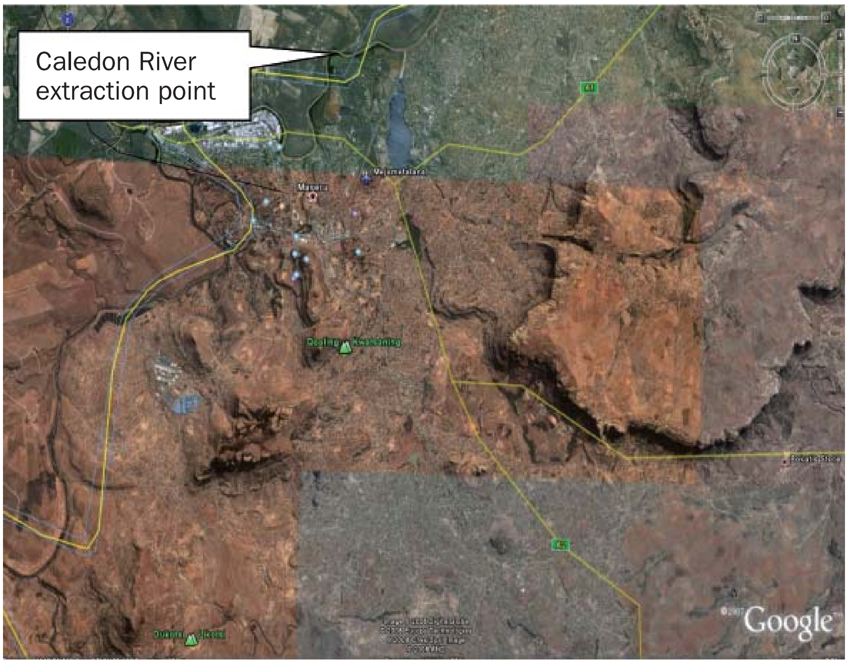


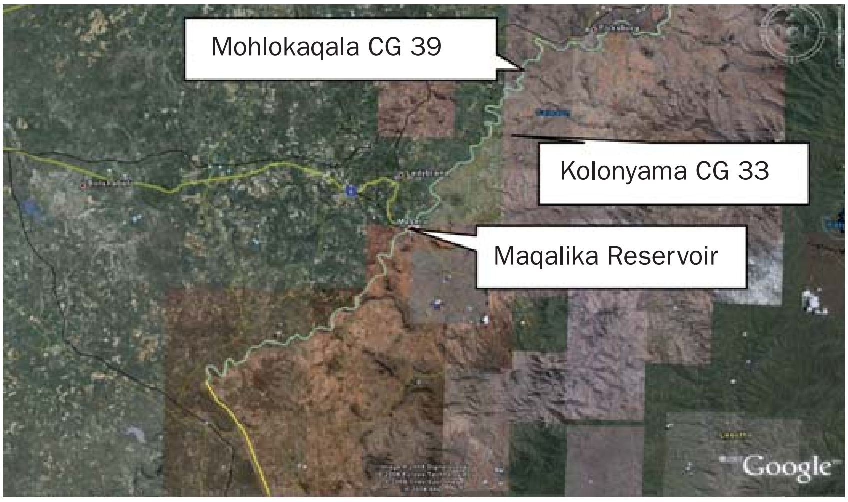
Fig 1.0 MaqalikaCatchment. Source: Google Earth (2007)

Sediment contribution through pumping

The idea was deduced from the cumulative mass curve concept. Wilson (1990) suggested that if the volume denoted by the product of the ordinate and the time interval of a hydrograph are plotted against time, by adding each new volume to the previous total, a cumulative mass curve of run-off is obtained.

Raw water from the river is pumped daily into the reservoir during the low river flows, that is from April to September, before purification (as per interview: WASA engineer, 2003), rendering the reservoir a settling pond which results in a negative impact on the capacity of the reservoir (see fig.1.0 below). To determine this, data from two hydrometric stations was analysed. The first was Mohokare at Mohlokaqala (CG 39) and the second was North Phuthiatsana at Kolonyama (CG 33).

North Phuthiatsana is one of the major tributaries of the Caledon River and is heavily sedimented, according to previous studies by Jacobi (1977) and Makhoalibe (1984). It joins the Caledon at the Berea district, which is about 50km upstream from Maseru and is a major supply of potable water for the Berea istrict. The Kolonyama station (CG 33) is one of the reliable stations with satisfactory data, hence it has been utilised in numerous studies. Map 1.0 illustrates the location of the Maqalika catchment, Mohlokaqala (CG 39) and Kolonyama (CG 33).



Map 1.0: Location of gauging stations. Source: Google Earth (2007)

North Phuthiatsana at Kolonyama

Fig. 1.1 shows the comparison of the average annual sediment yield, to that of total discharge passing the station, which was found to be: 27985/1521485.6(tons/day) / (m^3/day) * 100 = 1.84 %.

Fig 1.2 shows the Phuthiatsana River at Kolonyama Bridge during low flow and hence does not give clear indication of its sediment-carrying capacity through visual inspection.

Fig. 1.3 depicts sediment concentration against river discharge for the years

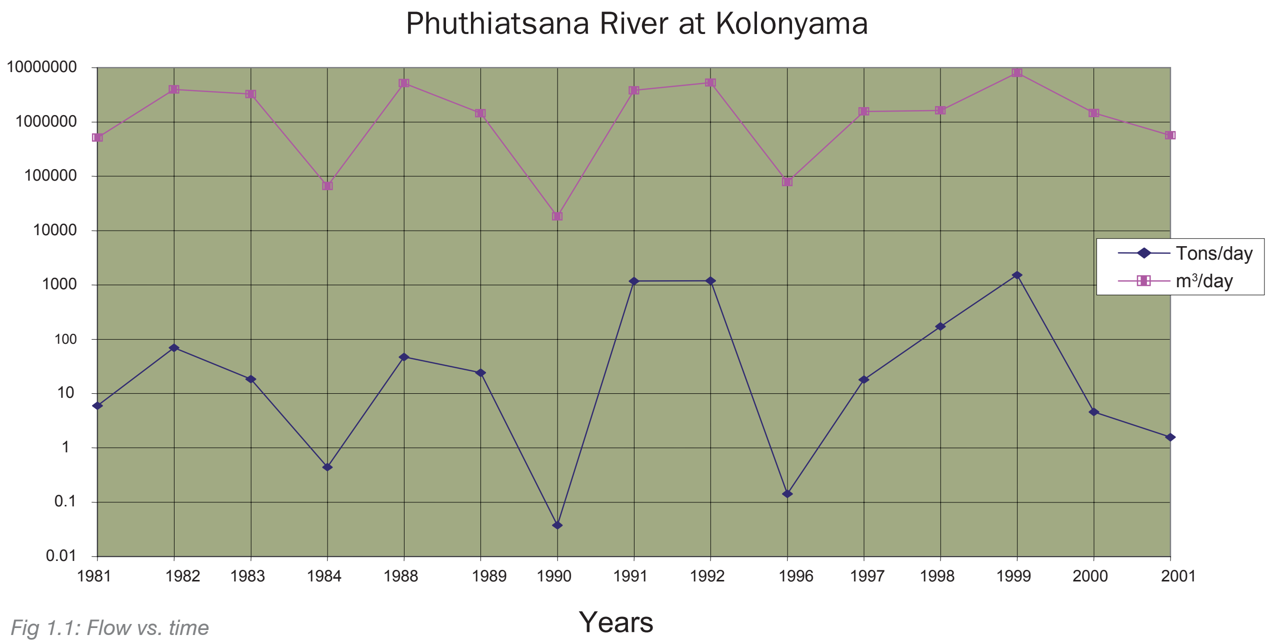


Fig 1.1: Flow vs. time

Fig 1.2: Phuthiatsana River at Kolonyama Bridge. Source: Author (2004)

1982 -1997, giving the linear regression equation y = 0.0002x – 0.0004. It is a common practice to draw a rating curve of sediment as a function of discharge, based on short-term planning and to use a rating curve in conjunction with long-term discharge records. A rating curve on limited data may also be used where a singular relationship exists between sediment concentration and discharge.

The correlation coefficient (r) for the Phuthiatsana River is 0.63 (see table 1.0) and this was deduced from the equation $r = S_{xy} / (S_{xx} * S_{yy})^{0.5}$ (Dowdy and Wearden, 1991) where:

$S_{xy} = \sum x^2 – (\sum x)^2 /n$

$S_{yy} = \sum y^2 – (\sum y)^2 /n$

$S_{xy} = \sum xy – (\sum x) (\sum y) /n$

When r = -1, there is a perfect negative relationship, when r = 1 there is a positive relationship. As r gets closer to zero, there is less association between variables with a sample correlation coefficient. When r = 0.89, there is a positive and relatively strong linear association (Dowdy and Wearden, 1991).

X	X^2	Y	Y^2	XY
$1.22 * 10^6$	$2.73 * 10^{11}$	$1.89 * 10^8$	$3.66 * 10^{15}$	$2.67 *10^{13}$

Table 1.0: Phuthiatsana summation results

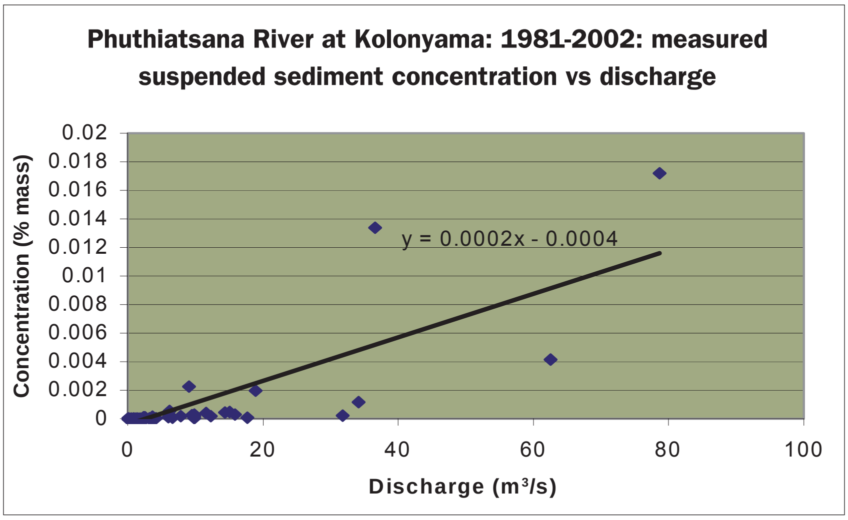


Fig 1.3: Phuthiatsana River measured suspended sediment vs. discharge

Mohokare (Caledon) at Mohlokaqala

Fig. 1.4 below shows a comparison of the average annual sediment yield to that of total discharge, which was found to be: 11392.598 / 2071244 (tonnes/day)/ (m^3/day) * 100 = 0.54 %.

Fig 1.5 shows the Caledon River 1km downstream of a pumping station.

Fig 1.6 shows a graph depicting the sediment concentration against river discharge for the years 1982 – 2002, yielding an equation of y = 0.0007x – 0.0009. Rooseboom (1992) suggested that the rating curves, based on scattered data, may only be used in conjunction with flow records which cover the same period as the recorded sediment concentrations.

The Mohlokaqala River correlation coefficient was calculated based on the previous equations, and it was found to be 0.82 (see table 1.1) which showed a greater link between variables.

Since the North Phuthiatsana River is a tributary of the Caledon River upstream of the study area, both equations that were found above could not be used as they did

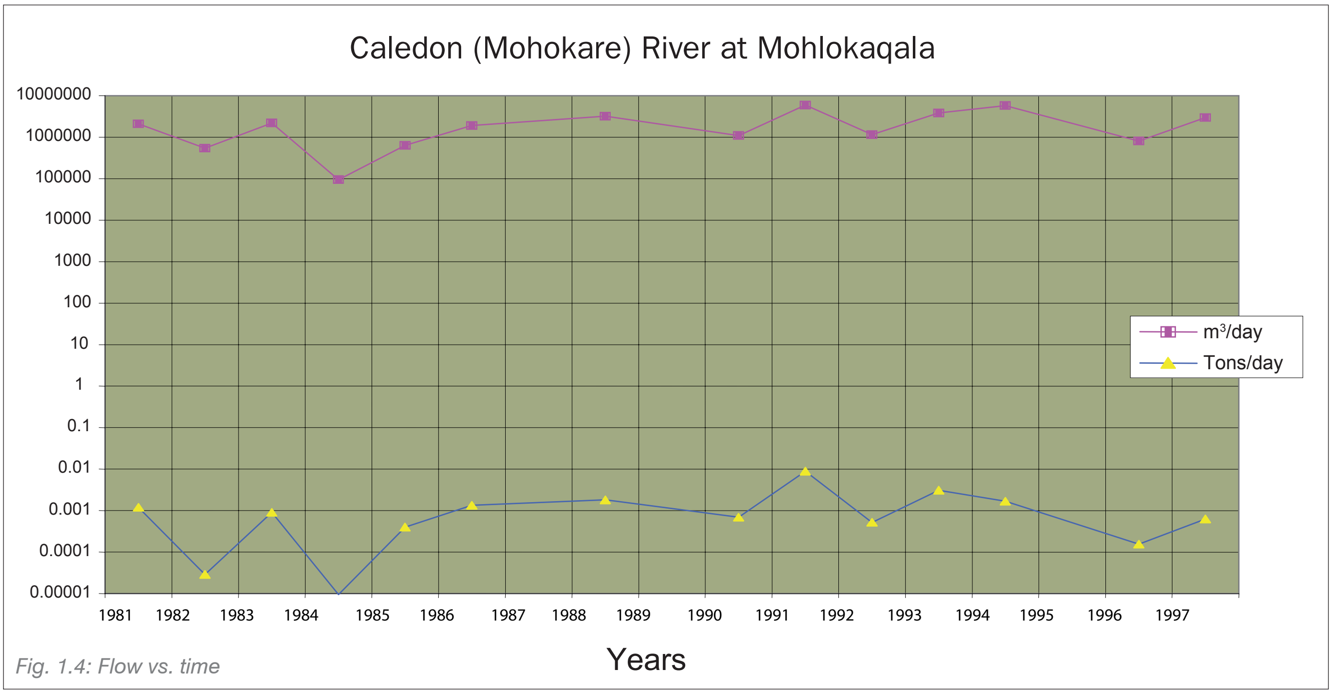


Fig. 1.4: Flow vs. time

not give the right concentration at the point where pumping is occurring. Therefore, data for both stations was combined in one graph to give the closer concentration equation at the pumping station, as reflected in fig. 1.7. The obtained linear regression equation, y = 0.0007x – 0.0019, was used throughout to attain the volume of sediment.

For justification, as per Linsley, Kohler and Paulus (1988), if there is no stream flow record at or near the site, monthly or annual flow volumes may be transferred from another location with adjustment for the size of drainage area and mean annual precipitation. Moreover, two or more upstream stations can be merged to form more representative and cumulative data for a downstream station, which is the case in this regard.

Pumping from the Caledon River into the Maqalika Reservoir is 14ml/day = 14 000 m^3/day = 0.162 m^3/s.

Assume the specific volume of 1.35m^3/t. Normally, a conservative value of 1.0m^3/t is used but as a 21-year period of data is considered in this study, Basson (2004) suggested that the value of 1.35m^3/t is appropriate (as per communication with Basson (2004).

As the volume: time relationship is highly non-linear, even though the mass of sediment within the reservoir may accumulate linearly with time, it is best to calculate the total mass entering the reservoir and convert this to volume by means of a function of time (Pitman et al, 1981).

From the equation y = 0.0007x – 0.0019:
where y = concentration from the river
x = discharge from the river;
'x' was kept constant at 0.162 m^3/s.
Therefore, y = 0.0007* 100* 0.162 – 0.0019 = 0.00944kg/s.
Convert to tonnes: y = 0.00944/1000 = 9.44* 10^{-6}t/s.
Convert to days: y = 9.44* 10^{-6}* 86400 = 0.815616 t/day = 297.70t/a.
To find an annual volume, considering a specific volume of 1.35 m^3/t:
Volume = 0.815616 t/day* 365 days* 1.35m^3/t = 401.895m^3.

Roosebom (1980) suggested the following equation for trap efficiency:
V_t/V50 = 0.376 ln t/3.5.
(Source: WRC report no 9/81, 1981)

Fig 1.5: Mohokare (Caledon) at the Maseru Bridge. Source: Author (2004)

X	X^2	Y	Y^2	XY
2.079 * 10^5	1.52 * 10^{10}	2.6 * 10^7	6.0 * 10^{13}	6.26 *10^{11}

Table 1.1: Mohlokaqala summation results

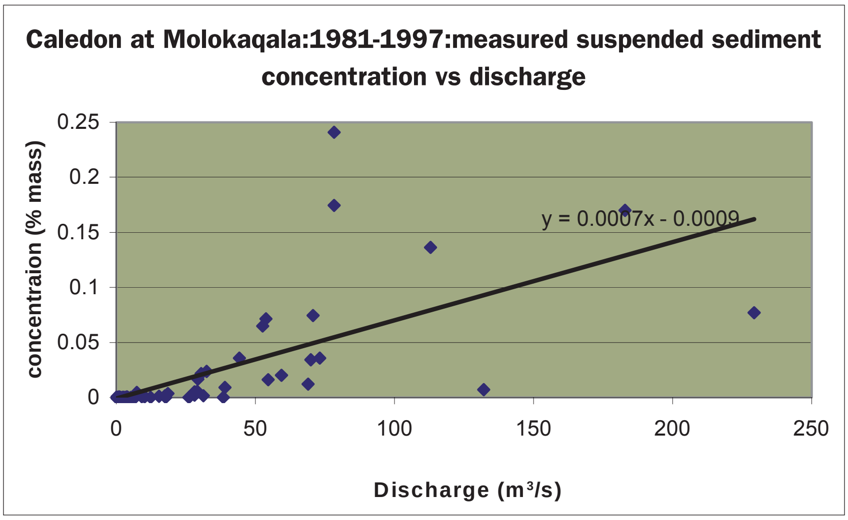


Fig. 1.6: Caledon measured sediment concentration vs. discharge

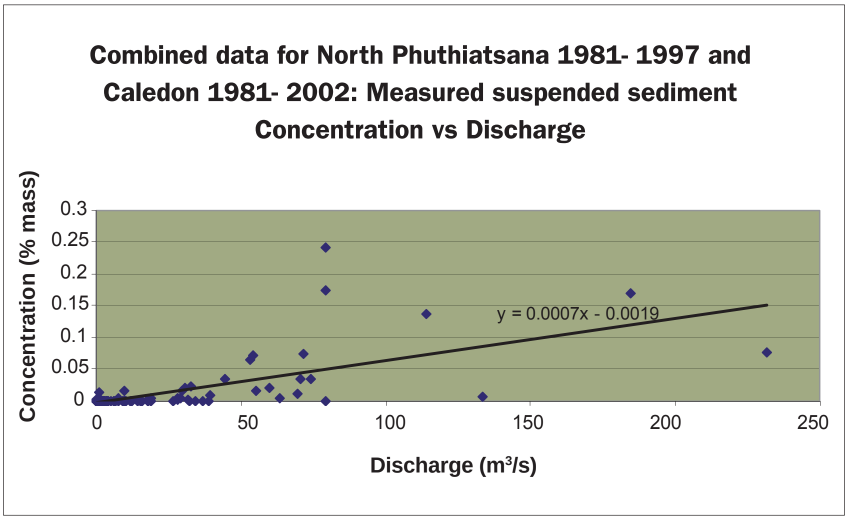


Fig 1.7: Combined data for the Phuthiatsana and Caledon Rivers

Therefore, the volume occupied for 21 years is:
V_{21}= 50 years * 401.895 = 20 094m^3
V_t = 20 094 * 0.376 ln (21.3.5) = 13 537m^3.

For simplicity reasons, it was conservatively considered that pumping continues throughout the whole year. Therefore, the obtained quantity was then divided by 2 to get 6 789m^3, showing that pumping is only done during six months of the year (April – September). However, it should be considered that climate change makes its own contribution to human reaction. Therefore if there is no rainfall during the rainy season, pumping still continues and vice versa.

The study by Jacobi (1977) estimates the following annual sediment, in table 1.3 below (TAMS, 1996):

RIVER NAME	AREA (KM^2)	TONS/KM^2/YR
North Phuthiatsana (CG 24)	386	2968

Table 1.3: Annual sediment yield

The other study was done by Makhoalibe in 1984 (TAMS, 1996). Table 1.4 shows estimates of sedimentation.

RIVER NAME	AREA (KM^2)	TONS/KM^2/YR
North Phuthiatsana (CG 33)	905	740
Caledon at Mohlokaqala (CG 39)	5600	930
North Phuthiatsana at Mapoteng (CG 34)	386	2050
Caledon at Mashili	1560	730

Table 1.4: Estimates of sedimentation

In August 2002, Stephenson and Associates was commissioned by the Water and Sewerage Authority (WASA) to carry out sedimentation impact studies in the Maqalika Reservoir. A hydrographic survey was done by means of a Garmin GPSMAP 185 depth sounder. The instrument was mounted on an inflatable boat and the dam was traversed backwards and forwards, picking up bed level beneath the water using the depth sounding facility. The data was downloaded to the computer, from which 'xy' coordinates and water depths of each point were computed. The results were then used for plotting new contour maps and cross sections of the reservoir at regular intervals (WASA, 2002).

The procured contours were then compared with those that existed before the construction of the reservoir. Via the comparison of plotted cross sections, it was deduced that 100 000m^3 of sediment deposition was estimated and found to be evenly distributed over the reservoir floor and it was concluded that catchment erosion was the main contributor. Nevertheless, deposition around the tower intake was found to be considerable (WASA, 2002).

Sediment contribution through Maqalika catchment run-off

In modelling sediment yields from small catchments, the yields are normally linked to the run-off transporting capacity (Roosebooom, 1992). Not only are the daily loads of rivers extremely variable, but even on an annual basis the variability is such that long-term records are requested in order to establish accurate estimates of average annual loads. It is therefore extremely risky to draw conclusions from limited records.

Following many attempts to try and use the Pitman Model for estimating sediment yields using rainfall data for the Maqalika catchment, a simplified statistical analysis adopted by Rooseboom (1992) was used. The method entails subdividing the area of interest into higher-, medium- and lower-sediment yield potential, whereby one has to consider:

(i) a basic yield index map, based primarily on soil types and slopes, prepared by Prof. E. Vester and cited by Rooseboom (1992)
(ii) land use
(iii) availability of recorded data.
(iv) boundaries of river catchments.

Fortunately, the area of interest is only 44km^2, hence there was no need for subdividing it any further. In addition it has only two regions to be considered, that is, the Elliot Formation for higher- and the Molteno Formation for medium-sediment yield potential. There is only a fraction of the Clarens Formation that was never considered.

Constant ratios between yields from subregions exist via association in all calibrated maps. By using these ratios, a standardised yield value could be calculated for each reservoir (Rooseboom, 1992).

For determining sediment yield values in the Maqalika catchment, the following tools were used:

(i) a map of Southern Africa, on which nine distinct sediment yield regions are indicated; the regions were divided into three categories: higher-, medium- and lower-sediment yield potential
(ii) a table containing a mean, standardised sediment yield value for each of the nine sediment yield regions
(iii) graphs showing, for each region, the variability displayed by existing data, linked to the catchment size
(iv) a table with sediment yield factors for each region, by means of which the standardised sediment yield values for any given catchment can be determined.

Methodology for applying the map

Rooseboom (1992) suggested that the first step is to determine the regional standardised sediment yield value, which is applicable to a catchment with a specific size and location, and then convert this value into the actual yield potential of the different soils in the catchment.

The method consists of the following steps:

(i) Determine the location and size of the catchment for which the estimated sediment yield is to be determined (44km^2 was used in this regard).

(ii) Obtain the yield region from the sediment yield region map (from one to nine) for the catchment, as well as the sizes of sub-areas within the catchment that consist of soil with different yield potential (higher-, medium- and lower-yield potential). Maseru falls within region 6, hence it was selected.

(iii) For the given region, use the regional standardised mean yield table. From the table, 335t/km^2.a was found to be appropriate and a sediment yield factor (FH) of 1 was selected.

(iv) From the graph for the region, select the multiplying factor with due consideration of catchment conditions. Note that the factors given are envelope values, and are expressed as multiples of the regional average standardised yield. Considering a 95% confidence limit, a value of 7 was determined as a multiplying factor.

(v) Convert the standardised sediment yield values to site-specific yield values, with the formula:

$Y_C = Y_S (F_H A_H / A_T + F_M A_M/A_T + F_L A_L/A_T)$

Source: (WRC report no. 297/1/92)

Where:

Y_C = estimated catchment sediment yield value (t/km^2.a)

Y_S = standardised sediment yield value (t/km^2.a)

F_H = high-yield potential factor

F_M = medium-yield potential factor

F_L = low-yield potential factor

A_H = size of area consisting of soils with high-sediment yield potential (km^2)

A_M = size of area consisting of soils with medium-sediment yield potential (km^2)

F_L = size of area consisting of soils with lower sediment yield potential (km^2)

A_T = total catchment area (km^2)

Since the lower yield potential was excluded, F_L (A_L/A_T) was excluded from formula.

Therefore the calculations were:

Y_S = 335 * 7.0 = 2345 t/km^2.a

Therefore Y_C = 2345 (1(22/44) + 1(22/44)) = 2345 t/km^2.a

which is 2345 t/km^2.a * 44 km^2 = 10^3.18 * 103 t/a

Rooseboom (1980) suggested that in determining sediment trap efficiency, Brune's (1953) diagramme should be used. From this diagramme, trap efficiency is about 98%.

Cascade earth dams, constructed upstream of Maqalika, play a major role in trapping sediment

Average silting rate will therefore be 98/100 * 103. 18 * 10^6 = 101.12 *103 t/a.

At a specific volume of 1.35 m^3/t, sediment accumulation is 136.51 * 103 m^3/a

Assuming sediment accumulation from 1982 – 2002, the storage volume capacity will be calculated by equation

V_t/V_{50} = 0.376 In t/3.5, where V50 = 50 * 136.51 *10^3 m^3 = 6.826 * 106 m^3

V21 = 6.286* 106 * 0.376 In 21/3.5 = 4.598 * 106 m^3.

NB: From both pumping and catchment run-off contribution, the total volume is 4.605 * 106 m^3 and the Maqalika Reservoir capacity is 3.7 * 10^6 m^3 therefore, 0.905 * 10^6 has been accumulated beyond capacity.

Conclusion

Human activities within the catchment, the type of geology and deep slopes of the catchment encourage both rill and sheet erosion during heavy rainfalls, leaving Maqalika as a settling pond. Cascade earth dams, constructed upstream of Maqalika, play a major role in trapping sediment but most of them are now full of sediment.

Studies by Jacobi (1977) and Makhoalibe (1984), cited by TAMS (1996), show that the North Phuthiatsana (CG 24) yields a sediment load of 1.14 * 10^6 tonnes/annum and (CG 33) yields 0.669 * 10^6 tonnes/annum respectively, while the Caledon at Mohlokaqala (CG 39) yields 5.2 * 10^6 tonnes/annum, showing that the catchment is heavily sedimented. Therefore, the procured results through pumping from the Caledon River yielded 297.70 t/annum, which is rather low when compared to the two studies mentioned above but reasonable when considering the fact that water is pumped through sumps with a lower yield of 0.162m^3/s.

From the catchment run-off, the sediment yield of 101 * 10^3 tonnes/annum is still acceptable but the conservative multiplying factor of 7 might just be too high. A sediment volume of 4.605 * 106 m^3, which is 0.905m^3 beyond the capacity of Maqalika, is high because the reservoir still has some recognisable capacity. This is supported by study conducted by Stephenson and Associates who found that only 100 000m^3 has been occupied by siltation but the value of 100 000m^3 seems to be too low from personal observation. This is because during the drought of the '90s, the reservoir was virtually dry and one could clearly see that siltation has really taken its toll.

The other reason why Maqalika might still have a recognisable capacity is the fact that Cascade Dam upstream, and the Sebaboleng Dam, play a major role in trapping sediment from the catchment, hence prolonging the life span of Maqalika. 3s

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