Sedimentation in small dams

Hydrology and drawdown computations

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Executive Summary

Sedimentation in small dams

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NGO's and Government Agencies have constructed thousands of small dams in semi-arid regions of East and Southern Africa to provide water for livestock and small-scale irrigation. The effective life of many of these dams is reduced by excessive siltation – some small dams silt up after only a few years. This issue is poorly covered in the many small dam design manuals that are available, as they mostly focus on the civil engineering design and construction aspects. While a capability to estimate future siltation is essential to ensure that dams are sized correctly, and are not constructed in catchments with very high sediment yields, little guidance is available to small dam planners and designers.

The British Government's Department for International Development commissioned HR Wallingford to carry out a study to develop guidelines presenting appropriate methods for predicting, and where possible reducing, siltation rates in small communal dams in semi-arid zones in Eastern and Southern Africa. Typical small dam designers must be able to use these methods; they usually have access to only limited local data, need to carry out assessments rapidly, or may not have software skills or computers.

The report describes procedures used in the guidelines to carry out the hydrological computations needed to support the design of small dams and to predict future siltation. Methods for estimating the following hydrological and water yield parameters are described:

- Catchment mean annual runoff (mm);
- Coefficient of variation of mean annual runoff;
- Mean Annual Inflow to a dam (m^3);
- Dam storage capacity at full supply level (m^3);
- Dam capacity to inflow ratio;
- Probability of a dam filling (%);
- Mean Annual flood (m^3/s);
- Design Floods for determining spillway capacity;
- Catchment sediment yield ($t/km^2/year$);
- Dam storage capacity loss due to sedimentation over 20 Years (%);
- Dam water yield reduction due to sedimentation over 20 years (%);
- Dry season total potential water abstraction (m^3);
- Dry season potential water abstraction for different levels of carry-over storage between years;
- Potential Irrigated Area (ha);
- Potential Number of livestock units that can be supported by a dam in an average year.

In most cases several methods are presented for estimating a parameter; the method selected will depend on the data that are available locally. Computations can be carried out manually or by using the user-friendly software supplied with the guidelines and described in Annex 1.

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1. Introduction

There are strong links between the availability of water for agriculture and livestock production, and incomes of the rural poor (HR Wallingford, 2003a). One means of increasing the resilience of the rural poor to the shocks produced by rainfall variations, particularly droughts, is to store water in small dams to irrigate crops and water cattle. NGO's and Government Agencies have constructed thousands of small dams in semi-arid regions of East and Southern Africa, but the useful life of many of these dams is reduced by excessive siltation – some small dams silt up after only a few years. This issue is poorly covered in the many small dam design manuals that are available, as they focus on civil engineering design and construction aspects[1]. Procedures for assessing the viability and sustainability of small dams are covered in a very rudimentary way, or ignored. The hydrological calculations needed to support the design of small dams and to predict future siltation are often either too simplistic, or on the other hand too complex and too dependent on data to be of use to small dam designers.

The British Government's Department for International Development (DFID) commissioned HR Wallingford to develop guidelines presenting appropriate methods for predicting, and where possible reducing, siltation rates in small communal dams in semi-arid zones in Eastern and Southern Africa. Typical small dam designers must be able to use these methods; they have to carry out assessments rapidly using simple procedures, may not have software skills or computers, and may only have access to very limited local data.

The series of reports describing the outputs from the small dams component of the project are listed below:

Report Title	Report Number
Guidelines for predicting and minimising sedimentation in small dams	OD 152
Sedimentation in small dams – impacts on the incomes of poor rural communities	OD TN 118
Sedimentation in small dams – hydrology and drawdown computations	OD TN 119
Sedimentation in small dams – development of catchment characterisation and sediment yield prediction procedures	OD TN 120
Sedimentation in small dams – the potential for catchment conservation, check dams and sediment bypassing to reduce dam siltation rates	OD TN 121

This report describes procedures used in the guidelines to carry out the hydrological and water computations needed to support the design of a small dam. The methods were selected using the following criteria:

- That they are appropriate for use by technicians and relatively junior engineers who may not have access to computing facilities;
- That they require only the limited data that are typically available to small dam designers.

The methods are suitable for application in regions where only limited specific local hydrological data are available. This is more or less the case in most of the countries of East and Southern Africa south of the Sahara, with the exception of South Africa, where

[1] The design manuals reviewed as part of this study are listed in Chapter 8.

the relatively large quantities of data that are available have enabled the development and routine application of more sophisticated methods than those outlined here.

Hydrological procedures are mostly drawn from the methods described in reports prepared by hydrologists from CEH Wallingford for use in small dam design studies in Botswana and Malawi (Bullock, 1993; PEMconsult, 1999). Dry season water yields are determined using a monthly "drawdown" computation based on that used by Hart Frost Consultants (Consulting Engineers, Zimbabwe, Personal communication, 2000) for small dams in Zimbabwe. The scope of drawdown calculations have been considerably extended, so that reductions in the dry season water yield can be predicted as dams silts up, thus enabling the sedimentation life of a dam, and hence its sustainability, to be determined.

Procedures for estimating the following hydrological and water yield parameters are described:

- Catchment mean annual runoff (mm);
- Coefficient of variation of mean annual runoff (%);
- Mean Annual Inflow to a dam (m^3);
- Dam storage capacity at full supply level (m^3);
- Dam capacity to inflow ratio;
- Probability of a dam filling (%);
- Mean Annual flood (m^3/s);
- Design Floods for determining spillway capacity (m^3/s);
- Catchment sediment yield[2] ($t/km^2/year$);
- Dam storage capacity loss due to sedimentation over 20 Years (%);
- Dam water yield reduction due to sedimentation over 20 years (%);
- Dry season total potential water abstraction (m^3);
- Dry season potential water abstraction for different levels of carry-over storage between years;
- Potential Irrigated Area (ha);
- Potential Number of livestock units that can be supported by a dam in an average year.

In most cases several methods are presented for estimating a parameter, the method selected will depend on the data that are available locally. Computations can be carried out manually or using the user-friendly software supplied with the guidelines and described in annex 1.

[2] The methods used to predict catchment sediment yields are described in more detail in HR Wallingford (2003b).

2. Mean annual runoff

Mean annual runoff (MAR) from a dam catchment is a key parameter in determining the required capacity for a dam. It is also used to estimate the dam capacity to annual inflow ratio, which is an important parameter in predicting future siltation rates. MAR is conventionally expressed as an equivalent runoff depth, in mm.

2.1 RUNOFF COEFFICIENT

The simplest method of estimating mean annual runoff is to apply a runoff coefficient to the mean annual rainfall.

$$MAR = K * MAP \qquad (2.1)$$

Where MAR = Mean annual runoff (mm)
MAP = Mean annual precipitation (mm)
K = Runoff coefficient

This approach is used in many of the more basic small dam design manuals, where for semi-arid areas the runoff coefficient is often set at 0.1. Runoff depends on many parameters in addition to rainfall and this is recognised in some procedures which adjust the runoff coefficient to account for land forms, soil type and drainage, and cover, etc. However this approach requires a considerable quantity of catchment specific data that will be unavailable to most small dam designers.

2.2 USE OF FLOW GAUGING DATA

There may be a river-gauging site located in or close to the catchment selected for the site of a small dam. On the rare occasions when this is the case then data from the gauging site should be used to estimate MAR at the dam site, provided the requirements set out below[3] are met.

i) Catchment characteristics should be similar.

ii) Catchment areas should differ by less than a factor of five.

iii) The distance between the centroids of the catchments should be less than 50 km.

iv) At least ten years of mean daily flows should be available.

MAR for the dam site should be determined by carrying out the following calculations:

i) Apply an appropriate MAR equation (see later) to estimate the MAR at the dam site (MAR_d);

ii) Apply the appropriate MAR equation (see later) to estimate the MAR at the gauged site (MAR_g);

iii) Determine the mean annual runoff (mm) at the gauged site (MAR_o);

iv) Determine the MAR at the dam site as $MAR_o * MAR_d/MAR_g$.

[3] Procedure recommended in PEMconsult (1999)

2.3 PUBLISHED TABLES OR MAPS OF RUNOFF DEPTHS

Maps or tables showing runoff depths for different hydrological zones are available in some of the countries of the region. Examples include the tables provided by Ministry of Lands and Water Resources, Zimbabwe (1984) (the "blue book"), or the runoff map included in the Malawi National Water Resources Master Plan (PEMconsult, 1999). There can be difficulties in using tables when a small dam catchment crosses zones which may have different unit runoffs, and judgement is needed to interpolate a sensible value. Similarly the methods used to draw isolines of equal unit runoff on maps can also lead to distortions when the maps are applied to small catchments.

However as runoff tables and maps are at least based on stream gauging data, in most cases they provide the best means of estimating runoff for small dam design when specific local data are unavailable. In all cases it is necessary to use judgement to relate the predicted runoff with that observed in similar nearby catchments.

2.4 EMPIRICAL RUNOFF PREDICTORS

Empirical equations relating runoff to mean annual precipitation (rainfall) and other parameters have been developed by the Southern Africa FRIEND project and are reported in IHP-V (1997). As these relationships are developed from very large data sets covering a wide variety of catchment conditions their predictive ability is quite low, r^2 = 0.37 or lower, and two earlier empirical runoff predictors are proposed for use in the guidelines.

Hill and Kidd's (1980) relationship, reported in PEMconsult (1999), was based on data from forty-seven Malawian catchments, and is included as it provides a means of estimating the effect of Dambos (swampy areas in the valley bottom) on runoff. The function is:

$$MAR = -92 + 0.16\ MAP + 0.0018\ MAP^2 - 640\ DAMBO \qquad (2.2)$$

($R^2 = 0.94$ se = 82 mm)

Where MAR = Mean annual runoff (mm)
MAP = Mean annual precipitation (mm)
DAMBO = Proportion of the catchment that is Dambo, value between 1 and 0

A second equation developed by Bullock *et al*. (1990) and reported in PEMconsult (1999) is from a wider data set of one hundred and two mostly semi-arid catchments in Malawi, Tanzania and Zimbabwe. The function is:

$$MAR = 0.0000467\ MAP^{2.204} \qquad (2.3)$$

($R^2 = 0.54$, se = 0.247)

PEMconsult recommend that equation 2.2 is used when more than 5% of the catchment is Dambo, and that equation 2.3 is used where the proportion of dambo is less than 5%.

Again it is necessary to use judgement to compare the runoff predicted by equations 2.2 and 2.3, with local experience in similar catchments. For example a catchment with low slopes, good cover, and deep, well drained soils will have a lower runoff than a steep catchment with thin, poorly drained soils, rock outcrops, and little cover. About 80% of Bullock's runoff data set, as presented in PEMconsult (1999), lies inside the range predicted runoff *0.5, to predicted runoff *2.0. Thus for practical purposes it would be sensible to restrict any ad hoc adjustments to predicted runoff to account for extreme catchment conditions within this range.

2.5 RECOMMEND METHODS

Four methods for estimating runoff are described above. The most reliable is to use long term river flow gauging data, but this will not be available at most small dam sites. Use of the tables or maps of unit runoff that are available in some countries may provide the next most reliable means of estimating runoff as they are at least based on measured runoff data. When neither method can be applied, runoff can be estimated using regional empirical equations. It may be necessary to make an adjustment to the runoff predicted by equations 2.2 and 2.3 to account for extreme catchment conditions that would either reduce or increase runoff.

2.6 CALCULATION OF RUNOFF VOLUMES

The annual volume of water entering a dam is calculated as the product of the MAR and the catchment area. Catchment areas should be measured using 1:50 000 maps, after marking the dam location and the catchment boundaries by using a digitiser, planimeter or squared overlay sheet. The result should be recorded in km^2.

$$\text{Annual Runoff Volume (ARV)} = \text{MAR} * \text{CA} * 1000 \qquad (2.4)$$

Where: ARV = Annual runoff volume (m^3)
MAR = Mean annual runoff (mm)
CA = Catchment Area (km^2)

3. Coefficient of variation of mean annual runoff

The coefficient of variation (Cv) of MAR is large in semi-arid areas. Information on this parameter is needed to determine the probability of a dam (with a given storage volume) filling. In some countries tabulated values, or maps giving the coefficient of variation of runoff are available and can be used to obtain a value for the coefficient of variation in mean annual runoff for the catchment being considered. At locations where these data are not available a value for Cv has to be estimated.

Variability in annual runoff increases with increasing aridity, see for example IHP-V (1997). Variations in runoff between years are most strongly affected by variations in rainfall, but are also influenced by catchment conditions, i.e. soils, slopes, cover, etc. In order to provide a means of estimating Cv's in semi-arid areas we have used the large "data" set in the Zimbabwe "Blue Book" to obtain a correlation of Cv of mean annual runoff with MAR (Ministry of Land and Water Resources, Zimbabwe, 1984). The correlation is shown in figure 3.1 below:

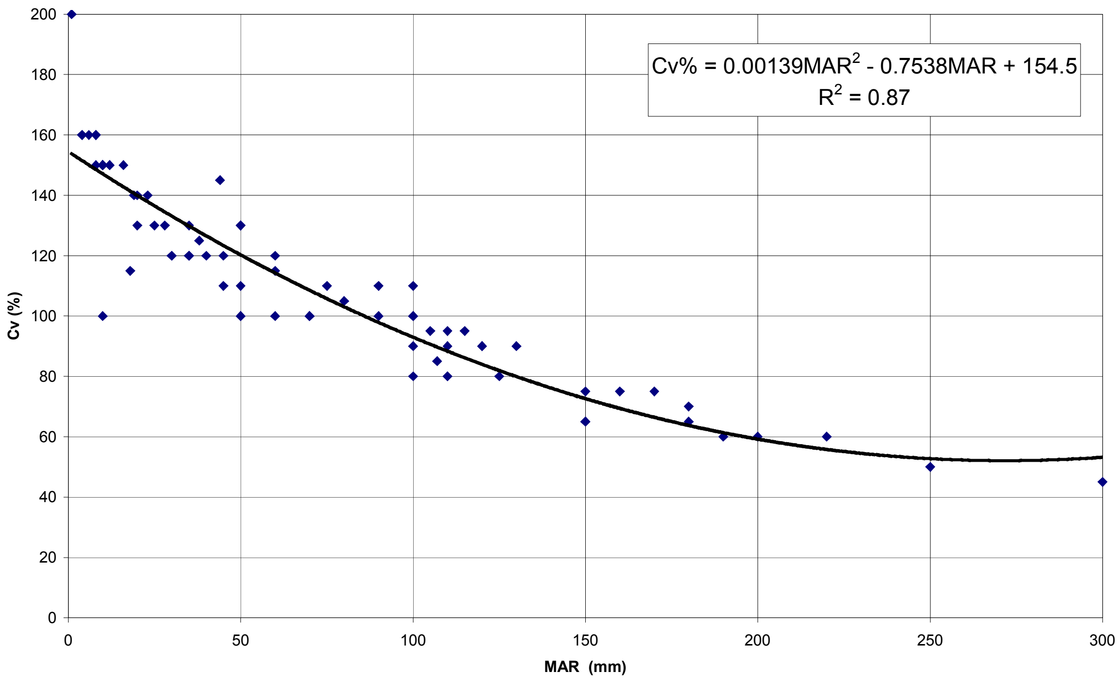

Figure 3.1 Correlation of Coefficient of variation of MAR with MAR

Where data are unavailable an estimate of Coefficient of Variation of MAR can be made using the correlation:

$$Cv\% = 0.00139\ MAR^2 - 0.7538\ MAR + 154.5 \qquad (3.1)$$

4. Probability of a dam filling

The probability of a dam filling is estimated from the coefficient of variation for annual runoff, and the dam capacity to annual inflow ratio, using a method developed for dams in Zimbabwe described in Mitchell (1987). Mitchell argues that given the relatively short records and other deficiencies in the available data, the use of complex statistical functions is not justified, and the simple Wiebul distribution can be used to represent the distribution of annual inflows to a dam:

$$P= e^{-k} \qquad (4.1)$$

Where

P = Probability of a dam filling from empty
$K = (cV/I)^n$
V = Dam storage volume (m^3)
I = Annual inflow (or ARV, m^3)

c and n are constants related to the coefficient of variation of the annual runoff volume. Mitchell (1987) provides the following table:

Table 4.1 Table relating c and n to the coefficient of variation of annual runoff

Cv	c	n
60	0.90	1.72
70	0.91	1.45
80	0.94	1.26
90	0.97	1.11
100	1.00	1.00
110	1.05	0.91
120	1.11	0.84
130	1.17	0.78
140	1.24	0.73

5. Evaporative losses and rainfall

5.1 EVAPORATION DATA

Evaporation rates from a dam can be estimated using pan data from a meteorological station located in the same region and climatic zone as the dam. As it is generally accepted that pan data overestimate evaporation rates from larger bodies of water such as small dams, the use of a pan factor of 0.7 is recommended to convert monthly pan evaporation rates to small dam evaporation rates (Linsley *et al*., 1982). In Zimbabwe it is customary to apply pan evaporation rates directly to reservoirs, with the assumption that any overestimation of evaporative losses will account for additional unaccounted losses such as seepage. While evaporative losses have only a small impact on potential abstractions from deep dams, they are very much more important in shallow dams, where evaporative losses may account for more than 50 % of the water that is stored. Thus it is recommended that a pan factor is applied in order to prevent large overestimates of evaporative losses from shallow dams.

FAO (1993) gives values of Et_0, a reference evapotranspiration rate, for a wide range of locations in Africa (available in the CLIMWAT data base[4]). Data from the nearest station in the data base with similar characteristics (elevation, temperature, rainfall etc) to the dam location could be used if local evaporation data are unavailable. It may be necessary to interpolate when a dam lies between two or more meteorological stations with distinctly different climatic characteristics. As Et_0 approximates to open water evaporation it is not necessary to apply a pan coefficient if the CLIMWAT ET_0 values are used.

5.2 RAINFALL DATA

Mean annual precipitation (MAP) at a dam catchment can be estimated using rainfall data from meteorological stations located in the same region and climatic zone as the dam. Standard methods (see hydrological textbooks) can be applied to interpolate a figure for rainfall at the dam site from the data recorded at nearby stations. (Monthly rainfall data are also available for a large number of locations in Africa in the CLIMWAT data base.)

Alternatively published maps showing rainfall isohets can be used to determine rainfall at a dam location, again interpolation may be necessary to derive a realistic value at the dam site.

[4] The CLIMWAT database includes data from a total of 3262 meteorological stations from 144 countries, is published as FAO Irrigation and Drainage paper No 49 (1993), and can be ordered through the FAO Sales and Marketing Group (Price US$ 35). Publications-sales@fao.org. The CLIMWAT data can also be freely downloaded from the FAO-FTP server.

6. Design floods and required spillway capacity

6.1 DESIGN FLOOD RETURN PERIODS

Dams have to be designed to comply with local dam safety regulations, which usually specify the return period of the flood that a dam spillway must be able to pass safely. Specific advice on the design floods cannot be given here, as the regulations and design codes differ in the different countries. In general the design flood is based on both the size of the dam and the hazard potential should the dam fail. As an example, dam safety requirements for Zimbabwe are given below.

In Zimbabwe dams are classified according to both storage capacity and dam height.

Table 6.1 Dam size classification – Zimbabwe

Size	Capacity (Million m^3)	Height (m)
Small	Below 1	Below 8
Medium	1 to 3	8 to 15
Large	3 to 20	15 to 30
Major	Above 20	Above 30

Small dams are classified as having a capacity of less than one million m^3, and a height of less than eight metres. This definition will include virtually all the dams likely to be considered by users of this report and the small dam sedimentation guidelines. The size of the design flood discharge used to specify the spillway capacity depends on the hazard potential in the event of a dam failure. For dams classified in the table above as "small", hazard potentials are as set out in Table 6.2 below.

Table 6.2 Dam design and peak flood discharges for small dams – Zimbabwe

Hazard Potential	Loss of life	Economic Loss	Return period of design flood (years)	Return period of peak flood (years)
Very low	Extremely unlikely	Minimal	100	250
Low	Improbable	Marginal	250	750
Moderate	Possible	Appreciable	500	2000
High	Probable	Excessive	2000	10000

The spillway must be designed to pass the design flood safely, and the peak return flood must be contained within the dry freeboard allowance, i.e. the dam must not overtop.

The return periods selected for Zimbabwe are stated to be conservative compared to some countries (PEMconsult, 1999), but they are intended to include safety factors to allow for likely inaccuracy in assessment. In many countries it is a requirement that a qualified civil engineer specifies the return periods and flood discharges for dams above a certain size. Even where this is not the case it is recommended that a qualified civil engineer advises on design and spillway capacity for dams larger than 5 m, and in all cases where the hazard potential is judged to be anything other than very low.

6.2 METHODS FOR ESTIMATING DESIGN FLOODS

Several relatively simple methods are used to estimate the magnitude of design floods for small dams. These include:

- Rational methods based on a uniform rainfall intensity over the catchment and a time of concentration and a runoff coefficient that depends on catchment conditions;
- Selection from tables where the design flood is a function of catchment area;
- Regional flood frequency relationships;
- Methods based on the probable maximum flood estimates (PMF).

The first group of methods requires some judgement to select appropriate runoff coefficients, and more data than may be available to small dam designers. It is not considered further here. The second method can be used for very small dams in small catchments, when a failure is unlikely to result in loss of life or significant damage. Recommended values for the 1:100 year design flood for small catchments, presented in Republic of Kenya small dams' design manual (Ministry of Water Development, 1992), are listed in the next section. The last two methods have limited data requirements, are relatively simple to apply, and are used in the guidelines.

6.3 KENYA MINISTRY OF WATER DEVELOPMENT MANUAL METHOD FOR SMALL CATCHMENTS

The guidelines for the construction and rehabilitation of small dams in Kenya (Ministry of Water Development, 1992) present a table of "tentative" values for the 1 in 100 year return period flood discharge for small catchments. (A rational method is recommended for larger catchments.)

Table 6.3 Recommended values of 1 in 100 year return period flood discharge

Catchment area	Q_{100} ($m^3/s/km^2$)
<1	15
1 to 3	12
3 to 5	10
5 to 8	8

6.4 REGIONAL FLOOD FREQUENCY RELATIONSHIPS

Regional flood frequency relationships are widely used for flood estimation. They are derived using data from gauged catchments within a hydrologically homogenous region, to develop a dimensionless flood frequency relationship that can then be applied to ungauged catchments in the same region. Measured floods are non-dimensionalised by dividing by an index value, usually the mean annual flood (MAF). Regional flood frequency curves are derived by fitting a statistical distribution to a pooled non-dimensionalised annual flood maxima series. Multiple regression analyses are conducted to determine a relationship between MAF and selected catchment characteristics, usually area or area and rainfall. More information is given in Farquharson *et al*. (1992), and in hydrological textbooks.

Bullock (1993) reviews the available empirical functions for predicting MAF in semi-arid regions in Southern Africa and recommends an equation developed by him using data from forty-three catchments in Botswana, Zimbabwe, South Africa and Namibia, with catchment areas of less than 1000km^2, and MAP of less than 850 mm. The equations is:

$$MAF = 0.114 * CA^{0.52} * MAP^{0.537} \quad (6.1)$$

Where MAF = Mean annual flood peak discharge (m^3/s)
CA = Catchment area (km^2)
MAP = Mean annual precipitation (mm)

Estimates derived using the equation have a high standard error, albeit smaller than the standard error associated with some of the other equations Bullock reviewed. Also for this application the function will often be used to estimate MAR for catchments that are an order of magnitude smaller than the smallest catchments in the data set from which the function was derived. In view of the certainties associated with estimates of MAF, Bullock recommends that adjustments are made by making use of any local observed data that may be available. This is discussed later.

A number of regional flood frequency relationships are available. For semi-arid areas in Botswana, Bullock (1993) recommends the Farquharson *et al*. (1992) relationship developed from semi-arid zone data for South Africa and Botswana. This gives very similar predictions to relationship developed from a world-wide arid and semi-arid zone data set (3637 station years) that is also presented in Farquharson *et al*. (1992).

Table 6.4 Growth factors for a range of return periods for both relationships

Return Period	**Growth factor Botswana and South Africa**	**Growth factor All arid and semi-arid regions**
50	4.70	4.50
100	6.51	6.15
150	7.83	7.34
200	8.92	8.31
250	9.86	9.15
300	10.69	9.89
350	11.45	10.55
400	12.15	11.17
500	13.40	12.27
1000	18.15	16.38

The MAF determined from equation 6.1 is multiplied by the growth factor to obtain the flood magnitude for the required return period.

6.5 INCORPORATING LOCAL INFORMATION TO IMPROVE ESTIMATES OF MAF

Estimates of MAF can sometimes be improved by making use of local information. Ideally long term annual maximum flood discharges from a reliably calibrated stream gauging site located near a dam site can be used to estimate MAF directly. More usually secondary information will need to be used. The additional work involved would be justified for the design of the larger "small dams" or where a dam failure could result in a threat to life or property.

The procedure involves obtaining information from local informants concerning the maximum river water levels that occurred in the last "historical" flood, when the flood occurred, and the number of years before the flood that an event of a similar size occurred. The estimated flood water level is used with a channel survey to make a slope-area estimate of the peak discharge. The approximate return period for the event can then be estimated if it is assumed that the probability of a flood of the given magnitude occurring in n years is 0.5:

$$T = 1/(1-0.5^{1/n}) \qquad (6.2)$$

Where T = Flood return period (years)
n = Number of years over which the flood level was not exceeded

Using the regional growth factors the ratio between the flood magnitude at the estimated return period and the MAF, and hence an estimate for the MAF, can be derived. Growth factors for any return period can be estimated using the relationship for semi-arid zones in Southern Africa presented in Farquharson (1992).

$$y = -\ln(-\ln(1-T^{-1})) \qquad (6.3)$$
$$q = u + a/k(1-e-ky) \qquad (6.4)$$

where: y = Gumbel reduced variate
T = Return period
q = Growth factor for flood with return perion T
u = a constant
a = a constant
k = a constant

Table 6.5 Values for "u" "a" and "k"

Parameter	Botswana and South Africa (semi-arid)	All regions (arid and semi-arid)
U	0.450	0.476
A	0.429	0.428
k	-0.4216	-0.4003

6.6 PMF METHOD

Although criticised in some quarters the PMF (Probable Maximum Flood) method is used to determine design floods in Zimbabwe (MOWD, Zimbabwe, 1977). The method is described in detail in Hydrology textbooks and is not described here. It has been included in the guidelines due to its routine use in Zimbabwe.

The Probable Maximum Flood (PMF), and subsequently the design flood and spillway capacity required, is determined using a relationship presented in MOWD, Zimbabwe (1977).

$$\ln(PMF+1) = 1.175[\ln(CA+1)]^{0.755}+3.133 \qquad (6.5)$$

Where:

PMF = Probable maximum Flood
CA = Catchment Area (km^2)
$Q_{100} = 0.292 * PMF$

and

$Q_{250} = 0.403 * PMF$

6.7 COMPARISON OF METHODS

Estimates of the 1 in one hundred year return period flood from the tables presented in the Republic of Kenya small dams design manual (MOWD, Kenya, 1992), the regional flood frequency method described by Bullock (1993) and the PMF method used in Zimbabwe (MOWD, Zimbabwe, 1977), are compared below. An annual rainfall of 650 mm was assumed to derive the regional flood frequency results.

Table 6.6 Comparison of 1:100 return period flood for 3 different methods

Catchment area (km^2)	1:100 return period flood (m^3/s)		
	Kenya Ministry of Water Development Manual (MOWD, Kenya, 1992)	Regional flood frequency method (Bullock, 1993)	PMF (MOWD, Zimbabwe, 1977)
2	24.0	34.5	23.4
4	40.0	49.4	35.8
6	48.0	61.0	46.4
10	-	79.6	64.8
20	-	114.2	101.7

Design floods from the Kenya manual table and the Zimbabwe PMF method are broadly similar while the regional flood frequency method predicts design floods that are a little larger. In view of the uncertainty that will usually be associated in the selection of design floods the regional flood frequency method is suggested as the principal method for use in the guidelines, as it provides more conservative predictions than the other two methods.

6.8 SPILLWAY DESIGN

Insufficient spillway capacity has been noted as the most significant reason for the failure of small dams in Kenya (Ministry of Water Development, 1992), and there have been similar findings elsewhere in the region (PEMconsult, 1999). A spillway must be designed to pass the design flood without damage, and the peak flood without the dam overtopping, i.e. the peak flood must be contained within the dry freeboard.

The discharge capacity of a spillway is computed using the equation below:

$$Q = C * L * (H)^{3/2} \qquad (6.6)$$

Where:

Q =	Discharge (m^3/s)
C =	Coefficient of discharge; 1.8 for masonry spillways and 1.65 for grassed spillways
L =	Spillway width (m)
H =	Head over the spillway (m)

Equation 6.6 is used to determine the combination of the wet freeboard and crest width necessary to provide the required discharge capacity, while accommodating any constraints on spillway width and construction costs imposed by local site conditions.

7. Dry season water yields

7.1 ESTIMATING DAM VOLUMES

In many cases small dams are designed without carrying out a full topographic survey, and the storage volume is estimated from the dam width, the throwback, and maximum impounded water depth. Several formulae are used for estimating small dam storage capacities. They are based on equation (7.1) below, with different values for the two constants.

Capacity (C) = K1 * K2 *D * W* L (7.1)

Where: K1 = A constant
K2 = A second constant related to the shape of the valley cross-section
D = The maximum water depth, i.e. the difference in elevation between the lowest point in the reservoir bed at the dam and the spillway crest level
W = The width of water surface at the dam at the spillway crest level
L = The "throwback"

Some examples derived from dam design manuals are listed below:

- USAID (1982), where K1 = 0.4 and K2 = 1
- Fowler (1977), where K1 = 0.25 and K2 = 1
- The "1/6" rule where a dam is represented as a triangular prism, K1 = 0.167 and K2 = 1
- Nelson (1996), where K1 = 0.22, and K2 is selected on the basis of the valley cross-section, in all cases in this study K2 is selected as 1.2.

Volume predictions from each of these methods are compared with the surveyed volumes for nine small dams in Zimbabwe, covering a range of dam heights and river valley cross-section shapes.

Table 7.1 Ratios of the predicted volumes to the surveyed volumes for each of the methods

Dam	**USAID (1982)**	**Fowler (1977)**	**1/6 Rule**	**Nelson (1986)**
Chengwe	1.25	0.78	0.52	0.82
Dove	0.98	0.61	0.41	0.65
Gari	1.66	1.04	0.69	1.09
Jechera	1.14	0.71	0.48	0.75
Murambi	1.33	0.83	0.56	0.88
Mutangi	1.00	0.63	0.42	0.66
Nymai	1.61	1.00	0.67	1.06
Sekenende	2.18	1.36	0.91	1.44
Tinogona	1.12	0.70	0.47	0.74
Mean	**1.36**	**0.85**	**0.57**	**0.90**

It can be seen that on average the USAID relationship over-predicts small dam volumes by 36%, the 1/6 rule under-predicts dam volumes by 43% while the Nelson and the Fowler relationships perform quite well, with an average under-prediction of 10% or

15%. The Nelson equation is recommended for use when a topographical survey is unavailable.

7.2 DRY SEASON "DRAWDOWN" COMPUTATIONS

The simpler small dam design manuals provide little guidance on the water yield obtained from small dams. Methods for determining the dam capacity needed to obtain water yields at specified levels of reliability are described in Bullock (1993) and PEMconsult (1999). These procedures are either relatively complex, requiring more data than are available in most small dam design studies, or are based on "average" storage yield relationships developed for larger dams. The latter may not be applicable to relatively shallow small dams, due to the much greater proportion of impounded water lost by evaporation in small dams, compared with the deeper dams for which the relationships were derived.

The approach adopted in the guidelines is to assume that a small dam's storage capacity is determined by the site conditions and economic considerations. A calculation is carried out to determine the water yield that will be obtained for a dam with a specified initial volume over the critical dry season period. This is considered to be a better alternative than going through a complicated procedure to determine the dam capacity needed to meet a specified yield, and reliability of supply, with no guarantee that the required capacity could be provided at an economic cost at typical small dam sites.

The dry season water yield for a year with an average inflow is determined by carrying out a simple "drawdown" computation. This assumes that the dam capacity is significantly smaller than the Mean Annual Inflow, and is thus full at the start of the dry season[5]. The size of irrigated garden or numbers of livestock that can be supported is estimated from the dry season water yield. It is implicitly assumed that in a year with an average inflow abstraction to provide supplementary irrigation or cattle watering during the wet season can be met from the dam, without compromising the probability of the dam filling. This is a reasonable assumption as most small dams have a capacity that is less than half the average annual inflow. The probability of the dam filling, and hence the reliability of obtaining the estimated water yield, is estimated separately, as described in chapter 4.

The computation assumes that a dam fills over a specified number of months forming the wet season, and after this is emptied (drawn down) by evaporative losses and abstractions over the following dry season, when there is no recharge from surface runoff. Computations are carried out using a monthly time step. In each month the drop in water level due to evaporation and water abstractions is used to calculate the water volume in the dam at the start of the next month, from a relationship between the water level and the volume of water stored in the dam[6]. An iterative procedure is used to determine the total abstraction that will draw the dam down to a specified depth, or to a specified remaining water volume, at the end of the drawdown period. The calculation adjusts the water volume taken out of the dam each month to account for monthly variations in evaporation rates, irrigation and livestock watering abstractions. These variations can have a significant impact on the water yield. A larger water yield is obtained from a dam if most of the stored water is abstracted early in the dry season, before it can be evaporated.

[5] The calculation is based on the procedure used by HART FROST to determine dry season water yields from small dams in Zimbabwe (HART FROST, Consulting Engineers, Zimbabwe, Personal communication, 2000).
[6] In the software supplied with the design manual the Nelson (1986) relationship is used to compute storage volumes from water depths.

7.3 ESTIMATING DAM CAPACITY REDUCTIONS DUE TO SILTATION

Siltation reduces dam storage capacities and water yields, and can be rapid in dams that store only a small proportion of the annual water runoff. Dam sedimentation rates are directly proportional to the sediment yields from catchments, and a method has been developed that enables annual sediment yields to be estimated from catchment characteristics. The method is described in detail in HR Wallingford (2003b). In summary the procedure is based on a rapid appraisal of the dam catchment. A checklist completed during a visit is used to score qualitative indicators of soil type and drainage, erosion status and crop cover. These factors are used with the slope of the main stem river, the catchment area, and the annual rainfall, to predict the sediment yield using an empirical function developed using measured data describing small dam sedimentation rates.

An alternative, simpler procedure based on a qualitative description of the catchment was also developed for use in semi-arid zones in Zimbabwe (or other regions where catchments have similar physical characteristics and land use) (see Table 7.2).

Table 7.2 Catchment classes to estimate the mean annual sediment concentration

Characterisation	Mean annual sediment concentration in the runoff from the catchment
Basins with low slopes and very well developed conservation	1200 ppm
Basins with moderate topography and well developed conservation	3600 ppm
Basins with steeper slopes and prone to erosion through poor conservation	10800 ppm
Basins with steep slopes and highly susceptible to erosion	32400 ppm

It is stressed that this is a very arbitrary classification. The sediment concentrations adopted for each class of catchment broadly correspond to those expected from catchments with characteristics rated “Low”, “Normal”, “High” or “Extreme” in the catchment characterisation procedure. Where possible use of the full catchment characterisation procedure described in HR Wallingford (2003b) is recommended, as it accounts for more of the parameters that influence sediment yields than the above.

The loss in a dam’s storage capacity over time is estimated using three non-dimensional parameters, and the settled density of the sediment deposits:

$$C_n = \frac{n * X * TE}{(C / ARV) * D} \tag{14}$$

Where:

n = Number of years
C/ARV = The dam capacity to inflow ratio
C = Dam capacity at full supply level (m^3)
ARV = Annual inflow (m^3)
C_n = Proportion of original gross storage capacity lost after n years
D = The settled density of dam sediment deposits, taken as 1.2 t/m^3
X = S_y*CA/ARV, The annual mean sediment concentration by weight in the water entering the dam
S_y = Catchment sediment yield (T/km^2)

CA = Catchment area (km^2)
TE = The annual mean sediment trap efficiency

Values for either Sy, or X, are obtained using one of the two methods summarised above.

The variation in sediment trap efficiency with dam capacity inflow ratio is derived from Brune's curves (Brune, 1953) (see Table 7.3).

Table 7.3 Sediment trap efficiencies as a function of capacity/inflow ratio

Dam Capacity/Inflow Ratio	Sediment Trap efficiency
1.0	1.00
0.5	0.99
0.4	0.98
0.3	0.97
0.2	0.95
0.1	0.88
0.08	0.86
0.06	0.82
0.04	0.75
0.02	0.63
0.01	0.48

7.4 ESTIMATING WATER YIELD REDUCTIONS DUE TO SILTATION

When shallow dams silt up water yields are reduced by more than the loss in storage capacity. This is due to the relatively larger proportion of the stored water that is lost by evaporation as dams become shallower.

The impact of siltation on water yield is estimated by carrying out a drawdown analysis for conditions following 20 years of siltation. In order to carry out the calculation the distribution of sediment deposits within the dam has to be predicted. This is not a trivial task, and would normally be carried out by numerical modelling. To enable estimates to be made in small dam design studies calculations are based on the following plausible assumptions:

- Sediment deposits are divided into the coarser sediments that settle to form a delta at the head of a dam, and finer sediments that settle in the pool between the downstream end of the inlet delta and the dam wall.
-
- 50 % of the sediment mixture settling in a dam consists of coarse sediments (i.e. sand sizes and larger). This assumption is based on the proportions of fine and coarse sediments settling in sixteen Zimbabwean dams as reported by Interconsult (1985).

Deposition of coarse sediments is represented by assuming that coarse sediments settling in the delta at the head of a dam can be represented by a reduction in the "throwback", so as to produce a loss in capacity equal to 50% of the predicted total capacity reduction. The remaining storage loss, due to the deposition of fine sediment, is assumed to occur in the pool at the deepest level of the dam. Sediment deposits here are assumed to form a new horizontal bed at a level such that the volume lost in the pool equals the other half of the total capacity loss (See figure 7.1).

Water yield reductions derived using the assumed sediment distribution can only be regarded as approximate. However they are definitely worth carrying out as part of the design process, as they highlight the large impact that relatively small amounts of siltation have on the water yields obtained from silted shallow dams.

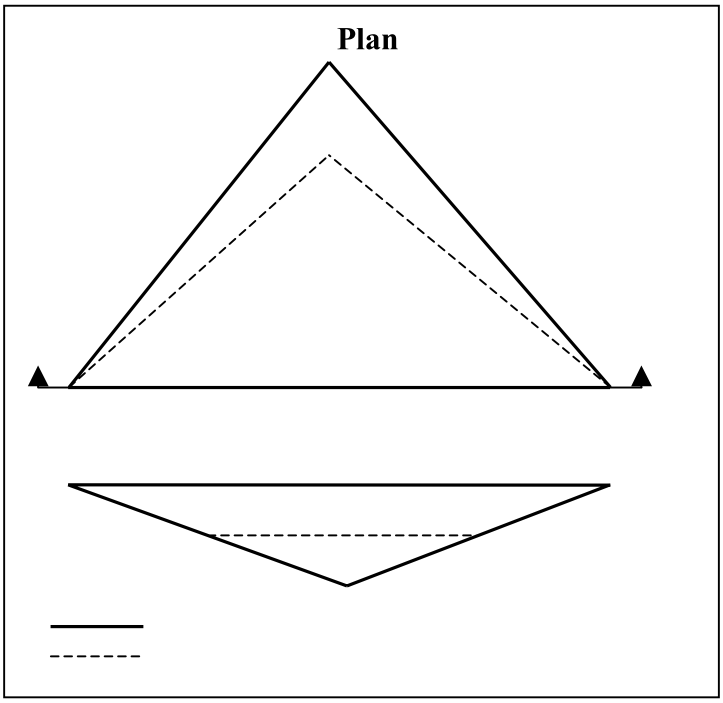

Figure 7.1 Assumed sediment distribution in a silted dam

8. References

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Annexes

Annex 1 "Drawdown" sedimentation and hydrological computation software – User guide

A1.1 Introduction

This annex describes the use of the Excel based software developed to carry out drawdown and hydrological calculations for small dams. The methods used are described in HR Wallingford (2003b).

For a specific dam and catchment the Excel spreadsheets calculate the following information:

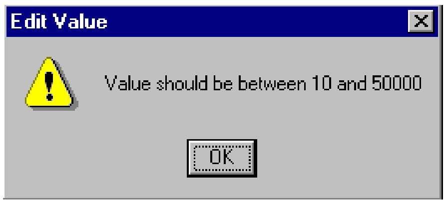
- Dam storage capacity, capacity to inflow ratio and the probability of a dam filling;
- Reductions in storage capacity and water yield due to sedimentation over 20 years;
- Design floods for 100 and 250 year return periods;
- Annual volumes of water that can be abstracted over dry seasons, potential irrigated area and/or the number of cattle that could be supported.

The programme allows a user to rapidly assess the impacts of future sedimentation and carry out simulations of different scenarios so that the impact of changing parameters that are under the control of a dam designer can be compared. Hydrological information, including the probability of the dam filling, and design flood discharges are also calculated.

A1.2 Data entry

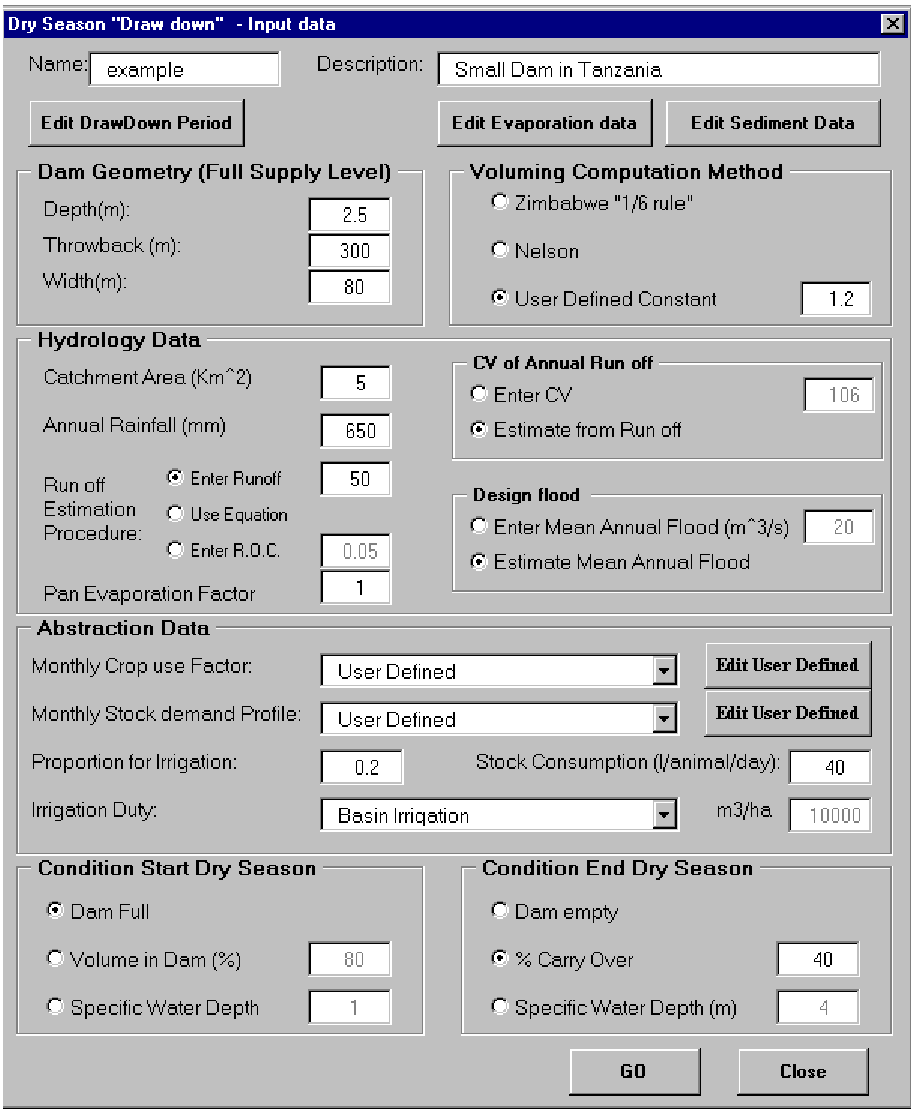
When the programme is started the data entry screen shown on the next page is displayed. This is used to enter all the data required to carry out computations. (Data displayed in the input screen when the programme is started are those used for the previous programme run.)

Data are entered in a series of text boxes. The programme verifies that entered data are within defined limits. If the input value is outside a limit, or contains an illegal character, the following error message is displayed. Note that the edit value message indicates the minimum and maximum values allowed for a parameter.



The software is designed to support the design and evaluation of small dams, and the input data limits prevent its use for dams larger than 8 m deep or with catchments larger than 50 km^2.

As the programme will always run (provided that valid data are present in the data entry screen) it is vital that the user checks that the correct data for the simulation being carried out have all been entered. The table shown in section A1.8 lists the input data that are required for the computation of each programme output, and can be used to check to ensure that all the information needed has been entered. Input data used in a simulation are listed in one of the tabbed sheets that can be viewed or printed when the programme has been run.



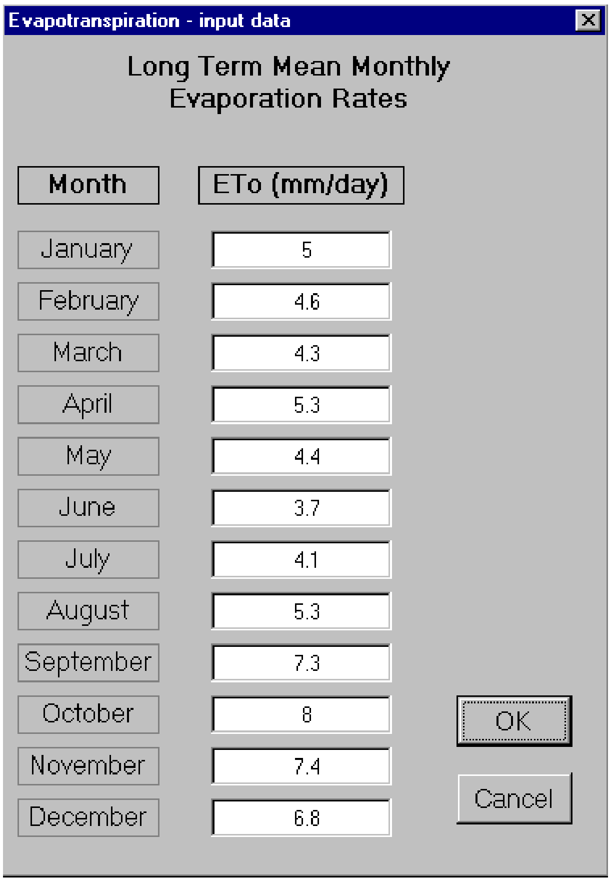
A1.2.1 Edit "drawdown" period

Select the **"Edit drawdown period"** option to select the first and last month of the dry season, over which drawdown calculations will be carried out.

The dry season is selected using monthly rainfall or river discharge data and should include the months when significant recharge of the dam does not occur. Many areas have a single wet season. Where the rainfall is bi-modal two dry seasons will occur, and these may need to be simulated separately. This is discussed in example A1.

A1.2.2 Edit Evaporation data

Select **"Edit Evaporation data"** to enter monthly evaporation data (mm/day) for each month of the year. The programme selects data for the months specified as the dry season or drawdown period. If reliable monthly data are not available then an estimate of the mean dry season evaporation rate (mm/day) can be entered for each month.

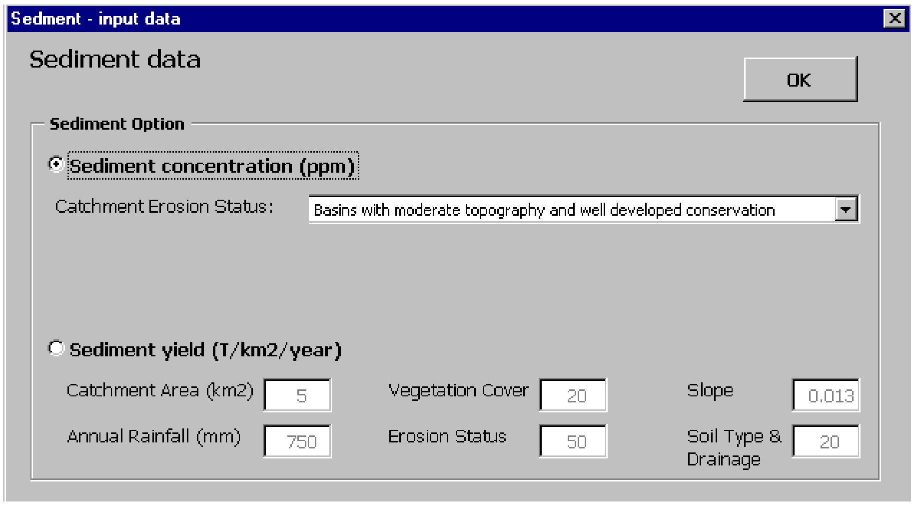


Click **OK** to save the data as set up on the screen. If **Cancel** is selected the data displayed are lost and the data used for the previous simulation are re-selected.

Now set the **Pan evaporation factor** in the hydrology window to a suitable value. If evaporation pan data have been entered a **Pan evaporation factor** of 0.7 is recommended. If values of ET_0 from the FAO "Climwat" database or another source have been entered, set the **Pan evaporation factor** to 1.0.

A1.2.3 Edit Sediment Data

Select **"Edit Sediment Data"** and choose one of the two options to select the method used to estimate the sediment yield from the catchment.



If a catchment characterisation has been carried out the **Sediment yield** option should be chosen, and characterisation values for vegetation cover, erosion status, soil type and drainage, and a value for the catchment slope entered. The sediment yield is computed using the empirical equation described in chapter 4 of the guidelines, and in HR Wallingford (2003b).

If a catchment characterisation has not been carried out then select the **sediment concentration** option. A drop down list is enables one of four catchment description descriptions to be selected. The description chosen selects the incoming mean annual sediment concentration, as shown in Table 4.2 of the guidelines. If the mean annual sediment concentration is known, or can be estimated from regional data, then it can be entered directly with the **User Defined** option. (This option should also be used if the catchment type seems to fall between two of the standard descriptions, and a mean sediment concentration – derived from the values shown in Table 4.2 in chapter 4 of the guidelines – is to be entered).

Note that the sediment concentrations associated with the catchment descriptions are based on sediment concentration data for semi-arid zones in Zimbabwe, and may not be appropriate for other regions.

A1.2.4 Dam Geometry and voluming computation method

The dam volume is computed using a simple relationship based on the dam depth, width and throwback. (In this case depth is the maximum water depth at the dam when the water level is at the spillway crest level) . Enter the **depth, width and throwback** derived from a site survey. Then select the method that is to be used to compute the dam volume. The **Nelson** method is recommended as it gives realistic volumes when compared with the volumes derived from small dam surveys. If the dam volume derived from a detailed survey is available, then select the **user defined** option, and enter a constant, calculated as shown below.

$$\text{Constant} = \frac{\text{Surveyed Dam Volume}}{\text{Depth} \cdot \text{Width} \cdot \text{Throwback}}$$

A1.2.5 Hydrology data

Enter the data requested, i.e.:

Catchment Area, which should be derived from 1:50 000 topographic maps.

Mean Annual rainfall, obtained using one of the methods described in Chapter 3 of the guidelines.

Mean Annual runoff, using one of the three options, i.e.:

- **Enter Runoff when** the runoff from the catchment is known from Tables or runoff maps or has been estimated by the user.
- **Use equation** when runoff data are unavailable, and the runoff is to be is estimated from rainfall using the Bullock (1990) equation described in chapter 3 of the guidelines.
- **Enter Runoff coefficient (ROC) when** the runoff coefficient for the catchment is expected to be significantly different from that derived from tables of the Bullock equation. It could be used for example when there is a significant proportion of fairly impermeable soils or rock outcrops in the catchment, and a larger runoff coefficient is expected than is indicated in tables or predicted by an empirical equation.

Coefficient of variation (CV) of annual runoff, using one of the two options:

- **Enter the CV** if the coefficient of variation of annual runoff for the catchment is known from tables, or national or regional maps.
- **Estimate from Runoff** if the CV is not known. In this case the CV will be estimated from the mean annual runoff, using the method described in chapter 3 of the guidelines.

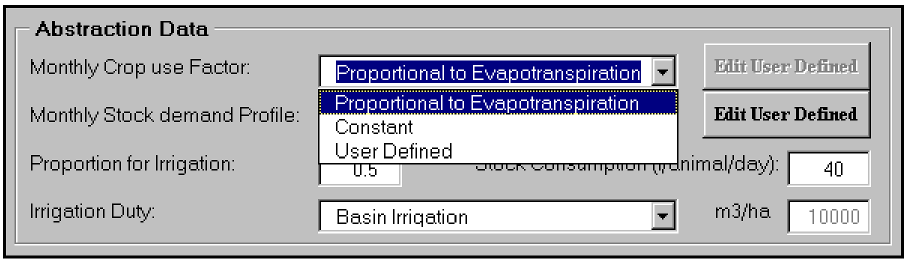
Design flood

Select **Enter Mean Annual Flood** and enter the discharge for the mean annual flood when this has already been estimated. Select **Estimate Mean Annual Flood,** if you wish the programme to estimate the mean annual flood using the Bullock (1993) equation described in Chapter 7 of the guidelines.

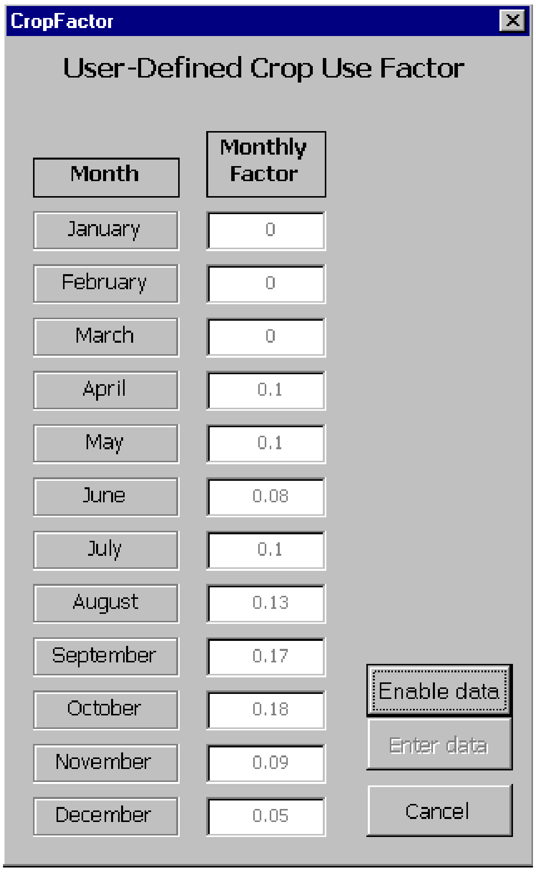
A1.2.6 Abstraction data

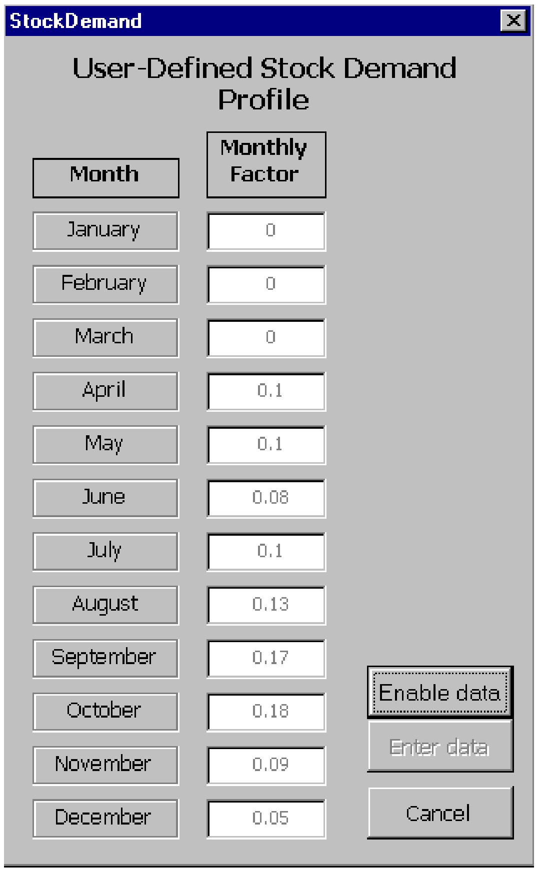
"Monthly Crop use factor" and **"Monthly Stock demand profile"** are used to represent the variations in monthly water abstraction due to varying crop and the livestock water demands during the dry season in the drawdown computation.

They are selected from the same drop down list:



- **Proportional to evapotranspiration** is selected when either the crop water requirement or stock water demand is to vary in proportion to monthly evaporation rate.
- **Constant** is selected when abstraction is assumed to be the same each month.
- **User defined** is selected when the user wishes to simulate any other monthly variation in demand. Selecting this option displays one of the following screens.





Clicking on **enable data** activates the text boxes for months selected to represent the dry season.

Monthly factors can then be entered. The entered figures are weighting factors varying between 1 and 100, representing relative crop or stock water demand for each month. (For example if the water demand in the first month is represented by the factor 1 then the factor for the second month would be 1.5 if the water demand in the second month was 1.5 times larger. As the programme distributes monthly abstractions in the ratio of the factor for the month divided by the sum of the factors for all months over the drawdown period the absolute magnitude of the factors used is unimportant.) **N.B. It is only possible to edit the months selected as the dry season.**

After the data have been entered click on **enter data** to store the information. Clicking **cancel** will loose the changes and retain the previous data.

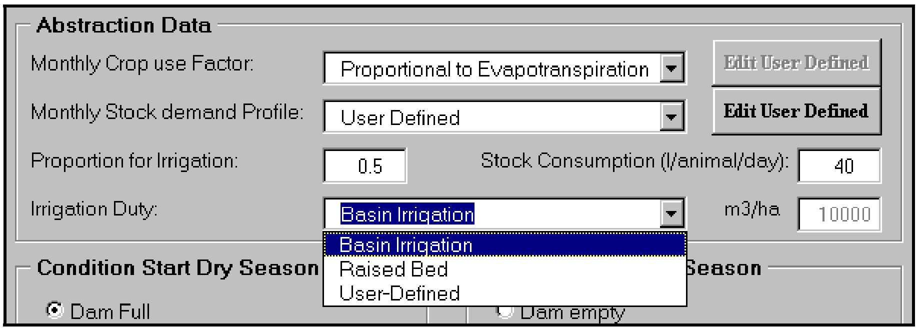
Proportion to Irrigation is the proportion of the water abstracted from the dam that is to be used for irrigation, and takes a value from 0, when there is no irrigation, to 1, when all the water abstracted from the dam is used for irrigation.

Stock Consumption is the average daily water consumption per livestock unit supported by the dam. It is used to convert the water volume abstracted, which is allocated to livestock watering, to an approximate number of livestock units that could be supported.

Irrigation Duty is the total volume of water per ha used by the irrigation method that is to be adopted. Two pre-set values are included in the software, derived from estimated water usage in small-scale communal irrigation plots in Zimbabwe. These are selected from the drop down list:

- **Basin irrigation** sets the Irrigation Duty at 12000 m^3/ha
- **Raised Bed** sets the Irrigation Duty at 8600 m^3/ha
- **User defined,** when selected, enables any required irrigation duty to be entered.

The irrigation duty is used in the programme to estimate the potential irrigated area from the volume of water available for irrigation.



A1.2.7 Condition at the start and end of the dry season

The input boxes **Condition Start Dry Season** and **Condition End Dry Season** are used to specify the start and end conditions for the drawdown computation – either as a specified water level or as a percentage of the dam capacity.

Select **Condition Start Dry Season** from the options **Dam Full, Volume in dam %,** or **Specific water depth.** Dams are normally sized so that they will be full at the start of the dry season and the second or third options will probably only be used when a second dry season is being simulated in a bi-modal rainfall area. In some cases only a relatively small rainfall may occur during the secondary wet season, and the dam may not be full at the start of the secondary wet season. **N.B. Check that the "Volume in dam" is not 100%, otherwise the programme will not run.**

Select **Condition End Dry Season** from the options **Dam empty**, **% Carry-over** or **Specific water depth**. The carry-over is the percentage of dam volume that is left in the dam at the end of the dry season. It is often recommended that earth dams are not completely drawn down to prevent problems caused by the embankment drying out. Also in many cases the communities using the dam will wish to retain a reasonable proportion of the water stored in a dam to provide some insurance against a failure of the next season's rains.

A1.3 Running the programme

The programme is run from the input data screen. If **close** is selected no calculation is carried out and the data set up in the input screen are saved. To initiate a computation select the command **GO.** Before the computation is started the programme carries out a basic verification of the input data.

One or more of the error messages or warnings listed in section A1.9 could be displayed.

Assuming the programme has run correctly, the drawdown output sheet will be displayed.

A1.4 Output tables

If the computation is completed successfully one of three excel spreadsheets are displayed. Move between sheets by clicking on the name tabs along the bottom of the screen.

A1.4.1 Drawdown Output

This table summarises the outputs of the drawdown simulation and provides a water balance. The following information is provided:

- **Drawdown season**
  - Start dry season (month; volume (%))
  - End dry season (month; volume (%))

- **Summary Drawdown dry season**
  - Volume evaporation (m^3; %)
  - Total volume abstracted (m^3; %)
  - Volume carry-over (m^3; %)
  - Initial volume (m^3)
  - Initial depth (m)
  - Final volume (m^3)
  - Final depth (m)

- **Abstraction summary**
  - Volume for irrigation (m^3)
  - Potential irrigated area (ha)
  - Volume for stock watering (m^3)
  - Number of cattle supported

A1.4.2 Input Data

This table summarises the input data used to run the programme. It should be checked to ensure that the programme was run with the intended input data.

The following information is listed:

- **Input – Dam geometry (full supply level)**
  - Depth (m)
  - Width (m)
  - Throwback (m)
  - Geometry coefficient

- **Input – hydrology data**
  - Catchment area (km^2)
  - Annual rainfall (mm)
  - Pan evaporation factor
  - Runoff (mm)
  - Coefficient of variation

- **Input – abstraction data**
  - Crop use factor
  - Stock demand profile
  - Proportion for irrigation (%)
  - Stock consumption (l/animal/day)
  - Irrigation duty (m^3/ha)

- **Drawdown season**
  - First month
  - Last month
  - Volume start (%)
  - Volume end (%)

- **Input – monthly data (user defined)**
  - Evapotranspiration (mm/day on a monthly basis)
  - Crop use factor (%)
  - Stock demand profile (%)

- **Input – sediment data**
  - Sediment Density (T/m³)
  - Sediment concentration method
    - Selected type of basin
    - Sediment concentration (ppm)
  - Sediment yield method
    - Catchment Area (km²)
    - Annual rainfall (mm)
    - Slope (m/m)
    - Vegetation cover (index)
    - Erosion status (index)
    - Soil type/Drainage (Index)

A1.4.3 Output Summary

This table summarises the programme outputs. The following information is provided:

- **Basic design data**
  - Mean annual inflow (m³)
  - Full supply dam capacity (m³)
  - Capacity inflow ratio
  - Probability of filling (dam empty) (%)
  - Probability of filling (with carry-over) (%)

- **Design Flood**
  - Regional flood frequency method
    - Mean Annual Flood (m³/s)
    - Design flood (1:100 year) (m³/s)
    - Design flood (1:250 year) (m³/s)
  - PMF method
    - Maximum Probable Flood (m³/s)
    - Design flood (1:100 year) (m³/s)
    - Design flood (1:250 year) (m³/s)

- **0% Carry-over – capacity and yield reductions**
  - Capacity loss in 20 years (%)
  - Design sediment concentration (ppm)
  - Design sediment yield (T/km²/year)
  - Maximum water yield Year 0 (m³)
  - Maximum water yield Year 20 (m³)
  - Yield reduction over 20 years (%)

A1.5 Printing the results

The three tabbed sheets can be printed for inclusion in a design file or report, etc., using the usual Excel print commands.

A1.6 Saving the data

If required the standard excel "save as" command can be used to re-name and save the spreadsheets for specific projects.

A1.7 Re-running the programme

Select the **Drawdown Output** sheet and Click on **"Data Entry"** button to activate the input screen and enter data for a new simulation.

A1.8 Input data required to produce programme outputs

Items in *italics* need to be entered

OUTPUTS	INPUTS
Mean Annual Runoff (mm)	*Value or* *Runoff coefficient, Annual Rainfall (mm)* *Or Annual Rainfall (mm)*
Coefficient of variation of runoff	*Value or* Mean Annual Runoff (mm)
Mean Annual Inflow (m^3)	*Catchment Area (km^2)* Mean Annual Runoff (mm)
Full Supply Level Dam Capacity (m^3)	*Full supply level dam depth (m)* *Full supply level dam width (m)* *Full supply level dam throwback (m)*
Capacity Inflow Ratio	Dam Capacity (m^3) Mean Annual Inflow (m^3)
Probability of Filling (%)	Coefficient of variation of runoff Capacity Inflow Ratio
Mean Annual flood (m^3/s)	*Value or* *Catchment Area (km^2)* *Annual Rainfall (mm)*
Design Floods - Regional growth curve method	Mean Annual flood (m^3/s)
Maximum Probable Flood method (m^3/s)	*Catchment Area (km^2)*
Design Floods – MPF method	Maximum Probable Flood (m^3/s)
Sediment Yield (T/Km^2/year)	*Catchment Area (km^2)* *Annual Rainfall (mm)* *Vegetation cover index* *Erosion status index* *Slope index* *Soil type and drainage index*
Capacity Loss in 20 Years (%) – sediment concentration method	*Catchment type or* *Sediment concentration (ppm)* Capacity Inflow ratio
Capacity Loss in 20 Years (%) – sediment yield method	Sediment Yield (T/Km^2/year) Capacity Inflow ratio
Seasonal Water Abstraction (m^3)	*First/Last month of period* *Initial/Final water depth (m) or* *Initial /Final volume (m^3)* *Evaporation (mm/day)*
Potential Irrigated Area (ha)	*Proportion for Irrigation (%)* *Irrigation Duty (m^3/ha)*
Number of Cattle Supported	*Proportion for Irrigation (%)* *Stock consumption (l/animal/day)*

A1.9 Error messages

The programme will generate an error message if the combination of input data that has been entered causes it to fail. The following messages may be displayed:

“Error in 1st Goal seek. Please revise input data!”

(The same message could also refer to the 2nd or 3rd Goal seek.)
This message will be displayed if the solver used by the programme to carry out an iterative drawdown calculation cannot find a solution. This message is usually associated with other messages that will help in identifying the problem and potential solutions.

“Total Evaporation over the silted drawdown period is X mm, Max Depth of the dam is Y mm.”

This message is generated during a drawdown computation for a silted dam, when evaporation over the dry season is larger than water depth at the start of the dry season. In this case no abstraction would be possible in the latter months of the season and the computation would predict negative abstractions.

After this message is displayed the programme carries out the calculation and the outputs can be checked by selecting **‘Close’** after the **“Analysis completed”** message is displayed. Outputs that are not related to drawdown computations are unaffected, but drawdown outputs will be invalid.

“Total Evaporation over the drawdown period is X mm, Max Depth of the dam is Y mm.”

This message is similar to the above and is generated during a normal drawdown simulation.

After this message is displayed the programme carries out the calculation. The outputs can be checked by selecting **‘Close’,** after the **“Analysis completed”** message is displayed. Outputs that are not related to drawdown computations are unaffected, but drawdown outputs will be invalid.

“Start and final conditions aren't consistent!”

This message is displayed if the selected initial and final conditions give a volume at the start of the simulation lower than the volume at the end. If this message is encountered, the run is stopped and revised initial and final conditions requested.

“Ensure that the requested water depth at the end of the season is not greater than the maximum depth!”

This message occurs when the requested final water depth is larger than the initial or the maximum depth.

“Introduce a correct starting and/or ending month!”

This message is displayed if the programme does not find an initial and/or final month of the drawdown period. Click on: “Edit drawdown period” and select the appropriate months.

“Dam silting in X years! Modify the input data to reduce the capacity inflow ratio”
If the selected initial conditions result in the dam silting up in less than 20 years the simulation is stopped and this message is displayed. A dam that silts up in less than 20 years is unlikely to be viable. One solution is to increase the dam volume to provide more storage for sediment. Another would be to estimate the impact of possible soil conservation measures in the

catchment, or the introduction of sediment bypassing, and to reduce the incoming sediment concentration.

A1.10 Limits on input parameters

The table below shows the maximum and minimum values that will accepted by the programme.

Table A1.10 Limits on input parameters

Parameter	Min	Max
Depth (m)	2.5	8
Throwback (m)	10	4000
Width (m)	10	1000
User defined geometry constant	0.1	1
Catchment Area (km^2)	0.5	50
Annual Rainfall (MAP, mm)	5	1000
Runoff coefficient	0.01	1
Mean Annual Runoff (mm)	5	1000
Coefficient of variation of runoff	50	200
Monthly evaporation (mm/day)	1	35
Pan evaporation factor	0.5	1
Mean Annual Flood (m^3/s)	1	100
Proportion to irrigation	0	1
Stock consumption (l/animal/day)	1	500
Irrigation duty (m^3/ha)	1	20000
Monthly crop/stock demand	1	1
Sediment Concentration (ppm)	1	500000
Erosion Status (Sediment Yield factor)	5	40
Vegetation Cover (Sediment Yield factor)	10	40
Slope (Sediment Yield factor)	0.00001	0.3
Soil Type and Drainage (Sediment Yield factor)	10	40