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Executive Summary

Guidelines for Predicting and Minimising Sedimentation in Small Dams

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Many of the small dams constructed in semi-arid regions of Africa rapidly fill with sediments, sometimes after only a few years. When dams silt up the rural communities that rely on them for cattle watering or small-scale irrigation are deprived of the water and food security that dams provide, and their livelihoods are seriously affected.

Predicting soil erosion, sediment yields and dam sedimentation rates can be a complex task, requiring specialist expertise, and is generally poorly covered in small dam design manuals. This results in many small dams being constructed with little or no consideration of the impact of future siltation of a dam’s life or on water yields. These guidelines were prepared to enable dams where siltation rates will be unacceptably large to be identified at the planning or design stage of small dam projects. Where siltation rates are expected to be large measures have to be taken to reduce sedimentation. Approximate methods for estimating the impact of remedial measures, such as catchment conservation or engineering interventions, on dam lives and water yields are also described. The methods were selected, or in some cases specifically developed, for use in typical small dam design studies. In such studies there is usually neither the site specific data nor the time and resources needed to carry out the more detailed studies that precede the construction of larger and more expensive dams.

The two most important factors that determine siltation rates are the sediment yield from the dam catchment, and the ratio of a dam’s storage volume to its annual water inflow. A procedure for estimating catchment sediment yields was developed by a research study that supported the preparation of the guidelines. The procedure is based on an empirical sediment yield predictor that combines quantitative information on the catchment area, annual rainfall and slope, with qualitative factors describing soils, vegetative cover, and evidence of accelerated erosion. Qualitative factors are scored in a rapid catchment characterisation exercise. The method was developed using data collected from catchments and dams in Zimbabwe and Northern Tanzania.

The importance of the second factor, dam capacity to annual inflow ratio, is not sufficiently emphasised in most small dam design manuals, and many dams continue to be constructed with storage capacities that are only a fraction of the annual water inflow. As even very small dams trap virtually all the incoming sediment load they can silt up very rapidly if the annual inflow of water is significantly larger than the storage capacity.

Some basic hydrological information is needed to estimate sedimentation rates, and appropriate hydrological methods for obtaining this information are described in the early chapters. Inadequate spillway capacity is often cited, along with sedimentation, as the most common reason for the failure of small earth dams. Although not related to sedimentation, advice on determining design floods and spillway capacities is presented in the final chapter.

Executive Summary continued

Guidance is given on the following topics:

- Selecting a small dam site;
- Screening for environmental impact and the conditions needed to ensure acceptability and sustainability of soil conservation measures.

Procedures are described for quantifying:

- Dam storage capacity at full supply level (m^3);
- Mean annual runoff from a dam catchment (mm);
- Coefficient of variation of mean annual runoff (%);
- The Mean Annual Inflow to a dam (m^3);
- Dam capacity to inflow ratio;
- Probability of a dam filling (%);
- Catchment sediment yield (t/km^2/year);
- Dam capacity loss and water yield reduction due to sedimentation over 20 years;
- Potential water abstraction during the dry season for different levels of carry-over storage;
- Potential Irrigated Area (ha);
- Potential number of livestock units that can be supported by a dam in an average year;
- Impact of check dams and soil and water conservation in reducing catchment sediment yields;
- Impact of sediment bypassing arrangements in reducing dam sedimentation rates;
- Design Floods used to specify spillway capacity (m^3/s).

Each chapter consists of a summary of existing knowledge, a description of methods, and a short example.

Annex 1 describes "Excel" software supplied with the guidelines. This can be used to carry out most of the computations needed to assess dam siltation rates and dry season water yields. Annex 2 presents tables to aid users who need to carry out manual calculations. Annex 3 contains checklists for environmental impacts, and for assessing the sustainability of catchment conservation interventions designed to reduce sedimentation rates in small dams.

List of Symbols

Area (or CA)	Catchment area (km^2)
ARV	Annual Runoff Volume (m^3)
C	Dam's original capacity at full supply level (m^3)
Cd	Coefficient of discharge; 1.8 for masonry spillways and 1.65 for grassed spillways
C_n	Proportion of original storage capacity left after n years of siltation
C_n (bp)	Proportion of original storage capacity left after n years of siltation with sediment bypassing
Cv	Coefficient of variation of annual runoff (%)
Cw	Dam crest width (m)
D	The maximum water depth, i.e. the difference in elevation between lowest point in the reservoir bed at the dam and the spillway crest level (m)
DAMBO	Proportion of the catchment that is dambo (seasonally inundated grasslands), a value between 1 and 0
Den	The settled density of dam sediment deposits, taken as 1.2 t/ m^3
DS	Downstream
ER	Erosion rate (t/ha/y)
Et_0	A reference evapotranspiration rate (mm)
h	Head over the spillway (m)
H	The dam crest height, i.e. the full supply depth plus the freeboard (m)
I	Annual inflow (the same as ARV (m^3))
K1	A factor to account for the additional sediment diverted to the dam during flood peaks
K2	A second factor to account for water and sediment diverted to the dam during the wet season to replace wet season water abstractions and evaporative losses
Kn	A constant related to the shape of the valley cross-section – taken as 1.2 in these guidelines
l	Distance between check structures (m)
L	The length of the dam at the crest height including the spillway (m)
MAP	Mean Annual Precipitation (mm)
MAR	Mean Annual Runoff (mm)
n	Number of years
ndam	The number of check dams
P	Probability of a dam filling from empty
P_{e0}	Proportion of dam's capacity lost by evaporation
PMF	Probable Maximum Flood (m^3/s)
Q	Discharge (m^3/s)
ROC	Runoff Coefficient
S	The combined upstream and downstream embankment slopes
SASE	Signs of Active Soil Erosion (Score from catchment characterisation)
SDR	Sediment Delivery Ratio
Slope	River slope from the catchment boundary to the dam
STD	Soil type and drainage (Score from catchment characterisation)
S_y	Catchment sediment yield (t/km^2/year)
S_y con	Sediment yield with conservation (t/km^2/y)
S_y20	Mean sediment yield over 20 years (t/km^2/y)
SYRF	Sediment Yield Reduction Factor
TB	The "throwback" at the spillway crest level (m) (the throwback is the distance from the dam along the reservoir axis usually to the point where the river enters)
TE	Sediment trap efficiency

List of Symbols continued

US	Upstream
V	The volume of earthworks (m^3)
VC	Vegetation Condition (Score from catchment characterisation)
Vcheck	Sediment stored by check dams (m^3)
V_s	Volume of sediment settling in a dam over twenty years (m^3)
W	The width of water surface at the dam at the spillway crest level (m)
wr	Average river width (m)
Ws	Spillway width (m)
X	Mean annual sediment concentration from Table 5.2 (ppm)
Y_0	Dry season water yield in year "0" (m^3)

Acknowledgements

HR Wallingford wish to acknowledge the enormous contribution to this study made by collaborators in Zimbabwe and Tanzania. In Zimbabwe these included staff and officials from the Harare and Masvingo offices of CARE and Agritex. Most of the small dam surveys in Zimbabwe were carried out by Hart Frost Consultants, Harare, with support from CARE. Silsoe Research Institute UK also provided support and socio-economic data.

In Tanzania principal collaborators were KINNAPA in Kibaya, and the engineers from the Regional Water Office in Arusha. Small dam surveys in Tanzania were carried out by WEGS Consultants, Arusha, with KINNAPA's assistance and facilitation.

Catchment characterisation procedures were developed by Dr P Goldsmith and the project collaborators in Zimbabwe and Tanzania. In Zimbabwe these were central and regional staff from Agritex and CARE, and in Tanzania engineers from the regional water office in Arusha and KINNAPA.

Assistance and encouragement in setting up and carrying out the study were received from the DFID office in Harare, and officials of the Irrigation Department of the Ministry of Agriculture in Tanzania.

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1. Background

1.1 INTRODUCTION

There are strong links between the availability of water for agriculture and livestock production, and incomes of the rural poor (HR Wallingford, 2003a). Rainfall variations, particularly droughts, affect the livelihoods of the rural poor. One means of increasing people's resilience to these shocks is to store water in dams – so that crops can be irrigated and cattle watered during the dry season. NGO's and Government Agencies have constructed many 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 silt up after only a few years. This issue is poorly covered in most small dam design manuals, which mostly focus on civil engineering design and construction aspects. A capability to estimate future siltation rates in small dams is essential to ensure that:

- Dams are not constructed in catchments with excessively high sediment yields;
- Dams are sized correctly;
- Catchments where the rapid introduction of soil and water conservation or other measures will be essential if a reasonable dam life is to be obtained are identified early enough for remedial activities to have a significant impact on dam siltation.

The British Government's Department for International Development (DFID) commissioned HR Wallingford to develop the guidelines presented here[1], which describe appropriate methods for predicting, and where possible reducing, siltation rates in small communal dams in semi-arid zones in Eastern and Southern Africa.

Predicting soil erosion, sediment yields and dam sedimentation rates can be a complex task, requiring specialist expertise. This has resulted in many small dams being constructed with little or no consideration of the impact of future siltation on the dam's life, or the inevitable large reduction in water yields as dams silt up. The guidelines enable the locations where dam siltation rates will be unacceptably large to be identified at the planning stage of small dam projects. If these dams are to be viable, measures have to be taken to reduce sedimentation rates. Methods for making approximate estimates of the impact of remedial measures, such as catchment conservation or engineering interventions on dam lives and water yields, are also described.

A series of technical reports providing more detailed information on the methods used in the guidelines are listed in Chapter 8.[2]

1.2 SEDIMENTATION IN SMALL DAMS

Estimates of the loss of storage in large dams due to sedimentation range from between 0.5% and 1% per annum (Mahmood, 1987; White, 2001). These averages mask wide variations between geographical regions, and also variations observed in dams of different sizes. A trend line fitted to data from the USA, demonstrating a strong inverse relationship between the annual loss of storage and the original dam capacity, is shown in Figure 1.1. The figure also shows annual siltation rates for medium and large dams in

[1] DFID KAR Project R7391.
[2] The reports are included on the CD that is supplied with these guidelines.

Zimbabwe, and for the small dams surveyed to support the development of the guidelines. The trend of increasing annual siltation rates as dams become smaller is evident in Figure 1.1. This is attributed to "sediment delivery" effects, which usually result in increasing catchment sediment yields per km^2 as catchment areas become smaller. Small dams are constructed on small rivers draining small catchments, and thus tend to silt up much more rapidly than major dams located on the main stem of large rivers. Small dams also usually have smaller ratios of storage capacity to annual inflow than larger dams, and this also has a major impact on siltation rates[3].

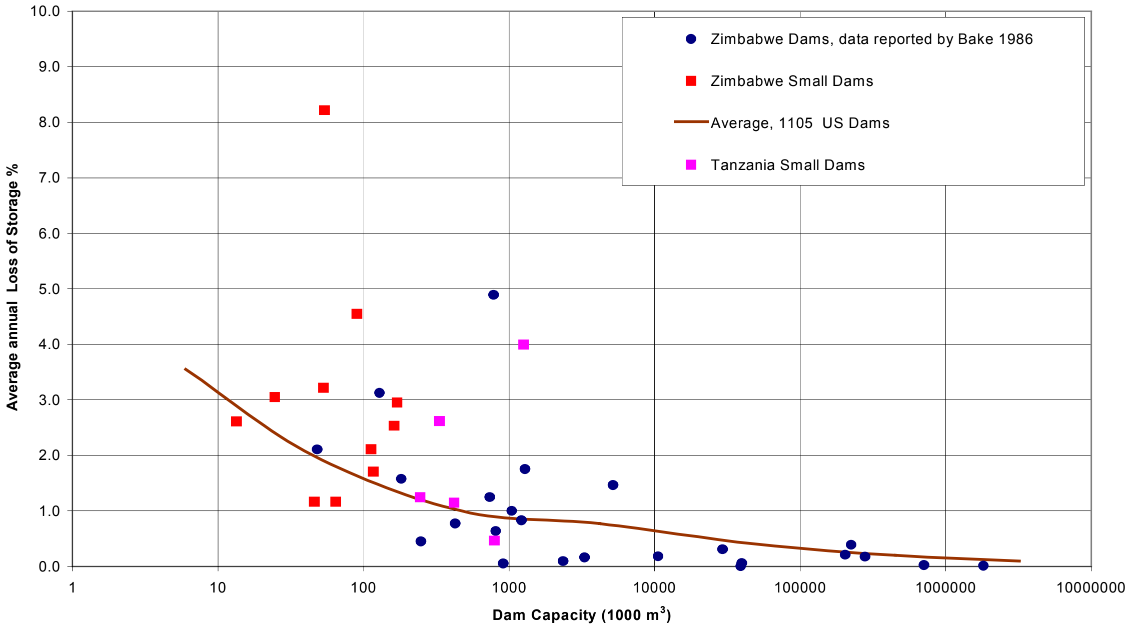

Figure 1.1 Dam size and capacity losses due to sedimentation

Sedimentation rates in the seventeen small dams in Zimbabwe and Tanzania surveyed for this project ranged from 50%/year to 0.5%/year. (The 50% point is excluded from Figure 1.1 to aid clarity.) These sedimentation rates translate to approximate dam sedimentation lifetimes ranging between two and two hundred years. The median sedimentation rate was 2.6%/year, giving a sedimentation lifetime for a "typical " small dam of approximately 38 years. Clearly the useful life of a "typical " small dam would be far shorter than 38 years, due to the proportionately larger evaporative losses that occur as siltation reduces water depths, resulting in an increasingly large proportion of the stored water being lost to evaporation as a dam silts up.

Figure 1.2 illustrates reductions in dry season water yields due to sedimentation, for dams of different initial depths. In each case 50% of the initial storage capacity is assumed to have been lost due to sedimentation. The figure illustrates the large impact that siltation has on water yields in very shallow dams. For example in a 3 metre deep dam, where 50% of the initial storage capacity has been lost, the dry season water yield

[3] A dam that stores all the annual runoff from a catchment will trap all the sediment carried by the runoff water. When the capacity of the dam is much less, say only 10% of the annual runoff, it will still trap about 90% of the incoming annual sediment load. Dams with a low ratio of storage capacity to inflow thus silt up more quickly than dams where the capacity/inflow ratio is larger.

is reduced to only 21% of the initial water yield. These calculations assume that there is no recharge of the dam during the dry season, which is the case for most small dams. Where there is recharge, yield reductions will be less than shown above, and dependent on the recharge rate.

Slightly less than half the small dams surveyed for this project will have sedimentation lives, i.e. the period before they are completely filled with sediment, of forty years or longer. Although small dams are usually designed to have a twenty-year economic life, we adopt forty years as the minimum sedimentation lifetime required to ensure that useful quantities of water can be stored and abstracted towards the end of a dam's twenty-year economic life.

Siltation has a large impact in reducing the benefits obtained from small dams, and must be considered at the site selection and design stage of small dam projects.

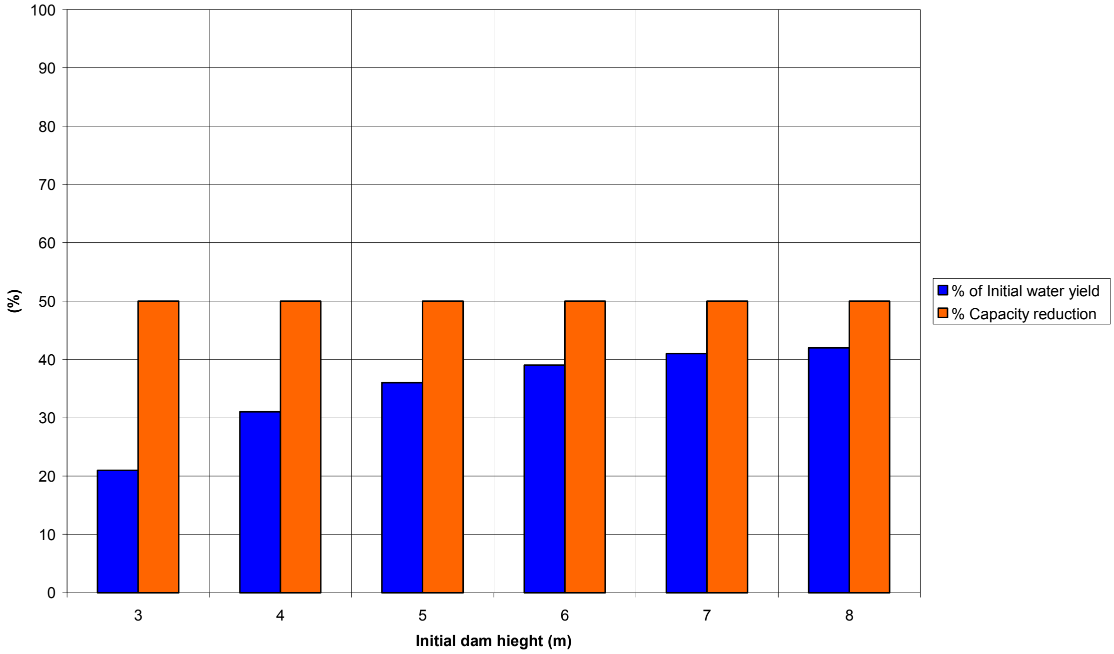

Figure 1.2 Reductions in water yields[4] from typical small dams (with different initial depths) that have lost 50% of their storage capacity due to siltation

1.3 THE GUIDELINES

The Guidelines are intended to supplement, rather than replace, existing local design manuals, which provide advice on methods used to design, construct and maintain small earth dams[5].

[4] Defined here as the dry season water yield, assuming that a dam is full at the onset of the dry season. The results in the figure were derived from dry season drawdown computations made using the software described in Annex 1.
[5] A selection from the large number of small dam design manuals reviewed to support the preparation of the guidelines is listed in chapter 8.

The procedures described have limited data requirements, and are appropriate for use by the technicians and junior engineers who usually design small dams, and who may not have access to computing facilities. They are intended for use in regions where only limited specific local hydrological data are available, and simple approximate methods have to be applied. This is more-or-less the case in most of the countries of the East and Southern Africa south of the Sahara, with the exception of South Africa. The procedure for estimating small catchment sediment yields was developed using data from semi-arid regions in Zimbabwe and Tanzania, and will not necessarily be appropriate in other regions. A procedure for “re-calibrating” the regression relationship used to predict sediment yields for other regions is described in HR Wallingford (2003c). In South Africa the relatively large quantities of data that are available from the large number of surveyed dams have enabled the development of more sophisticated methods for predicting dam sedimentation rates than those described here, see Rooseboom (1992).

The procedure used to determine the sedimentation lifetime of a small dam and to estimate the impact of remedial measures is set out in Figure 1.3. Some basic hydrological information is needed in order to estimate sedimentation rates, and appropriate hydrological procedures are described in the early chapters. Although not related to sedimentation, advice on determining design floods and spillway capacities is included in the final chapter as inadequate spillway capacity is often cited as the most common reason for the failure of small earth dams.

Procedures are presented in the order that they would normally be carried out, although as in any design exercise there will be an element of iteration as designs are adjusted and refined. Some specific examples of the use of the methods are presented at the end of each chapter; more wide ranging examples are presented in Annex 1. While the calculations involved are best carried out using the software supplied with the guidelines (see Annex 1), most of the examples are presented using manual calculations. Aids for users who need to carry out manual calculations are presented in Annex 2.

Guidance is given on the following topics:

- Selecting a dam site;
- Screening for environmental impact and conditions needed to ensure acceptability and sustainability of soil conservation measures.

Procedures are described for quantifying:

- Dam storage capacity at full supply level (m^3);
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- Impact of check dams and soil and water conservation in reducing sediment yields;

- Impact of sediment bypassing arrangements in reducing dam sedimentation rates;
- Design Floods used to specify spillway capacity (m^3/s).

Each chapter contains a summary of existing knowledge, a description of methods, and a short example.

Annex 1 describes the “Excel” software supplied with the guidelines that can carry out most of the computations needed to assess dam siltation rates. Annex 2 presents tables to aid users who need to carry out manual calculations. Annex 3 contains checklists for environmental impacts and for assessing the sustainability of catchment conservation interventions designed to reduce small dam sedimentation rates.

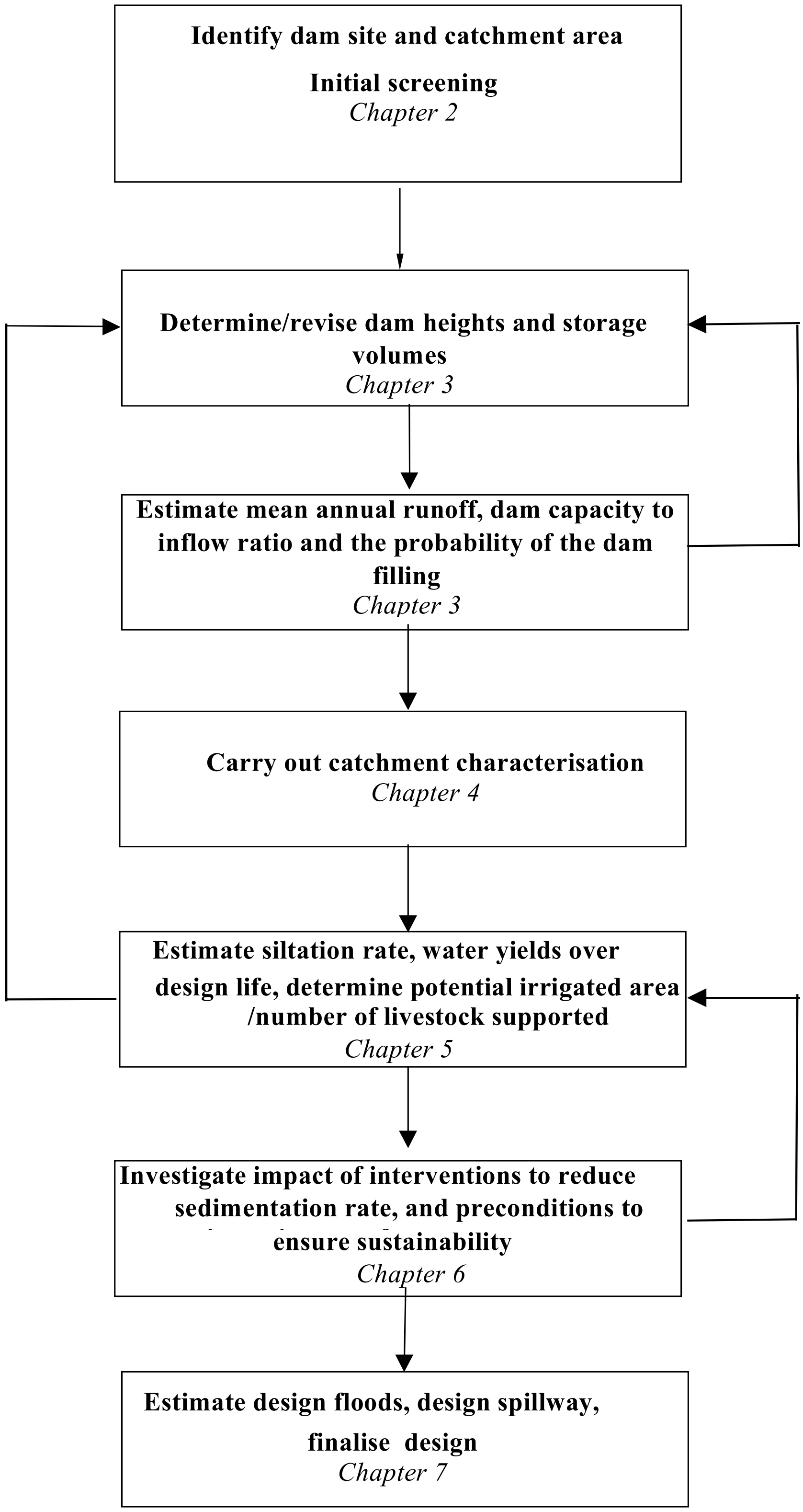

Figure 1.3 Outline procedure used to determine the sedimentation lifetime of a small dam and to estimate the impact of remedial measures

2. Site selection and initial screening of potential dam sites at feasibility stage

2.1 KNOWLEDGE

Specific advice on selecting sites for small dam construction or rehabilitation projects is contained in local design manuals. The summary presented here is mostly concerned with the features of dam sites that affect sedimentation and water yields, and is based on the advice given in manuals from the Ministry of Water Development, Zimbabwe (MOWD) (1977), Watermeyer (1989), Stephens (1991), the Ministry of Water Development, Kenya (1992) and Nelson (1996).

2.1.1 *Communal involvement*

The full involvement in and "ownership" of communal small dam projects by communities is considered to be essential to ensure sustainability. Usually communities appoint one or more dam committees, who will hold regular meetings to:

- Participate in planning the dam;
- Resolve land ownership and compensation issues;
- Organise management of the dam, keep accounts;
- Identify beneficiaries and communal inputs;
- Carry out maintenance and long-term soil and water conservation activities in the catchment.

Small dam projects are not usually implemented without a minimum agreed level of community involvement from the start, including an agreed constitution and bylaws for the group who will take on ownership and management of the dam. Adequate community involvement and support is thus the starting point for selection of dam sites and catchment areas.

Decisions on the location and height of a dam are dependent on technical and cost considerations as well as the preferences of communities, although the latter should be the starting point in selecting sites. Technical constraints, alternative options and cost issues must be carefully explained so that agreement on the location and capacity of the dam, together with any remedial works needed in the catchment to control sedimentation, are agreed at the outset. These issues are central to ensuring the sustainability of small dam projects.

2.1.2 *Selecting a dam site*

Ideally a dam should be located at a narrow section of a river valley located immediately downstream from a wider section, and where the river slope is not too steep. The water volume that can be stored will then be relatively large compared with the volume of earthworks required to construct the dam. The ratio of the volume of stored water to the volume of earthwork required to justify constructing a dam (in economic terms) depends on the value of the stored water compared to the dam construction costs. The Ministry of Water Development (MOWD), Kenya (1992), Guidelines suggest that this ratio should be above 8, and if it is below 5 the dam site should be rejected.

The dam embankment must be founded on suitable material, and preferably on a rock sill or an impervious layer. Locations where sand layers would result in piping should be avoided. In dry sandy areas infiltration losses may be too large for a small dam to be viable. The presence of a rock outcrop that can be used for the spillway is also an important consideration.

2.1.3 Catchment area

The catchment must be large enough to ensure that the annual runoff fills a dam. The manual produced by the Ministry of Water Development (MOWD), Kenya (1992), suggests a lower limit for the catchment area derived by dividing the dam capacity by 10% of the annual rainfall. (Dam capacity in m^3, rainfall in m, gives the minimum catchment area in m^2.) If the runoff coefficient for the catchment is 0.1, a typical value for small, semi-arid catchments, this criterion results in a ratio of dam capacity to annual inflow volume of 1, i.e. the dam would store all of the annual runoff generated in an average year.

A catchment area larger than the minimum area derived using the criteria described above will increase the probability of the dam filling from empty in drier than average years. However there is also an upper limit on catchment areas, particularly in regions with significant sediment yields. Dams in catchments with a large annual runoff in comparison to their storage volume will have rapid siltation rates, and will also require large and costly spillways. A lower limit on the ratio between dam capacity to the annual inflow of 0.1 is recommended for small dams in Zimbabwe (Ministry of Lands and Water Resources, Zimbabwe, 1984). As discussed in Chapter 3, in catchments where significant sediment yields are anticipated dams with a capacity to inflow ratio of less than 0.3 are not recommended.

Ideally the catchments of small dams should be well conserved, and have a low sediment yield, so as to ensure a long life for the dam. This will rarely be the case in semi-arid catchments, where the combination of intense rainfall events, scanty natural vegetation, cycles of overgrazing in drought years, and cultivation of rainfed subsistence crops on steep slopes often results in high rates of soil erosion and large sediment yields.

Catchments with very high sediment yields can be identified fairly easily from the presence of active gullies, or signs of excessive sheet and rill erosion. A history of excessive siltation in dams located in similar catchments nearby also provides a warning of potentially large siltation rates. Dams should not be constructed in such catchments unless the rapid implementation of effective and sustainable soil conservation measures can be guaranteed.

It can be more difficult for non-specialists to identify catchments where sediment yields are large enough to significantly reduce the useful life of a dam, but which do not exhibit the extreme features associated with excessive erosion. Carrying out the procedures described in Chapter 5 and 6 enable the catchment sediment yield and dam siltation rate to be estimated, but these procedures would not necessarily be carried out during the initial site selection stage. If this is the case it is prudent to ensure that the capacity of the dam is larger than about 0.3 times the annual water inflow from the catchment. In highly degraded catchments where a large sediment yield is expected, a larger ratio, at least 0.5, is recommended.

2.1.4 Dam site surveys

Surveys are often carried out in two stages. Initially a reconnaissance survey is carried out to confirm that a site is suitable for a dam. At a minimum this should consist of a cross-section at the dam site, with measurements taken at horizontal intervals not exceeding five metres, and a long section extending up the river, possibly supplemented with two or three intermediate cross-sections. Sections should be extended well above the maximum height of any potential dam. Preliminary surveys provide the information needed to make estimates of the width, height and storage capacity of a dam, and also to locate the spillway. More detailed surveys may be justified later, when a site has been confirmed as being suitable for a dam.

2.1.5 Selecting the dam height and storage capacity

Some design manuals recommend that dam storage capacities are selected on the basis of the anticipated water demand, and describe methods for estimating what this will be. In rural areas in semi-arid zones a small dam will often be the only source of water in the dry season. The potential demand for water is usually far larger than the volumes that could be supplied from a small dam constructed at an economic cost at typical small dam sites. Thus in practice the heights and storage capacities of small dams are mostly set by the topographical conditions at the dam site, the construction costs, and in some cases local regulations concerning the height of dam that can be designed and constructed without supervision from a fully qualified civil engineer.

A narrow deep reservoir will have much lower evaporative losses than a wide shallow reservoir with the same storage volume. Shallow dams should generally be avoided. The Ministry of Water Development, Kenya (1992), manual recommends that dams having water depths less than 3 or 4 metres should not be constructed in semi-arid and arid zones. These guidelines were compiled assuming that small dam heights might range between 3 m and 8 m.

2.2 METHODS – SITE SELECTION AND INITIAL SCREENING

2.2.1 Measuring the catchment area

The dam location and the catchment boundaries are marked on 1:50,000 maps, and using a digitiser, planimeter or a squared transparent overlay sheet, catchment areas are then recorded in km^2.

2.2.2 Annual rainfall runoff and evaporation

Methods for obtaining information on rainfall runoff and evaporation rates are described in the next chapter. For a feasibility study information on rainfall could be taken from a national or regional rainfall map and used with an appropriate runoff coefficient to estimate the annual runoff volume. Regional evaporation data can be used to determine the likely evaporation depth, in mm, over the dry season.

2.2.3 Dam capacity

Dam capacity estimates can be made using the proposed dam depth, dam width and the "throwback" at the full supply level. Throwback is the distance between the dam axis and the upstream limit of the reservoir pool, at the spillway crest elevation. In Chapter 3 the Nelson (1991) equation is recommended to estimate dam capacities, see also HR Wallingford (2003b).

The Nelson equation is:

Capacity (C) = 0.264* D* W*TB (2.1)

Where:

C = Dam capacity (m^3)
D = The maximum water depth, i.e. the difference in elevation between lowest point in the reservoir bed at the dam and the spillway crest level (m)
W = The width of water surface at the dam at the spillway crest level (m)
TB = The "throwback" at the spillway crest level (m)

2.2.4 Volume of earthworks

An equation derived by the Ministry of Agriculture in Zimbabwe and reported as being "reasonably accurate" by Stephens (1991), can be used to estimate the volume of earthworks at the feasibility or site selection stage of small dam projects. The equation is:

V = 0.216* H* L* (2*Cw +H*S) (2.2)

Where:

V = The volume of earthworks (m^3)
H = The dam crest height, i.e. at the full supply depth plus the freeboard (m)
L = The length of the dam at the crest including the spillway (m)
Cw = The crest width (m)
S = The combined upstream and downstream embankment slopes
(For example, if the slopes of the embankment are 2:1 and 1.75:1, S = 3.75)

2.2.5 Dry season evaporative losses and preliminary estimate of water yield

The use of drawdown computations to estimate water yields is described in Chapter 5. At the feasibility stage of a project the proportion of a small dam's storage capacity lost to evaporation over a dry season, assuming water is being evaporated and abstracted for use at a constant rate, can be estimated using Figure 2.1[6], or Table A2.1 in Annex 2. The X ordinate in the figure is the difference between the dam depth (D) and the evaporation depth (E) over the dry season drawdown period, divided by dam depth (D).

[6] Figure 2.1 is derived from "drawdown" simulations carried out using the software described in Annex 1 for geometrically similar small dams with different depths and evaporation rates, over an eight month drawdown period.

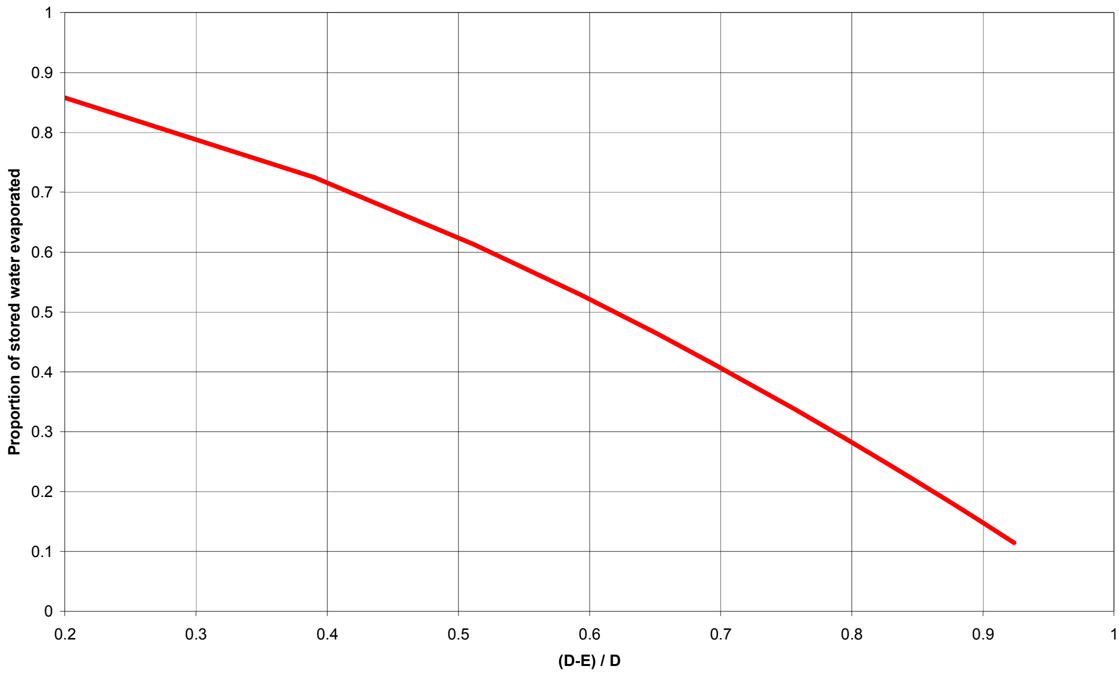

Figure 2.1 Approximate evaporative losses for small dams

2.3 EXAMPLE CALCULATIONS FOR CHAPTER 2

This example demonstrates the use of the criteria and information presented in Chapter 2 to assist in the selection of a dam site.

Example 1

A request for a dam has been received from a community in a semi-arid region who wish to set up an irrigated garden and a cattle watering point close to their village. Communal leaders and the local extension agent have identified two potential dam sites along a small ephemeral river. The farmers would prefer the dam to be located at the downstream site, as this is closer to their village, and is adjacent to a large area of fairly fertile flat land that could be irrigated by gravity. It is known that some small dams in the region have silted up after ten or fifteen years and siltation will be a key issue. Information gathered during a site visit, when a reconnaissance level survey was carried out, and the other available local data are listed in Table 2.1.

Table 2.1 Data used in Example 1

Parameter	Upstream Dam	Downstream dam
Catchment area (km^2)	4.3	9.7
Mean annual rainfall (mm)	650	650
Assumed run of coefficient	0.15	0.15
Annual evaporation (m) (note 1)	2.0	2.0
Outline dam dimensions (note 2)		
Maximum depth (m)	5	3
Length @ full supply level (m)	90.0	124.0
Length @ crest level (m)	112.0	171
River slope	0.01	0.005
Throwback (m)	500.0	600.0
Freeboard (m)	1.0	1.0
Crest width (m)	2.0	2.0
Upstream embankment slope	2:1	2:1
Downstream embankment slope	1.75:1	1.75:1

Note 1 Evaporation over the eight month dry season is estimated to be 1.7 m.
Note 2 Probable maximum dimensions based on the cross-sections at the dam sites.

Annual runoff volume

The dam construction agency assumes a runoff coefficient of 15% for catchments in the region where the dam is to be constructed. For screening purposes the annual runoff volume (ARV, see Chapter 3) is estimated from the product of the rainfall, the assumed runoff coefficient and the catchment area.

For the upstream catchment:

$ARV_{us\ dam} = 0.65 * 0.15 * 4.3 * 10^6 = 419250\ m^3$

Similarly for the downstream catchment:

$ARV_{ds\ dam} = 0.65 * 0.15*9.7*10^6 = 945750\ m^3$

Dam capacity

From equation 2.1:

$\text{Capacity } (C)_{us\ dam} = 0.264 * 5*90*500 = 59400\ m^3$

and

$\text{Capacity } (C)_{ds\ dam} = 0.264 * 3*124*600 = 58925\ m^3$

The dam capacities are virtually identical, although the downstream dam will be shallower and have larger evaporative losses.

Evaporative losses

Using dam depths of 3 and 5 metres, and a dry season evaporative loss of 1.7 m gives the following estimates for the proportion of the stored water that is lost by evaporation over the dry season (Table A2.1 in Annex 2).

$\text{Proportion evaporated}_{us\ dam} = 0.46$

Proportion evaporated $_{ds\ dam}$ = 0.69

Evaporative losses from the shallow downstream dam will be very large. Assuming that there is no recharge from base flows or groundwater a maximum of 31% of the gross water storage capacity can be abstracted from the dam for irrigation or cattle watering, compared with 54% at the upstream site.

Volume of earthworks

Using equation 2.2:

Volume of earthworks $_{us\ dam}$ = 0.216* 6* 112* (2*2 +6*3.75) = 3847 m^3

Volume of earthworks $_{ds\ dam}$ = 0.216* 4* 171* (2*2 +4*3.75) = 2807 m^3

Summary and discussion

The results of the calculations are summarised below:

Table 2.2 Summary of results of calculations for Example 1

Parameter	Upstream dam	Downstream dam
Capacity (m^3)	59400	58924
ARV (inflow, m^3)	419250	945750
Capacity/inflow ratio	0.14	0.06
Volume earthworks (m^3)	3847	2807
Capacity/earthworks volume	15.4	21.0
Proportion of stored water evaporated during dry season	0.46	0.69
Dry season water yield/earthworks volume	8.3	6.5

At both sites the ratio of the storage volume to the volume of earthworks comfortably exceeds the minimum recommended value of 8. As the storage capacity of two dams is very similar the downstream dam is initially more attractive due to the much larger ratio of the storage capacity to the volume of earthworks. This indicates that a downstream dam will be less expensive to construct per m^3 of stored water. However the downstream site would have two important technical deficiencies. The first is that the capacity inflow ratio is below the recommended lower limit of 0.1, and well below the 0.3 recommended for catchments with significant sediment yields. As sediment yields are expected to be appreciable this will be a critical factor in determining the suitability of this location.

The second factor going against the downstream site is that a much larger proportion of the stored water will be lost to evaporation during the dry season. Although the dam capacities are similar, the upstream dam would yield about 50% more water.[7] The ratio of the dry season water yield to the volume of earthwork required to construct a dam, shown in the last row of Table 2, indicates that the upstream dam would be a better choice if the comparison is based on the volume of "usable" water/volume of earthworks.[8]

[7] The useful water yield over the dry season is estimated as the nominal capacity * (1- proportion lost to evaporation).

[8] If the material to construct the dam is taken from the reservoir area then the dam capacity should be increased to account for additional storage created.

Other factors such as foundation conditions, availability of suitable material to construct a dam, arrangements for the spillway, the location of land suitable for an irrigated garden and of course the community's preference for a downstream dam would need to be considered before a choice of site was finalised. From a technical standpoint neither dam is attractive due to the low ratio of storage capacity to water inflow, and ideally an alternative site should be identified that enables a deeper dam with a larger capacity to be constructed.

3. Estimating mean annual runoff, dam capacity to inflow ratio and probability of a dam filling

The first two topics covered in this chapter were discussed in the context of a feasibility level investigation in the preceding chapter. They are covered in more detail here.

3.1 KNOWLEDGE

3.1.1 Mean annual runoff

Estimates derived from long-term river flow gauging data provide the most reliable means of estimating the mean annual runoff from a catchment, but this data will not be available at most small dam sites. Use of tables or maps of unit runoff, which are available in some countries, may provide the next most reliable means of estimating runoff, as they are based on measured runoff data. When neither method can be applied runoff can be estimated using regional empirical equations, where runoff is predicted from the mean annual rainfall.

3.1.2 Dam capacity to inflow ratio

In catchments with significant sediment yields the ratio of a dam's capacity to its annual inflow is the most important parameter affecting the siltation rate. A dam that has the capacity to store all of the annual runoff from a catchment (so that no water passes over the spillway) traps all the sediment carried by the runoff from the catchment. When the capacity of the dam is much less, storing say 10% of the annual runoff, the low water velocities in the dam result in it still trapping about 90% of the incoming annual sediment load. Although approximately the same volumes of sediment settle in either case, dams with low ratio of storage capacity to annual inflow silt up more quickly than dams where the capacity/inflow ratio is larger. For this reason the Ministry of Lands and Water Resources, Zimbabwe (1984), recommends that dams in Zimbabwe with a capacity/inflow ratio of less than 0.1 should not be constructed. In catchments supplying significant sediment loads we recommend that the capacity inflow ratio should be larger than 0.1 to ensure a reasonable dam life. A minimum value of 0.3 is suggested.

3.1.3 Probability of a dam filling

In an average year a dam with a small capacity in relation to its annual inflow obviously has a higher probability of filling than a larger dam in the same catchment. The probability of a dam filling is also related to the variability of annual runoff, measured by the coefficient of variation of annual runoff (the standard deviation divided by the mean) of a long series of annual runoff totals. Variability increases with decreasing rainfall (IHP, 1997), and in semi-arid or arid catchments, where the Cv can exceed 100%, dams with a small capacity inflow ratio are needed to ensure there is a reasonable probability of filling. Formal irrigation systems are usually designed so that they can be supplied with design water volumes in four years out five (80% reliability). The same criteria are sometimes adopted for small dams that are used to support small irrigated gardens.

An indication of the capacity to inflow ratio needed to achieve an 80% probability of a dam filling, and illustrative sedimentation "half lives" are shown in Table 3.1 as a function of the coefficient of variation of annual runoff, for dams located in a catchment with a typical sediment yield.

Table 3.1 Dam capacity inflow ratios and illustrative sedimentation half lives

Cv of annual runoff	80%	100%	120%	140%
Maximum capacity/inflow ratio to achieve 80% probability of filling	0.33	0.22	0.14	0.10
"Half life" (years) of a dam in a catchment with a sediment yield of 330 t/km^2/y	40	27	18	13

Notes: The capacity to inflow ratio needed to achieve an 80% probability of filling was computed using the method described in Mitchell (1987). Half life is the time taken for a dam to lose 50% of its capacity due to sedimentation. 330 t/km^2/y is the median sediment yield from seventeen small dam catchments studied preceding the preparation of these guidelines, see HR Wallingford (2003c). The other assumptions adopted to calculate dam half life are: MAR = 60 mm, settled sediment density = 1.2 t/m^3 and sediment trap efficiencies as predicted by Brune's (1953) relationship.

Table 3.1 illustrates that dams designed with the capacity inflow ratio needed to achieve an 80% reliability of filling will silt up rapidly in catchments with a "typical" sediment yield, and a Coefficient of Variation of annual runoff larger than 120%. In catchments where these conditions apply it would be prudent to size the dam so that it has a larger capacity than indicated in the table, and accept a lower probability of filling during the early years of its life.

The dam half lives shown in Table 3.1 are calculated using the median sediment yield from the catchments of small dams measured in Zimbabwe and Tanzania. More rapid siltation would occur in the 50% of dams with catchment sediment yields larger than the median. As mentioned above, an obvious means of increasing the life of dams, which will have a large sediment input, is to provide a large initial storage capacity, so that sedimentation can occur over the design life of the dam, without compromising the "design" storage capacity.

The proportion of the storage capacity allocated to sedimentation is often called "dead storage". While this is assumed to be the volume below the elevation of the water off-take, considerable volumes of the coarser sediment entering a reservoir settle in the delta that is formed at the head of a reservoir, in the "live" storage zone. This has to be considered when the additional storage capacity that is to be provided by a dam is being determined.

Another strong reason for not constructing "small" dams in "large" catchments is that they will require a large spillway capacity in relation to the size of the dam, and will thus be expensive to construct.

3.2 METHODS

3.2.1 Mean annual runoff

Mean annual runoff (MAR) from a dam catchment is conventionally expressed as an equivalent runoff depth, in mm.

Runoff coefficient

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

$$MAR = ROC * MAP \qquad (3.1)$$

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

This approach is used in many of the simpler 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 not be readily available to most small dam designers.

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 (described in hydrological textbooks), can be applied to interpolate a figure for rainfall at the dam catchment from the data recorded at nearby stations.

Monthly rainfall data are also available for a large number of locations in Africa in the CLIMWAT database (FAO, 1993[9]).

Alternatively, published maps showing rainfall isohets can be used to determine annual rainfall. Interpolation between isohets will usually be necessary to derive a value at the catchment location.

River 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 mean annual runoff (MAR) at the dam site, provided the requirements set out below[10] 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:

[9] 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 (1994), and can be ordered through the FAO Sales and Marketing Group Publications-sales@fao.org. The CLIMWAT data can also be freely downloaded from the FAO-FTP server http://www.fao.org/ag/agl/aglw/climwat.stm.

[10] Procedure as recommended in PEMconsult (1999).

a) Apply an appropriate MAR equation (see later) to estimate the MAR at the dam site (MAR_d).
b) Apply the appropriate MAR equation (see later) to estimate the MAR at the gauged site (MAR_g).
c) Determine the mean annual runoff (mm) at the gauged site (MAR_o).
d) Determine the MAR at the dam site as $MAR_o * MAR_d/MAR_g$.

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. 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 based on stream gauging data, in many cases they will provide the best means of estimating runoff for small dam design. In all cases it is necessary to use judgement to relate the predicted runoff with that observed in similar nearby catchments.

Empirical runoff predictors

Empirical equations relating runoff to mean annual precipitation (rainfall) and evaporation have been developed for large catchments in the Southern African region, see for example IHP (1997). Others are available for more localised regions.

Hill and Kidd's (1980) relationship, cited in PEMconsult (1999), is based on data from 47 catchments in Malawi. It provides a means of estimating the effect of Dambos (swampy areas in a valley bottom) on runoff. The function is:

$$MAR = -92 + 0.16 * MAP + 0.00018 * MAP^{2} - 640 * DAMBO \qquad (3.2)$$

($R^2 = 0.94$ 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 was developed by Bullock *et al*. (1990) and is also reported in PEMconsult (1999). It was developed from a wider data set of one hundred and two catchments in Malawi, Tanzania and Zimbabwe. The function is:

$$MAR = 0.0000467 * MAP^{2.204} \qquad (3.3)$$

($R^2 = 0.54$, se = 247 mm)

PEMconsult recommend that equation 3.2 is used when more than 5% of the catchment is Dambo, and that equation 3.3 is used where the proportion of dambo is less than 5%. Table A2.2 in Annex 2 can be used to determine the runoff depth using either equation.

It is necessary to use judgement to compare the MAR predicted by equations 3.2 and 3.3, with estimates based on local knowledge and experience. Catchments with low slopes, good cover, and deep well-drained soils will in general have a lower runoff than steep catchments with thin, poorly drained soils, rock outcrops, and little cover. About 80% of Bullock *et al*.'s runoff data set, as presented in PEMconsult (1999), lies inside the range, predicted MAR *0.5, to predicted MAR * 2.0. It would be sensible to restrict any ad hoc adjustments to account for extreme catchment conditions to the MAR predicted by the Bullock *et al*. (1990) equation, so that the adjusted MAR lies within this range.

3.2.2 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. It is known that pan data overestimate evaporation rates from larger bodies of open water such as small dams, and, following Linsley *et al*. (1982), using a pan factor of 0.7 is recommended to convert monthly pan evaporation rates to small dam evaporation rates. 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. Evaporative losses have only a small impact on potential abstractions from large (deep) dams, but they are very much more significant in small (shallow) dams, where evaporation can 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.

FAO (1994) gives monthly values of Et_0, a reference evapotranspiration rate, for a wide range of locations in Africa (available in the CLIMWAT database[11]). In the database, data from the nearest station 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 will not be necessary to apply a pan factor if the CLIMWAT Et_0 values are used.

3.2.3 Calculation of runoff volumes

The annual runoff volume (ARV) from a catchment is calculated as the product of the MAR and the catchment area.

$$ARV = MAR * CA * 1000 \tag{3.4}$$

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

3.2.4 Coefficient of variation of annual runoff

Information on this parameter is needed to determine the probability of a dam filling. In some countries, tables or maps are available which give the coefficient of variation of

[11] 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 downloaded from the FAO-FTP server for free.

runoff (Cv). Where these data are not available a value for Cv has to be estimated, and we have used the large "data" set in the Ministry of Lands and Water, Zimbabwe (1984), to correlate the Coefficient of variation of mean annual runoff with MAR. The correlation is shown in Figure 3.1.

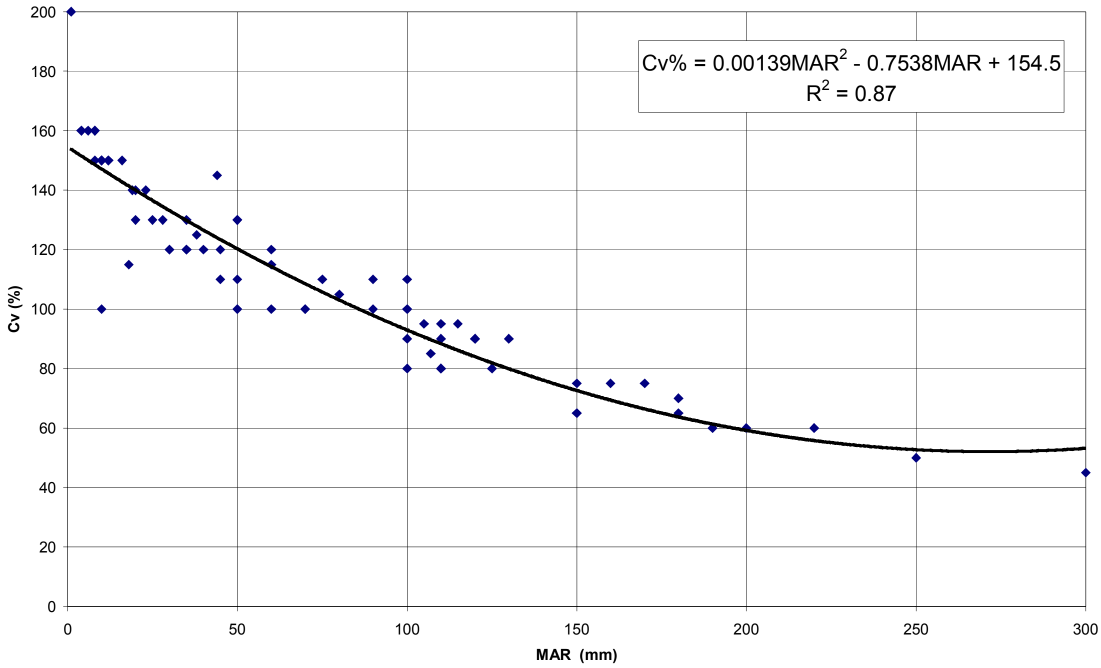

Figure 3.1 Correlation of coefficient of variation of MAR with MAR

Where data are unavailable an estimate of Coefficient of Variation of annual runoff can be made using either Figure 3.1, or the fitted relationship:

$$Cv = 0.00139*MAR^2 - 0.7538*MAR + 154.5 \quad (3.5)$$

Where:
Cv = Coefficient of variation of annual runoff (%)
MAR = Mean annual runoff (mm)

If MAR is estimated using the Bullock *et al*. (1990) equation then the coefficient of variation of annual runoff can be read directly from Table A2.2 in Annex 2.

3.2.5 Probability of a dam filling

The probability of a dam filling can be estimated from the coefficient of variation of annual runoff and the dam capacity to annual inflow ratio, using a procedure 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 that the Wiebul distribution can be used to represent the distribution of annual inflows to a dam:

$$P = e^{-km} \quad (3.6)$$

Where:

P = Probability of a dam filling from empty
km = $(c*V/I)^n$
V = Dam storage volume (m^3)
I = Annual inflow (or ARV, m^3)
c = Constant related to Cv as shown in Table 3.2
n = Constant related to Cv as shown in Table 3.2

Table 3.2 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

The probability of a dam filling is tabulated for a range of capacity inflow ratios and Cv's in Table A2.3 in Annex 2.

3.2.6 Dam storage volume

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 for estimating small dam storage capacities are reviewed in HR Wallingford (2003b), which concludes that Nelson's (1996) equation provides the best results when it is compared with volumes derived from hydrographic surveys.

The equation is:

$$\text{Capacity (C)} = 0.22 * Kn * D * W * TB \qquad (3.7)$$

Where:

Kn = A constant related to the shape of the valley cross-section – taken as 1.2 in these guidelines
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 spillway crest level
TB = The "throwback" at the spillway crest level (the throwback is the distance from the dam along the reservoir axis usually to the point where the river enters)

Depending on the size of the dam, and the organisations involved in design and construction, more detailed surveys may be carried out, as described in the design manuals prepared by the Ministry of Water Development, Kenya (1992), and in Stephens (1991). If a topographical survey has been carried out, a contoured site plan covering the reservoir area can be used to prepare water level/capacity relationship. When a water depth capacity curve is available then the water volume retained in the dam at any water level can be read from the curve.

3.3 EXAMPLES CALCULATIONS FOR CHAPTER 2

The example demonstrates the use of the methods described in Chapter 2 to estimate the mean annual inflow to a dam, the dam storage volume, the capacity inflow ratio and the implications this might have for selecting the principle dimensions of a dam.

Example 2

Further investigations at the location described in Example 1 showed that there is a potential dam site located a short distance upstream from the site originally preferred by the local farmers that will allow a deeper dam to be constructed without resorting to an excessively long embankment. It is decided to proceed with the outline design of a dam at this location. The first task is to estimate the annual inflow of water from the catchment and to determine the dam height and storage capacity. This information, along with estimates of the volume of earthworks required for dams of different heights, is used to choose the dam height and hence the other principal dimensions.

Mean annual rainfall

The catchment is located at approximately the same altitude and about halfway between two meteorological stations with long-term rainfall records. The mean annual rainfall at the dam catchment is estimated to be 636 mm. This has been calculated by averaging the mean annual rainfall totals from the two rainfall stations. The catchment lies close to the 650 mm isohet on a national rainfall map, which indicates that the estimate is reasonable.

Evaporation depth

Locally, the dry season is assumed to have a duration of eight months and the total evaporation depth over the dry season was taken as 1.7 m.

Mean annual runoff (MAR)

There is a river gauging station located on another, larger, river about 35 km from the dam site. The mean annual discharge at the gauging site derived from seventeen years of flow data is 2.44 million m^3. The characteristics of the dam catchment and the gauged catchment are listed below.

Table 3.3 Characteristics of the dam catchment and the gauged catchment

Parameter	Dam catchment	Gauged catchment
Catchment area (CA) (km^2)	7.8	34.5
Mean annual rainfall (MAP) (mm)	636	660

As the catchments are regarded as being physically similar, the criteria listed in Section 3.1.3 are met, and the MAR from the gauged catchment will be used to estimate the MAR at the small dam catchment.

Following the procedure set out in Section 3.2.1:

i. Apply an appropriate MAR equation to estimate the MAR at the dam site (MAR_d).

   From the Bullock *et al*. (1990) equation:

   $MAR_d = 0.0000467 * MAP^{2.204} = 70.5$ mm

ii. Apply the appropriate MAR equation to estimate the MAR at the gauged site (MAR_g).

$MAR_g = 0.0000467*MAP^{2.204} = 76.5$ mm

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

$MAR_o = 2.44 * 10^6/(34.5*10^6) = 0.0707$ m = 70.7 mm

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

$MAR_o = 70.7*70.5/76.5 = 65.2$ mm

Annual runoff volume

Using equation 3.4:

Annual Runoff Volume (ARV) = MAR * CA* 1000 = 65.2*7.8*1000 = 508600 m^3

Coefficient of variation of mean annual runoff

From equation 3.5:

Cv (%) = $(0.00139 * MAR^2) - (0.7538 * MAR) + 154.5 = 111\%$

Dam capacity

In this example a depth/volume curve prepared from a contoured plan of the dam site is available.

The relationship between the depth and capacity is shown in Figure 3.2.

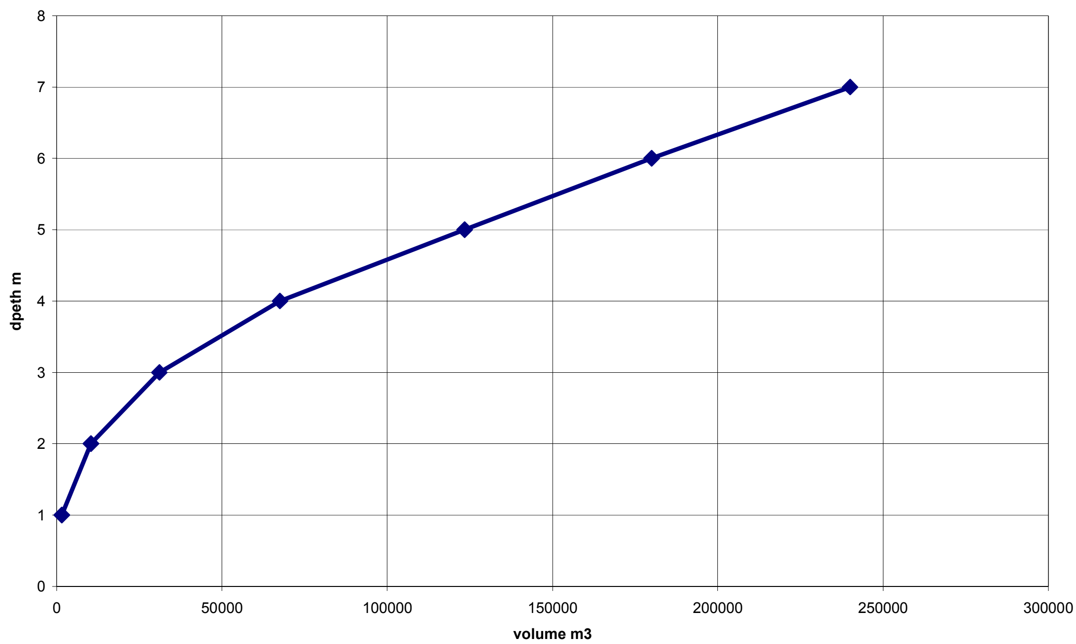

Figure 3.2 Depth capacity curve for Example 2

Table 3.4 below was constructed using Figure 3.2; a cross-section at the dam site (not shown) to determine the embankment lengths; equation 2.2 to estimate the volumes of earthworks; and Table A2.1 in Annex 2 to estimate dry season evaporative losses.

Table 3.4 Water and embankment volumes for Example 2

Full supply depth (m)	Volume (m^3) Note 1	Proportion evaporated in the dry season Note 2	Usable volume (m^3)	Embankment length (m) Note 3	Embankment volume (m^3) Note 4	Usable water volume/ embankment volume
3.0	31070	0.69	9632	66.0	1255	7.7
4.0	67559	0.55	30402	92.0	2633	11.5
5.0	123407	0.46	66640	125.0	5022	13.3
6.0	180000	0.39	109800	172.0	9232	11.9

Note 1 From the data used to prepare Figure 3.2
Note 2 From Table A2.1 in Annex 2
Note 3 From a cross-section at the dam site (not shown)
Note 4 From equation 2.2 with an assumed crest width of 2m, upstream and downstream slopes of 2.5:1 and 2:1, and a freeboard of 1m

Discussion of Example 2

As we would have expected from a significant sediment yield from the catchment, the capacity to annual inflow ratio should ideally be 0.3 or larger. For the annual runoff volume of 508200 m^3 (estimated above) this indicates that we want a storage volume larger than 0.3 * 508200 = 152460 m^3. From Figure 3.2 this corresponds to a full supply depth of about 5.5 m. The most "economic" dam, in terms of the volume of usable water stored per m^3 of embankment, can be seen from the volume ratios shown in the last column of Table 3.4. This indicates that a 5 m dam might be selected as this gives the best ratio of volume of water stored to the volume of earthworks.

A dam with a full supply level of 5 m will have a capacity/inflow ratio of 123407/508200 = 0.24. For the coefficient of variation of 111% estimated earlier, Table A2.3 in Annex 2 indicates a probability of filling of 75%. This is less than the 80%, or 4 years in 5, sometimes adopted as a target value for conventional irrigation systems. This would probably be acceptable as it is customary in the area to retain some water in the dam at the end of the dry season (carry-over) to provide insurance against low rainfall in the following year. As the dam will not be empty at the end of the dry season the probability of its filling will be greater than the 75% estimated above. (These topics are discussed in more detail in the example application presented in Annex 1.)

A dam constructed at this site would be a technically better option than the alternative sites discussed in Example 1, although it would require a larger volume of earthworks. If it were to proceed, the next step would be to follow the procedures outlined in the following chapters to estimate the sedimentation rate, and the impact of measures that might reduce this, before refining and finalising the design.

4. Sediment yield prediction – catchment characterisation

4.1 KNOWLEDGE

Sediment yield from a small dam catchment is determined by rates of soil erosion, and the sediment transport and deposition processes that control the delivery of eroded sediment via the fluvial system to the catchment outlet. The characteristics of the catchment, including soil types, land use, rainfall distribution and intensity, and conservation activities all affect sediment yields, which in semi-arid regions vary widely from year to year.

Sediment yield data from some catchments in East and Southern Africa are plotted as a function of catchment area in Figure 4.1.

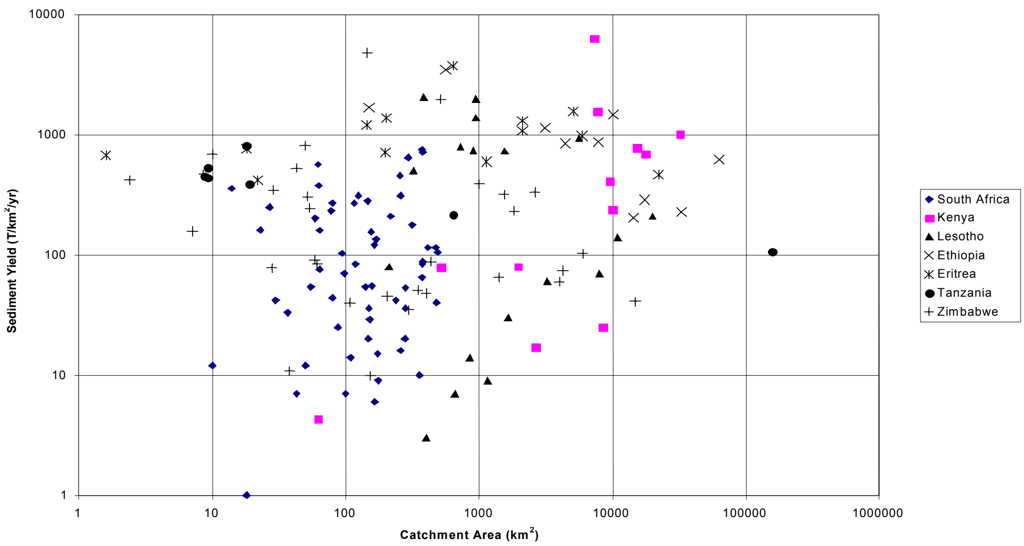

Figure 4.1 Sediment yield data for East and Southern Africa

Virtually all the data in Figure 4.1 are for catchments with areas that are orders of magnitude larger than the catchments of typical small dams. As sediment yields expressed on a per unit area basis tend to increase as catchment areas become smaller, many of the existing data are not directly applicable to small dam catchments without adjustment to reflect the effects of catchment size.

With this qualification in mind it is clear that a procedure to estimate sediment yields from small dam catchments has to be capable of predicting a very wide range of sediment yields, from less than ten t/km^2/y to many thousand t/km^2/y. Precise predictions of future sediment yields will not be possible due to the high inter-annual variability of rainfall and the resulting large variations in sediment yields between years, the low accuracy of available methods for predicting soil erosion and sediment delivery, and the impact of future changes in the catchment condition. Fortunately, precise predictions are not essential, and quite large inaccuracies in predicted sediment yields will be acceptable, provided the prediction procedure allows dams that will have a very short lifetime to be identified rapidly at the design stage of projects. The objective is to apply simple methods, with small data requirements, that will distinguish between dams that will silt up rapidly from dams that will have an acceptably long sedimentation lifetime.

The development of a procedure to carry out this task is described in HR Wallingford (2003c). It is based on an empirical sediment yield predictor that combines quantitative information on the catchment area, annual rainfall and slope, with qualitative factors describing soils, vegetative cover, and evidence of accelerated erosion. The qualitative factors are scored in a rapid catchment characterisation exercise. The method is based on data collected from catchments in Zimbabwe and Northern Tanzania, and the predictions derived using the procedure may need to be adjusted for other regions with very different catchment characteristics. This is discussed further in HR Wallingford (2003c).

A simpler and potentially far less reliable method can be used in cases where it has not been possible to carry out a catchment characterisation. It is based on a procedure for dams in Zimbabwe described in Kabell (1984), which links simple descriptions of a catchment with a representative sediment concentration.

4.2 METHODS

4.2.1 Catchment characterisation

The essential tools needed to carry out a catchment characterisation are 1:50 000 topographic map(s) covering the catchment area, and a compass. As it can be very difficult to locate positions in relatively flat featureless catchments, particularly under scrub or woodland, a hand held GPS (global positioning satellite equipment) is also very useful, as are up-to-date aerial photographs of the catchment, preferably at a scale of about 1:25 000.

Before going into the field, the proposed (or actual) dam site and the physical catchment boundary should be marked accurately on the 1:50 000 topographic map. Where the topography is very flat it can sometimes be difficult to define the catchment boundaries from maps, and it may be necessary to confirm the location of the catchment boundaries during the field visit. If the catchment is larger than about 30 km^2 it should be subdivided into two or three sub-catchments, which should be characterised separately. Where there is a wide range in relief, soil type and/or land use, it may also be useful to subdivide smaller catchments.

Ideally a local officer and/or farmer who knows the location and direction of the footpaths should accompany the person(s) making the assessment. Characterisation is based on information collected partly from interviewing local residents who are familiar with the catchment, and partly on observations made while walking a number of randomly chosen transects across the catchment. The direction and siting of the transects can be chosen by careful study of the 1:50 000 topographic map. Transects may follow footpaths and tracks where they cross the catchment (running down from the upper slopes down to the watercourses and up the other side). At times, where there are no suitable footpaths, it will be necessary to walk on a bearing. It is also important to walk along random sections of the main watercourses to examine the condition of the riverbanks and riverbeds.

With practice, it is possible to assess the catchment characteristics at a rate of about 1.5 km^2/hour, and to characterise a catchment smaller than 10 km^2 within a day's work. If there are roads or motorable tracks across the catchment, these may be used to speed up the work rate, but to avoid missing key characteristics some of the transects must be walked. Catchments with relatively flat relief and uniform land use and soil type may take much less time to characterise (perhaps 20-30 km^2/day). Taking observations from the top of nearby hills as well as interviewing local residents on catchment conditions and characteristics can be very fruitful in improving both work rates and the accuracy of the resulting catchment characterisation.

Results are recorded using the form shown in Table 4.1, selecting the most appropriate factor in each column on the basis of text descriptions, and circling the number indicated. The factors that are scored are:

Soil Type and Drainage

Although the assessment should be carried out at the driest time of the year, soil drainage can be gauged by noting soil surface texture (coarse, medium or fine) together with information from local farmers as to whether there is extensive ponding on the soil surface after heavy rains.

Vegetation Cover over the Whole Catchment

The extent of annual cropping and the nature and quality of the grassland and any woodland/forests in the catchment should be assessed separately. For example, although less than 20% of a catchment may be cultivated with annual crops, at the same time less than 30% may be under good grass or protected forest cover giving only fair cover. There are thus two rows for carrying out this assessment on the form (Table 4.1).

Signs of Active Soil Erosion

Obvious signs of active erosion should be recorded, particularly the presence or absence of actively eroding gullies draining directly into the dam and/or watercourses, and/or active undercutting of riverbanks along the main watercourses.

Factors may be averaged between two columns where more than one description applies to significant proportions of the area being characterised. If the catchment has been subdivided into sub-catchments, the individual factors are averaged after weighting each factor by the proportion of the catchment that it represents. (An example of this procedure is given in Annex 1.)

Assessments are best carried out at the end of the main dry season. The vegetation cover is then at its lowest, with the soils exposed. It is under these conditions that soils are most prone to erosion during intensive storms in the early part of the rainy season.

Table 4.1 Catchment characterisation form

Factor	Extreme	Score	High	Score	Normal	Score	Low	Score
Soil Type & Drainage	No effective soil cover; either rock or thin shallow soils	40	Poorly drained compacted soils; much ponding on soil surface after heavy rains	30	Moderately well drained medium-textured soils; some ponding on soil surface after heavy rain	20	Well drained coarse-textured soils; little ponding on soil surface after heavy rain	10
Vegetation Condition over Whole Catchment	Little effective plant cover, ground bare or very sparse cover over 80% of catchment	40	Fair cover: >50% of catchment is cultivated with annual crops	15	Good cover: 20-50% of catchment is cultivated with annual crops	10	Excellent cover: <20% of catchment is cultivated with annual crops	5
			<30% of catchment is under good grass cover or protected forest cover	15	30-60% of catchment is under good grassland or protected forest cover	10	>60% of catchment is under well-maintained grassland and/or protected forest cover	5
Signs of Active Soil Erosion	Many actively eroding gullies (dongas) draining directly into dam and/or watercourses; active undercutting of riverbanks along main watercourses	40	Some actively eroding gullies (dongas) draining directly into dam and/or watercourses; moderate undercutting of riverbanks along main watercourses	20	Few actively eroding gullies (dongas) draining directly into dam and/or watercourses; little undercutting of riverbanks along main watercourses	10	No actively eroding gullies (dongas) draining directly into dam and/or watercourses; no undercutting of riverbanks along main watercourses	5

4.2.2 Estimating the sediment yield

Scores for soil type and drainage, erosion status and vegetation cover will be available if the characterisation procedure has been carried out. The scores are used with data describing the slope of the main stem river, the catchment area, and the annual rainfall. From this information the sediment yield can be predicted, using an empirical function developed from small dam catchment and sedimentation data. The methods used to obtain the catchment annual rainfall and area were described in Chapter 3.

The slope of the main stem river is obtained from 1:50 000 maps. The elevation difference between the catchment boundary and the river bed at the dam location is divided by the distance, measured along the main stem river, from the catchment boundary to the dam site.

The sediment yield is estimated using equation 4.1 directly, or by using tables A 2.4 to A2.7 in Annex 2 to evaluate the individual terms.

$$S_y = 0.0194 * \text{Area}^{-0.2} * \text{MAP}^{.7} * \text{Slope}^{0.3} * \text{SASE}^{1.2} * \text{STD}^{0.7} * \text{VC}^{0.5} \quad (4.1)$$

Where:
S_y = Sediment yield (t/km^2/year)
Area = Catchment area (km^2)
MAP = Mean annual precipitation (mm)
Slope = River slope from the catchment boundary to the dam
SASE = Signs of active soil erosion (Score from catchment characterisation)
STD = Soil type and drainage (Score from catchment characterisation)
VC = Vegetation condition (Score from catchment characterisation)

The development of this equation is described in HR Wallingford (2003c).

A simpler and less reliable procedure can be used in cases where it has not been possible to carry out a catchment characterisation. The description which best fits the catchment being considered is selected from Table 4.2 below, and the sediment yield is calculated from the representative sediment concentration associated with the catchment description. Where a catchment seems to fall between two descriptions the sediment concentrations can be averaged, giving a range of seven possible mean annual sediment concentrations in the flows leaving the catchment.

Table 4.2 Catchment types and mean annual sediment concentration (ppm)

Catchment description	Mean annual sediment concentration in the runoff from the catchment (ppm)
Basins with low slopes and very well developed conservation	1200
Basins with moderate topography and well developed conservation	3600
Basins with steeper slopes and prone to erosion through poor conservation	10800
Basins with very steep slopes, poor conservation, and soils that are highly susceptible to erosion	32400

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. The catchment characterisation procedure should be used wherever possible as it accounts for more of the parameters that influence sediment yields than the above.

Sediment yield is calculated from the tabulated sediment concentrations using equation 4.2 below:

$$S_y = X * MAR / 1000 \tag{4.2}$$

Where:
S_y = Catchment sediment yield (t/km^2/y)
X = Mean annual sediment concentration from Table 4.2 (ppm)
MAR = Mean annual runoff (mm)

4.3 EXAMPLE FOR CHAPTER 4

Example 3

This example is based on a characterisation carried out for a fairly small catchment of a dam rehabilitated as part of a programme carried out by CARE Zimbabwe. (Characterisation of a larger and more varied catchment, after splitting into sub-catchments, is illustrated in Annex 1.)

The catchment is described in the field notes below, prepared by the local officers carrying out the assessment.

Field notes - Gari Dam Zimbabwe

Map Sheet:	2030 D3
Air Photos (1985):	Available
Map reference:	TN 603000
Slopes:	Rolling to gently sloping land (5-10%) with steeply sloping rocky hills covered by open woodland (mostly in relatively good condition)
Soils & Land Use:	Approximately 60% arable with some “new” fields opened on steeply sloping land immediately below rocky hills with no conservation measures like terracing or bunds
Erosion Hazard:	Moderate (high on newly opened lands)
Information/Observations:	70 farm families reported to live in physical catchment
Conclusions:	Need to control any encroachment of cultivation onto steeper slopes

The results of the characterisation exercise were recorded as shown in Table 4.3a, where the scores for each factor are highlighted in **bold.** The other information needed to calculate the sediment yield is shown in Table 4.3b.

Table 4.3a Gari Catchment characterisation form

Dam Site: Gari Date: 11 Dec 2000 Observer: Mahachi/Gutu

Factor	Extreme		High		Normal		Low	
Soil Type & Drainage	No effective soil cover; either rock or thin shallow soils	40	Poorly drained compacted soils; much ponding on soil surface after heavy rains	30	Moderately well drained medium-textured soils; some ponding on soil surface after heavy rain	**20**	Well drained coarse-textured soils; little ponding on soil surface after heavy rain	10
Vegetation Condition over Whole Catchment	Little effective plant cover, ground bare or very sparse cover over 80% of catchment	40	Fair cover: >50% of catchment is cultivated with annual crops;	**15**	Good cover: 20-50% of catchment is cultivated with annual crops;	10	Excellent cover: <20% of catchment is cultivated with annual crops;	5
			<30% of catchment is under good grass cover or protected forest cover	**15**	30-60% of catchment is under good grassland or protected forest cover	10	>60% of catchment is under well-maintained grassland and/or protected forest cover	5
Signs of Active Soil Erosion	Many actively eroding gullies (dongas) draining directly into dam and/or watercourses; active undercutting of riverbanks along main watercourses	40	Some actively eroding gullies (dongas) draining directly into dam and/or watercourses; moderate undercutting of riverbanks along main watercourses	20	Few actively eroding gullies (dongas) draining directly into dam and/or watercourses; little undercutting of riverbanks along main watercourses	**10**	No actively eroding gullies (dongas) draining directly into dam and/or watercourses; no undercutting of riverbanks along main watercourses	5

Table 4.3b Summary of catchment characteristics

Parameter	Value	Note
Area (km^2)	3.5	From 1:50 000 mapping
MAP (mm)	568	From interpolation between isohets on rainfall map
MAR (mm)	30	From published tables
Slope	0.051	From 1:50 000 mapping
SASE (score)	10	From catchment characterisation
STD (score)	20	From catchment characterisation
VC (score)	30	From catchment characterisation

The sediment yield is estimated using the information in Table 4.3b with equation 4.1, or using tables A2.4 to A2.7 in Annex 2.

$$S_y = 0.0194 * \text{Area}^{-0.2} * \text{MAP}^{0.7} * \text{Slope}^{0.3} * \text{SASE}^{1.2} * \text{STD}^{0.7} * \text{VC}^{0.5} \qquad (4.1)$$

$S_y = 370$ t/km^2/year

If the characterisation had not been carried out the sediment yield could have been estimated using the simpler but less reliable method based on Table 4.2. The description that best fits the catchment lies somewhere between “Basins with moderate topography and well developed conservation” and “Basins with steeper slopes and prone to erosion through poor conservation”. In this case the representative sediment concentration is taken as the mean of 3600 ppm and 10800 ppm, i.e. 7200 ppm. From equation 4.2 the sediment yield is:

$S_y = X * \text{MAR} / 1000 = 216$ t/km^2/year

Discussion of Example 3

The sediment yield estimates provided by the two methods are of a similar order of magnitude, and the difference between them is to be expected given the large uncertainties associated with both methods of estimation. Sediment yields predicted using equation 4.1 were generally within a range of 0.5 time to 2 times the observed sediment yields, in a comparison with the sediment yield data used to develop the equation. This should be borne in mind when comparing estimates of dam siltation rates made using these methods.

The example uses data recorded at the Gari small dam catchment in Zimbabwe, where the sediment yield was measured from surveyed sediment accumulations in the dam over three years. The measured sediment yield was 243 t/km^2/y.

5. Estimating siltation rates, water yields, potential irrigated areas and number of livestock supported

5.1 KNOWLEDGE

5.1.1 Capacity losses due to siltation

The proportion of the incoming sediment load that is trapped in a dam varies with the sizes of the sediments transported to the dam, the water velocities or retention time in the dam, and the proportion of the incoming flows that is passed over the spillway. The interrelationship between these parameters is too complex to be considered in the design of small dams, and in these guidelines sediment trapping efficiencies are estimated using a well established empirical relationship developed in the 1950's from American data (Brune, 1953). This predicts the annual sediment trapping efficiency of a dam from the ratio of the dam capacity to the annual inflow. Sediment trapping efficiencies for a range of capacity to inflow ratios are shown in Table 5.1 below.

Table 5.1 Sediment trapping efficiency

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

For the range of practical interest, capacity to inflow ratios are between 0.1 and 1.0, the trapping efficiency varies between 90% and 100%. Thus virtually all the sediment entering a small dam will be trapped in it.

In order to convert the mass of sediment settling in a dam to a volume, a representative density for settled sediment is needed. In the guidelines, sediment deposition calculations are carried out over twenty years, and the sediment deposits are thus relatively young and unconsolidated. A fairly conservative value of 1.2 t/m^3 is adopted.

The loss in a dam's storage volume over time is calculated from the product of the annual sediment yield, the number of years being considered, the catchment area, the dam's sediment trap efficiency and the density of the settled sediment.

5.1.2 Water yields, potential irrigated area and number of livestock that can be supported

These calculations are carried out using the "Drawdown" software supplied with the guidelines and described in Annex 1.

The calculation assumes that a small dam's storage capacity will be determined by the topography at potential dam sites and in some cases by the available budget. The dam capacity is thus an input to water yield calculations. Water yields are estimated by carrying out calculations to determine the water yield that will be obtained from a dam over the critical dry season period. This is considered to be a more realistic approach than the methods adopted for larger dams, where the dam capacity is an output from complex calculation procedures reliant on long term river flow statistics, to determine the dam capacity needed to meet a specified water yield with a specified reliability of supply.

As the capacity of small dams is usually significantly smaller than the annual water inflow, dams will normally be full at the start of the dry season. The dam is then emptied (drawn down) by evaporative losses and abstractions over the following dry season, when it is assumed that there is no recharge. 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 water level and the volume of water stored in the dam[12]. An iterative procedure is used to determine the total abstraction, following a specified monthly abstraction pattern, which will draw the dam down to a specified depth, or to a specified percentage of the gross capacity, at the end of the drawdown period. The computations can be started from any required depth or percentage of the gross capacity[13].

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, variations that can have a significant impact on the water yield. A larger water yield is obtained from a dam if the stored water is abstracted early in the dry season, before it is evaporated.

The size of irrigated garden or numbers of livestock that can be supported is then estimated from the dry season water yield, on the basis of water requirements per ha for irrigation of basins or raised beds, or per day per livestock unit. The proportion of the abstracted water allocated between irrigation and cattle watering also has to be specified.

It is implicitly assumed that in a year with average water inflow, abstractions 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 of obtaining the estimated water yield, is calculated separately, as described in Chapter 3.

5.1.3 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.

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[12] In the software supplied with the guidelines the Nelson (1986) relationship is used to compute storage volumes from the water levels.
[13] 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).

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 using numerical modelling, which is not feasible in small dam design studies. To enable estimates to be made 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 average proportions of fine and coarse sediments settling in sixteen Zimbabwean dams, as reported by Interconsult (1985).

Deposition of coarse sediments is simulated assuming that coarse sediments settling 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 capacity loss, due to the deposition of the fine sediment fraction, 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 50% of the total capacity loss (see Figure 5.1).

Water yield reductions derived using these assumptions 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 shallow dams.

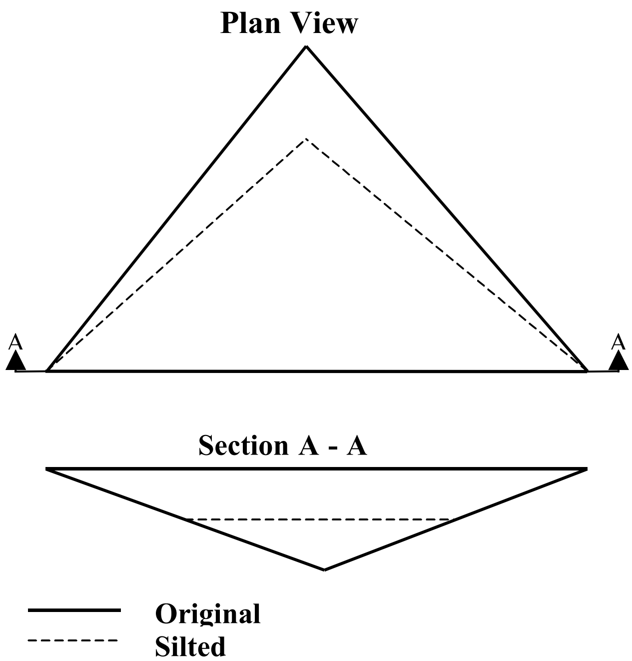

Figure 5.1 Assumed sediment distribution in a silted dam

5.2 METHODS

5.2.1 Estimating dam capacity reductions

The loss in a dam's storage capacity over a specified time period is estimated using equation 5.1 below:

$$C_n = 1- [n * S_y * CA * TE /(C * Den)] \tag{5.1}$$

Where:
C_n = Proportion of original storage capacity left after n years of siltation
n = Number of years
S_y = Catchment sediment yield ($t/km^2/y$)
CA = Catchment area (km^2)
TE = Sediment trap efficiency
C = Dam's original capacity at full supply level (m^3)
Den = The settled density of dam sediment deposits (taken as 1.2 t/m^3)

A value for the catchment sediment yield is obtained using one of the methods described in Chapter 4. An estimate for sediment trap efficiency can be obtained from Table 5.1.

5.2.2 Estimating water yields before siltation

Drawdown computations are carried out using the software supplied with the guidelines and described in Annex 1. The calculations involved are generally too time-consuming to calculate manually. The simple, approximate method based on Table A2.1 in Annex 2 can be used if manual calculations are needed.

Using Drawdown software

The procedure is:

a) Use rainfall or stream flow data to determine the months that are to be classified as forming "dry" and "wet" seasons. The wet season is considered to be the period when substantial river flows occur and the dam is filled. (In locations where two wet seasons occur in a year simulations would be carried out for the main wet season.)

b) Assemble monthly evaporation data following the recommendations of Section 3.2.2.

c) Follow the instructions given in Annex 1 and use the drawdown software to determine the water yield, potential irrigated area and number of livestock that can be supported for one or more scenarios.

Manual calculation

a) Determine which months are to be classified as forming the wet and dry season, as in (a) above.

b) Assemble monthly evaporation data following the recommendations of Section 3.2.2, and calculate the total evaporation depth for the months representing the dry season.

c) Use Table A2.1 in Annex 2 to estimate the proportion of a dam's storage that is lost to evaporation, P_{e0}.

d) Calculate the useful dry season water yield, Y_0, as:

$$Y_0 = C * (1- P_{e0}) \tag{5.2}$$

Where:
Y_0 = Dry season water yield in year "0" (m^3)
C = Dam's original capacity at full supply level (m^3)
P_{e0} = Proportion of dam's capacity lost by evaporation

(Note: If the dry season is shorter than eight months adjust the proportion lost to evaporation by the ratio (dry season months/8).)

e) Use figures for dry season irrigation demand (m^3/ha) or livestock consumption (m^3/Livestock unit) to estimate the potential irrigated area and/or the number of livestock that could be supported.

5.2.3 Estimating the impact of siltation on dry season water yield

This calculation should be carried out using the drawdown software. Users who do not have access to a computer can obtain a very approximate indication of the impact of siltation on water yields from Figure 1.2 in Chapter 1, which assumes that 50 % of the storage capacity has been lost by siltation.

5.3 EXAMPLE FOR CHAPTER 5

Example 4

A small communal dam in Zimbabwe is to be rehabilitated. What impact will siltation have on the life of the dam?

The community wishes to use the dam to irrigate a small garden, and also to store water at the end of the dry season to provide some insurance against poor rains in the following wet season. The local recommendation is that dams "carry over" 30 % of the dam's storage capacity. What impact will the proportion of the storage capacity allocated to "carry over" have on the area that can be irrigated in years with average rainfall?

The dam and catchment used for this example is the same as that used for Example 3. Information on the characteristics of the catchment is listed in Table 5.2:

Table 5.2 Data for Example 4

Catchment Area (km²)	3.5	From 1:50 000 mapping
MAR (mm)	30	From published tables
Annual runoff volume (m^3)	105000	
Sediment yield ($t/km^2/year$)	370	Estimated in Example 3
Dam depth (m)	5.9	From survey
Dam width (m)	168	From survey
Dam throwback (m)	272	From survey
Dam Volume (m^3)	71176	From equation 2.1
Capacity inflow ratio	0.68	
Coefficient of variation of runoff (%)	133	From equation 3.5
Dry season	April to November	
Evaporation depth over the dry season (m)	0.98	From Climwat data base

Manual calculations are demonstrated for the first part of this example. All the calculations can be carried out rapidly and simply using the drawdown software, as described in Annex 1, and use of the software is recommended wherever possible.

Step 1: Estimate the annual sediment trapping efficiency of the dam

From equation 3.4 the Annual runoff volume is:

$$ARV = MAR * CA * 1000 \quad (3.4)$$

$$ARV = 3.5 * 30 * 1000 = 105000 \text{ m}^3$$

The Capacity/Inflow ratio is:

71176/105000 = 0.68

From Table 5.1 the sediment trapping efficiency will be 0.99.

Step 2: Estimate the proportion of the dam capacity lost over twenty years

From equation 5.1 the proportion of the dam's original capacity that remains after 20 years of siltation is:

$$C_n = 1- [n * S_y * CA * TE /(C * Den)] \quad (5.1)$$

$$C_n = 1- [20 * 370 * 3.5 *0.99/(71176 *1.2)] = 0.70$$

Thus it is predicted that the dam will lose 30% of its storage capacity over twenty years. The reduction in water yield over the same period is expected to be larger than 30 %, due to the reduction in the dam's depth and the greater proportion of the stored water that is lost to evaporation.

Step 3: Estimate the dry season water yield of the dam before siltation

The dam depth is 5.9 m and the evaporation depth over the dry season is 0.98 m. Interpolating in Table A2.1 (Annex 2) the proportion of a dams storage that is lost to evaporation, P_{e0} = 0.25.

The dry season water yield is:

$$Y_0 = C * (1- P_{e0}) = 71176 * (1-0.25) = 53382 \text{ m}^3$$

Step 4: Estimate the dry season water yield of the dam after siltation

This calculation should be carried out using the drawdown software. For this case the predicted reduction in water yield after siltation is 42% compared with a capacity loss of 30.3 %.

Step 5: Estimate the effect of carry-over storage

The impact of carry-over storage on the water yields is investigated using drawdown simulations, as manual computations would require many iterations, and are too complex to be used routinely as part of a small dam design study. For this example the results of drawdown simulations are quoted which have varying evaporation and water abstraction rates through the dry season. (Use of the software is explained in Annex 1.) Selected results for computations where the dam is drawn down to 0%, 10%, 20% and 30% of its original storage capacity are shown in Table 5.3 below.

Table 5.3 Dry season water balance, potential irrigated areas and probability of the dam filling for a range of carry-over volumes

Carry-over (%)	0%	10%	20%	30%
Volume Evaporated (m^3)	20343	22328	24111	25764
Volume Abstracted (m^3)	50833	41730	32829	24059
Initial Volume (m^3)	71176	71176	71176	71176
Final Volume, end of dry season (m^3)	0	7118	14235	21353
Potential Irrigated Area (ha)	5.1	4.2	3.3	2.4
Probability of the dam filling with the specified carry-over (%)	44.5	47.6	51.0	54.6

As the carry-over storage is increased the volume that can be abstracted reduces, while the volumes of water evaporated increase slightly[14]. The potential irrigated area is proportional to the volume of water abstracted from the dam, calculated in this case assuming an irrigation duty of 10,000 m^3/ha.

Discussion of Example 4

Sedimentation is predicted to have a relatively large impact on this dam, in spite of its relatively large initial depth, and for a small dam, a relatively large capacity to inflow ratio. The catchment sediment yield is significant, but not excessive when compared with the African catchment data shown earlier in Figure 4.1. The potential for reducing sedimentation through the introduction of better conservation in the catchment would need to be investigated with the community and local soil conservation officers if the sedimentation rate in the dam is to be reduced.

There is clearly an important trade-off between the carry-over volume and the area that can be irrigated. With a 30 % carry-over it looks as though an irrigated garden with a gross area of about 2.4 ha could be supported, but this is only part of the story. With a 30% carry-over the probability of filling the dam is predicted to be only about 55%, i.e. the dam would be expected to fill only about one year in two. (Table A2.3 in Annex 2 indicates that the capacity to inflow ratio of the dam would need to be reduced to about 0.1 to achieve an 80 % reliability of filling.)

A designer could recommend that a smaller area than 2.4 ha was developed for irrigation, to ensure that the full area could be irrigated four years out of five. On the

[14] The volume of water evaporated increases with increasing carry-over storage as the water surface is maintained at higher levels, and has a larger surface area.

other hand it might be better to develop the 2.4 ha area for irrigation, on the understanding that it would not be possible to irrigate the full area every year. The farmers would need to decide on the area that could be planted each year on the basis of the volume of water stored in the dam at the end of the wet season.

If livestock watering is important, then an indication of the number of livestock that could be supported by a dam can be obtained by dividing the proportion of the abstracted water that is allocated to livestock by the daily consumption per livestock unit. In reality the numbers of livestock watered by a dam will vary enormously thorough seasons, and between years, in response to variations in rainfall, grazing conditions and stocking levels. In drought years the presence of a dam may greatly increase the numbers of livestock using a dam.

6. Measures to reduce siltation rates

6.1 KNOWLEDGE

The two most important parameters controlling siltation rates in small dams are the sediment yield from the dam catchment and the proportion of the annual runoff from the catchment that is stored in a dam. The second factor is to some extent under the control of the designer through selection of the dam location and its storage capacity. In situations where dams with very low capacity inflow ratio are unavoidable, siltation rates could in theory be reduced by introducing a water and sediment bypassing arrangement.

Sediment yields from catchments can be reduced over the medium to long term by the introduction of soil conservation measures. To be sustainable, conservation interventions need to be developed using participatory methodologies and be attractive to catchment users by providing immediate and substantial benefits.

6.1.1 Provision of storage for sediment

This was discussed in Chapter 3. In summary, annual runoff from catchments in semi-arid zones varies widely between years. Because of this small dams may be designed with a small capacity when compared to the inflow in an average year, to ensure that they will fill in relatively dry years. This has a large impact on the rate at which a dam fills with sediment. Table 3.1 in Chapter 3 shows that dams constructed in catchments with significant sediment yields (and which have the small capacity needed to ensure an 80% probability of filling) will have a short useful life. An obvious means of increasing the life of such dams is to provide a larger initial storage volume, so that a dam has the capacity to absorb the sedimentation expected over its design life.

The storage volume below the elevation of the water outlet in a dam is often termed dead storage. It is often assumed that dead storage provides the capacity to cope with future sedimentation, but in reality a significant proportion of sediment deposition occurs in "live" storage, above the level of the water outlet, at the delta formed at the entrance to the dam. Additional capacity for future sedimentation thus has to be provided in both the "dead" and "live" storage zones.

6.1.2 Sediment bypassing

Sediment bypassing is an operational procedure that has been used successfully (World Bank, 2003) at a small number of locations where the local topography has allowed a reservoir to be constructed in a side valley, and operated "off line". Water is only diverted to the reservoir when it is not full, and as a result sedimentation rates are much lower than would be the case in a conventional dam with a low capacity/inflow ratio, where water and sediments are passed into the dam, even when it is full. The principle could be applied to small dams if a "bypass" channel was constructed from the head of the dam to the spillway. Sediment bypassing has obvious potential to lengthen the life of small dams with a low capacity/inflow ratio, although we know of no applications of this concept in small communal dams.

The objective is to only allow water, and the sediment that it transports, to enter a dam when the water level in the dam is below the spillway level. Once a dam has filled, all the incoming water and sediment should be diverted over the spillway. For a dam with a capacity to inflow ratio of 0.1 this should result in about 90% of the sediment that would have entered and settled in the dam being passed over the spillway, massively reducing the sedimentation rate. A bypass canal connecting the river at the head of the dam to the spillway, with a side weir allowing flow to enter the reservoir storage area when the dam is not full, is needed. A possible arrangement is shown in Figure 6.1.

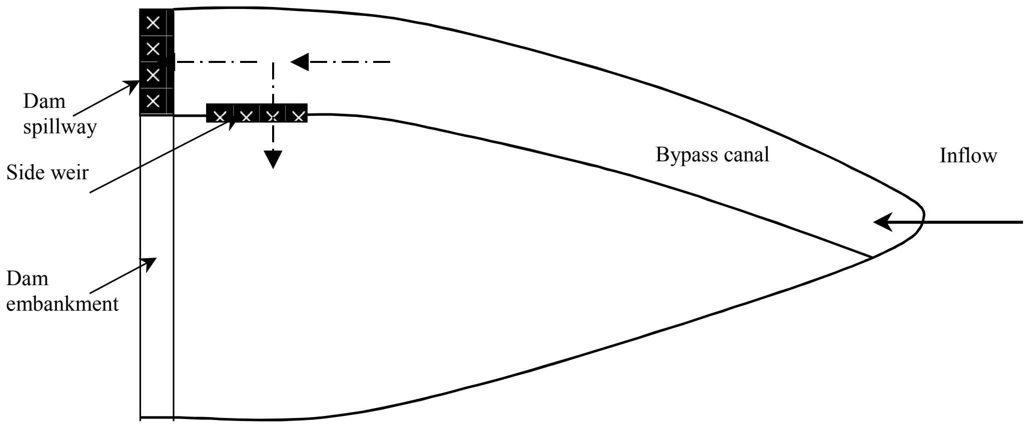

Figure 6.1 Plan view of sediment bypassing arrangement for a small dam

When the dam is empty, incoming flows initially fill the bypass canal to the crest level of the side weir. Water then spills over the side weir into the dam until the dam is filled and the water level in the dam and the bypass canal reaches the spillway crest level. Up to this time all the sediments carried by the flow enter the dam and settle. As river flows continue the water level in the dam rises above the dam spillway level. A small proportion of the flow continues to pass over the side weir, but most of the incoming flow and the sediment flow pass over the main spillway. When the discharge entering the bypass canal starts decreasing, the flow over the side weir changes direction, passing from the dam to the bypass channel, until the level in both canal and dam stabilise at the spillway crest level.

Numerical model tests on a number of sediment bypassing arrangements, described in HR Wallingford (2003d), led to the following conclusions:

- In any particular wet season the benefit obtained will be strongly influenced by the sequence of river discharges and hence the sediment transporting capacity of the runoff events that arrive at the dam. If a dam is filled from a number of small floods that carry low sediment concentrations and if after the dam is full larger floods are passed over the spillway then a very large reduction in the sediment load settling in the dam is obtained. Conversely if a dam is filled from one or more very large runoff events occurring at the start of the wet season substantial quantities of sediment will be diverted to and settle in the dam.

- In general the sequence of runoff events through wet seasons will be randomly distributed. Thus over a long time period the benefit of sediment bypassing, in terms of the reduction in the proportion of the incoming sediment load settling in a dam, will be approximately proportional to 1/(capacity/inflow ratio). The actual benefit will be a little smaller due to the effect of wet season water abstractions, dam filling to replace water lost by evaporation, and the effects of flows passing into and out of the storage area when water levels rise above the dam spillway level in flood peaks. These flows transport additional sediment that settles in the dam.

- Sediment bypassing has the potential to significantly decrease sedimentation rates in dams with a high sediment input and a small capacity/inflow ratio. To be viable the topography of the dam site must be suitable or the cost of constructing a bypass canal and side weir must be offset by the increase in a dam's effective life. These issues are discussed further in HR Wallingford (2003d).

6.1.3 Catchment conservation

In small catchments the introduction of comprehensive soil and water conservation programmes can provide reductions in small dam sedimentation rates within a relatively short time period. In order to estimate the impacts of such programmes it is necessary to determine:

a) The effectiveness and sustainability of the conservation activities that are proposed;
b) The magnitude of the benefit obtained;
c) The time period before the benefit is realised.

Effectiveness and sustainability

In soil conservation programmes designed to protect small dams the primary interest is in reducing sediment yields. However the land users who will need to carry out conservation activities in a catchment will not necessarily benefit from a dam, and will probably not be prepared to change the way they use the land unless there are immediate and direct benefits for them. Decisions as to what land is used for, and the management practices that are followed, are primarily controlled by the socio-economic circumstances in which individual rural households operate. Existing land use enterprises and management practices may accelerate land degradation and increase sediment yields, but technical remedies to solve these problems can only succeed when they function within, and address, individual family's socio-economic constraints.

It is now generally accepted that sustainable soil conservation programmes are more likely to be achieved when they are based on an approach where catchment users, assisted by external facilitation where necessary, select and implement their own conservation activities. Conservation interventions are based on the understanding that farmers managing and improving their land for productive and profitable purposes sustain the land's productive potential, and it is this that reduces erosion. Control of erosion and sediment yields is a consequence of good land husbandry, a reversal of earlier concepts that it is necessary to conserve the soil in order to get better crops.

In many catchments the processes of degradation will already have had an adverse impact on soil productivity and sediment yields. A corrective strategy will be needed that has parallels with traditional physical conservation planning, in that it may involve:

- The use of physical structures or vegetative techniques to control runoff and soil loss;
- The rehabilitation of severely degraded land by mechanical means (e.g. filling in gullies, construction of gully control structures, ripping to break surface crusts and subsurface compacted horizons);
- The closing of severely degraded areas, relying on the self-regenerating capacity of the soil over time to restore land to a condition where it could again be used for productive purposes.

Where it is cost-effective to farmers measures might also involve:

- The planting of pasture leys, contour hedgerows of leguminous shrubs, and other forms of improved fallows to restore topsoil structure and raise soil organic matter levels;
- The use of engineering structures to reduce/control stream bank erosion and reduce the supply of sediment to downstream reservoirs or irrigation works (check dams, etc.).

There are many soil conservation manuals that describe soil conservation measures suitable for the catchments of small dams. A range of practical examples of farmer managed conservation interventions for use in small dam catchments in Zimbabwe is described in publications edited by Silsoe Research Institute in collaboration with local partners, ZFU and Agritex (1998). Similar manuals are available in most countries in East and Southern Africa.

The magnitude of the benefit

There are surprisingly few data that can be used to quantify the impact of farmer managed conservation interventions on long-term sediment yields in the catchments of small dams. A considerable amount of data from plot and micro-catchment studies carried out by research stations is available, and shows very large reductions in sediment yields from small land areas under highly managed conditions. However, as discussed in FAO (1993), these sorts of data are virtually useless for assessing sediment yield reductions that might be achievable in the real world at the catchment scale.

Measurements of sediment yield increases in catchments subjected to land use changes are summarised in HR Wallingford (2003d). In general overgrazing or a change from natural vegetation to arable land use has resulted in increases in sediment yields ranging from four to more than one hundred times. Measurements made in four similar micro-catchments in Malawi demonstrated that a steep catchment under uncontrolled maize production produced about one hundred times more sediment than catchments with similar characteristics with a full soil conservation package, or a similar catchment under mature forest cover. A fourth catchment, where only physical conservation works were introduced, had sediment yields ten times larger than the fully conserved catchment (Amphlett, 1989). This study was carried out with a relatively high level of management on research farms, and it is not expected that hundred-fold, or even ten-fold reductions in yields would be readily achievable in the larger catchments of small dams under communal management.

There is a very wide range of possible catchment types and conservation interventions. It is not possible to make specific recommendations as to the scale of the reduction in sediment yield that can be expected following the introduction of soil conservation without carrying out much larger and more complex studies than are feasible for small dam projects. A simple and approximate procedure has been developed that enables estimates of the scale of potential impacts of conservation on sediment yields to be carried out at the design stage of small dam projects.

The procedure is based on the following assumptions:

- Conservation interventions are implemented over all areas of a catchment that make a significant contribution to the sediment yield, and are both effective and sustainable;
- There will be a lower limit to the sediment yields from well conserved catchments;

- The largest reduction in yields will be achieved in catchments with the largest untreated yields.

The sediment delivery ratio, the proportion of sediment eroded from the land that is transported to the catchment outlet, needs to be considered when the impact of conservation interventions is being quantified. Sediment delivery depends on many factors but is often estimated using simple area based delivery functions. These reflect the observation that in many, but not all, catchments, sediment yield reduces as catchment areas increase, slopes reduce, and opportunities for sediment deposition within the catchment increase. The Roehl (1962) relationship, simplified so that the sediment delivery ratio is a function only of catchment area, is used to estimate sediment delivery ratios in the procedure proposed later.

$$SDR = 0.343 * CA^{-0.175} \qquad (6.1)$$

Where:
SDR = Sediment delivery ratio
CA = Catchment area (km^2)

Estimates for the lowest erosion rates that can be expected on well-conserved arable lands show wide variations. We have a adopted a figure of 5 t/ha/y, which is lower than the limits sometimes adopted for conservation farming in Southern Africa (10 to 12 t/ha/y). It corresponds with the erosion rate derived using equation 6.1 with the lowest measured small dam catchment sediment yield reported in HR Wallingford (2003c), and is also the erosion rate often quoted for well-managed commercial arable farmland in Zimbabwe. This is taken as the lowest erosion rate that is expected in an extremely well conserved small dam catchment. Adopting an assumption that conservation might produce a five-fold reduction in the sediment yield in catchments with the relatively high erosion rate recently reported for communal lands in Zimbabwe (Nemasasi *et al*., 2001), led to the sediment yield reduction factors suggested in Table 6.1. Reduction factors become smaller as pre-treatment erosion rates reduce.

Table 6.1 Suggested sediment yield reduction factors

Untreated erosion rate t/ha/y	Suggested sediment yield reduction factor
10	2
20	3
40	4
80	5
160	6

Time period before benefit is realised

In large catchments there are time lags of decades or even centuries between the introduction of effective conservation and significant reductions in sediment yield at catchment outlets. The vast store of easily erodable sediments at the base of slopes, and in river systems, continues to contribute to sediment yields even where it is possible to reduce or eliminate erosion over most of a catchment area (Walling, 1983). In small dams, with catchment areas up to 10 km^2, the length of time before the full benefits of conservation are reflected in reduced sediment yields at catchment outlets obviously depends greatly on the interventions that are to be implemented. Information on "recovery times" for small basins subjected to various disturbances suggests a return to predisturbance sediment loads as vegetation is re-established in as little as a few years in humid areas, and up to one or two decades in semi-arid areas. It is often assumed that overgrazed rangeland can recover in as little as two to three years. For typical small dam catchments we have assumed the "lag times" listed in Table 6.2 before conservation measures become fully effective. The lag time is the period following the completion of the conservation intervention before the sediment yields are assumed to have reduced to the "fully conserved" level.

Table 6.2 Conservation lag times

Catchment type	Intervention	Lag time (years)
Degraded rangeland	Closure or managed grazing	3
Degraded annually cropped arable land	Catchment-wide physical and biological conservation	5
Any	Re-forestation	10 years + or - , depending on species planted

6.1.4 Check dams

Check dams in rivers are often included as a component of soil conservation programmes. In Zimbabwe they are sometimes the only conservation measure that is introduced in small dam catchments. Check dams have a small sediment storage capacity compared with the dams they are protecting, and usually fill up fairly rapidly with coarse bedload sediments. Their effective life as sediment trapping structures can thus be quite short, as little as one or two years in some catchments. They also have a longer-term role to play in stabilising gullies and reducing stream gradients (and hence scour from channel beds and banks). Unless the supply of coarser sediments from the catchment is reduced by other conservation measures the effectiveness of check dams as sediment trapping structures inevitably reduces over time, due to the sedimentation that occurs in the river reaches between the check structures. This will continue until a new river bed is established at a higher level, and parallel to the original bed.

The initial impact of check dams on the sediment loads delivered to a small dam is assessed by considering:

- The volume of sediment that is deposited on the river bed following the construction of check dams;
- The time taken for this sedimentation process to be completed.

If sediment settled at a uniform rate during the deposition process, the time taken for the check dams to silt up is simply the available storage volume divided by the annual volume of coarse bed material sediments transported by the river. In practice the proportion of sediment load settling between check structures reduces with time, as the bed rises, and the sediment transporting capacity increases.

These effects were investigated in a series of simulations using HR Wallingford's "SHARC" sediment routing software. The results indicate that actual deposition times might be increased by between approximately 2 and 3 times when compared with the deposition time derived from dividing the storage volume by the annual volume of bed material sediments transported by the river. The actual storage time will, of course, be a function of the river and sediment characteristics and the height and spacing of the check dams and could vary between wide limits. For a typical small sand bed river a factor of 2.6 might be appropriate.

6.2 METHODS

6.2.1 *Additional storage for sediment*

The methods set out earlier in the guidelines can be used to determine a dam's capacity and the sediment yield from the catchment. If it is possible to increase the capacity of a dam to provide additional storage for sediment the benefits can be assessed by carrying out the following calculations:

a) Estimate the dry season water yield following twenty years of siltation using the procedure set out in Chapter 5;
b) Repeat for dams with a larger storage capacity, bearing in mind the limits set by the site and construction costs on dam heights, widths and throwback.

6.2.2 *Sediment bypassing*

Sediment bypassing is only likely to be an attractive option for dams with a low capacity to inflow ratio, say less than 0.3; a fairly short throwback so as to minimise the length of the bypass channel; and at sites where construction of a bypass channel is not complicated by the presence of tributaries or side valleys. If these conditions are satisfied then the benefits of sediment bypassing can be assessed as follows:

a) Using equation 5.1 estimate the proportion of the original capacity remaining after twenty years of siltation.
b) Repeat the calculation for the "with sediment bypassing" case using equation 6.2, which assumes that all the sediment passed over the side weir settles in the dam:

$$Cn(bp) = 1- [n * S_y * CA * K_1. * K_2 /(ARV * Den)] \tag{6.2}$$

Where:

C_n (bp)	=	Proportion of original storage capacity left after n years of siltation with sediment bypassing
n	=	Number of years
S_y	=	Catchment sediment yield (t/km^2/y)
CA	=	Catchment area (km^2)
K_1	=	A factor to account for the additional sediment diverted to the dam during flood peaks
K_2	=	A second factor to account for water and sediment diverted to the dam during the wet season to replace wet season water abstractions and evaporative losses
ARV	=	Annual runoff volume (m^3)
Den	=	The settled density of dam sediment deposits, taken as 1.2 t/m^3

The factor "K_1" is included to account for the additional sediment diverted into a dam during flood peaks when the dam is full, but the water level in the bypass canal rises above the crest level of the side weir and some flow enters the dam. As the highest sediment concentrations occur during flood peaks this can result in significant additional quantities of sediment being diverted into a dam. The value of K will depend on the proportion of the annual runoff that occurs at high discharges, but simulations described in HR Wallingford (2003d) indicate that a value for K of 1.1 is appropriate.

The factor "K_2" is included to account for water and sediment diverted to the dam during the wet season to replace water that is abstracted and lost through evaporation. K_2 can be estimated if it is assumed that water abstraction and evaporative loss are the same in each month of the year:

$$K_2 = 12/(12\text{-number of months in the dry season}) \qquad (6.3)$$

In a dam with sediment bypassing, the reduction in the dry season water yield (over 20 years) can be estimated using the "drawdown" software by adjusting the sediment input. This is illustrated in the example included in Annex 1.

The design of sediment bypassing structures will mostly be determined by site specific factors and local practice regarding the design of channels and weirs. However some guidance on general design features is presented in HR Wallingford (2003d).

6.2.3 Catchment conservation

The following procedure is suggested:

a) Estimate the pre-treatment sediment yield using the methods set out in Chapter 4.
b) Estimate the "erosion" rate from the sediment yield using equation 6.4:

$$ER = S_y /(34.3 * CA^{-0.175}) \qquad (6.4)$$

Where:
ER = Untreated catchment erosion rate (t/ha/y)
S_y = Sediment yield (t/km^2/y)
CA = Catchment area (km^2)

(Values for (34.3 * CA $^{-0.175}$) are given for Table A2.6 in Annex 2)

c) Select a sediment yield reduction factor from Table 6.1 or by using equation 6.5 below:

$$SYRF = 1.44 * \text{Ln}(ER) - 1.32 \qquad (6.5)$$

Where:

SYRF = Sediment yield reduction factor
ER = Erosion rate calculated from equation 6.4 (t/ha/y)

d) Estimate the post-treatment catchment sediment yield from equation 6.6:

$$S_y con = Sy/SYRF \qquad (6.6)$$

Where:
S_y con = Sediment yield with conservation (t/km2/y)
Sy = Pre-treatment catchment sediment yield (t/km^2/y)
SYRF = Sediment yield reduction factor

For planning purposes it can be assumed that there will be a linear reduction in sediment yield with time, from the existing to the predicted conservation level. For example, if conservation activities are completed in the year that the dam is commissioned, and a five-year lag time is appropriate the mean sediment yield over twenty years will be:

$$S_{y20} = \frac{(5 * (S_y + S_y\,con)/2) + (15 * S_y\,con)}{20} \qquad (6.7)$$

Where:
S_{y20} = Mean sediment yield over 20 years
S_y con = Sediment yield with conservation ($t/km^2/y$)
S_y = Pre-treatment catchment sediment yield ($t/km^2/y$)

In view of the sweeping assumptions used it is necessary to take a pragmatic approach when interpreting the results of these calculations. For example if the conservation activity being considered only applied to part of the catchment then the final sediment yield should be estimated by weighting the estimated post-conservation sediment yields by the proportions of the catchments that are untreated and treated. The estimated post-treatment sediment yields may also need to be adjusted up or down to account for the effectiveness of the conservation measures that are to be implemented.

6.2.4 Check dams

Initial reductions in sediment yields derived from check dams can be estimated by considering the time required for the volume behind check dams to be filled with deposited sediment. The calculation is conservative, as it takes no account of the effect of check dams in reducing bed and bank scour. The suggested procedure is:

a) Estimate the pre-treatment sediment yield using the methods set out in Chapter 4.
b) Determine the height and spacing of the proposed check dams using one of the methods described in local soil conservation manuals.
c) Estimate the storage volume between the check dams assuming that a river will eventually silt up to the new bed located h metres above the existing river bed, where h is the height of the check dams:

$$Vcheck = l * h_{check} * wr * (ndam-1) \qquad (6.8)$$

Where:
Vcheck = Sediment volume stored between check dams (m3)
l = Distance between check structures (m)
h_{check} = Average height of the check dams above the original river bed (m)
wr = Average river width (m)
ndam = The number of check dams

(Sedimentation upstream of the first check dam is ignored in this calculation. If a single larger “debris” dam is being considered then the sediment volume stored between the check dams should replace the storage volume in the check dam in subsequent calculations.)

In the absence of more specific information, assume that 50% of the sediment yield from a catchment consists of sand and coarser sediments, which can be expected to settle behind check dams. A settled density for sand sized sediment of 1.4 t/m^3 is also assumed.

The time before the check dams silt up is then:

$$T = Vcheck * 2.6 / (0.5 * S_y * CA /1.4) \qquad (6.9)$$

Where:
Vcheck = Sediment storage volume (m3)
S_y = Pre-treatment catchment sediment yield (t/km^2/y)
CA = Catchment area (km^2)

6.3 EXAMPLES

6.3.1 *Increasing the dam capacity*

Example 5

The catchment of the dam used in Example 2 has been characterised using the procedure described in Chapter 4. The sediment yield is predicted to be 315 t/km²/y. How will changing the dam height affect the maximum water yield after 20 years of siltation?

The details of the dam are given in Example 2 in Chapter 3. Table 6.3 below, from Example 2, gives design parameters for a range of dam heights.

Table 6.3 Design parameters for a range of dam heights

Full supply depth (m)	Initial maximum Volume (m^3) Note 1	Embankment length (m) Note 2	Throwback (m) Note 2
3.0	31070	56.0	701
4.0	67559	82.0	780
5.0	123407	101.0	926
6.0	180000	112.0	1015

Note 1 From the data used to prepare Table 3.3
Note 2 At the full supply level

The other information needed to carry out the example is:

- Mean annual runoff = 65.1 mm;
- Catchment area = 7.8 km^2;
- Catchment sediment yield = 315 t/km^2/y.

Evaporation rates and wet season months are the same as used in Example 4.

Table 6.4 below shows the results of drawdown calculations for the dam heights and other data in Table 6.3 (above):

Table 6.4 Results of drawdown calculations for the dam heights and other data (from Table 6.3)

Full supply depth (m)	Initial maximum water yield (m^3)	Silted maximum water yield after 20 years (m^3)	% reduction in water yield following 20 years of siltation
3.0	13808	0	100
4.0	38108	2978	92
5.0	79321	41873	47
6.0	125550	87072	31

The advantages of larger dams are very clear from the above. Increasing the dam height from 4 m to 5 m increases the maximum water yield (following 20 years of siltation) by a factor of 14.

6.3.2 Sediment bypassing

Example 6

In this example we assume that the maximum depth of dam that can be constructed in Example 5 above is limited to 4m. What benefit could be expected from constructing a sediment bypassing arrangement?

From Example 5, the capacity of a 4 m dam is 67559 m^3, and the annual runoff volume is 507780 m^3. The capacity to annual inflow ratio is 77559/507780 = 0.133, which is substantially less than 0.3 and thus sediment bypassing may be beneficial.

The capacity loss over twenty years without sediment bypassing is estimated using equation 5.3:

$$C_n = 1 - [n * S_y * CA * TE / (C * Den)] \tag{5.3}$$

Where:

C_n = Proportion of original storage capacity left after n years of siltation
n = Number of years
S_y = Catchment sediment yield ($t/km^2/y$)
CA = Catchment area (km^2)
TE = Sediment trap efficiency
C = Dam's original capacity at full supply level (m^3)
Den = The settled density of dam sediment deposits, taken as 1.2 t/m^3

With a sediment trap efficiency of 0.9, estimated from Table 5.1, C_n is:

$$C_n = 1 - [20 * 315 * 7.8 * 0.9 / (67559 * 1.2)] = 0.46$$

The proportion of the capacity remaining after 20 years of siltation with sediment bypassing is estimated using equation 6.2:

$$Cn(bp) = 1 - [n * S_y * CA * K_1 * K_2 / (I * Den)] \tag{6.2}$$

Where:

C_n (bp) = Proportion of original storage capacity left after n years of siltation with sediment bypassing
n = Number of years
S_y = Catchment sediment yield (t/km^2/y)
CA = Catchment area (km^2)
K_1 = A factor to account for the additional sediment diverted to the dam during flood peaks
K_2 = A second factor to account for water and sediment diverted to the dam during the wet season to replace wet season water abstractions and evaporative losses
I = Annual runoff volume (m^3)
Den = The settled density of dam sediment deposits, taken as 1.2 t/m^3

(K_2 is estimated using equation 6.3, and for a four month wet season is 1.5).

$$Cn(bp) = 1-[20 * 315 * 7.8 * 1.1 * 1.5 /(507780 * 1.2)] = 0.87$$

Sediment bypassing approximately doubles the storage capacity remaining after twenty years of siltation. The impact on water yields is more difficult to calculate with manual methods but can be estimated using the drawdown software by reducing the sediment concentrations entering the dam. This is illustrated in the example presented in Annex 1. In this case the reduction in dry season water yield after twenty years of siltation is predicted to drop from 92% without sediment bypassing, to 23% with sediment bypassing. This is a very substantial improvement, and might justify the additional costs of constructing a bypass channel and side weir.

6.3.3 Catchment conservation

Example 7

This example is based on the dam and catchment used for examples 5 and 6. The catchment characterisation predicts a sediment yield of 315 t/km^2/y. What impact on sediment yield should a dam designer assume following the implementation of a soil conservation programme (consisting of both physical and biological conservation measures)?

Equation 6.4 is used with Table A2.6 in Annex 2 to estimate the source erosion rate from the sediment yield and the catchment area.

$$ER = S_y /(34.3 * CA^{-0.175}) \qquad (6.4)$$

Where:
ER = Untreated catchment erosion rate (t/ha/y)
S_y = Sediment yield (t/km^2/y)
CA = Catchment area (km^2)

$$ER = 315/(34.3 * 7.8^{-0.175}) = 13.2 \text{ t/ha/y}$$

(Note that the erosion rate is expressed per ha rather than per km^2 to allow easy comparison with published erosion rates.)

A sediment reduction factor is estimated using either Table 6.1 or equation 6.5.

The equation is used in this example:
SYRF = 1.44 * Ln (ER) - 1.32 (6.5)

Where:

SYRF = Sediment yield reduction factor
ER = Erosion rate calculated from equation 13.2 (t/ha/y)

SYRF = 1.44 * Ln (13.2) –1.32 = 2.4

Thus the post-treatment sediment yield is predicted to be:

Sediment yield (S_y) with conservation = S_y/SYRF = 315/2.4 = 131 t/km^2/y

The sediment yield averaged over 20 years will be:

$$S_{y20} = \frac{(5 * (S_y + S_y\,con)/2) + (15 * S_y\,con)}{20} \qquad (6.7)$$

Where:
S_{y20} = Mean sediment yield over 20 years
S_y con = Sediment yield with conservation (t/km^2/y)
S_y = Pre-treatment catchment sediment yield (t/km^2/y)

$$S_{y20} = \frac{[5 * (315 + 131)/2] + (15 * 131)}{20} = 154 \text{ t/km}^2\text{/y}$$

Thus the mean sediment yield to the dam is predicted to be halved over the sedimentation lifetime of the dam.

It important to stress that these can only be regarded as indicative calculations. The actual impact of conservation measures are critically dependent on the effectiveness and sustainability of the measures that are implemented, and the proportion of the catchment that is covered.

6.3.4 Check dams

Example 8

A series of Gabion check dams 1 m high are to be constructed every one hundred metres along a 2.0 km reach of a river. The river flows into a small dam that has a catchment area of 7.2 km^2. The river has an approximately rectangular cross-section, with an average width of 5 m, and an average bed slope of 0.01 m/m. The catchment sediment yield, estimated using the catchment characterisation procedure described in Chapter 4, is 620 t/km^2/y. What reduction in sediment yield to the dam can be expected?

The storage volume created by the check dams, assuming the river eventually silts up to its original bed slope at a new level 1 m above the existing river bed, is estimated using equation 6.6:

Vcheck = l * h_{check} * wr * (ndam-1) (6.8)

Where:

Vcheck = sediment volume stored between check dams (m3)
l = Distance between check structures (m)
h_{check} = Average height of the check dams above the original river bed (m)
wr = Average river width (m)
ndam = The number of check dams

V = 100 * 1.0 * 5 *20 = 10000 m^3
The annual sediment yield from the catchment is 7.2* 620 = 4464 tonnes. We assume that 50% of this is bed material load sediments, i.e. sand sizes and larger, which would be trapped behind the check dams. If the settled density for sand sized sediments is 1.4 t/m^3, this is equivalent to 1594 m^3. If sediment settled at a uniform rate during the deposition process it would take 10000/1594 = 6.3 years for the new bed to form at the higher level and at the original river bed slope. After this the sediment transporting capacity will be the same as the transporting of the original river, and no further long-term deposition would occur.

In practice the proportion of sediment load settling reduces with time as the bed rises. This effect is allowed for by multiplying the 6.3 years estimated above by 2.6. The "corrected" deposition time for this example is thus 6.3 * 2.6 = 16.4 years. After this time there will be no benefit in terms of reduced sedimentation in the downstream small dam.

In this example the sediment storage provided by the check dams will be filled in less than twenty years. The volume of the incoming sediment that is trapped, and which will therefore not be transported to a downstream small dam, is 10000 m^3, or 10000 * 1.4 = 14000 tonnes. The sediment load that would enter the dam in the absence of check dams over twenty years is 20 * 7.2 * 620 = 89280 tonnes. In this case we expect that the introduction of check dams in the river might reduce the average annual sediment yield from the catchment to:

$$\frac{(89289 - 14000)}{(20 * 7.2)} = 523\ t/km^2/y$$

The sedimentation rate in the dam would be expected to be reduced by about 16%.

Much larger reductions in sedimentation rates could be obtained if check dams were emptied regularly. While this is sometimes suggested (World Bank, 2003), it is almost never carried out in communally managed catchments. It would take extreme dedication on the part of dam beneficiaries to remove hundreds of cubic metres of sediment from the river bed every year, when the siltation of the downstream dam would probably not even become obvious for ten or more years following its construction.

7. Design floods and spillway design

7.1 KNOWLEDGE

It is widely reported that inadequate spillway capacity is one of the most common reasons for the failure of small earth dams. While the spillway capacity is not related to the sedimentation characteristics of a dam this topic is included in the guidelines due to its importance in small dam projects. The methods used are discussed in more detail in HR Wallingford (2003b).

7.1.1 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 regulations and design codes are different in 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 7.1 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 these 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 below.

Table 7.2 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

Most small dams considered here will have a "very low" hazard potential. 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 acknowledged 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 the design and capacity of spillways in all cases where the hazard potential is judged to be anything other than very low.

7.1.2 Estimating design floods

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

- Rational methods based on a design rainfall intensity over the catchment, a calculated time of concentration derived from catchment characteristics and a runoff coefficient that depends on catchment crop cover, soil type and slopes, etc.;
- 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 method requires some judgement to select appropriate design rainfall intensities and suitable runoff coefficients, and needs more data than are often available to small dam designers. Rational methods are not included in these guidelines but are described in some small dam design manuals and in hydrology textbooks. 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, and are relatively simple to apply.

7.1.3 Kenya Ministry of Water Development Manual method for small catchments

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 (see Table 7.3).

Table 7.3 Recommended values of 1 in 100 year return period flood discharge

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

7.1.4 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 be applied to un-gauged catchments in the same region. Measured floods are non-dimensionalised by dividing by the mean annual flood (MAF). Regional flood frequency curves are derived by fitting a statistical distribution to 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) reviewed empirical functions for predicting MAF in semi-arid regions in Southern Africa and recommended an equation developed by him using data from catchments in Botswana, Zimbabwe, South Africa and Namibia, with catchment areas of less than 1000km^2, and MAP less than 850 mm. The equation is:

$$MAF = 0.114 * CA^{0.52} * MAP^{0.537} \qquad (7.1)$$

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. For small dam studies the function will often be used to estimate MAF 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 using any local observed data that may be available. This is discussed further in HR Wallingford (2003b).

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 the relationship developed from a worldwide arid and semi-arid zone data set (3637 station years), which is also presented in Farquharson *et al*. (*ibid*.).

Table 7.4 Growth factors for a range of return periods

Return Period (years)	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 is multiplied by the growth factor to obtain the flood magnitude for the required return period.

7.1.5 PMF method

Although criticised in some quarters the PMF (Probable Maximum Flood) method is used to determine design floods in Zimbabwe (Ministry of Water Development

(MOWD), Zimbabwe, 1977). The method is described in detail in several hydrology textbooks. It is included in the guidelines due to its routine use in Zimbabwe.

The Probable Maximum Flood (PMF) is determined using a relationship presented in MOWD, Zimbabwe (1977).

$$Ln(PMF+1) = 1.175 * [Ln(CA+1)]^{0.755}+3.133 \tag{7.2}$$

Where:

PMF = Probable maximum Flood
CA = Catchment Area (km^2)

Design floods are calculated as a proportion of the PMF, i.e.

$Q_{100} = 0.292 * PMF$
and
$Q_{250} = 0.403 * PMF$

7.1.6 Comparison of methods

Estimates of the 1:100 year return period flood (from the tables presented in the Republic of Kenya small dams design manual (MOWD, Kenya), the regional flood frequency method described by Bullock (1993) and the PMF method used in MOWD, Zimbabwe (1977)) are compared below. An annual rainfall of 650 mm was used to derive the regional flood frequency results.

Table 7.5 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 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 use of the regional flood frequency method is suggested as it provides more conservative predictions than the other two methods.

7.1.7 Spillway design

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 an equation presented in the next section. This is used to determine the combination of spillway width, which may be fixed by site constraints, and the operating head to pass the 1: 100 return flood. The design is then checked by ensuring that the 1 in 250 year return period flood can be passed with out the dam overtopping, i.e. without the additional head needed exceeding the dry freeboard. Note that the spillway and energy dissipation works are designed for the 1 in 100 return period flood, therefore some damage is accepted if larger floods occur, provided that the dam does not overtop.

7.2 METHODS

7.2.1 *Design floods*

The following calculations are carried out:

For the regional flood frequency method

a) Estimate the mean annual flood using equation 7.1[15]. Alternatively Tables A2.7 and A2.8 in Annex 2 give values for CA $^{0.52}$ and MAP $^{0.537}$.

$$MAF = 0.114 * CA^{0.52} * MAP^{0.537} \qquad (7.1)$$

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

b) The 1 in 100 year and the 1 in 250 year return period floods are then calculated as multiples of MAF:

Q_{100} = 6.51 * MAF
and
Q_{250} = 9.86 * MAF

For the PMF method

a) Estimate the probable maximum flood using equation 7.2 or Table A2.9 in Annex 2.

$$Ln(PMF+1) = 1.175 * [Ln(CA+1)]^{0.755}+3.133 \qquad (7.2)$$

Where:

PMF = Probable Maximum Flood
CA = Catchment Area (km^2)

Calculate the deign floods as a proportion of the PMF, i.e.:

Q_{100} = 0.292 * PMF
and
Q_{250} = 0.403 * PMF

[15] Or, where available, using local data following the recommendations in HR Wallingford (2003b).

7.2.2 Spillway dimensions

Equation 7.3 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 that may be imposed by local site conditions.

$$Q = Cd * Ws * (h)^{3/2} \qquad (7.3)$$

Where:
Q = Discharge (m^3/s)
Cd = Coefficient of discharge; 1.8 for masonry spillways and 1.65 for grassed spillways
Ws = Spillway width (m)
h = Head over the spillway (m)

7.3 EXAMPLE

Example 9

A small dam is to be constructed in a catchment in Zimbabwe. The catchment has an area of 7.8 km^2, and a mean annual rainfall of 600 mm. The maximum width of the spillway, which will be constructed from masonry on a rock sill, is 45 metres. What will be the head over the spillway for the design flood, and what dry freeboard will be needed to ensure that the dam does not overtop in a 1 in 250 year return period flood?

In this example both the regional flood frequency and the PMF methods will be used to estimate design floods.

a) PMF method:

Equation 7.2 or Table A2.9 in Annex 2 can be used to estimate the PMF.

PMF = 188.7 m^3/s

Q_{100} = 0.292 * PMF = 55.1 m^3/s
and
Q_{250} = 0.403 * PMF = 76.0 m^3/s

b) Regional flood frequency method:

Equation 7.1 or Tables A2.7 and A2.8 in Annex 2 can be used to estimate MAF.

MAF = 10.3 m^3/s

Q_{100} = 6.51 * MAF = 67.1
and
Q_{250} = 9.86 * MAF = 101.6

As the dam is in Zimbabwe we adopt the PMF design flood estimates to determine the dimensions of the spillway.

The head over the spillway is calculated using equation 7.3 or Table A2.10a and A2.10b, which list discharge per unit width for grassed and masonry spillways. Table 7.6 below lists the head needed to pass design flows for three spillway widths.

Table 7.6 Design heads for Example 9

Spillway width (m)	Head for 1:100 year return period flood (55.1 m^3/s)	Head for 1:250 year return period flood (76.0 m^3/s)
35	0.91	1.13
40	0.84	1.04
45	0.77	0.96

A designer will determine the best combination of spillway width and operating head by taking into account construction costs and any local site constraints. A designer will also select the freeboard, including an allowance for wave action, and determine the total height of the dam embankment.

8. References

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Annexes

Annex 1 "Drawdown" sedimentation and hydrological computation software - User guide and examples

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 and c).

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

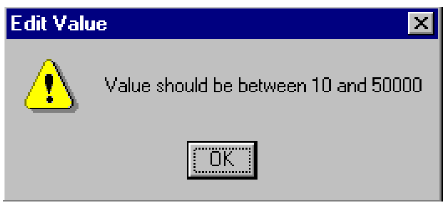
- Dam storage capacity, capacity to inflow ratio and the probability of a dam filling
- Reductions in storage capacity and water yield due to sedimentation over 20 years
- Design floods for 100 and 250 year return periods
- Annual volumes of water that can be abstracted over dry seasons, potential irrigated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

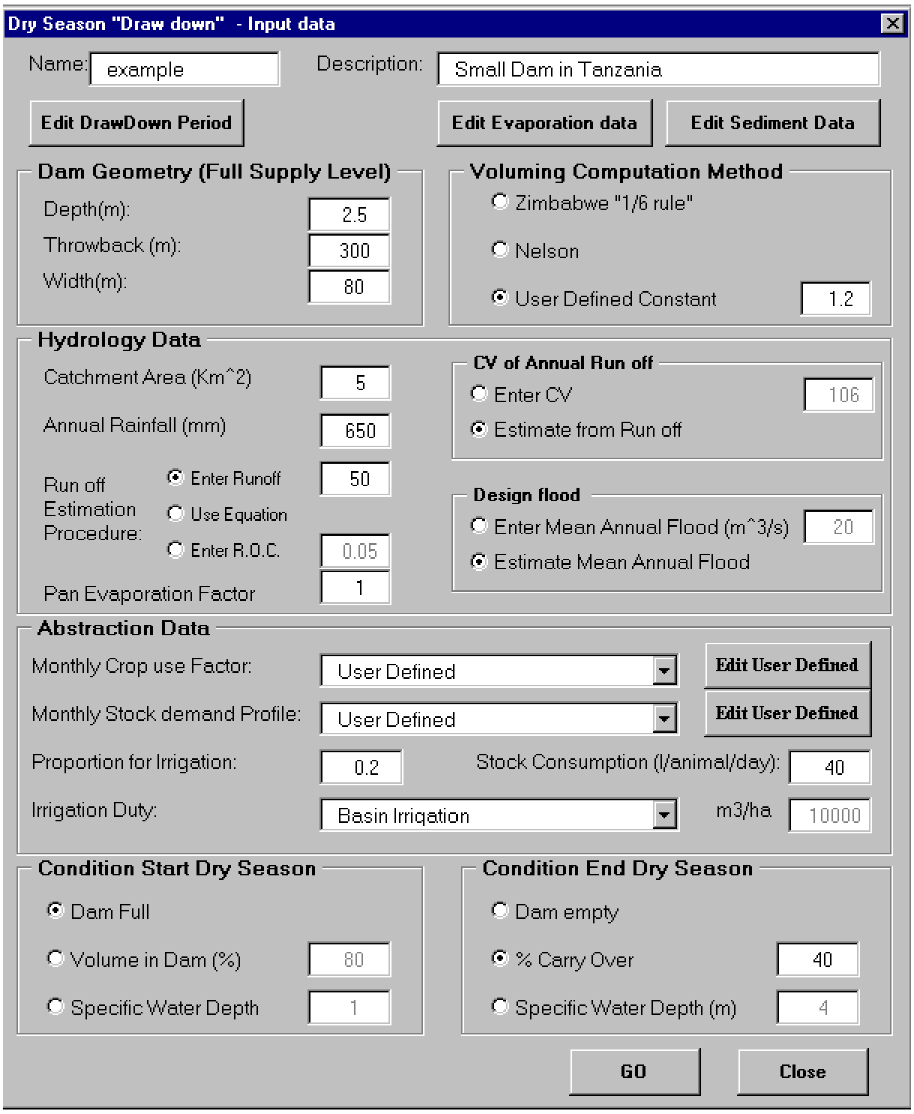
When the programme is started the data entry screen (shown on the next page) is displayed. This is used to enter all the data required to carry out computations. (Data displayed in the input screen when the programme is started are those used for the previous programme run.)

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 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.



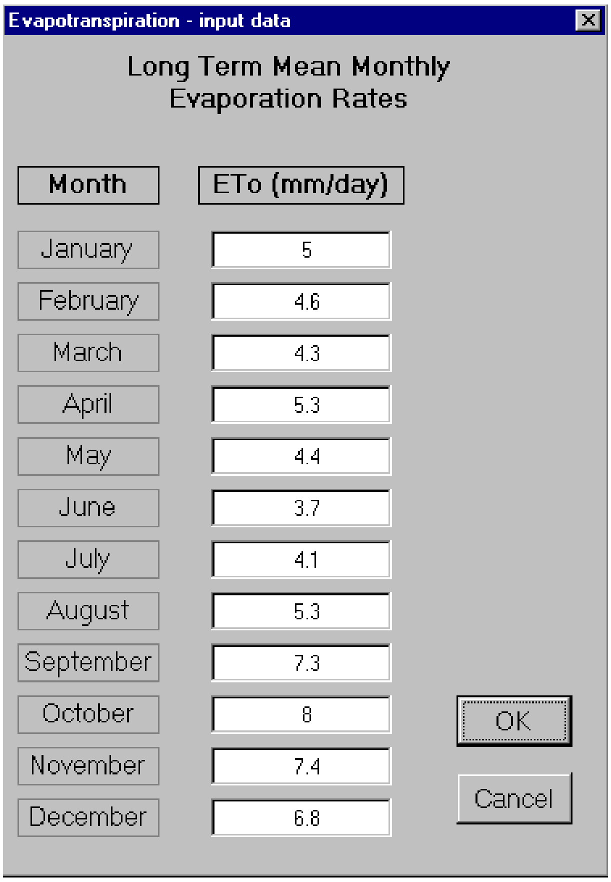
A1.2.1 Edit "drawdown" period

Select the **"Edit drawdown period"** option to select the first and last month of the dry season, the period 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.

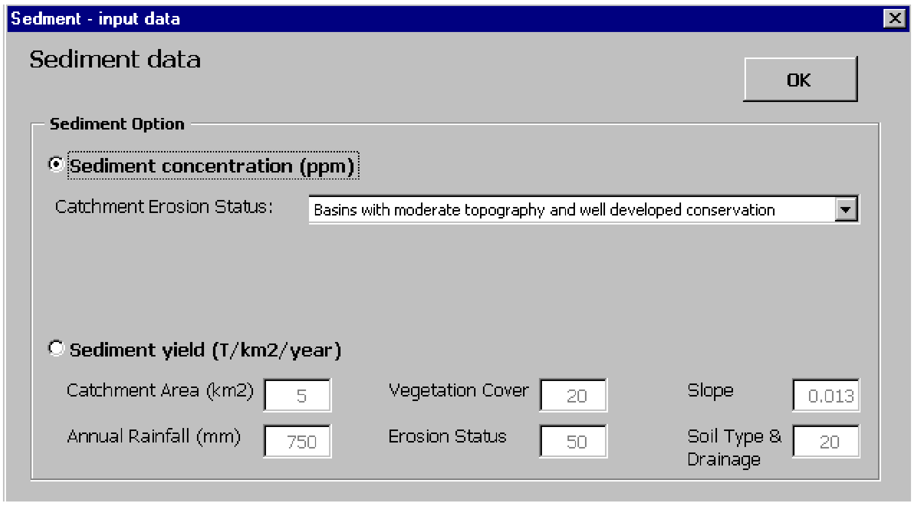


Click **OK** to save the data as set up on the screen. If **Cancel** is selected the data displayed are lost and the data used for the previous simulation are re-selected.

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 (2003c).

If a catchment characterisation has not been carried out then select the **sediment concentration** option. A drop down list enables one of four catchment 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 the 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.

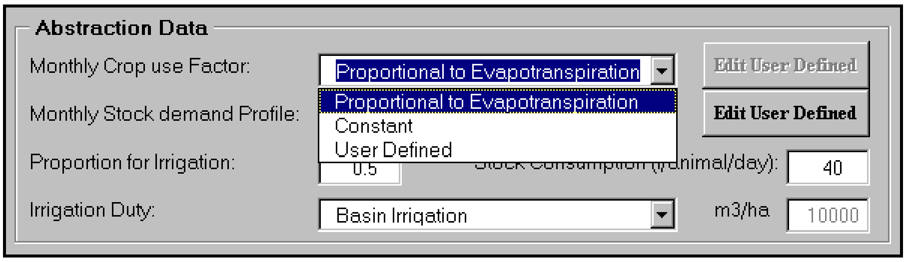
Design flood

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.

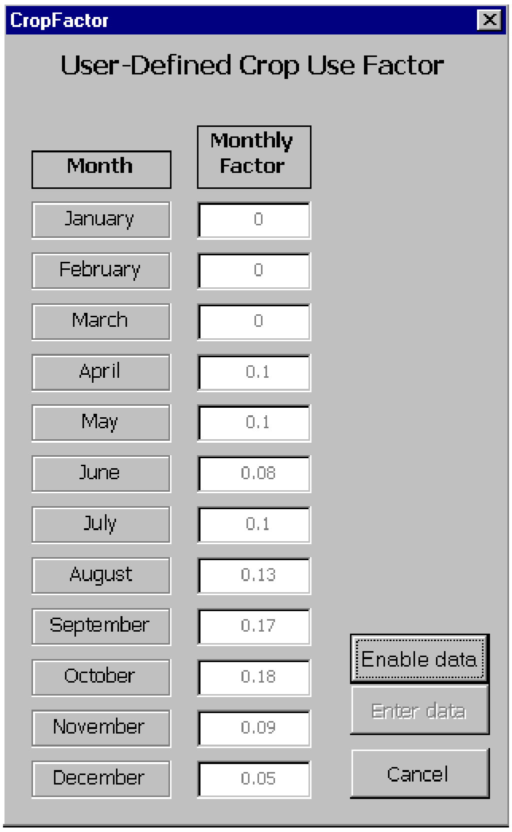
A1.2.6 Abstraction data

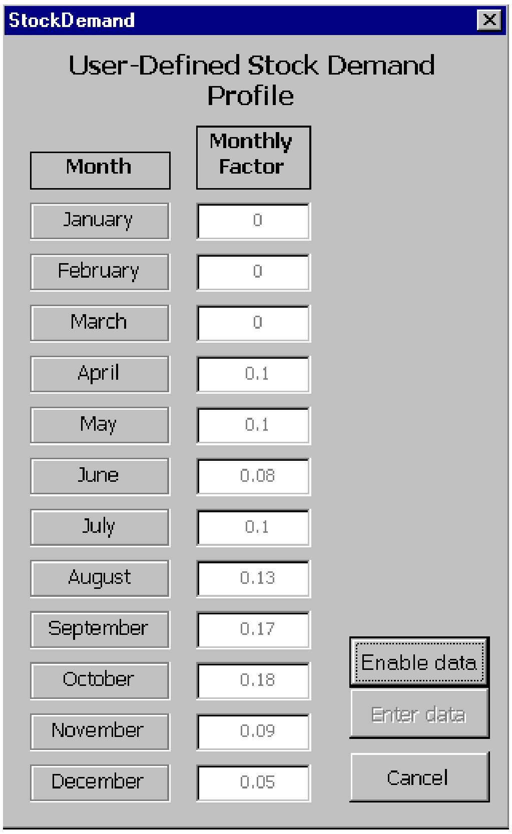
"Monthly Crop use factor" and **"Monthly Stock demand profile"** are used to represent the variations in monthly water abstraction due to varying crop and the livestock water demands during the dry season in the drawdown computation.

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 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 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 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 lose the changes and retain the previous data.

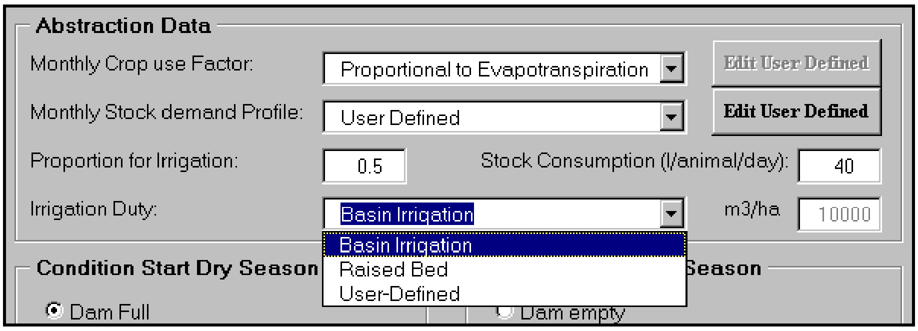
Proportion to Irrigation is the proportion of the water abstracted from the dam that is to be used for irrigation, and takes a value from 0, when there is no irrigation, to 1, when all the water abstracted from the dam is used for irrigation.

Stock Consumption is the average daily water consumption per livestock unit supported by the dam. It is used to convert the water volume abstracted that 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.



1.2.7 Condition at the start and start and end of 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. 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 % 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/m^3)
  - Sediment concentration method
    - Selected type of basin
    - Sediment concentration (ppm)
  - Sediment yield method
    - Catchment Area (km^2)
    - 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 (m^3)

- Full supply dam capacity (m^3)
- Capacity inflow ratio
- Probability of filling (dam empty) (%)
- Probability of filling (with carry-over) (%)

- **Design Flood**
  - Regional flood frequency method
    - Mean Annual Flood (m^3/s)
    - Design flood (1:100 year) (m^3/s)
    - Design flood (1:250 year) (m^3/s)
  - PMF method
    - Maximum Probable Flood (m^3/s)
    - Design flood (1:100 year) (m^3/s)
    - Design flood (1:250 year) (m^3/s)

- **0% Carry-over – capacity and yield reductions**
  - Capacity loss in 20 years (%)
  - Design sediment concentration (ppm)
  - Design sediment yield ($T/km^2/year$)
  - Maximum water yield Year 0 (m^3)
  - Maximum water yield Year 20 (m^3)
  - 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* must 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 for 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

A1.12 Example

This example illustrates the use of the drawdown software with other procedures described in the guidelines to support the design of a small dam. As many alternatives are investigated in the example far more calculations than would normally be needed for the design small dam are described. The same example is carried out using manual calculation methods in Annex 2.

Example A1

A small dam is proposed for a catchment in a semi-arid region of Zimbabwe where some small dams have silted up quite rapidly. The local community wants to use the water stored in the dam to irrigate a small communal garden growing vegetables for home consumption, and to provide water for cattle during dry periods. Small volumes of water will also be taken from the dam to support a small brick making enterprise and the dam will enable other enterprises, like fish farming, to be started. There is a need to store some water in the dam at the end of the dry season to maintain the fish, and to provide some insurance against a failure in the following year's rains. After discussion it was agreed that 30% of the storage volume will be left in the dam at the end of the dry season (carried over). The dam is located in a region where malaria is endemic in the wet season.

A good site for the dam has been identified and surveyed, and a catchment characterisation was carried out following the procedures described in Chapter 4.

The information available to the designer is summarised below:

Table A.1.11 Data used in Example A1.1

Parameter	Value	Note
Catchment area (km²)	15.2	From 1:50 000 maps
Mean annual precipitation (mm)	625	Interpolated from national rainfall isohet map
Mean annual runoff (mm)	60	From tables
Cv of mean annual runoff	120	From tables
Monthly evaporation rates (mm/day):	-	From pan evaporation data at a local met. site
January	5.9	
February	5.3	
March	5.1	
April	4.5	
May	3.9	
June	3.2	
July	3.6	
August	5.0	
September	6.7	
October	7.2	
November	6.5	
December	5.6	
Catchment slope	0.016	From 1: 50 000 maps
SASE (score)[1]	14	From catchment characterisation
STD (score)[1]	24	From catchment characterisation
VC (score)[1]	24	From catchment characterisation

Note 1 The catchment consists of two zones with differing characteristics that were scored separately. The characterisation parameters listed are weighted averages, with the score for each zone weighted by the proportion of the catchment area in each zone. In this case 40% of the catchment scored higher on the three qualitative indicators for erosion potential, SASE, STD, and VC. Thus, for example, the Vegetation Cover (VC) scores were 20 for the larger part of the catchment and 30 for the smaller part. The weighted score was thus calculated as:

VC (whole catchment) = 0.6* 20 +0.4 * 30 = 24

The surveyed cross-section at the proposed dam site indicates that the maximum height for the dam embankment has to be limited to 6.8 m unless a very long and expensive embankment can be constructed. It was decided to carry out initial calculations for three dam depths as shown below. The tabulated dam widths and throwbacks are derived from a surveyed cross-section at the dam site, and refer to the dam dimensions at the spillway crest level.

Table A.1.12 Dam dimensions used in Example A1.1

Maximum depth (m)	Width (m)	Throwback (m)
5.8	149	808
4.8	118	742
3.8	88	667

To carry out drawdown and capacity loss calculations open the drawdown spreadsheet, and enter the data needed to carry out computations for the first dam height.

- Enter an appropriate name, i.e. “Example A1”, and description, for example “5.8 m dam”.

- Select “Edit Drawdown period” and enter April and November as the first and last months of the dry season.
- Select “Edit Evaporation data” and enter the daily evaporation rates from Table A1.11 above.
- Select “Edit sediment data”, edit the value for settled sediment density to 1.2 t/m^3. Select the “Sediment yield” option and enter the data for Vegetation cover, Erosion status, Slope and soil type and drainage listed in Table A1.11 above.
- Enter the depth, width and throwback for the 5.8 m dam, and select the “Nelson” method for the dam volume calculation.
- Enter the catchment area, annual rainfall, select the “enter runoff” option, and enter the mean annual runoff. As pan data were entered in the evaporation data entry screen enter a pan coefficient of 0.7.
- Select “enter CV” and enter the coefficient of variation of annual runoff, select “Estimate mean annual flood”.
- Select the “Proportional to evapotranspiration” option for crop use factor and stock demand profile.
- Enter the “proportion for irrigation” at 0.7 initially, select “raised beds” to set the irrigation duty and enter 40 l/animal/day for the stock consumption.
- Select the “dam full” option for the start condition and the “% carry-over” option for the end condition, enter 30% for the proportion of the dam’s initial volume that is to be “carried over”.

All the data needed to run a drawdown simulation have been entered and a drawdown simulation can be initiated by pressing “GO”, followed by “OK” when the analysis has been completed.

The input data used and results are presented in three tabbed sheets. It is recommended that users first select the “input data” sheet, and carefully check that the correct data have been inserted. The “output summary” and “drawdown output” sheets can then be viewed or printed and the spreadsheet saved with a new name if a copy of the results needs to be kept.

As an exercise the user should carry out new runs for the 4.8 m and 3.8 m high dams. (Only the text in the “name” or “description” boxes needs to changed, plus of course the dam height width and throwback.) The data entry page is selected by clicking on the “Data entry button” located at the top of the “drawdown output” sheet. If required the results for each dam height can be saved by using the excel “save as” function with appropriate file names. Note the warnings that are generated when the simulation is run for the 3.8 m high dam.

A summary of some key results is given below.

Table A1.13 Summary results for 5.8 m, 4.8 m and 3.8 m dams

Parameter	5.8 m dam	4.8 m dam	3.8 m dam
Volume (m^3)	184344	110951	58884
Capacity inflow ratio	0.20	0.12	0.06
% extracted (with 30% carry-over)	46.3	41.5	34.4
Potential irrigated area (ha, with 30% carry-over)	6.94	3.75	1.65
Potential number of livestock supported (with 30% carry-over)	2628	1419	623
% capacity loss over 20 years	41.2	65.3	>100
% yield loss over 20 years (with no carry-over)	49.7	81.9	>100
Probability of the dam filling % (with 30% carry-over)	79.9	86.2	91.5

Since the community wish to irrigate about 2 ha and support about five hundred cattle the 3.8m dam would be satisfactory if sedimentation could be controlled. However the capacity to inflow ratio for a 3.8m high dam, 0.06, is so low that the relatively moderate sediment yield of 317 $t/km^2/y$ (see the output summary sheet) results in the dam completely filling with sediment over its 20 year design life.

The 4.8 m high dam also exceeds the suggested minimum criteria that the dam loses less than 50% of its capacity in 20 years, and a higher dam with a larger capacity is needed to satisfy the criteria. For the purposes of this example we assume that the designer decides to rule out the 3.8m dam after further consideration, and to investigate the impact of measures likely to reduce the sedimentation rate in a 4.8 m high dam. These are:

- Provision of additional storage for sediment;
- Sediment bypassing;
- Catchment conservation;
- Check dams.

Additional storage
This option has already been investigated. A dam with a height of 5.8 m will provide more storage for sediment, larger water yields, and a much longer and useful life. It will be more expensive, in terms of money or communal labour inputs, as the volume of earthworks required for a dam varies approximately with the cube of the dam height.

Sediment bypassing
Equations 6.2 and 6.3 are used to estimate the reduction in sediment load entering the dam, in terms of a sediment yield reduction factor resulting from the provision of a sediment bypassing arrangement.

$$Cn(bp) = 1- [n^* S_y * CA * K_1 *K_2 /(ARV * D.)] \qquad (6.2)$$

Where:
C_n (bp) = Proportion of original storage capacity left after n years of siltation with sediment bypassing
n = Number of years
S_y = Catchment sediment yield ($t/km^2/y$)
CA = Catchment area (km^2)
K_1 = 1.1 factor to account for the additional sediment diverted to the dam during flood peaks

K_2 = A second factor to account for water and sediment diverted to the dam during the wet season to replace wet season water abstractions and evaporative losses (from equation 6.3)
ARV = Annual runoff volume (m^3)
D = The settled density of dam sediment deposits, taken as 1.2 t/m^3

K_2 is estimated using equation 6.3.

K_2 = 12/(12-number of months in the dry season) (6.3)

Thus for a four month wet season K_2 is 1.5.

Cn(bp) = 1- [20*317*15.2*1.1*1.5 /(912000*1.4)] = 1-0.136 = 0.875

From the programme output the loss of storage capacity over twenty years for the 4.8 m high dam is 65.3%. The introduction of sediment bypassing reduces the capacity loss to 12.5%, i.e. reducing the sediment input to the dam by a factor of more than 5. If the topography of the dam site was suitable and the additional expense of providing the channel and side weir needed for bypassing could be justified this option might be considered.

The drawdown software can now be re-run to estimate the loss in dry season water yield due to sedimentation when the sediment input is reduced. The reduction in sediment load entering the dam is proportional to the reduction in the capacity loss, i.e. 0.635/0.125 = 5.08.

The easiest way to simulate this is to re-run the programme with the sediment concentration reduced by this ratio:

a) Determine the incoming sediment concentration from the programme output produced by the previous run (Output summary, design sediment concentration = 5287 ppm).
b) Reduce this by the factor determined above, i.e. 5287/5.08 = 1041 ppm.
c) Select the data entry screen (**Drawdown Output sheet,** and click the **Data Entry** button), select **Edit Sediment Data** and then the **Sediment Concentration** option. Select **User Defined** from the drop down list, and enter the new value 1041 in the data entry box, click **OK** and then **GO**.
d) Note the output for the 4.8 m dam with sediment bypassing on the two tabbed output sheets.

Results with and without bypassing are compared in the table below:

Table A1.14 Summary results for 4.8 m dam with and without bypassing

Parameter	4.8 m dam	4.8 m dam with sediment by-passing
Volume (m^3)	110951	110951
Capacity inflow ratio	0.12	-
% extracted (with 30% carry-over)	41.5	41.5
Potential irrigated area (ha, with 30% carry-over)	3.75	3.75
Potential number of livestock supported (with 30% carry-over)	1419	1419
% capacity loss over 20 years	65.3	12.9
% yield loss over 20 years (with no carry-over)	81.9	16.3
Probability of the dam filling (%) (with 30% carry-over)	86.2	-

Catchment conservation

The third option, catchment conservation, is evaluated using the procedure described in Chapter 6 or:

a) Estimate the pre-treatment sediment yield using the methods set out in Chapter 4.

From the programme output this is 317 $t/km^2/y$:

b) Estimate the "erosion" rate from the sediment yield using equation 6.4 or with the aid of Table A2.6 in Annex 2.

$$ER = S_y/(34.3 * CA^{-0.175}) \qquad (6.4)$$

Where:
ER = Untreated catchment erosion rate (t/ha/y)
S_y = Sediment yield ($t/km^2/y$)
CA = Catchment area (km^2)

$$ER = 317/(34.3*15.2^{-0.175}) = 14.9 \text{ t/ha/y}$$

c) Select a sediment yield reduction factor using Table 6.1 in Chapter 6 or equation 6.5.

$$SYRF = 1.44 * \ln(ER) - 1.32 \qquad (6.5)$$

Where:

SYRF = Sediment yield reduction factor
ER = Erosion rate calculated from equation 6.2 (t/ha/y)

SYRF = 2.66

d) Estimate the post-treatment catchment sediment yield from equation 6.6:

$$S_y con = Sy/SYRF \qquad (6.6)$$

Where:
S_y con = Sediment yield with conservation ($t/km^2/y$)
Sy = Pre-treatment catchment sediment yield ($t/km^2/y$)

SYRF = Sediment yield reduction factor

$S_y con = 317/2.66 = 119\ t/km^2/y$

The mean sediment yield over twenty years is estimated using equation 6.7 – assuming a five year lab time before conservation activities become fully effective.

$$S_{y20} = \frac{(5 * (S_y + S_y\,con)/2) + (15 * S_y\,con)}{20} \tag{6.7}$$

Where:
S_{y20} = Mean sediment yield over 20 years
S_y con = Sediment yield with conservation ($t/km^2/y$)
S_y = Pre-treatment catchment sediment yield ($t/km^2/y$)

$$S_{y20} = \frac{(5 * (317 + 119)/2) + (15 * 119)}{20} = 144\ t/km^2/y$$

Drawdown simulations can now be re-run using this revised sediment yield. This is most conveniently carried out by noting the "design sediment concentration" displayed on the "output summary sheet", multiplying this by the ratio S_{y20} / S_y, and re-running the 4.8 m dam drawdown simulation using the input sediment concentration option, rather than the sediment yield option.

The pre-treatment sediment concentration (design sediment concentration) from the previous drawdown simulation is 5287 ppm. With conservation this is predicted to reduce to:

5287*144/317 = 2402 ppm

To re-run the simulation ensure that the spreadsheet with the data for the 4.8 m dam is loaded. Select the data entry screen (**Drawdown Output sheet,** and click the **Data Entry** button), select **Edit Sediment Data** and then the **Sediment Concentration** option. Select **User Defined** from the drop down list, and enter the new value 2402 in the data entry box, click **OK** and then **GO**.

In the data entry screen select "edit sediment data" and the "sediment concentration ppm" option and then "user defined" from the drop down list. Enter 2402 ppm in the data and box and click "OK" and then "GO" and then "OK" when the analysis is completed. The impact of conservation can then be seen in the output summary sheets. Selected outputs for the "with" and "without" conservation options are listed below.

Table A1.15 comparison of dam capacity and water yield reductions with and without catchment conservation

	4.8 m dam Sy = 317 $t/m^2/y$	4.8 m dam Sy = 144 $t/m^2/y$
Capacity Loss in 20 Years (%)	65.3	29.7
Design Sediment Concentration (ppm)	5287	2402
Design Sediment Yield ($T/Km^2/year$)	317	144
Max Water Yield Year 0 (m^3)	84512	84512
Max Water Yield Year 20 (m^3)	15314	52840
Yield reduction over 20 Years (%)	81.9	37.5

The capacity loss and yield reduction over twenty years is predicted to be approximately halved.

However this conclusion would only be valid provided that the conservation measures:
a) Included all the areas of the catchment producing significant sediment inputs to the dam;
b) Are effective;
c) Are sustainable.

The designer would need to make a judgement on whether or not these conditions are satisfied before accepting that the introduction of conservation would ensure that the dam has an acceptable life.

Check dams

Reductions in sediment yields derived from check dams in the main stem river can be estimated as described in Chapter 6. The reduction obtained depends on the river slope, and the number, height and spacing of the check dams. The impact can be estimated by calculating “with check dam” sediment yield following the method described in Chapter 6, and using the procedure described above to revise the sediment input used in the drawdown simulation.

Annex 2 Aid for Manual Calculations

A2.1 Introduction

This annex presents graphs and tables for users who do not have access to a computer and who need to carry out calculations manually.

A2.2 Evaporative losses

Table A2.1 shows the proportion of a small dam's storage capacity that is lost to evaporation over an eight month drawdown period. It is based on drawdown simulations carried out assuming the dam is drawn down to empty with constant evaporation depths and water abstractions over the drawdown period. The effect of carry-over storage is not accounted for. Operating a dam with carry-over storage increases the proportion of the storage volume lost to evaporation as water levels in the dam are maintained at higher levels, with larger water surface areas.

Table A2.1 Approximate evaporative losses from small dams

Dam depth (m)	Dry season evaporation depth (m)									
	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
3.0	0.10	0.19	0.28	0.37	0.45	0.52	0.59	0.66	0.72	0.77
3.2	0.10	0.18	0.27	0.35	0.42	0.49	0.56	0.62	0.68	0.74
3.4	0.09	0.17	0.25	0.33	0.40	0.47	0.53	0.60	0.65	0.71
3.6	0.09	0.16	0.24	0.31	0.38	0.45	0.51	0.57	0.62	0.68
3.8	0.08	0.16	0.23	0.30	0.36	0.43	0.49	0.54	0.60	0.65
4.0	0.08	0.15	0.22	0.28	0.35	0.41	0.47	0.52	0.57	0.62
4.2	0.07	0.14	0.21	0.27	0.33	0.39	0.45	0.50	0.55	0.60
4.4	0.07	0.14	0.20	0.26	0.32	0.37	0.43	0.48	0.53	0.58
4.6	0.07	0.13	0.19	0.25	0.30	0.36	0.41	0.46	0.51	0.56
4.8	0.07	0.12	0.18	0.24	0.29	0.35	0.40	0.45	0.49	0.54
5.0	0.06	0.12	0.18	0.23	0.28	0.33	0.38	0.43	0.48	0.52
5.2	0.06	0.12	0.17	0.22	0.27	0.32	0.37	0.42	0.46	0.50
5.4	0.06	0.11	0.16	0.21	0.26	0.31	0.36	0.40	0.45	0.49
5.6	0.06	0.11	0.16	0.21	0.25	0.30	0.35	0.39	0.43	0.47
5.8	0.05	0.10	0.15	0.20	0.25	0.29	0.34	0.38	0.42	0.46
6.0	0.05	0.10	0.15	0.19	0.24	0.28	0.32	0.37	0.41	0.45
6.2	0.05	0.10	0.14	0.19	0.23	0.27	0.32	0.36	0.40	0.43
6.4	0.05	0.10	0.14	0.18	0.22	0.27	0.31	0.35	0.38	0.42
6.6	0.05	0.09	0.14	0.18	0.22	0.26	0.30	0.34	0.37	0.41
6.8	0.05	0.09	0.13	0.17	0.21	0.25	0.29	0.33	0.36	0.40
7.0	0.05	0.09	0.13	0.17	0.21	0.24	0.28	0.32	0.35	0.39
7.2	0.05	0.09	0.12	0.16	0.20	0.24	0.28	0.31	0.35	0.38
7.4	0.04	0.08	0.12	0.16	0.20	0.23	0.27	0.30	0.34	0.37
7.6	0.04	0.08	0.12	0.16	0.19	0.23	0.26	0.30	0.33	0.36
7.8	0.04	0.08	0.12	0.15	0.19	0.22	0.26	0.29	0.32	0.35
8.0	0.04	0.08	0.11	0.15	0.18	0.22	0.25	0.28	0.31	0.35

A2.2 Mean annual runoff

The table shows mean annual runoff as a function of mean annual precipitation and is calculated using Bullock's (1990) and Hill and Kidd's (1980) relationships. The table also lists the coefficients of annual runoff derived from the correlation described in Chapter 3 with runoff depths derived from the Bullock equation.

Table A2.2 Mean annual runoff and coefficient of variation of annual runoff

MAP mm	Bullock (1990)	Hill and Kidd (1980)					Coefficient of variation of annual runoff (%)
	MAR mm	Proportion DAMBO					
		0.02	0.04	0.06	0.08	0.10	
		MAR mm	MAR mm	MAR mm	MAR mm	MAR mm	
400	25						137
420	28						134
440	31	0					132
460	35	7					130
480	38	13					128
500	41	20	7				126
520	45	27	14				123
540	49	34	21	8			121
560	53	41	28	16	3		118
580	58	49	36	23	10		115
600	62	56	43	30	18	5	113
620	67	64	51	38	25	12	110
640	71	71	59	46	33	20	108
660	76	79	66	54	41	28	105
680	82	87	74	62	49	36	102
700	87	95	83	70	57	44	99
720	93	104	91	78	65	53	96
740	98	112	99	87	74	61	94
760	104	121	108	95	82	70	91
780	111	130	117	104	91	78	88
800	117	138	126	113	100	87	85
820	123	147	135	122	109	96	83
840	130	157	144	131	118	105	80
860	137	166	153	140	128	115	77
880	144	175	163	150	137	124	75
900	152	185	172	159	147	134	72
920	159	195	182	169	156	144	70
940	167	205	192	179	166	153	67
960	175	215	202	189	176	163	65
980	183	225	212	199	186	174	63
1000	191	235	222	210	197	184	61

A2.3 Probability of a dam filling

The table shows the probability of a dam filling as a function of the coefficient of variation of the annual runoff and a dam's capacity-inflow ratio, calculated using the method described in Mitchell (1987).

Table A2.3 Probability of dam filling

Capacity –inflow ratio	Coefficient of variation of annual runoff (%)								
	60	70	80	90	100	110	120	130	140
0.02	99.9	99.7	99.3	98.7	98.0	97.1	95.9	94.6	93.1
0.04	99.6	99.1	98.4	97.3	96.1	94.5	92.8	90.9	88.8
0.06	99.3	98.5	97.3	95.8	94.2	92.2	90.1	87.8	85.3
0.08	98.8	97.7	96.2	94.3	92.3	90.0	87.5	84.9	82.2
0.1	98.3	96.8	95.0	92.7	90.5	87.9	85.2	82.4	79.4
0.15	96.6	94.4	91.8	88.9	86.1	83.0	79.8	76.6	73.3
0.2	94.5	91.6	88.4	85.0	81.9	78.4	75.0	71.6	68.2
0.25	92.0	88.5	84.9	81.2	77.9	74.3	70.7	67.2	63.7
0.3	89.3	85.3	81.4	77.5	74.1	70.4	66.8	63.3	59.8
0.35	86.2	82.0	77.8	73.9	70.5	66.8	63.2	59.7	56.2
0.4	83.0	78.6	74.4	70.4	67.0	63.4	59.8	56.4	53.0
0.45	79.6	75.1	70.9	67.0	63.8	60.2	56.7	53.4	50.0
0.5	76.1	71.7	67.5	63.8	60.7	57.2	53.8	50.6	47.4
0.6	68.8	64.8	61.0	57.7	54.9	51.7	48.5	45.6	42.6
0.7	61.4	58.1	54.9	52.1	49.7	46.8	43.9	41.2	38.5
0.8	54.2	51.8	49.2	46.9	44.9	42.4	39.8	37.4	34.9
0.9	47.2	45.8	43.9	42.2	40.7	38.5	36.2	34.0	31.7
1	40.7	40.3	39.1	37.9	36.8	35.0	33.0	31.0	28.9

A2.4 Estimating catchment sediment yields from characterisation data

Sediment yields are estimated from characterisation data using equation 4.1:

$$S_y = 0.0194 * \text{Area}^{-0.2} * \text{MAP}^{0.7} * \text{Slope}^{0.3} * \text{SASE}^{1.2} * \text{STD}^{0.7} * \text{VC}^{0.5} \qquad (4.1)$$

Where :

S_y = Sediment yield (t/km^2/year)
Area = Catchment area (km^2)
MAP = Mean annual precipitation (mm)
Slope = River slope from the catchment boundary to the dam
SASE = Signs of active soil erosion (Score from catchment characterisation)
STD = Soil type and drainage (Score from catchment characterisation)
VC = Vegetation condition (Score from catchment characterisation)

Values for each term in the equation can be obtained from tables A2.4 to A2.7. The tabulated values are multiplied together to obtain the sediment yield.

Table A2.4 (0.0194* Area $^{-0.2}$)

Catchment Area	0.0194* Area $^{-0.2}$	Catchment Area	0.0194* Area $^{-0.2}$
0.5	0.0223	11.0	0.0120
0.6	0.0215	12.0	0.0118
0.7	0.0208	13.0	0.0116
0.8	0.0203	14.0	0.0114
0.9	0.0198	15.0	0.0113
1.0	0.0194	16.0	0.0111
1.2	0.0187	17.0	0.0110
1.4	0.0181	18.0	0.0109
1.6	0.0177	19.0	0.0108
1.8	0.0172	20.0	0.0107
2.0	0.0169	21.0	0.0106
2.2	0.0166	22.0	0.0105
2.4	0.0163	23.0	0.0104
2.6	0.0160	24.0	0.0103
2.8	0.0158	25.0	0.0102
3.0	0.0156	26.0	0.0101
3.2	0.0154	27.0	0.0100
3.4	0.0152	28.0	0.0100
3.6	0.0150	29.0	0.0099
3.8	0.0149	30.0	0.0098
4.0	0.0147	32.0	0.0097
4.5	0.0144	34.0	0.0096
5.0	0.0141	36.0	0.0095
5.5	0.0138	38.0	0.0094
6.0	0.0136	40.0	0.0093
6.5	0.0133	42.0	0.0092
7.0	0.0131	44.0	0.0091
8.0	0.0128	46.0	0.0090
9.0	0.0125	48.0	0.0089
10.0	0.0122	50.0	0.0089

Table A2.5 $MAP^{0.7}$

MAP	$MAP^{0.7}$	MAP	$MAP^{0.7}$	MAP	$MAP^{0.7}$
400	66.3	600	88.0	800	107.7
405	66.9	605	88.6	805	108.2
410	67.4	610	89.1	810	108.6
415	68.0	615	89.6	815	109.1
420	68.6	620	90.1	820	109.6
425	69.2	625	90.6	825	110.0
430	69.7	630	91.1	830	110.5
435	70.3	635	91.6	835	111.0
440	70.9	640	92.1	840	111.4
445	71.4	645	92.6	845	111.9
450	72.0	650	93.1	850	112.4
455	72.5	655	93.6	855	112.8
460	73.1	660	94.1	860	113.3
465	73.7	665	94.6	865	113.7
470	74.2	670	95.1	870	114.2
475	74.8	675	95.6	875	114.7
480	75.3	680	96.1	880	115.1
485	75.9	685	96.6	885	115.6
490	76.4	690	97.1	890	116.0
495	77.0	695	97.6	895	116.5
500	77.5	700	98.1	900	116.9
505	78.0	705	98.6	905	117.4
510	78.6	710	99.1	910	117.8
515	79.1	715	99.5	915	118.3
520	79.7	720	100.0	920	118.8
525	80.2	725	100.5	925	119.2
530	80.7	730	101.0	930	119.7
535	81.3	735	101.5	935	120.1
540	81.8	740	102.0	940	120.6
545	82.3	745	102.4	945	121.0
550	82.8	750	102.9	950	121.5
555	83.4	755	103.4	955	121.9
560	83.9	760	103.9	960	122.3
565	84.4	765	104.4	965	122.8
570	84.9	770	104.8	970	123.2
575	85.5	775	105.3	975	123.7
580	86.0	780	105.8	980	124.1
585	86.5	785	106.3	985	124.6
590	87.0	790	106.7	990	125.0
595	87.5	795	107.2	995	125.5
600	88.0	800	107.7	1000	125.9

Table A2.6 (Slope $^{0.3}$)

Slope	Slope $^{0.3}$	Slope	Slope $^{0.3}$
0.00001	0.0316	0.02000	0.3092
0.00002	0.0389	0.03000	0.3492
0.00003	0.0440	0.04000	0.3807
0.00004	0.0479	0.05000	0.4071
0.00005	0.0512	0.06000	0.4300
0.00006	0.0541	0.07000	0.4503
0.00007	0.0567	0.08000	0.4687
0.00008	0.0590	0.09000	0.4856
0.00009	0.0611	0.10000	0.5012
0.00010	0.0631	0.11000	0.5157
0.00020	0.0777	0.12000	0.5294
0.00030	0.0877	0.13000	0.5422
0.00040	0.0956	0.14000	0.5544
0.00050	0.1023	0.15000	0.5660
0.00060	0.1080	0.16000	0.5771
0.00070	0.1131	0.17000	0.5877
0.00080	0.1177	0.18000	0.5978
0.00090	0.1220	0.19000	0.6076
0.00100	0.1259	0.20000	0.6170
0.00200	0.1550	0.21000	0.6261
0.00300	0.1750	0.22000	0.6349
0.00400	0.1908	0.23000	0.6435
0.00500	0.2040	0.24000	0.6517
0.00600	0.2155	0.25000	0.6598
0.00700	0.2257	0.26000	0.6676
0.00800	0.2349	0.27000	0.6752
0.00900	0.2434	0.28000	0.6826
0.01000	0.2512	0.29000	0.6898

Table A2.7 (SASE $^{1.2}$, STD $^{0.7}$,VC $^{0.5}$)

Characterisation score	SASE $^{1.2}$	STD $^{0.7}$	VC $^{0.5}$
5	6.90	-	-
6	8.59	-	-
7	10.33	-	-
8	12.13	-	-
9	13.97	-	-
10	15.85	5.01	3.16
11	17.77	5.36	3.32
12	19.73	5.69	3.46
13	21.71	6.02	3.61
14	23.73	6.34	3.74
15	25.78	6.66	3.87
16	27.86	6.96	4.00
17	29.96	7.27	4.12
18	32.09	7.56	4.24
19	34.24	7.85	4.36
20	36.41	8.14	4.47
21	38.61	8.42	4.58
22	40.82	8.70	4.69
23	43.06	8.98	4.80
24	45.32	9.25	4.90
25	47.59	9.52	5.00
26	49.88	9.78	5.10
27	52.20	10.05	5.20
28	54.52	10.30	5.29
29	56.87	10.56	5.39
30	59.23	10.81	5.48
31	61.61	11.07	5.57
32	64.00	11.31	5.66
33	66.41	11.56	5.74
34	68.83	11.80	5.83
35	71.27	12.05	5.92
36	73.72	12.29	6.00
37	76.18	12.52	6.08
38	78.66	12.76	6.16
39	81.15	12.99	6.24
40	83.65	13.23	6.32

The sediment yield is estimated as the product of 0.0194 and the factors for Area, Mean Annual Precipitation, slope and the catchment characterisation factors derived from Tables A2.4 to A2.7.

Table A2.8 Estimating "Source erosion rates" from catchment area

The table lists values of the term ($34.3 * CA^{-0.175}$) included in equation 6.4.
Where:
CA = Catchment area (km^2)

CA km^2	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	34.3	33.7	33.2	32.8	32.3	32.0	31.6	31.3	30.9	30.7
2	30.4	30.1	29.9	29.6	29.4	29.2	29.0	28.8	28.6	28.5
3	28.3	28.1	28.0	27.8	27.7	27.5	27.4	27.3	27.2	27.0
4	26.9	26.8	26.7	26.6	26.5	26.4	26.3	26.2	26.1	26.0
5	25.9	25.8	25.7	25.6	25.5	25.5	25.4	25.3	25.2	25.1
6	25.1	25.0	24.9	24.9	24.8	24.7	24.7	24.6	24.5	24.5
7	24.4	24.3	24.3	24.2	24.2	24.1	24.1	24.0	23.9	23.9
8	23.8	23.8	23.7	23.7	23.6	23.6	23.5	23.5	23.4	23.4
9	23.4	23.3	23.3	23.2	23.2	23.1	23.1	23.0	23.0	23.0
10	22.9	22.9	22.8	22.8	22.8	22.7	22.7	22.7	22.6	22.6
11	22.5	22.5	22.5	22.4	22.4	22.4	22.3	22.3	22.3	22.2
12	22.2	22.2	22.1	22.1	22.1	22.0	22.0	22.0	22.0	21.9
13	21.9	21.9	21.8	21.8	21.8	21.8	21.7	21.7	21.7	21.6
14	21.6	21.6	21.6	21.5	21.5	21.5	21.5	21.4	21.4	21.4
15	21.4	21.3	21.3	21.3	21.3	21.2	21.2	21.2	21.2	21.1
16	21.1	21.1	21.1	21.0	21.0	21.0	21.0	21.0	20.9	20.9
17	20.9	20.9	20.8	20.8	20.8	20.8	20.8	20.7	20.7	20.7
18	20.7	20.7	20.6	20.6	20.6	20.6	20.6	20.5	20.5	20.5
19	20.5	20.5	20.5	20.4	20.4	20.4	20.4	20.4	20.3	20.3
20	20.3	20.3	20.3	20.3	20.2	20.2	20.2	20.2	20.2	20.1
21	20.1	20.1	20.1	20.1	20.1	20.1	20.0	20.0	20.0	20.0
22	20.0	20.0	19.9	19.9	19.9	19.9	19.9	19.9	19.8	19.8
23	19.8	19.8	19.8	19.8	19.8	19.7	19.7	19.7	19.7	19.7
24	19.7	19.7	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.5
25	19.5	19.5	19.5	19.5	19.5	19.5	19.4	19.4	19.4	19.4
26	19.4	19.4	19.4	19.4	19.3	19.3	19.3	19.3	19.3	19.3
27	19.3	19.3	19.2	19.2	19.2	19.2	19.2	19.2	19.2	19.2
28	19.1	19.1	19.1	19.1	19.1	19.1	19.1	19.1	19.1	19.0
29	19.0	19.0	19.0	19.0	19.0	19.0	19.0	18.9	18.9	18.9
30	18.9	18.9	18.9	18.9	18.9	18.9	18.8	18.8	18.8	18.8
31	18.8	18.8	18.8	18.8	18.8	18.8	18.7	18.7	18.7	18.7
32	18.7	18.7	18.7	18.7	18.7	18.7	18.6	18.6	18.6	18.6
33	18.6	18.6	18.6	18.6	18.6	18.6	18.5	18.5	18.5	18.5
34	18.5	18.5	18.5	18.5	18.5	18.5	18.4	18.4	18.4	18.4
35	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.3	18.3	18.3
36	18.3	18.3	18.3	18.3	18.3	18.3	18.3	18.3	18.3	18.2
37	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2
38	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1
39	18.1	18.1	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
40	18.0	18.0	18.0	18.0	18.0	17.9	17.9	17.9	17.9	17.9
41	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.8	17.8
42	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8
43	17.8	17.8	17.7	17.7	17.7	17.7	17.7	17.7	17.7	17.7

Table A2.8 Estimating "Source erosion rates" from catchment area (continued)

CA km^2	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
44	17.7	17.7	17.7	17.7	17.7	17.7	17.6	17.6	17.6	17.6
45	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6
46	17.6	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5
47	17.5	17.5	17.5	17.5	17.5	17.5	17.4	17.4	17.4	17.4
48	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4
49	17.4	17.4	17.3	17.3	17.3	17.3	17.3	17.3	17.3	17.3
50	17.3	17.3	17.3	17.3	17.3	17.3	17.3	17.3	17.2	17.2

Table A2.9 Catchment area $^{0.52}$

The table lists values for $CA^{0.52}$ for use in equation 7.1
Where
CA = Catchment area (km^2)

CA km^2	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	1.00	1.05	1.10	1.15	1.19	1.23	1.28	1.32	1.36	1.40
2	1.43	1.47	1.51	1.54	1.58	1.61	1.64	1.68	1.71	1.74
3	1.77	1.80	1.83	1.86	1.89	1.92	1.95	1.97	2.00	2.03
4	2.06	2.08	2.11	2.14	2.16	2.19	2.21	2.24	2.26	2.29
5	2.31	2.33	2.36	2.38	2.40	2.43	2.45	2.47	2.49	2.52
6	2.54	2.56	2.58	2.60	2.63	2.65	2.67	2.69	2.71	2.73
7	2.75	2.77	2.79	2.81	2.83	2.85	2.87	2.89	2.91	2.93
8	2.95	2.97	2.99	3.01	3.02	3.04	3.06	3.08	3.10	3.12
9	3.13	3.15	3.17	3.19	3.21	3.22	3.24	3.26	3.28	3.29
10	3.31	3.33	3.35	3.36	3.38	3.40	3.41	3.43	3.45	3.46
11	3.48	3.50	3.51	3.53	3.54	3.56	3.58	3.59	3.61	3.62
12	3.64	3.66	3.67	3.69	3.70	3.72	3.73	3.75	3.76	3.78
13	3.80	3.81	3.83	3.84	3.86	3.87	3.89	3.90	3.92	3.93
14	3.94	3.96	3.97	3.99	4.00	4.02	4.03	4.05	4.06	4.07
15	4.09	4.10	4.12	4.13	4.14	4.16	4.17	4.19	4.20	4.21
16	4.23	4.24	4.26	4.27	4.28	4.30	4.31	4.32	4.34	4.35
17	4.36	4.38	4.39	4.40	4.42	4.43	4.44	4.46	4.47	4.48
18	4.50	4.51	4.52	4.53	4.55	4.56	4.57	4.59	4.60	4.61
19	4.62	4.64	4.65	4.66	4.67	4.69	4.70	4.71	4.72	4.74
20	4.75	4.76	4.77	4.79	4.80	4.81	4.82	4.83	4.85	4.86
21	4.87	4.88	4.89	4.91	4.92	4.93	4.94	4.95	4.97	4.98
22	4.99	5.00	5.01	5.02	5.04	5.05	5.06	5.07	5.08	5.09
23	5.11	5.12	5.13	5.14	5.15	5.16	5.18	5.19	5.20	5.21
24	5.22	5.23	5.24	5.25	5.27	5.28	5.29	5.30	5.31	5.32
25	5.33	5.34	5.35	5.37	5.38	5.39	5.40	5.41	5.42	5.43
26	5.44	5.45	5.46	5.47	5.49	5.50	5.51	5.52	5.53	5.54
27	5.55	5.56	5.57	5.58	5.59	5.60	5.61	5.62	5.64	5.65
28	5.66	5.67	5.68	5.69	5.70	5.71	5.72	5.73	5.74	5.75
29	5.76	5.77	5.78	5.79	5.80	5.81	5.82	5.83	5.84	5.85
30	5.86	5.87	5.88	5.89	5.90	5.91	5.92	5.93	5.94	5.95
31	5.96	5.97	5.98	5.99	6.00	6.01	6.02	6.03	6.04	6.05
32	6.06	6.07	6.08	6.09	6.10	6.11	6.12	6.13	6.14	6.15
33	6.16	6.17	6.18	6.19	6.20	6.21	6.22	6.23	6.24	6.25
34	6.26	6.27	6.28	6.29	6.30	6.30	6.31	6.32	6.33	6.34
35	6.35	6.36	6.37	6.38	6.39	6.40	6.41	6.42	6.43	6.44
36	6.45	6.46	6.46	6.47	6.48	6.49	6.50	6.51	6.52	6.53
37	6.54	6.55	6.56	6.57	6.57	6.58	6.59	6.60	6.61	6.62
38	6.63	6.64	6.65	6.66	6.67	6.67	6.68	6.69	6.70	6.71
39	6.72	6.73	6.74	6.75	6.76	6.76	6.77	6.78	6.79	6.80
40	6.81	6.82	6.83	6.84	6.84	6.85	6.86	6.87	6.88	6.89
41	6.90	6.91	6.91	6.92	6.93	6.94	6.95	6.96	6.97	6.98
42	6.98	6.99	7.00	7.01	7.02	7.03	7.04	7.04	7.05	7.06
43	7.07	7.08	7.09	7.10	7.10	7.11	7.12	7.13	7.14	7.15

Table A2.9 Catchment area $^{0.52}$ (continued)

CA km^2	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
44	7.15	7.16	7.17	7.18	7.19	7.20	7.21	7.21	7.22	7.23
45	7.24	7.25	7.26	7.26	7.27	7.28	7.29	7.30	7.31	7.31
46	7.32	7.33	7.34	7.35	7.36	7.36	7.37	7.38	7.39	7.40
47	7.40	7.41	7.42	7.43	7.44	7.45	7.45	7.46	7.47	7.48
48	7.49	7.49	7.50	7.51	7.52	7.53	7.53	7.54	7.55	7.56
49	7.57	7.57	7.58	7.59	7.60	7.61	7.61	7.62	7.63	7.64
50	7.65	7.65	7.66	7.67	7.68	7.69	7.69	7.70	7.71	7.72

Table A2.10 MAP $^{0.537}$

The table lists values of MAP $^{0.537}$ for use in equation 7.1

MAP	MAP$^{0.537}$	MAP	MAP$^{0.537}$	MAP	MAP$^{0.537}$
400	25.0	600	31.0	800	36.2
405	25.1	605	31.2	805	36.3
410	25.3	610	31.3	810	36.5
415	25.5	615	31.5	815	36.6
420	25.6	620	31.6	820	36.7
425	25.8	625	31.7	825	36.8
430	26.0	630	31.9	830	36.9
435	26.1	635	32.0	835	37.1
440	26.3	640	32.1	840	37.2
445	26.4	645	32.3	845	37.3
450	26.6	650	32.4	850	37.4
455	26.8	655	32.5	855	37.5
460	26.9	660	32.7	860	37.7
465	27.1	665	32.8	865	37.8
470	27.2	670	32.9	870	37.9
475	27.4	675	33.1	875	38.0
480	27.5	680	33.2	880	38.1
485	27.7	685	33.3	885	38.2
490	27.8	690	33.5	890	38.4
495	28.0	695	33.6	895	38.5
500	28.1	700	33.7	900	38.6
505	28.3	705	33.8	905	38.7
510	28.4	710	34.0	910	38.8
515	28.6	715	34.1	915	38.9
520	28.7	720	34.2	920	39.0
525	28.9	725	34.4	925	39.2
530	29.0	730	34.5	930	39.3
535	29.2	735	34.6	935	39.4
540	29.3	740	34.7	940	39.5
545	29.5	745	34.9	945	39.6
550	29.6	750	35.0	950	39.7
555	29.8	755	35.1	955	39.8
560	29.9	760	35.2	960	39.9
565	30.1	765	35.4	965	40.1
570	30.2	770	35.5	970	40.2
575	30.3	775	35.6	975	40.3
580	30.5	780	35.7	980	40.4
585	30.6	785	35.9	985	40.5
590	30.8	790	36.0	990	40.6
595	30.9	795	36.1	995	40.7
600	31.0	800	36.2	1000	40.8

Table A2.11 PMF as a function of catchment area

The table lists values for PMF derived from equation 7.2
Where:
CA = Catchment area (km^2)

CA km^2	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	54.9	57.6	60.3	62.8	65.4	67.9	70.4	72.8	75.3	77.6
2	80.0	82.3	84.6	86.9	89.2	91.4	93.6	95.8	97.9	100.1
3	102.2	104.3	106.4	108.5	110.5	112.5	114.6	116.6	118.5	120.5
4	122.5	124.4	126.3	128.3	130.2	132.0	133.9	135.8	137.6	139.5
5	141.3	143.1	144.9	146.7	148.5	150.3	152.1	153.8	155.6	157.3
6	159.0	160.7	162.5	164.2	165.8	167.5	169.2	170.9	172.5	174.2
7	175.8	177.5	179.1	180.7	182.3	183.9	185.5	187.1	188.7	190.3
8	191.8	193.4	195.0	196.5	198.1	199.6	201.1	202.7	204.2	205.7
9	207.2	208.7	210.2	211.7	213.2	214.7	216.1	217.6	219.1	220.5
10	222.0	223.4	224.9	226.3	227.7	229.2	230.6	232.0	233.4	234.8
11	236.3	237.7	239.1	240.4	241.8	243.2	244.6	246.0	247.3	248.7
12	250.1	251.4	252.8	254.1	255.5	256.8	258.2	259.5	260.8	262.1
13	263.5	264.8	266.1	267.4	268.7	270.0	271.3	272.6	273.9	275.2
14	276.5	277.8	279.1	280.3	281.6	282.9	284.2	285.4	286.7	287.9
15	289.2	290.4	291.7	292.9	294.2	295.4	296.7	297.9	299.1	300.4
16	301.6	302.8	304.0	305.2	306.4	307.7	308.9	310.1	311.3	312.5
17	313.7	314.9	316.1	317.2	318.4	319.6	320.8	322.0	323.2	324.3
18	325.5	326.7	327.8	329.0	330.2	331.3	332.5	333.6	334.8	335.9
19	337.1	338.2	339.4	340.5	341.6	342.8	343.9	345.0	346.2	347.3
20	348.4	349.6	350.7	351.8	352.9	354.0	355.1	356.2	357.3	358.5
21	359.6	360.7	361.8	362.9	364.0	365.0	366.1	367.2	368.3	369.4
22	370.5	371.6	372.6	373.7	374.8	375.9	376.9	378.0	379.1	380.2
23	381.2	382.3	383.3	384.4	385.5	386.5	387.6	388.6	389.7	390.7
24	391.8	392.8	393.9	394.9	395.9	397.0	398.0	399.1	400.1	401.1
25	402.2	403.2	404.2	405.2	406.3	407.3	408.3	409.3	410.3	411.4
26	412.4	413.4	414.4	415.4	416.4	417.4	418.4	419.4	420.4	421.4
27	422.4	423.4	424.4	425.4	426.4	427.4	428.4	429.4	430.4	431.4
28	432.4	433.3	434.3	435.3	436.3	437.3	438.2	439.2	440.2	441.2
29	442.1	443.1	444.1	445.0	446.0	447.0	447.9	448.9	449.9	450.8
30	451.8	452.7	453.7	454.6	455.6	456.5	457.5	458.4	459.4	460.3
31	461.3	462.2	463.2	464.1	465.1	466.0	466.9	467.9	468.8	469.7
32	470.7	471.6	472.5	473.5	474.4	475.3	476.3	477.2	478.1	479.0
33	480.0	480.9	481.8	482.7	483.6	484.5	485.5	486.4	487.3	488.2
34	489.1	490.0	490.9	491.8	492.7	493.7	494.6	495.5	496.4	497.3
35	498.2	499.1	500.0	500.9	501.8	502.7	503.5	504.4	505.3	506.2
36	507.1	508.0	508.9	509.8	510.7	511.5	512.4	513.3	514.2	515.1
37	516.0	516.8	517.7	518.6	519.5	520.3	521.2	522.1	523.0	523.8
38	524.7	525.6	526.4	527.3	528.2	529.0	529.9	530.8	531.6	532.5
39	533.4	534.2	535.1	535.9	536.8	537.6	538.5	539.4	540.2	541.1
40	541.9	542.8	543.6	544.5	545.3	546.2	547.0	547.9	548.7	549.5
41	550.4	551.2	552.1	552.9	553.8	554.6	555.4	556.3	557.1	557.9
42	558.8	559.6	560.4	561.3	562.1	562.9	563.8	564.6	565.4	566.3
43	567.1	567.9	568.7	569.6	570.4	571.2	572.0	572.9	573.7	574.5

Table A2.11 PMF as a function of catchment area (continued)

CA km^2	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
44	575.3	576.1	577.0	577.8	578.6	579.4	580.2	581.0	581.8	582.7
45	583.5	584.3	585.1	585.9	586.7	587.5	588.3	589.1	589.9	590.7
46	591.5	592.3	593.1	594.0	594.8	595.6	596.4	597.2	597.9	598.7
47	599.5	600.3	601.1	601.9	602.7	603.5	604.3	605.1	605.9	606.7
48	607.5	608.3	609.1	609.8	610.6	611.4	612.2	613.0	613.8	614.6
49	615.3	616.1	616.9	617.7	618.5	619.2	620.0	620.8	621.6	622.4
50	623.1	623.9	624.7	625.5	626.2	627.0	627.8	628.6	629.3	630.1

Table A2.12a Discharge per unit width for masonry spillways

H (m)	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.1	0.06	0.07	0.07	0.08	0.09	0.10	0.12	0.13	0.14	0.15
0.2	0.16	0.17	0.19	0.20	0.21	0.23	0.24	0.25	0.27	0.28
0.3	0.30	0.31	0.33	0.34	0.36	0.37	0.39	0.41	0.42	0.44
0.4	0.46	0.47	0.49	0.51	0.53	0.54	0.56	0.58	0.60	0.62
0.5	0.64	0.66	0.67	0.69	0.71	0.73	0.75	0.77	0.80	0.82
0.6	0.84	0.86	0.88	0.90	0.92	0.94	0.97	0.99	1.01	1.03
0.7	1.05	1.08	1.10	1.12	1.15	1.17	1.19	1.22	1.24	1.26
0.8	1.29	1.31	1.34	1.36	1.39	1.41	1.44	1.46	1.49	1.51
0.9	1.54	1.56	1.59	1.61	1.64	1.67	1.69	1.72	1.75	1.77
1.0	1.80	1.83	1.85	1.88	1.91	1.94	1.96	1.99	2.02	2.05
1.1	2.08	2.11	2.13	2.16	2.19	2.22	2.25	2.28	2.31	2.34
1.2	2.37	2.40	2.43	2.46	2.49	2.52	2.55	2.58	2.61	2.64
1.3	2.67	2.70	2.73	2.76	2.79	2.82	2.85	2.89	2.92	2.95
1.4	2.98	3.01	3.05	3.08	3.11	3.14	3.18	3.21	3.24	3.27
1.5	3.31	3.34	3.37	3.41	3.44	3.47	3.51	3.54	3.57	3.61
1.6	3.64	3.68	3.71	3.75	3.78	3.82	3.85	3.88	3.92	3.95
1.7	3.99	4.03	4.06	4.10	4.13	4.17	4.20	4.24	4.27	4.31
1.8	4.35	4.38	4.42	4.46	4.49	4.53	4.57	4.60	4.64	4.68
1.9	4.71	4.75	4.79	4.83	4.86	4.90	4.94	4.98	5.01	5.05
2.0	5.09	5.13	5.17	5.21	5.24	5.28	5.32	5.36	5.40	5.44
2.1	5.48	5.52	5.56	5.60	5.63	5.67	5.71	5.75	5.79	5.83
2.2	5.87	5.91	5.95	5.99	6.03	6.08	6.12	6.16	6.20	6.24
2.3	6.28	6.32	6.36	6.40	6.44	6.48	6.53	6.57	6.61	6.65
2.4	6.69	6.73	6.78	6.82	6.86	6.90	6.95	6.99	7.03	7.07
2.5	7.12	7.16	7.20	7.24	7.29	7.33	7.37	7.42	7.46	7.50

Table A2.12b Discharge per unit width for grassed spillways

H (m)	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.1	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14
0.2	0.15	0.16	0.17	0.18	0.19	0.21	0.22	0.23	0.24	0.26
0.3	0.27	0.28	0.30	0.31	0.33	0.34	0.36	0.37	0.39	0.40
0.4	0.42	0.43	0.45	0.47	0.48	0.50	0.51	0.53	0.55	0.57
0.5	0.58	0.60	0.62	0.64	0.65	0.67	0.69	0.71	0.73	0.75
0.6	0.77	0.79	0.81	0.83	0.84	0.86	0.88	0.90	0.93	0.95
0.7	0.97	0.99	1.01	1.03	1.05	1.07	1.09	1.11	1.14	1.16
0.8	1.18	1.20	1.23	1.25	1.27	1.29	1.32	1.34	1.36	1.39
0.9	1.41	1.43	1.46	1.48	1.50	1.53	1.55	1.58	1.60	1.63
1.0	1.65	1.67	1.70	1.72	1.75	1.78	1.80	1.83	1.85	1.88
1.1	1.90	1.93	1.96	1.98	2.01	2.03	2.06	2.09	2.11	2.14
1.2	2.17	2.20	2.22	2.25	2.28	2.31	2.33	2.36	2.39	2.42
1.3	2.45	2.47	2.50	2.53	2.56	2.59	2.62	2.65	2.67	2.70
1.4	2.73	2.76	2.79	2.82	2.85	2.88	2.91	2.94	2.97	3.00
1.5	3.03	3.06	3.09	3.12	3.15	3.18	3.21	3.25	3.28	3.31
1.6	3.34	3.37	3.40	3.43	3.47	3.50	3.53	3.56	3.59	3.63
1.7	3.66	3.69	3.72	3.75	3.79	3.82	3.85	3.89	3.92	3.95
1.8	3.98	4.02	4.05	4.08	4.12	4.15	4.19	4.22	4.25	4.29
1.9	4.32	4.36	4.39	4.42	4.46	4.49	4.53	4.56	4.60	4.63
2.0	4.67	4.70	4.74	4.77	4.81	4.84	4.88	4.91	4.95	4.99
2.1	5.02	5.06	5.09	5.13	5.17	5.20	5.24	5.27	5.31	5.35
2.2	5.38	5.42	5.46	5.49	5.53	5.57	5.61	5.64	5.68	5.72
2.3	5.76	5.79	5.83	5.87	5.91	5.94	5.98	6.02	6.06	6.10
2.4	6.13	6.17	6.21	6.25	6.29	6.33	6.37	6.41	6.44	6.48
2.5	6.52	6.56	6.60	6.64	6.68	6.72	6.76	6.80	6.84	6.88

Annex 3 Environmental impact and sustainability of small dam projects

This annex is included to assist designers and planners to consider aspects such as socio-economic and environmental factors, which are not covered in this manual, when small dam projects are being planned and implemented.

A3.1 Environmental impacts

Small dam projects have much smaller impacts than those associated with larger dams. The table below summarises impacts that may be expected. It is based on the recommendations made in the Ministry of Water Development (MOWD), Kenya (1992) design manual[16], and follows the format adopted for the ICID (1993) environmental checklist.

Table A3.1 Environmental impacts

Potential Impact		Positive impact possible	Negative impact possible	Comment
Hydrology	Low flow regime		**X**	Significant downstream impact – base flows substantially reduced or eliminated. Water rights of downstream users must be investigated and if necessary the dam designed and operated to provide compensation flows.
	Flood flow regime	**X**		Storage and attenuation in the dam may reduce downstream flood peak discharges.
	Fall in water table		**X**	Dams constructed on rock sills may cut off groundwater flow and result in reduced recharge of groundwater downstream from a dam.
	Rise in water table	**X**		Recharge from dam may increase water table.
Pollution	Sewage - industrial pollution, agricultural pollution		**X**	Pollutants released into or intercepted by upstream rivers will enter dam. If it is not possible to eliminate pollution at source alternative dam sites should be considered.
	Herbicides and pesticides		**X**	May enter river due to crop spraying or cattle dipping. Dams should be located upstream from cattle dips.
	Cattle		**X**	Cattle should not be allowed to enter the dam area. Downstream watering points should be provided.
	Anaerobic effects		**X**	Very deep dams can stratify, but this is unlikely in small dams or in dams that are that are drawn down.

[16] Full reference is given in section 8.2 of the main report

Table A3.1 Environmental impacts (continued)

Potential Impact		Positive impact possible	Negative impact possible	Comment
Sediments	Local erosion		**X**	Dam may attract and concentrate large populations of cattle leading to overgrazing and accelerated erosion. Indiscriminate and unplanned provision of dams for cattle watering should be avoided.
	River Morphology		**X**	Dam will cut off supply of sediment to downstream river system, lowering river bed levels and inducing bank scour in the reach downstream from the dam.
	Reservoir sedimentation		**X**	Discussed in the guidelines.
Ecology	Project lands		**X**	Land use changes triggered by construction of dam may trigger undesirable ecological impacts.
	Water bodies	**X**		Water stored in dam provides new range of aquatic habitats for fish and birds, etc. Fish farming may be introduced.
	Wetlands	**X**		Wetland habitats may be created.
	Rare species	**X**	**X**	Construction of a dam may threaten rare species, conversely, new habitats may sustain threatened rare species.
	Animal Migration		**X**	Impounding in a dam may disrupt wildlife movements and prevent upstream migration of fish.
Socio-economic	Resettlement		**X**	Not usually a serious issue in small dam projects. Adequate compensation for families who may need to move and for any loss of land must be agreed at the outset of small dam projects.
	Incomes	**X**		Water stored in the dam can be used for a number of income generating activities, i.e. garden irrigation of cash crops, livestock watering, fish farming, brick making, etc.
	Womens role	**X**		Women are traditional family providers of water and special emphasis is usually given to ensure the involvement and representation of women in decision-making structures such as Dam committees.
	Participation	**X**		Small dam projects are usually developed using participatory methods. Activities relating to planning and building dams and setting up an irrigated garden often lead to additional communal activities, for example, savings clubs or communal cash generating enterprises.

Table A3.1 Environmental impacts (continued)

Potential Impact		Positive impact possible	Negative impact possible	Comment
Health	Water and sanitation	**X**	**X**	Water supplies used for drinking must be protected. Recharge from dams can improve water supplies from local boreholes. Toilets and clothes washing facilities are sometimes provided downstream of the dam to reduce the possibility of contamination.
	Nutrition	**X**		The vegetables grown in irrigated gardens enhance family diets.
	Disease hosts and control		**X**	Earthen dams can be a risk factor for malaria and schistosomiasis infection. Locating dams away from dwellings and use of impregnated bed-nets has proved to be efficient in reducing the risk of malaria. Snail control through use of endod (Phytolacca dodecandra) may be feasible at dam sites.

A3.2 Sustainability of catchment conservation measures used to reduce dam siltation rates

Many benefits might be obtained from improving the management of catchments containing small dams:

(a) Reduced siltation rates in the dam.

(b) Avoiding the losses that result from unchecked land degradation such as decreasing soil productivity, land going out of production through gully erosion, and the cost of fertiliser that would have to be purchased to maintain yields on eroded soils.

(c) Increased crop yields resulting from improved land husbandry.

(d) Enhanced livestock products from restored or improved pasture, better use of crop residues or from growing fodder species.

(e) Value of wood and non-wood products to be obtained from increased tree planting and improved management of natural forest areas.

In order to be sustainable soil conservation technologies should be:

- **Simple –** be readily understood and implemented by farmers;
- **Low cost –** be within the financial reach of farmers, require limited labour and require no foregone benefits (e.g. land taken out of production);
- **Productive –** lead to substantially increased benefits, some 50-100% better than existing practices (i.e. higher crop yields, increased fuel wood, guaranteed fodder supplies), preferably within the first year of adoption;

- **Maintainable** – requiring limited effort or purchased inputs to maintain on an annual basis;

- **Low risk** – non-susceptible to climatic variations (particularly drought) or local market fluctuations (supply exceeding demand);

- **Flexible** – leave scope for future developments (a cereal variety can be changed after one season but a decision to plant a long-lived perennial tree crop is not so easily reversed);

- **Conservation effective** – contribute to the maintenance of soil productivity (e.g. increase ground cover and soil organic matter levels, improve surface infiltration, reduce runoff, prevent surface movement).

Conservation interventions are best developed using participatory methodologies. Conservation measures and the approach advocated for the catchments of small communal dams in Zimbabwe are described in ZFU and Agritex (1998).

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