Sedimentation in Small Dams

Estimating the impact of catchment conservation, check dams and sediment bypassing in reducing dam siltation rates

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Summary

Sedimentation in Small Dams

Estimating the impact of catchment conservation, check dams and sediment bypassing in reducing dam siltation rates

P Lawrence A Lo Cascio

Report ODTN 121 January 2004

NGO's and Government Agencies have constructed thousands of small dams in semi-arid regions of East and Southern Africa to provide water for livestock and small-scale irrigation. The useful life of many of these dams is reduced by excessive siltation – some small dams silt up after only a few years. This issue is poorly covered in the many small dam design manuals that are available, as they mostly focus on civil engineering design and construction aspects.

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

A capability to estimate the impact of measures to reduce small dam sedimentation rates is needed to enable the sedimentation lifetime of dams to be estimated at the planning and design stage of small dam projects. This report describes approximate methods for carrying out these calculations. The measures considered are check dams, soil and water conservation measures and sediment bypassing.

Given the large temporal and spatial variations in sediment yields from small catchments in semi-arid regions, and the very sparse quantitative information on the impacts of soil conservation in communally farmed areas, the methods described can only provide very approximate results. Nevertheless, when used in conjunction with the other outputs from the project they enable designers of small dams to assess the potential for increasing the effective life of dams subject to high siltation rates.

Check dams in rivers are often included as a component of soil conservation programmes. They usually consist of a cascade of low weirs, often constructed from gabions or rubble masonry, which reduce the gradient of the river supplying a dam, and trap sediment in the backwater zone upstream of the check structures.

Check dams have a small sediment storage capacity compared with the storage volume of the dams they are protecting, and usually fill up fairly rapidly with coarse bed load sediments. Their effectiveness as sediment trapping structures inevitably reduces over time, due to the sedimentation that occurs in the river reaches between the check structures. If the flows and sediment loads supplied from a catchment are not reduced, sedimentation will continue to occur until a new river bed is eventually established at a higher level, and parallel to the original bed. Usually check dams are constructed as a component of a wider soil conservation strategy, which

Summary continued

may take some years to become effective, with the intention that activities in the catchment will control runoff and the supply of sediments from a catchment when the check dams have silted up. Check dams also have a longer-term role to play in stabilising gullies and reducing stream gradients, and hence scour from channel beds and banks.

The initial impact of check dams on the sediment loads delivered to a downstream dam is assessed by considering the volume of sediment that is deposited between check structures, and the time taken for this sedimentation process to be completed. This allows the impact of the check dams on the sediment loads delivered to a small dam to be quantified.

Impacts of soil and water conservation interventions In the small catchment areas of small dams soil conservation programmes can provide significant reductions in sediment yields within a relatively short time period. In order to estimate these impacts it is necessary to determine:

- The effectiveness and sustainability of the conservation interventions that are proposed;
- The magnitude of the benefit that will be obtained;
- The time period before this benefit is realised.

In order to be sustainable, soil conservation technologies need to be simple, low cost, productive, maintainable, low risk, flexible and conservation effective.

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 reductions in sediment yields are seen as a consequence of good land husbandry.

Strategies to correct the processes of degradation that have already had an adverse impact on soil productivity and sediment yields may involve:

- The use of physical structures or vegetative techniques to control runoff and soil loss;
- The rehabilitation of severely degraded land (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 fallow 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.).

The impacts of conservation are quantified using a sediment yield reduction factor which is based on the pre-treatment sediment yield.

Summary continued

Sediment bypassing In semi-arid zones the volume of the annual runoff from small catchments varies widely between years. Because of this small dams are sometimes designed to have a relatively small capacity when compared with the inflow in an average year, to ensure that they will fill in relatively dry years. While this ensures the reliability of storage at a specified probability level, it is potentially disastrous when sedimentation is considered. Sediment bypassing is a mechanism that has the potential to reduce siltation rates, and extend the useful life of small dams that have a low capacity to annual inflow ratio.

With sediment bypassing water and sediment are diverted past the reservoir storage area when a dam is full. This reduces sedimentation considerably in the reservoir storage area. The principle could be applied to small dams, if a bypass canal is constructed connecting 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.

A numerical model was set up using HR Wallingford's ISIS software to investigate the performance that could be expected from sediment bypassing arrangements applied to a small dam. The model was used to quantify the proportions of the flows, and sediment loads, entering and settling in the reservoir or passed over the spillway, for a range of side weir arrangements, flood discharges and flood event sequences.

The following conclusions were drawn:

- In any particular wet season the benefit obtained will be strongly influenced by the sequence of 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 larger floods occurring after the dam is full 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 reducing 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 for the construction of a bypass canal and side weir, at a cost that can be justified by an increase in a dam's effective life.
- Sediment bypassing is only likely to be an attractive option for dams with a low capacity to inflow ratio, say less than 0.3, which have 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.





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1. Introduction

NGO's and Government Agencies have constructed thousands of small dams in semiarid regions of East and Southern Africa to provide water for livestock and small-scale irrigation. The useful life of many of these dams is reduced by excessive siltation – some small dams silt up after only a few years. This issue is poorly covered in the many small dam design manuals that are available, as they mostly focus on civil engineering design and construction aspects.

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

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

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

A capability to estimate the impact of measures to reduce small dam sedimentation rates is needed to enable the sedimentation lifetime of dams to be estimated at the planning and design stage of small dam projects. This report describes approximate methods for carrying out these calculations. The measures considered are:

- Check dams, discussed in chapter 2;
- Soil and water conservation measures, discussed in chapter 3;
- Sediment bypassing, discussed in chapter 4.

Given the large temporal and spatial variations in sediment yields from small catchments in semi-arid regions, and the very sparse quantitative information on the impacts of soil conservation in communally farmed areas, the methods described can only provide very approximate results. Nevertheless, when used in conjunction with the other outputs from the project, described in the report series listed above, they will enable designers of small dams to make an assessment of the potential to increase the effective life of dams subject to high siltation rates.

2. 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. They usually consist of a cascade of low weirs, often constructed from gabions or rubble masonry, that reduce the gradient of the river supplying a dam, and trap sediment in the backwater zone upstream of the check structures. The design of check dams is described in many soil conservation handbooks and manuals, and is not covered here.

Check dams have a small sediment storage capacity compared with the storage volume of the dams they are protecting, and usually fill up fairly rapidly with coarse bed load sediments. Their effectiveness as sediment trapping structures inevitably reduces over time, due to the sedimentation that occurs in the river reaches between the check structures. If the flows and sediment loads supplied from a catchment are not reduced sedimentation will continue to occur until a new river bed is eventually established at a higher level, and parallel to the original bed. Usually check dams are constructed as a component of a wider soil conservation strategy, which may take some years to become effective, with the intention that activities in the catchment will control runoff and the supply of sediments from a catchment when the check dams have silted up. Check dams also have a longer-term role to play in stabilising gullies and reducing stream gradients, and hence scour from channel beds and banks.

The initial impact of check dams on the sediment loads delivered to a downstream dam can be assessed by considering the volume of sediment that is deposited between check structures, and the time taken for this sedimentation process to be completed. If sediment settled at a uniform rate during the deposition process the number of years before a check dam silted up would simply be the available storage volume divided by the annual volume of coarse bed material sediments transported by the river. In practice the volume of coarse sediments settling between check structures reduces with time, as the river bed rises and the water velocities and sediment transporting capacity increase.

These effects were investigated in a series of numerical simulations using HR Wallingford's "SHARC" sediment routing software. The results indicate that for typical conditions in small sand bed rivers actual deposition times might be 2 and 3 times longer than the deposition time derived from dividing the storage volume by the annual volume of bed material sediments transported by the river. The actual deposition time is controlled by the river and sediment characteristics, and the height and spacing of the check dams, and could vary between wide limits. For a typical case a factor of 2.6 might be appropriate.

Initial reductions in sediment yields (derived from check dams) from a catchment to a small dam are estimated by applying this factor. The suggested procedure is:

- a) Estimate the sediment yield from the catchment using the methods set out in the HR Wallingford report OD 152.
- b) If the range of sediment sizes transported by the river is not known, as will usually be the case, assume that 50 % of the annual sediment load consists of sand and larger sediment sizes. (This assumption is based on the sediment sizes settling in dams in Zimbabwe as reported by Interconsult (1985).)

(2.1)

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

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

Where:

Vcheck = Sediment volume stored between check dams (m^3) 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 be replaced by the storage volume in the debris dam in the subsequent calculation.)

A settled density for sand sized sediment of 1.4 t/m³ is assumed.

The time before the check dams silt up is then:

$$T = 2.6 * Vcheck / (0.5 * S_v * CA / 1.4)$$
(2.2)

Where:

Vcheck = Sediment storage volume (m³) S_y = Pre-treatment catchment sediment yield (t/km²/y) CA = Catchment area (km²)

If "T" is less than the twenty years usually assumed as the design life of a small dam then the volume of sediment entering the dam over twenty years will be reduced by Vcheck. If T is longer than twenty years then the reduction will be smaller than Vcheck, and could be approximately estimated as Vcheck *20/T.

Very much larger reductions in sedimentation rates than estimated above 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 small dam 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. Disposal of the sediments removed from check dams would also be a problem in most catchments.

3. Impacts of soil and water conservation interventions

It is not possible to predict the impacts of soil conservation on sediment yields from a particular catchment without carrying out detailed site-specific studies. These are not usually feasible as part of a small dam design study, which is often limited in terms of time and resources. Nevertheless some means of making estimates of the impact of conservation interventions on the sedimentation life of small dams is needed. An approximate procedure for making these estimates is described in this chapter.

A wide range of soil conservation measures is described in local manuals and guidelines. A recent example describing a range of conservation interventions suitable for the catchments of small dams is described in a series of booklets produced with DFID support in Zimbabwe by ZFU and Agritex (1998). Similar manuals are available in most countries in East and Southern Africa. The benefits that might be obtained from improved soil conservation in small dam catchments include:

- Reduced siltation rates in the downstream dam.
- Avoiding the losses that result from land degradation, such as decreasing yields due to declining soil productivity, land going out of production through gully erosion, and reductions in the cost of fertiliser that would have to be purchased to maintain yields on eroded soils.
- Increased crop yields resulting from improved land husbandry.
- Enhanced livestock products from restored or improved pasture, better use of crop residues or fodder species.
- Value of wood and non-wood products to be obtained from increased tree planting and improved management of natural forest areas.

In the small catchment areas of small dams soil conservation programmes can provide significant reductions in sediment yields within a relatively short time period. In order to estimate these impacts it is necessary to determine:

- The effectiveness and sustainability of the conservation interventions that are proposed;
- The magnitude of the benefit that will be obtained;
- The time period before this benefit is realised.

Quantitative data that would enable any of the above to be determined with confidence for the wide range of conservation measures and catchment types found in East and Southern Africa are almost entirely lacking. A considerable amount of data from plot and micro-catchment studies carried out by research stations is available from semi-arid regions, which shows very large reductions in sediment yields from small land areas under highly managed conditions. However these types of data are virtually useless for assessing sediment yield reductions achievable at the catchment scale (see FAO (1993)).

3.1 EFFECTIVENESS AND SUSTAINABILITY

In soil conservation programmes designed to protect small dams the primary interest is in reducing sediment yields. The land users who will need to carry out conservation activities in a catchment do 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 themselves. 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 reductions in sediment yields are seen as 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 order to be sustainable soil conservation technologies need to 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 annually limited effort or purchased inputs to maintain;
- Low risk non-susceptible to climatic variations (particularly drought) or local market fluctuations (supply exceeding demand);
- Flexible leave scope for future developments (a crop 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).

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 (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 fallow to restore topsoil structure and raise soil organic matter levels;
- The use of engineering structures to reduce or control stream bank erosion and reduce the supply of sediment to downstream reservoirs or irrigation works (check dams, etc.).

3.2 THE MAGNITUDE OF THE BENEFIT

There are few data that can be used to quantify the reductions in sediment yields resulting from farmer-managed conservation interventions in the catchments of small dams. A broad indication of the scale of changes in sediment yield attributed to changes in land use can be obtained from a summary of measurements shown in Table 3.1, from HR Wallingford (1995).

Region	Land use change	Increase in
e	e	sediment vield ¹
		Seament yield
Rajasthan, India	Overgrazing	4 to 18
Utah USA	Overgrazing	10 to 100
Olkahama, USA	Overgrazing and cultivation	50 to 100
Olkahama, USA	Cultivation	5 to 32
Texas USA	Forest clearance and cultivation	340
N California USA	Steep forest to grassland	5 to 25
Missippi, USA	Forest clearance and cultivation	10 to 100
S Brazil	Forest clearance and cultivation	4500
Westland New Zealand	Clear felling	8
Oregon USA	Clear cutting forest	39
Southern Malawi	Forest to traditional agricultural	100
Southern Kenya	Bush to cultivation	15
Southern Kenya	Bush to denuded grazing land	50
Ivory coast Africa	Forest clearance	50 to 1000
Loess Plateau, China	Natural cover to cultivation	40

Table 3.1	Increases in sediment	t vields following	land use changes ¹
		Jieres romo mana	and ase endinges

Note 1 The factor by which sediment yield increased following the land use change.

In general overgrazing or a change from natural vegetation to arable land or overgrazed rangeland has resulted in increases in sediment yields ranging from four to more than one hundred times. Measurements made by HR Wallingford and the Land Husbandry Branch of the Ministry of Agriculture in Malawi in four micro-catchments demonstrated that a steep catchment under uncontrolled rainfed maize production produced about one hundred times more sediment than catchments with similar physical characteristics conserved by using a range of physical and biological conservation measures, or 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, 1986). This study was carried out with a high level of management on research farms covering a few hectares, and it is not expected that a hundred-fold, or

¹ The table is based on the table given in Walling and Webb (1983), with additional data compiled by HR Wallingford (1995).

even ten-fold reductions in yields would be easily achievable in the larger catchments of small dams under communal management.

A simple and approximate procedure has been developed to enable estimates of reductions in sediment yields to be made following the introduction of conservation activities. It is based on the following assumptions:

- Conservation interventions are implemented over all the 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 potential for reducing yields will be in catchments with the largest untreated yields.

The proportion of the sediment eroded from the land that is transported to the catchment outlet, i.e. the sediment delivery ratio, 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 the opportunities for sediment deposition within the catchment increase. The Roehl (1962) relationship, simplified so that the sediment delivery ratio is a function only of the catchment area (Abernerthy, 1987) is used to estimate sediment delivery ratios in the procedure proposed for use in small dam catchments.

$$SDR = 0.343 * CA^{-0.175}$$
 (3.1)

Where: SDR = Sediment delivery ratio CA = Catchment area (km²)

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 3.1 with the lowest measured small dam catchment sediment yield and catchment area reported in HR Wallingford (2003c), and is also the erosion rate often quoted for well-managed commercial arable farm land in Zimbabwe. This is taken as the lowest erosion rate that is expected in an extremely well-conserved small dam catchment. Adopting the conservative assumption that conservation activities might produce a five-fold reduction in the sediment yield in catchments with the relatively high erosion rate (80 t/ha) recently reported for communal lands in Zimbabwe (Nemasasi *et al.*, 2001), led to the sediment yield reduction factors suggested in Table 3.2. Reduction factors become smaller as pre-treatment erosion rates reduce.

Table 3.2	Suggested sediment yield reduction factors
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Untreated erosion rate t/ha/y	Suggested sediment yield reduction factor
10	2
20	3
40	4
80	5
160	6

3.3 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 will continue to contribute to sediment yields even where it is possible to reduce or eliminate erosion over most of a catchment area (Walling and Webb, 1983). In the catchments of small dams, with catchment areas up to 10 km², the period before the full benefits of conservation are reflected in reduced sediment yields at catchment outlets obviously depends on the specific interventions that are to be implemented. Information on "recovery times" for small basins subjected to various disturbances suggests a return to pre-disturbance sediment loads as vegetation is reestablished in as little as a few years in humid areas, and up to one or two decades in semiarid areas. It is often assumed that overgrazed rangeland can recover is as little as two to three years. For typical small catchments of small dams we have assumed the "lag times" listed in Table 3.3. 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 3.3	Conservation	lag	times
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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

3.4 PROCEDURE FOR ESTIMATING THE IMPACTS OF CONSERVATION

A procedure to estimate the impact of conservation based on the assumptions discussed above is:

- a) Estimate the pre-treatment catchment sediment yield using the methods set out in HR Wallingford reports ODTN 120 or OD 152.
- b) Estimate the "erosion" rate from the sediment yield using equation 3.1.

$$ER = S_{y} / (34.3 * CA^{-0.175})$$

Where: ER = Untreated catchment erosion rate (t/ha/y) S_y = Sediment yield (t/km²/y) CA = Catchment area (km²)

c) Select a sediment yield reduction factor from Table 3.2 or by using equation 3.2:

SYRF = 1.44 * Ln (ER) - 1.32 (3.2)

Where:

(3.1)

(3.3)

SYRF = Sediment yield reduction factor ER = Erosion rate calculated from equation 3.1 (t/ha/y)

d) Estimate the post-treatment catchment sediment yield from equation 6.5:

 $S_y con = Sy/SYRF$

Where:

 S_y con = Sediment yield with conservation (t/km²/y) Sy = Pre-treatment catchment sediment yield (t/km²/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 the dam is commissioned, and a five year lag time is appropriate the mean sediment yield over twenty years will be:

$$S_{y20} = (5 * (S_y + S_y con)/2) + (15 * S_y con) 20$$

Where:

 S_{y20} = Mean sediment yield over 20 years $S_y \text{ con}$ = Sediment yield with conservation (t/km²/y) S_y = Pre-treatment catchment sediment yield (t/km²/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 is only applied over 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.

4. Sediment bypassing

4.1 CONCEPT

In semi-arid zones the volume of the annual runoff from small catchments varies widely between years. Because of this small dams are sometimes designed to have a relatively small capacity when compared with the inflow in an average year, to ensure that they will fill in relatively dry years. The table below shows the ratio of dam capacity to mean annual inflow ratio, required to achieve an 80% probability of filling², in catchments with different coefficients of variation of annual runoff.

I V			•	
Coefficient of variation of	80%	100%	120%	140%
annual runoff				
Dam capacity to annual	0.33	0.22	0.14	0.10
inflow ratio (note 1)				

Dam capacity	y inflow	ratios to	o achieve an	80%	probability	of filling
	Dam capacity	Dam capacity inflow	Dam capacity inflow ratios to	Dam capacity inflow ratios to achieve an	Dam capacity inflow ratios to achieve an 80%	Dam capacity inflow ratios to achieve an 80% probability

Note 1 Calculated using the method described in Mitchell (1987).

As the table indicates, when small dams are designed so that they are expected to fill in four years out of five, they need to have an increasingly smaller capacity to inflow ratio as the variability in annual runoff increases. As the coefficient of variation of annual inflow exceeds 100 % in most small catchments in semi-arid zones the table implies that in four years out of five a large proportion of the annual inflow to such dams will be passed over the spillway. While this ensures the reliability of storage at the specified probability level, it is potentially disastrous when sedimentation is considered³.

The sediment trap efficiency of a small dam with a typical capacity to inflow ratio of 0.2 is approximately 95%. In a year with an average runoff this dam would store only 20% of the water running off a catchment, but will trap about 95% of sediment carried by the runoff. This will clearly lead to rapid siltation. An obvious means of reducing siltation rates, and thus of lengthening a dam's effective life, is to provide a larger storage capacity. A dam with a capacity inflow ratio of one, located in the same catchment as in the example above, would trap all of the runoff and all of the sediment contained in the runoff. Because of the larger capacity it would take about five times longer to silt up. The larger dam would store far more water, and in most years this additional water would be available for use by communities.

If siltation rates in dams are to be minimised the capacity to annual ratio should ideally be set close to one. While this is desirable, in many cases it is not feasible, due to the limits on the storage volume that can be provided at an economic cost at the sites that are available, and in some countries, limits on the height of dams that can be constructed without supervision from a qualified civil engineer.

² An 80 % reliability of filling is selected as this criterion is adopted for the design of conventional irrigation projects supplied from rivers or reservoirs.

³ The capacity of small dams is also set by the topographical limitations at dam sites, which often make it prohibitively expensive to construct dams with the large capacity that would be needed in a large catchment. For example for nine dams rehabilitated as part of a CARE programme in Zimbabwe, and surveyed for this study, the mean capacity to annual inflow ratio was only 0.2 (HR Wallingford report ODTN 120).

<u>Sediment bypassing</u> is a mechanism that has the potential to reduce siltation rates, and extend the useful life of small dams that have a low capacity to annual inflow ratio.

With sediment bypassing water and sediment are diverted past the reservoir storage area when a dam is full. This reduces sedimentation considerably in the reservoir storage area. The principle has been applied in some large reservoirs where the local topography has allowed the reservoir to be constructed in a side valley and operated "off line" (World Bank, 2003). This approach is only feasible at a very limited number of sites. The principle could be applied to small dams, if a bypass canal is constructed connecting 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. The figure below illustrates the concept.



Figure 4.1 Plan view of sediment bypassing arrangement

A sediment bypassing arrangement would operate as follows:

- Initially, in-flowing water fills the bypass canal to the crest level of the side weir.
- Water then spills over the side weir into the reservoir, until the water level in the reservoir reaches the spillway crest level. Up to this point all the sediments carried by the incoming flow enter the reservoir and settle.
- As river flows continue the level in the reservoir rises above the dam spillway level. Some flow continues to spill over the side weir, but most of the river flow and sediment it transports are now passed straight over the spillway.
- When the flow entering the canal starts decreasing, the flow over the side weir changes direction, passing from the reservoir into the canal. The water level in the reservoir then decreases until the level in both the canal and dam reach the spillway crest level.

4.2 MODELLING STUDIES

A numerical model was set up using HR Wallingford's ISIS software to investigate the performance that could be expected from sediment bypassing arrangements applied to a small dam. The model was used to quantify the proportions of the flows, and sediment loads, entering and settling in the reservoir or passed over the spillway, for a range of side weir arrangements, flood discharges and flood event sequences. A preliminary study was carried out to investigate alternative side weir arrangements.

4.2.1 Model inputs

Flood sequence

The siltation rate in a dam with sediment bypassing is strongly related to the sequence in which floods arrive at a dam. A standard flood sequence was used for the initial tests, based on observed stream flows for a small river in a semi-arid zone in Zimbabwe, and representing a year with an average mean annual runoff. The flood sequence comprised seven runoff events, each characterised by a duration and a peak flow. The shape of the flood hydrograph was based on the observed data.

Table 4.2	Modelled	flood	events

Flood size	Number of events	Duration (days)	Peak flow (m ³ /s)
	per year		
Large	1	8	12
Medium	1	5	3.5
Small	2	2	2
Very small	3	1	1

The flood sequence was modelled as a single hydrograph with the very low or zero flow periods removed; it has a total volume of 3.32Mm³, and is shown in Figure 4.2.



Figure 4.2 Standard flood sequence

Dam

The dam geometry was described by the following parameters:

- Throwback;
- Embankment crest level, reservoir full supply level and spillway crest level;
- Maximum width of water surface at the full supply and lower water levels.

The dam dimensions were selected to provide a capacity inflow ratio of 0.2 with the modelled annual inflow of 3.32Mm³. The throwback was selected as 1000 m, the other dimensions are shown below.

Dam geometry	At embankment crest level	At full supply level (spillway crest level +wet freeboard)	At spillway crest level
Width (m)	602	560	460
Elevation (m)	7.2	6.7	5.5
Volume (m ³)	-	990528	667920

Table 4.3	Dimensions	of dam	used in	the simu	lations
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The storage volume was estimated using the Nelson (1991) equation, which gives volume as a function of the water depth, water surface width at the dam, and the throwback:

Volume = K1*K2*D*W*L

4.1

Where:

 $K1 = A \text{ constant, equal to } 0.22 \\ K2 = A \text{ constant, dependent on the shape of the valley cross-section, taken as } 1.2 \\ D = Water depth \\ W = Width \\ L = Throwback$

The spillway was modelled as a broad crested weir and was sized to pass the 1:100 year return flood, which in this case was taken as $130 \text{ m}^3/\text{s}$, with a head over the weir crest of 1.2 m. The spillway crest was set at an elevation of 5.5m, with a width of 60m.

Bypass canal

The canal was modelled with a trapezoidal cross-section with side slopes of 2H:1V, and a bed width of 40 m. Initially the bed slope was set to be the same as that of the deep water channel through the reservoir (0.0027). In time the bypass canal will fill with sediments, until a channel is formed with a bed slope and cross-section similar to the upstream river.

Sediment concentration

The concentration of sediment entering the system was related to the river discharge using a sediment rating relationship:

$$X = K Q^{1.2}$$
 (4.2)

Where X = Incoming sediment concentration (ppm) Q = Discharge m^3/s K = A constant

The exponent of 1.2 was selected as it is typical of semi-arid river sediment rating relationships measured in HR Wallingford studies. The constant cancels in the calculations described later and does not need to be specified.

4.2.2 Modelling approach

Modelling was carried out using the HR Wallingford ISIS software. ISIS is a onedimensional, unsteady, open channel flow model that can be used for simulating water levels and flow velocities in rivers and estuaries. The objective of the modelling was to estimate, for a range of design options, the proportion of the sediment entering the bypass canal at the upstream end of the dam which would be diverted to and settle in the storage area. It was assumed that all the sediment passing over the side weir settled in the dam.

The **upstream boundary** condition was a hydrograph based on Figure 4.2 but with varying sequences of floods depending on the tests being carried out.

The **bypass canal** was represented with five cross-sections placed at equal distances, from 50m d/s (downstream) of the canal upstream end to the dam spillway.

The **dam spillway** was placed at the d/s end of the bypass canal.

The **side weir** spilling the flow from the canal into the reservoir was modelled with two alternative hydraulic structures:

Conventional side weir - This is located downstream of the last bypass canal section. The length and elevation of the side weir was selected so that the dam was filled before the flow overtopped the spillway. The side weir arrangement is shown in Figure 4.3.



Figure 4.3 Side weir and bypass canal

Distributed side weirs – This is a possibly lower cost alternative to a fixed side weir. Flows are diverted to the reservoir storage area through gaps in the bund forming the left hand bank of the bypass channel. For this simulation four gaps were located along the bypass canal, at the downstream end of the four cross-sections defining the bypass canal in the model. The total length of the gaps was 50 m. The side weir and gaps were modelled as lateral spillways.

4.2.3 Model outputs

Water levels and discharge in each cross-section, the side weir and the dam spillway were available from the model for each time step. A sediment balance was calculated by applying the sediment rating relationship (equation 4.2) to calculate the sediment loads entering the bypass canal and diverted to the reservoir storage area at each time step. It was assumed that all the sediment entering the storage area was trapped. (This is a slightly conservative assumption, as a small proportion of the fine sediment entering the reservoir storage area in suspension would be transported out of the reservoir and over the dam spillway during periods of reverse flow over the side weir.)



Figure 4.4 shows the water balance between the canal, reservoir and spillway for the basic model with a single side weir run with the standard flood sequence shown in Figure 4.2.



Figure 4.4 Water balance with a side weir

The figure shows how the three small floods at the start of the sequence are all diverted into the reservoir storage area, which is filled near the peak of the following large flood. There is a reverse flow across the side weir during the flood recession, when the water levels at the spillway are lower than the level in the dam. Flow into and out of the dam occurs during the last three small floods of the sequence.

4.3 PRELIMINARY SIMULATIONS

An initial study was carried out to investigate the relative performance of the two side weir systems, i.e. a side weir or the bund with "gaps", and different levels of sedimentation in the bypass canal. The scheme that was modelled was described in Section 4.2. The results indicated that the level of sediment in the bypass canal did not have a significant impact on the performance of the system.

The comparison of a single side weir with the arrangement where flows are diverted to the reservoir through a series of gaps showed that a single side weir system results in much lower sedimentation in the reservoir. The reason is that a significant proportion of the flows entering the bypass channel are diverted into the reservoir through the upstream gap even when the reservoir is full. These flows are returned to the bypass channel through the downstream gap, and pass over the spillway. As most of the sediment load entering the reservoir area will settle this process results in much larger sedimentation rates, many times larger than with the single side weir.

Following this result subsequent simulations were conducted with the single side weir arrangement.

4.4 RESULTS

Tests were carried out to determine sedimentation rates in the reservoir for a range of side weir dimensions, dam capacity inflow ratios and flood sequences. Conditions for the "base model" used in these simulations are summarised in Table 4.4.

Table 4.4	Base model	parameters
	20000 1110000	Parameters

Flood sequence	See Figure 4.2
Dam dimensions	See Table 4.2
Capacity / Annual inflow ratio	0.2
Side weir length (m)	50
Side weir elevation (m)	4.5
Bypass channel bed level at u/s (upstream) end	4.5 m (see Figure 4.3)
of side weir	

4.4.1 Effect of the side weir discharge capacity

The discharge capacity of the side weir when the water level is at the dam spillway crest level is an important design parameter. If it is too small then the water that may be needed to fill the dam in a "dry" year will pass over the dam spillway in the larger flood events. If it is larger than needed then the side weir will be unnecessarily long and expensive. Ideally the side weir crest level and length should provide sufficient capacity to ensure that no water is spilled over the dam spillway until the storage area has filled. This condition would be satisfied when the capacity of the side weir equals that of the peak discharge of the largest flood that is expected to occur in a dry year. This of course depends on the return period adopted for design, and is discussed later. The impact of changing the side weir crest length, and hence the discharge capacity, on the quantities of water and sediments diverted to the storage area was considered initially with the base model run with the standard inflow hydrograph. The results are tabulated below:

Side weir crest	% annual flow diverted to	% annual sediment load diverted
length (m)	reservoir storage area	to reservoir storage area
1	22.8	5.3
10	24.0	23.4
25	23.2	21.7
50	23.0	21.5
100	23.5	22.4

Table 15	Docults with	vorving sid	o woir	aanaaity
1 abie 4.5	Results with	varying sid	e werr	capacity

As expected, when the capacity to inflow ratio is as low as 0.2 there is more than enough water entering the bypass canal to fill the dam, even when the discharge capacity of the side weir severely restricts flows into the reservoir storage area. Thus the volumes of water diverted are similar irrespective of the side weir crest length. (The percentage of the annual flow diverted to the storage area is slightly larger than the capacity/inflow ratio, due to the small flows into and out of the storage area that occur during flood peaks after the storage area has filled.)

The impact of the very low discharge capacity provided by the one metre crest length is only apparent in the results for sediment deposition. When flows are restricted a much larger proportion of the water diverted into the reservoir storage area comes from lower flows carrying low sediment concentrations. Thus less sediment is diverted to the reservoir storage area. Criteria for setting the capacity of the side weir are discussed later.

4.4.2 Capacity to inflow ratio

The effect of the capacity inflow ratio on the proportion of the incoming sediment load settling in the dam was investigated with the standard inflow hydrograph by adjusting the dam width to change the volume of the reservoir storage area. The dam height and throwback were kept constant and are listed in Table 4.3.

Model outputs are summarised in Table 4.6.

Reservoir capacity to annual inflow ratio	% annual flow diverted to reservoir storage area	% annual sediment load diverted to reservoir
		storage area
0.05	5.5	0.5
0.20	23	22
0.50	57	84
1.00	100	100

Table 4.6Results of varying capacity inflow simulations

These results are of course strongly affected by the flood sequence used for the simulation. With a Capacity to Inflow ratio of 0.05 the reservoir storage area is filled during the initial low flows carrying very low sediment concentrations. When the Capacity Inflow ratio is 0.2 the reservoir is filled during the rising limb of the largest flood in the sequence, and when the capacity inflow ratio is 0.5 nearly all the inflow to the reservoir storage area is diverted from the large flood.

4.4.3 Impact of flood pattern on sediment mitigation

The last set of simulations investigated the effect of different flood sequences on sedimentation in the reservoir storage area. The base model was run using three different inflow hydrographs, prepared from flood events used in the standard flood sequence. These were the standard hydrograph used for the previous simulations (sequence 1), a hydrograph consisting of the same events run in a sequence with descending peak discharges (sequence 2), and a hydrograph prepared from the same events run in a sequence with ascending peak discharges (sequence 3).

The results are summarised in Table 4.7.

 Table 4.7
 Results with varying flood sequences

Flood sequence	% annual flow diverted to reservoir storage area	% annual sediment load diverted to reservoir storage area
Sequence 1	23	22
Sequence 2	23	40
Sequence 3	24	5

This result demonstrates the importance of the flood sequence in determining the benefit that sediment bypassing will produce in a particular year. With sequence 2 the dam is filled from the largest discharge event and consequently a large volume of sediment is passed over the side weir and settles in the dam. With sequence 3 the dam is

filled from a series of very small floods and only a small volume of sediments are deposited.

As noted earlier the distribution of flood peaks through and between years will in general be randomly distributed. Over a long time period the proportion of the incoming sediment load settling in a dam with a sediment bypassing arrangement will be similar to, but slightly larger than, the capacity inflow ratio. (Larger due to the effects of flows passing into and out of the storage areas when water levels rise above the dam spillway level in flood peaks, which divert additional sediment to the storage area of the dam.

4.5 CONCLUSIONS FROM MODEL TESTS

- In any particular wet season the benefit obtained will be strongly influenced by the sequence of 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 larger floods occurring after the dam is full 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 reducing 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 for the construction of a bypass canal and side weir, at a cost that can be justified by an increase in a dam's effective life.

4.6 DESIGN ASPECTS

The design of sediment bypassing structures will be mostly determined by site specific factors. However some guidance on general design features can be enunciated.

Bypass channel

It is assumed that a bypass channel will be formed by constructing an earth bund from the point where the river enters the dam to the spillway. This may not be feasible if the channel has to cross major tributaries, or through rock outcrops. The channel dimensions should be based on the width of the natural river sections upstream from the head of the dam, and should be designed to pass the design flood adopted for the dam spillway without overtopping. It should be assumed that the channel bed will eventually silt up to a level close to the dam spillway crest elevation.

Side weir

It is important that the discharge capacity of the side weir does not unduly restrict flows into the dam. The capacity required clearly depends on the number and size of the floods that are expected during the wet seasons of comparatively dry years, and the capacity inflow ratio of the dam. If the capacity to inflow ratio is very small, then a smaller spillway capacity will be satisfactory as only a small proportion of the inflow will be needed to fill the dam. On the other hand if the capacity to inflow ratio is relatively large, and only one flood occurs in a very dry year then it may be necessary to abstract water at quite high discharges to ensure that the dam will be filled. A designer would need to obtain information on the number and sizes of floods that can be expected in typical and dry years from local informants before setting the side weir capacity.

5. Method for predicting the performance of sediment bypassing systems

Sediment bypassing is only likely to be an attractive option for dams with a low capacity to inflow ratio, say less than 0.3, which have 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 by:

a) Estimating the proportion of the original capacity remaining after twenty years of siltation using equation 5.1.

$$C_n = 1 - [n * S_v * CA * TE / (C * Den)]$$
 (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/km²/y)

CA = Catchment area (km²)

TE = Sediment trap efficiency

C = Dam's original capacity at full supply level (m³)

Den = The settled density of dam sediment deposits (taken as 1.2 t/m^3)

b) Repeat the calculation for the with sediment bypassing case using equation 5.2, which assumes that all the sediment that is passed over the side weir settles in the dam:

$$Cn(bp) = 1 - [n * S_y * CA * K_1 * K_2 / (ARV * Den)]$$
(5.2)

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/km²/y)

 $\overrightarrow{CA} = Catchment area (km²)$

 $K_1 = A$ 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 (m³)

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_1 will depend on the proportion of the annual runoff that occurs at high discharges. A value for K_1 of 1.1 may be appropriate.

(5.3)

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:

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

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