Sutton Bingham reservoir sedimentation study

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SYNOPSIS. There is evidence of significant siltation in the Sutton Bingham reservoir near Yeovil. Halcrow Group was commissioned to study the siltation problem while the reservoir water level was kept low during the remedial works at the dam in 2007. This study reviews and discusses the options available for alleviating further siltation in the reservoir. Desk studies were carried out to gather information and data to review the past and current state of sediment deposition and to propose solutions which would help to alleviate the siltation problem.

Two feasible solutions to reduce sediment inflow into Sutton Bingham reservoir were proposed. One approach is to store incoming sediment behind a submerged weir and to periodically flush sediment downstream of the dam via closed conduits. Alternatively a desander basin could be operated at the head of the reservoir to trap a proportion of incoming sediment. The trapped sediment can be removed periodically by excavation.

The paper discusses operation constraints and the practicality of flushing this reservoir. The benefits and disadvantages of the selected option are also discussed.

INTRODUCTION

Sutton Bingham reservoir was constructed in the period 1951 to 1954 for the Yeovil Rural District Council under powers conferred by the Yeovil Rural Water Order 1950 as part of a new water supply scheme and the reservoir was brought into service in 1955. The catchment area is about 30.23km^2. The estimated rainfall is about 890mm and the average annual run-off is 425mm estimated in the 1970s but this has been revised to 520mm based on more recent database gathered by the Environment Agency (EA). Similarly the long term annual runoff was estimated to be 12,850Ml in the 1970's and the new estimate is 15,704Ml by the EA. Clearly there are discrepancies in the estimated long term inflow into the reservoir and there is an absence of any gauging station within the catchment. The estimation of inflows for this study is based on the average inflows from 1997 to 2004 provided by the EA established from the measured change in reservoir storage and abstraction rates to and from the reservoir. The average inflow from 1997 to 2004 based on this data set is 5,522Ml/year. Sutton Bingham Reservoir has a surface area of about 57.5ha and extends from the dam about 2.5km to the southwest. A shorter limb of the reservoir extends westwards and is crossed, on a causeway, by Yeovil Road to Halstock. The reservoir has a mean depth of about 4.5m, and the current estimated capacity is 2,137Ml (2006).

HISTORICAL PERSPECTIVE ON SILTATION PROBLEMS

Bathymetric surveys have shown that siltation has been a significant problem at Sutton Bingham. As coarse sediment continues to be deposited in the backwater region, sediment deltas are formed. On the reservoir rim, sheep grazing was stopped due to parasites in droppings in the mid 1990s. This has resulted in a marked increase in the number of willows on the reservoir rim as the sheep no longer feed on the willow shoots. The willows have encroached into the reservoir near the head of the reservoir, trapping sediment within their root systems. The delta area is incised by deep channels but flow rises out of bank during winter months, depositing silt where the flow velocity is reduced.

Figure 1. Aerial view of Sutton Bingham reservoir

There is no obvious explanation for why the apparent sediment yield is so high for this reservoir catchment but changes in land use in the catchment area may be the reason. Diary production has been largely replaced by crop production entailing an increase in ploughed land. It has been observed that during floods, a brown plume of very fine sediment can be seen as far as the downstream end of the main limb of the reservoir by the sailing club. This suggests that flood flows carry a significant proportion of very fine sediment particles in suspension. There is no evidence of past efforts to restore the storage capacity except for the dredging work in the early 1990s when an estimated 10,000t to 30,000t of silt was removed in the backwater region by excavation.

BATHYMETRIC SURVEY

The results of two bathymetric surveys were used to inform this study. The first hydrographic survey was completed in November 1991 and a more recent bathymetric survey was carried out in July 2006. The 1991 survey showed that the reservoir capacity was 2,394Ml compared to the estimated original capacity of 2,614Ml when the reservoir was completed in 1955. This represents a loss in storage capacity of 220Ml over a period about 36 years. It is unclear if this figure includes an amount of silt which was reportedly dredged from the head of the reservoir in the early 1990s. As there was no modification to the reservoir or significant change in reservoir operation over this period, it can be assumed that the storage loss was entirely due to sediment accumulation. The 2006 survey estimated that a total of 257Ml of sediment had accumulated since the previous bathymetric survey carried out in 1991. The current estimated gross volume of the reservoir is 2,137Ml which is about 10% less than previous estimate. There are no continuous turbidity measurements of the incoming flow. Therefore the annual sediment yield was estimated from the results of both bathymetric surveys and as discussed below.

SEDIMENT DEPOSITION AND SEDIMENT YIELD AT SUTTON BINGHAM

Sediment yield from bathymetric surveys

The sedimentation rate in the reservoir was estimated by comparing previously completed bathymetric survey results. The mean annual sediment deposition rate in the reservoir was estimated by dividing the total mass of sediment accumulation by the number of years between bathymetric surveys (Table 1).

Table 1. Mean Annual Sediment Deposition

Period between bathymetric surveys	No of years	Total sediment accumulation (t)	Mean annual deposition (t/yr)
1955[2] to 1991	36	430,000[1,3]	11,944[1,3]
1991 to 2006	15	514,000[1]	34,267[1]

(1) Bulk density of $2g/cm^3$ has been assumed to derive mass of sediment.

(2) Bathymetric survey was not conducted in 1955. The storage at 1955 was based on the design storage capacity of 2,614Ml.

(3) This figure takes account of the estimated 10,000t of sediment which was dredged in the 1990s.

These estimates do not reflect probable differences in sedimentation from year to year. In addition, as an estimated mean bulk density was used in the calculation, mean annual sediment deposition may be understated if the actual density is higher. As there are no reliable incoming sediment data available at the Sutton Bingham Reservoir, sediment yield was estimated by exploiting the trap efficiency function of the reservoir. As shown in Table 2 the average annual sediment yield varied from 403 $t/km^2/year$ to 449 $t/km^2/year$ between 1955 to 1991. The average estimated sediment yield increases to about 1218 $t/km^2/year$ from 1992 to 2006. This estimate does not reflect the variation of yearly sediment yield between the periods studied. Figure 2 shows the average estimated sediment yields at Sutton Bingham between 1955 and 2006.

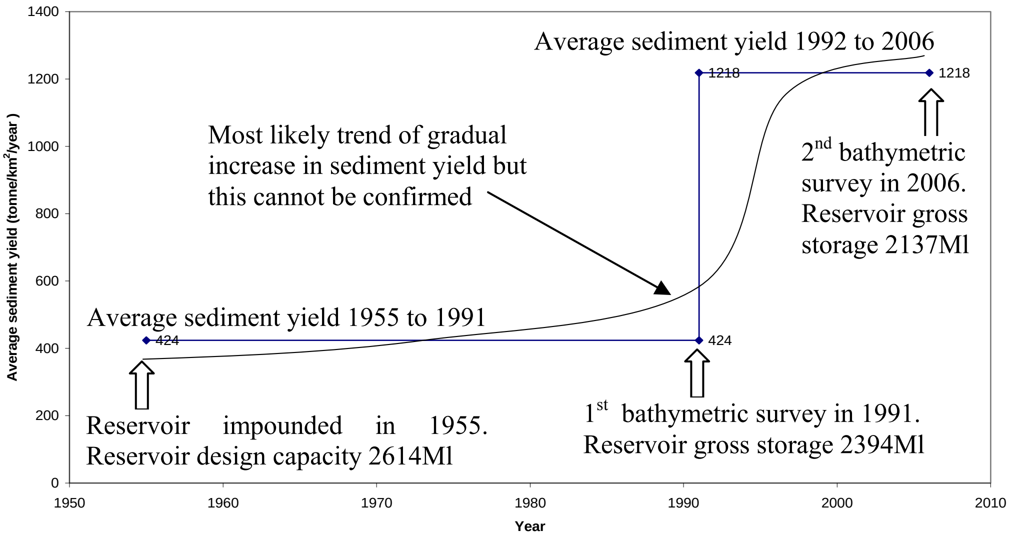

Figure 2. Sediment yield at Sutton Bingham Reservoir from 1955 to 2006

Table 2. Sediment Yield Estimation

Trap efficiency functions	Mean annual deposition (t/yr) 1955-1991	Mean annual deposition (t/yr) 1991-2006	Trap efficiency (%) (1) 1955-1991	Trap efficiency (%) (1) 1992-2006	Mean Annual Sediment Yield (t/km²/year) 1955-1991	Mean Annual Sediment Yield (t/km²/year) 1992-2006
Churchill (1948)	11944	34267	88	88	449	1288
Brown (1950)	11944	34267	94.3	93.7	419	1210
Brune (1953)	11944	34267	98	98	403	1157
				Average values	424	1218

<u>Projection of storage capacity</u>

Assuming sediment yield remains at the current estimated rate of 1,218 t/km²/year and there are no changes to the reservoir operations, the storage capacity at Sutton Bingham is projected to be further reduced by 40% (of the 2006 capacity) over the next 50 years. The measured storage capacity in 2006 is 2,137Ml and this will reduce to 1,295Ml in 2056 as shown in Figure 3. A capacity of 1,295Ml represents around 50% of the original design capacity.

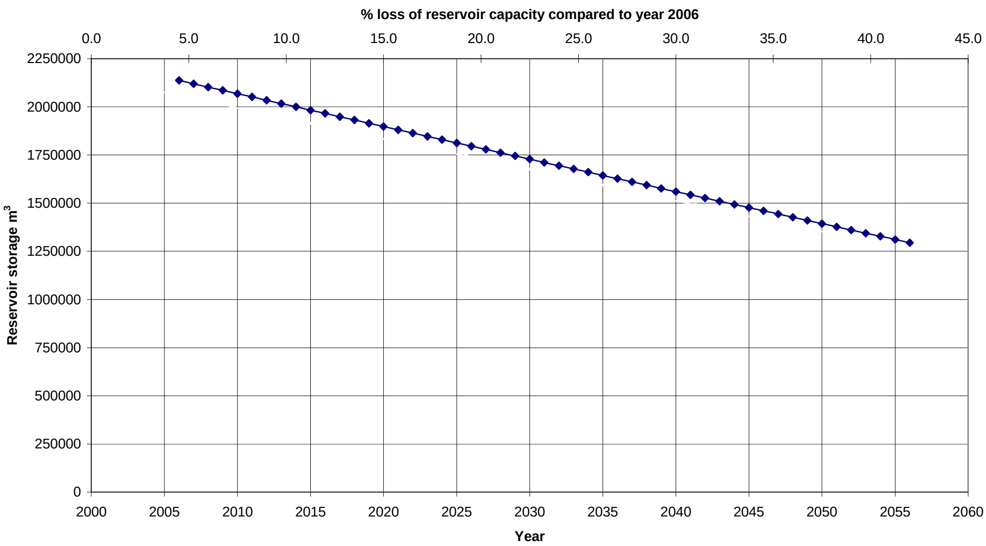

Figure 3. Projected loss of storage capacity to 2056

Notes: 1. Linear relationship of sediment yield and storage loss assumed

2. Trap efficiency of reservoir based on Brown's empirical formula

OUTLINE OF AN "IN- RESERVOIR" APPROACH AT SUTTON BINGHAM RESERVOIR

A flushing system which features a submerged weir with intakes connecting to a pipeline system was considered to transport the incoming or recently deposited sediment in the backwater region of the reservoir to the downstream of the dam. The proposed method developed at Bristol University has great flexibility in blocking the advancement of the deposited delta, minimising sediment deposition into the deeper region of the reservoir and can be used for sediment removal. The primary reason for deposition in reservoirs is due to the reduction of flow velocity when stream flow enters a reservoir. The obvious solution therefore is to reverse this process i.e. to increase flow concentration. The bypass system features components similar to a Hydrosuction bypassing system. However the permanent intake structure is a submerged weir within the reservoir to separate incoming sediment and bypass the dam so arresting the advance of the deposition delta towards the deeper region of the reservoir, thus preserving the storage capacity between the submerged weir and the main dam as shown in Figure 4.

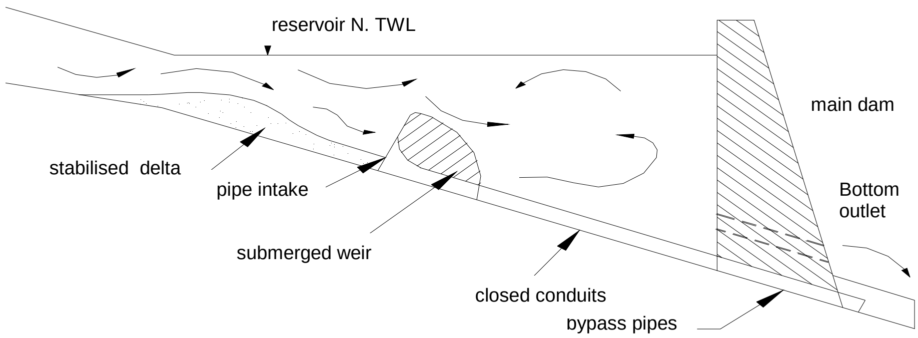

Figure 4. Layout of the submerged weir closed conduit system

Intakes and control valves could be positioned at the submerged weir to aid hydraulic dredging or flushing of the deposited sediment. The submerged weir has a manifold of pipes at the intake distributed across the weir which are routed in a pipeline to a discharging point at the downstream of the dam. A labyrinth weir shown in Figure 5 has merit in its ability to increase the local trap efficiency in the head of the reservoir and also boost effective flushing properties. The labyrinth-shaped channel arrangement increases the weir storage capacity and this increases the system capability in trapping incoming sediment, although the discharge efficiency across the weir is decreased significantly in drowned condition. The water level would normally be lowered to initiate the flushing operation and this would create a high velocity region upstream of the weir which would help to mobilise deposited sediment. Valves incorporated into the system could be operated to either increase or decrease flow velocity within the channels depending on the mode of operation. Low flow velocity will promote deposition while high velocity over the apron will improve the flushing efficiency of the system.

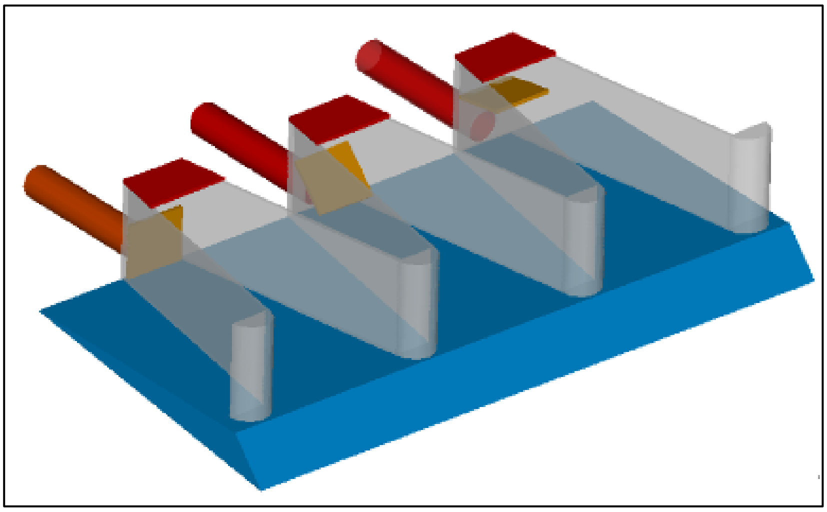

Figure 5. Submerged labyrinth weir

Some proportion of the incoming sediment, especially the finer materials, may pass over the submerged weir and settle in the bottom of the reservoir between the main dam and the submerged weir. This was not viewed as a significant problem as it is the deposits at the head of the reservoir that pose the greatest operational impact on live reservoir storage.

By locating the submerged weir towards the upstream top end of the reservoir the majority of the reservoir storage capacity is retained when the reservoir is lowered to below weir crest level. In contrast, the traditional reservoir flushing technique requires emptying the reservoir to flush sediment through the dam. Hence this method allows for uninterrupted water supply during sediment extraction. The method also provides excellent flow control characteristics so the extent of sediment removal can be varied to suit the conditions in the receiving watercourse. This is seen as important as too much outflow will result in degradation of the downstream channel while insufficient discharge will cause sediment deposition.

OUTLINE DESIGN OF DESANDING FACILITIES

The second option considered to address the reservoir sedimentation was to install a desanding basin immediately upstream of the reservoir. This approach is not commonly used. However, in Victorian times in the UK, engineers sometimes provided a 'residuum lodge' upstream of the main reservoir to intercept coarse sediment. The design of such basins has been developed principally for use in irrigation schemes and hydropower intakes where it is necessary to exclude all but the finest particles.

By providing a basin of sufficient cross-sectional area to reduce the flow velocity to about 0.2m/s and providing a sufficient plan area to allow adequate settling times, suspended particles will settle out of suspension, as the sediment removal performance of the basin is a function of the basin plan area. Sufficient cross-sectional area is also required to prevent settled particles being re-entrained by the prevailing bed shear stress. A desanding basin is designed to extract a particular sediment particle size with a particular efficiency. The basin size was established for a range of particle sizes between 0.1mm and 0.2mm with an efficiency of 90%. It becomes impractical to design for the removal of particles smaller than 0.1mm (very fine sand). Although a proportion of silt-size particles will be removed by the basin, fine silt particles and clay flocs will not be intercepted. It follows that the effectiveness of the basin in reducing sedimentation (and the frequency at which the basin has to be cleaned) depends on the particle size distribution of the suspended sediment.

<u>Outline Design</u>

The sediment removal efficiency of the basin was estimated for outline design purposes using Vetter's equation:

$$\text{Removal efficiency, } \eta = 1 - e^{-wA/Q}$$

Where w is the fall velocity of the particle (m/s), A is the basin plan area (m^2) and Q is the design flow (m^3/s). Table 3 provides the results gained for various particle sizes

The larger basin associated with the capture of 0.1mm particles can be accommodated within the space available upstream of the reservoir. The optimisation of the basin size for detailed design demands improved knowledge of the inflow characteristics and, in particular, the particle size distribution.

Table 3. Basin sizes for various design particle sizes at 90% removal efficiency based on Vetter's equation.

Particle size ($\eta = 0.9$)	0.2mm	0.15mm	0.10mm
Plan area (m^2)	230	460	768
Basin length (m)	43	61	78
Width at water surface (m)	5.4	7.6	9.8
Depth of settling zone (m)	2.4	1.8	1.5

Figure 6 shows the proposed location of the desander in the backwater region of the reservoir and possible sites to store the sediment removed.

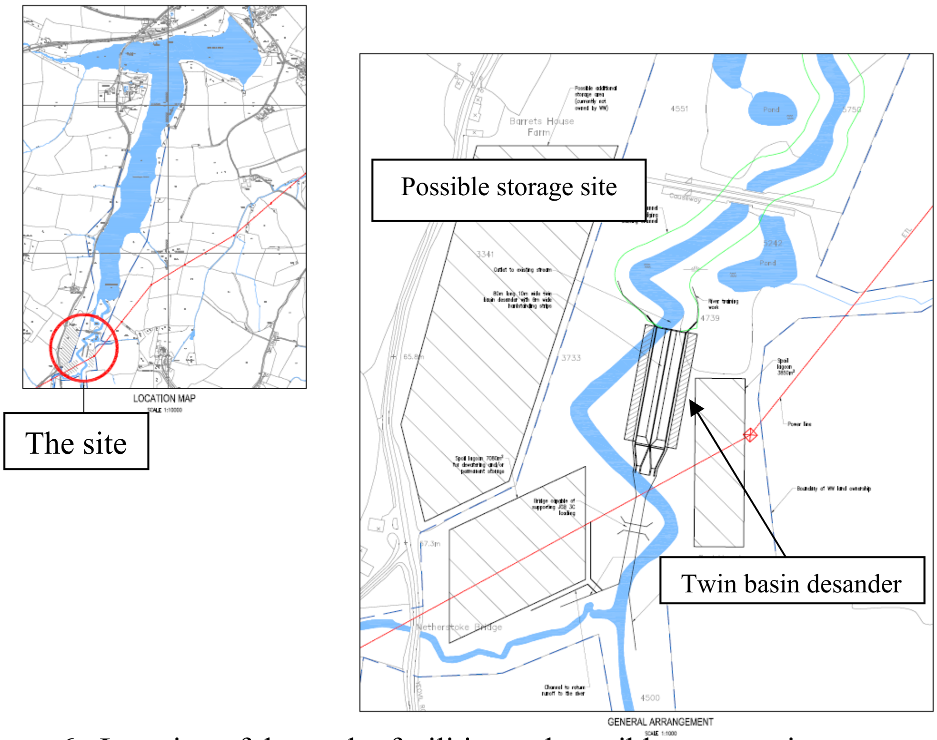

Figure 6. Location of de-sander facilities and possible storage sites

BENEFIT EVALUATION OF THE OPTIONS DEVELOPED

<u>In reservoir approach</u>

The submerged weir system is capable of trapping and removing coarse sediment upstream of the weir hence reducing the sediment transport into the deeper region of the reservoir. The facility also has an effective flushing capability where the deposited delta formed in front of the weir could be flushed and carried downstream via a bypass pipe. The flushing bypass system is designed to satisfy most of the effective flushing requirement and is not dependent on excess seasonal stream flow, often required in the normal flushing operations. The main storage capacity between the submerged weir and main dam is preserved and available for extraction even during flushing operations where water level upstream of the submerged weir is drawn down completely for effective flushing. Despite the many advantages of this novel flushing system, the system has several critical limitations in relation to its use at Sutton Bingham:

- The water used for sediment flushing might otherwise be abstracted for water supply.

- Sediment would need to be removed from the diverted flow before it is returned to the watercourse. This would not be so in all cases but most UK rivers would be adversely impacted by the very high turbidity levels and environmental regulators would require some means of mitigation. Settlement ponds could be located downstream of the dam but only at significant cost.
- There is a risk of pipelines becoming clogged with sediment unless very carefully designed.
- Installing and operating a submerged weir and gates would be difficult and expensive.
- The installation of the by-pass pipes through or around the dam would be both expensive and technically challenging.

The 'in-reservoir' approach was therefore not recommended for use at Sutton Bingham and the outline design focussed on sediment interception and removal at the head of the reservoir.

Desanding basin approach

The studies indicated that there is a suitable site for a desander structure located a short distance upstream of the reservoir which would be capable of removing 90% of 0.1mm particles (very fine sand). The basin would intercept nearly all coarse material and a proportion of finer silt particles. The basin would be periodically cleaned by excavator and sediment would be dried before being placed in permanent storage. Taking the sediment yield estimate of 1,218 t/km^2/yr, the annual yield to the desander was estimated as 30,365t.

The proportion of this load that the desander is capable of excluding from the reservoir depends on many factors which were difficult to estimate with the data available. In particular, the mean particle grading curve for the yield was not available. Furthermore the conditions under which the mean trap efficiency would occur could not be confirmed. Sediment load will increase as a power function of flow and therefore it was not reasonable to use mean flow conditions to assess the trap efficiency of the basin. Ideally a sediment rating curve would be available but there was insufficient data to establish such a relationship between flow and sediment concentration. Therefore engineering judgement was used to assess the effectiveness of the desanding basin. Under these conditions it was estimated that the basin will remove approximately 21,200t of silt each year. This represents about 57% of the total mean annual sediment influx to the reservoir. Assuming that the material is 40% dry solids and using a bulk density of 1.5t/m^3, this equates to about 35,333m^3 per year or about 680m^3 per week.

Sediment monitoring

The current design is based on very limited hydrological and sediment data. There are no gauging stations in the catchment area and the inflow used in the design is estimated from the abstraction rates at the reservoir. There was considerable uncertainty with the design flow used for sizing the basin and the estimated flood flow. The sediment yield was based entirely on two previous bathymetric surveys conducted in 1991 and 2006. The deposition rates between surveys were analysed together with the estimated reservoir trap efficiency to estimate the sediment yield. The design value of 1,218 t/km²/year estimated from deposition rates is substantially higher than surveyed average values for rivers in Britain which has been estimated to be in the range of 50-75 t/km²/year. Clearly the accuracy of the bathymetric surveys which were relied on to derive the sediment yield is questionable although the apparent sediment concentration and reported rate of deposition is clearly high.

A particle grading curve for incoming sediment was not available for this study and the particle size distribution was informed from disturbed bed load samples taken from the foreset slope within the reservoir. A programme of continuous data monitoring within the main tributary entering the reservoir was established to help develop the design of the desander and to more accurately predict the operational requirements for maintaining the desander. Preliminary results of the year long hydrological and sediment data monitoring were anomalous, and efforts are currently being made to investigate the apparent inconsistency between the observed deposits in the reservoir, where significant sand deltas are formed, and the monitoring results, which suggest that incoming sediment contain almost no sand. It maybe the case that monitoring needs to be carried out for a longer period and perhaps more detailed bathymetric surveys should be carried out on a regular basis. If the amount of sand observed at the delta cannot be reconciled with the monitoring results then the monitoring must be flawed in some way. Some of the possible explanations could be overland flow during flood events, which were not captured, or a simple case of not selecting the right location to set up the monitoring station.

CONCLUSIONS AND RECOMMENDATIONS

The bathymetric survey in 2006 showed that the storage capacity of Sutton Bingham reservoir has been reduced by nearly 19% of the original capacity. Assuming that sediment yield from the catchment area remains constant from this point forward; the projected storage capacity in 2056 would be 1,295Ml which is about 50% of the initial capacity. A desander facility in the upstream of the reservoir would be suitable to mitigate the future rate of storage loss through sedimentation, assuming that a significant proportion of the total yield is of very fine sand or coarser. The desilting basin would trap a significant proportion of the incoming coarse sediment and a smaller proportion of fine sediment. The sediment would then be mechanically removed from the basins, dried and placed at the site as compacted fill. Based on preliminary studies, the proposed basin at Sutton Bingham would trap approximately 21,200 t/year. The reduction of incoming sediment would result in a new estimated reservoir capacity of 1,768Ml in 2056.

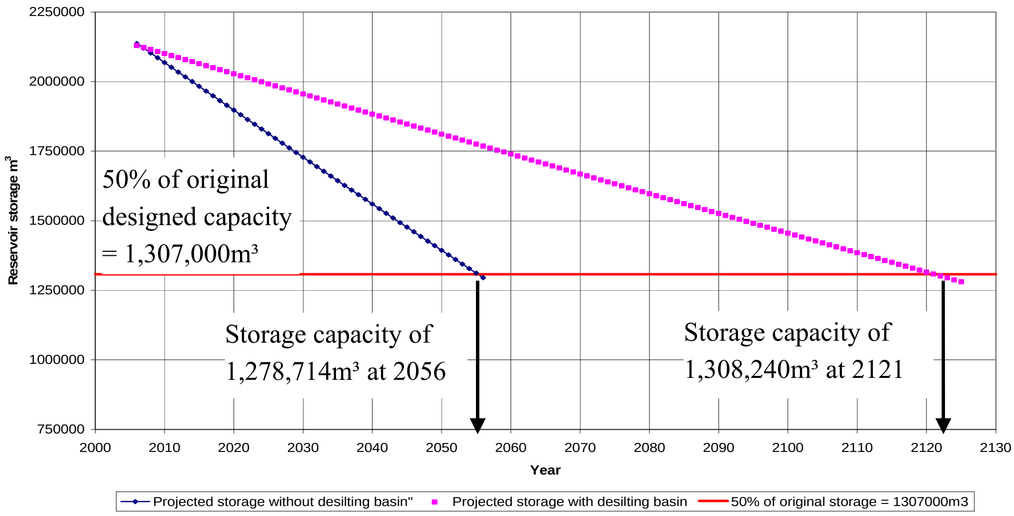

Figure 7. Storage capacities with and without a desilting basin at Sutton Bingham

If the useful life of the reservoir is defined by when the reservoir capacity drops below 50% of its initial capacity; the installation of this desilting facility will extend the reservoir useful life by about 66 years (see Figure 7). Sediment monitoring needs to be carried out over many years to be meaningful and it is useful to cross-reference the results with bathymetric surveys and sediment modelling of the reservoir. Sedimentation is rarely an important issue in UK conditions but the Sutton Bingham reservoir demonstrates that can be a concern in a minority of cases.