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Staff paper

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RESERVOIR DESILTING METHODS

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ABSTRACT

Reservoir sedimentation and the consequent loss of valuable water is a cause for concern, particularly in countries where the livelihood of many people depends upon reliable supplies of impounded water for drinking and irrigation.

This report is a review of what information and techniques are available to avoid sediment deposition in reservoirs and on how to remove deposited sediment. It is recognised that the most effective technique, in the long term, is to prevent excessive sediment reaching the reservoir by means of drainage basin management. However, techniques described in this report are about what can be done with the sediment once it has reached the main tributary rivers of a reservoir or been deposited in the reservoir.

The experience gained from working in collaboration with reservoir managers in Indonesia, The Philippines, Kenya and Zimbabwe is used to assess the advantages and disadvantages of each method. A simple economic analysis is used to demonstrate the value of including dredging, using small portable dredgers, in the planning and design of small reservoirs in Africa and SE Asia. A more rigorous analysis with access to the results of a field trial is called for.

Reservoirs will continue to fill with sediment and as suitable sites are used up so the need for desilting will increase.

Future research should be aimed at understanding sedimentation so as to design suitable desilting systems. Future plans and designs for reservoirs in areas of high sediment yield should allow for the control of sediment.

CONTENTS

FIGURES

1 INTRODUCTION

The purpose of this technical note is to review what information is available on the subject of desilting reservoirs, to examine what has been attempted and what are the advantages of each method. Published literature on the subject of sediment removal from reservoirs is fairly scarce, so the technical note can not be considered as an authoritative guide to desilting methods. For example, there are many reports from around the world indicating how rapidly reservoirs are filling with sediment but, unfortunately, very few reports indicate the economic cost of such sediment deposition and the benefits to be gained from sediment removal.

There are several methods that can be employed to minimize sedimentation and restore capacity but few attempts have been made to estimate the economic viability of the methods employed. This report will therefore concentrate upon some of the techniques that have been used so as to draw attention to future research needs for the engineering and economic aspects of reservoir desilting.

Desilting is defined in this report as the removal of some or all of the sediment that has been deposited within the reservoir basin. The word 'desilting' implies only the removal of silt. This report does not restrict the definition to silt only. The deposition of sand and large sized material can be quite significant in some reservoirs and its removal is often considered to be economically attractive as materials can be sold for construction purposes.

Brown (1943) presented a comprehensive survey of the problem of reservoir silting and how it could be tackled. It is interesting to note that virtually all other documents written on this subject refer to the work of Brown. He presents three philosophies of approach to the problem of controlling silting. The first one is to assume that the rate of sediment output from the drainage basin can not be changed and that the only way to minimize the effect of sediment is to allow sufficient volume for the deposited material when choosing a site and designing the dam. The second philosophy accepts a fixed rate of sediment production and a fixed size of reservoir and attempts to minimize permanent deposition in the reservoir basin. (Note that no allowance is made for increasing sediment yields.) The third philosophy is to approach the problem of reducing the sediment load reaching the reservoir by means of conservation practice. Brown makes the important point that 'a sound policy of reservoir-silting control requires important consideration of all three philosophies .... a careful weighting of all advantages and disadvantages of the various methods before the reservoir is definitely located and designed is most likely to lead to the best solution of the problem'. This point is still valid today, nearly 50 years since it was first made.

As indicated in the UNESCO report on 'Methods of computing sedimentation in lakes and reservoirs' (1985) reservoirs have been constructed over the last few decades without sufficient knowledge about sedimentation. Excessive sedimentation now threatens the success of reservoir projects and the question to be addressed in this report is, is it possible to remove sediment from a reservoir basin? The feasibility of removing sediment is not just restricted to the practical, engineering considerations but must also recognise the economic aspects. Whilst it is not the intention to give priority to the economic criteria in this report we should consider the costs of constructing reservoirs, the cost of catchment conservation, the cost of sediment removal and the cost of doing nothing in our discussions. These costs should be compared to the benefits of the project, now and in the long term. This could be considered in a simple sense as the value of a unit volume of water to the community. Obviously the value of water in an impoundment will depend on the location of the dam and its use. For example, the value of water in a dam used solely for farm irrigation in the UK will be different from the value of the water used for a township supply in semi-arid Africa.

2 METHODS OF DESILTING

The UNESCO report states that in the long run drainage basin management is the best method to reduce sediment yield and the entry of sediment into a reservoir impoundment. Hitzhusen et al (1984) show that by reducing sediment yield by 25% it was possible to extend the life of a reservoir in Dominica from 19 years to 25 years. However such a technique cannot give quick results and the construction of sediment traps to retain sediment, and vegetative screens may in some circumstances provide a more rapid solution in the short term.

The discussion of how to reduce the sediment yield arriving at a reservoir has been dealt with in other papers. Nevertheless, it is worth repeating the observations of many researchers and engineers that, to quote Breusers et al (1982), 'prevention is the best cure, because once sediments have settled in a reservoir, it is generally very difficult and costly to remove them'. Reforestation and soil conservation have many advantages and are probably the methods most favoured in the best interests of the community.

Very often the large size of drainage basins precludes any comprehensive soil conservation strategy over the whole basin. The identification of smaller priority drainage basins with particularly high erosion risks has worked well in some countries. Reports from Indonesia by Sutadipradja and Hardjowitjitro (1984), Suryono (1987), and Sunarno and Sutadji (1982) indicate how substantial efforts are being made to control soil erosion and sedimentation on priority watersheds (drainage basins).

This report, though, is concerned more with what can be done with the sediment once it has reached the main tributary rivers of a reservoir. The methods can be divided into distinct categories:

(a) Interception of sediment, such as sediment traps, detention basins, vegetative screens.

(b) Avoidance of sediment, off-channel storage, bypass canals.

(c) Removal of sediment which can be sub-divided into:

  (i) Hydraulic methods, scouring, flushing, sluicing (sometimes referred to as operational methods)

  (ii) Mechanical methods, dredging and digging.

The following sections describe these methods.

3 INTERCEPTION OF SEDIMENT

3.1 Sediment traps and detention basins

The technique of constructing small dams upstream of major reservoirs to trap sediment and therefore protect the major impoundment has been used in many countries. In Japan there are more than 500 sediment storage dams with a height of 15m or more. When conditions are favourable the deposits can be dredged out and used for construction purposes.

In Indonesia the construction of 'sabo dams' and 'sand pockets' has accompanied the development of larger reservoirs. Tokol sabo dam was constructed in 1975 to protect the Selorejo reservoir basin several kilometres downstream. DPU/Proyek Brantas (1976) give the original capacity as 138 400m^3, from a catchment area of 130km^2. The design has been very effective in trapping sediment as can be seen from the comparison of Figure 1 to Figure 2. From survey information collected by Proyek Brantas approximately 41 000m^3 was deposited in the year from 1975 to 1976 and in the following year 66 000m^3 was deposited. It is clear that this material was not deposited in Selorejo reservoir. However, by 1984 the Tokol sabo dam was effectively full, Figure 2, so any further material was not being trapped but flowing into Selorejo.

Similar check dams have been constructed in the Brantas drainage basin and cascades of small dams made from gabions have assisted in stabilising the river channels of the major tributaries. Sometimes sediment traps can be quite large as is the case of Sengguruh dam on the Brantas river upstream of Karangkates. Suryono says that the dead storage of Sengguruh is designed to be 19 x $10^6 m^3$ which can contribute to the reduction of sediment in Karangkates reservoir. In this case, though, Sengguruh is also being used for hydropower generation and not solely for the retention of sediment.

The main disadvantages of sediment traps and auxillary dams built to trap sediment and thereby protect downstream works is their expense and the fact that the sedimentation problem is transferred from one large reservoir to many smaller reservoirs. In areas where debris flows, due to the combination of volcanic materials and high rainfall, are a problem then sediment traps, particularly the 'sand pockets' used on Genung Kelud in East Java have been justified and shown by Takanashi (1981) to be very effective in preserving life, homes and agricultural land as well as reservoir storage. However it must be remembered that once the storage is full in the trap reservoir then it ceases to have any useful function unless the debris can be cleared.

Brown points out that 'settling basins generally cost more per unit of storage than the reservoirs they protect'. Therefore, in most cases, it would seem unwise to adopt a plan of using settling basins as a primary method of silting control at the time a new reservoir is built. On the farm reservoirs that Brown was considering a larger volume of sediment storage could be obtained at a lower cost by raising the main dam a few metres rather than constructing a settling basin.

3.2 Vegetative screens

A vegetative screen is a dense growth of vegetation through which sediment-laden water must flow to enter the reservoir. The purpose is to diffuse or spread the flow of water, reduce its velocity and cause sediment to deposit around and between the plants. Brown gives six requirements for the type of vegetation to be used:

(a) deep rooted to prevent it being scoured out
(b) small stemmed with plants growing close together
(c) tough and fibrous
(d) low-growing with foliage reaching ground level
(e) resistant to drought and flow inundation
(f) non-palatable to stock

The natural growth of tamarisk (thought to be Tamarix gallica) along the Pecos river in New Mexico, USA was considered by Stevens (1936) to be a major new factor in reducing the sedimentation in Lake McMillan. In Hongshan reservoir in China a screen of Scirpus yagara and Typha latifolia, 4km wide and 10km long is reported to trap 90% of incoming sediment (Zhao, 1980).

The use of vegetation screens is effective so long as land is available for planting. Inevitably the land gets converted into impenetrable swamp with the attendant hazards to health. The use of native vegetation is recommended so as to avoid the spread of exotic species to canals and farm land. Vegetative screens are probably inexpensive to establish and require minimal maintenance. They do have the same problem as settling basins, with respect to the future raising of the dam. If all the sediment deposited in the area of vegetation is within the area of an enlarged reservoir then preservation of existing storage would mean the loss of future storage. One side effect of increased vegetation cover is the increase of water consumption. Garde et al (1978) indicate a 10% loss of the mean annual flow due to the growth of tamarisk in some rivers.

4 AVOIDANCE OF SEDIMENT

4.1 Off-channel storage

Transferring the water to an off-channel storage would avoid any appreciable degree of siltation. This is possible where the topography is suitable and when the cost of pumping water into the off-channel reservoir is commensurate with the benefits. Provision of a desilting plant will be required at the intake works. Small high quality supplies for drinking water or industrial purposes are likely to be the main reasons for choosing this option. Kabell (1984) believes that in cases where a small water supply is required and the only suitable source is a large river, it is preferable to construct an off-river storage that can be filled annually by pumping or diversion. This solution is only feasible for small supplies.

4.2 Bypass channels

By making the sediment laden flows pass round the reservoir in a specially constructed canal excessive sediment can be avoided. Additional diversion works are required and care has to be taken in the design of the canal. Brown quotes Schoklitsch (1935) in saying 'that such arrangements can be considered providing the reservoir is short and locality permits construction of such a device at legimate expense'. Various examples from the USA, South Africa and Switzerland are given by Brown. More recent use of diversion galleries has been made in Switzerland. The Swiss National Committee on Large Dams (1982) report that at Palagnedra a 1760m gallery was added in 1974. The gallery has a section of $30m^2$, slope of 2% and capacity of $225m^3s^{-1}$. This has had the benefit of leading sediment away from the Palagnedra reservoir. Further examples of the bypassing of sediment laden flows in China and the USSR, are given by Fan Jiahua in the UNESCO report.

5 REMOVAL OF SEDIMENT

This section considers the removal of sediment after it has been first deposited in the reservoir basin either to somewhere else in the basin where is does less harm or to somewhere outside of the reservoir basin. By the very nature of the problem removal of sediment will be an extra cost for the maintenance budget of a project unless some allowance is made for recurrent costs at the feasibility stage. Several engineers have made the plea for flexibility of design to permit easier maintenance and desilting. Pitt and Thompson (1984) call for sufficient flexibility to be included in the design so that the operator of the reservoir can alter his rule curves according to the sedimentation experience. From the experience of Ackers and Thompson (1985) it is clear that flexibility of operation should, where possible, be designed into the project, by such things as the generous provision of low level outlets. They go on to say that it is not always possible and seldom desirable to lay down rigid operation rules for a reservoir: the hydrology of rivers varies from one year to another, the water and power requirements may have to respond to social and climatic conditions that are not wholly predictable, and above all, knowledge of the many sediment processes at work is imperfect so that even the best forecasts for the behaviour of sediments are imprecise.

Therefore, the following methods can be more effective if the designer of the dam has allowed for a certain amount of flexibility in the operation of the reservoir. For example, if bottom outlet sluices have been provided or sufficient water is stored to permit flushing activities then it is possible to contemplate use of one or a combination of some of the methods described below.

5.1 Hydraulic (operational) methods - definitions

The use of the water in the reservoir either to move sediment from 'live' to 'dead' storage or to remove the sediment from the reservoir is considered in this section and termed hydraulic methods of sediment removal. Perhaps an easier way of understanding the techniques is to consider them as operational methods since operation of the reservoir in a particular manner, either short term or long term, prevents or removes sediment. There is some confusion in the literature as to the terms used and the following paragraph may assist in clarifying what is meant by a particular term.

Flushing is the action of releasing water from the reservoir (sometimes releasing all the stored volume) so that the rapid fall in water level and high water discharges will cause local *scouring*. The maintenance of the reservoir pool at a low level particularly at the onset of the rainy season will enhance the *scouring* effect of flood flows upon previous sediment deposits. The general principle is to encourage sediment deposits into suspension and to keep those particles in suspension until they can be released from the reservoir (usually at the dam). The release of this sediment laden water is usually referred to as *flushing* though Brown and later Chow (1964) call it *venting*. *Flushing* is therefore the overall action of *scouring* sediment into suspension and transporting it out of the reservoir basin by means of releasing most of the water stored. *Flushing* can only be achieved if bottom outlets are provided in the dam or barrage. The operation of the reservoir to cause scouring of deposits from live storage into dead storage only (thereby not releasing all the water) is termed reworking and is not flushing as the material has not been removed from the reservoir basin. Sluicing is the operation of opening sluice gates or valves to start the process of flushing. Sluicing, in the short term, is often used to cause local scouring around intakes.

5.2 Hydraulic Methods
- Flushing

Breusers et al claim that hydraulic methods are not very effective in general for the removal of sediment from a reservoir basin. They believe that even with considerable discharges of water only limited amounts of sediment close to the outlet can be removed. The task committee of the American Society of Civil Engineers, ASCE (1973) believed, at the time of compiling their report, that flushing of sediment in all the cases they examined was seldom practicable. In every case (they do not give references) the result was the development of a deep, narrow channel into the deposit. However it has been possible to find some reports of success claimed for the removal of sediment by this method. For example, Graf (1984) quotes various reports from the Soviet Union on the success and relative cheapness of the flushing technique. These are supported by the findings of Mikhalev (1971) and Gvelesiani and Shamal'tzel (1971) based upon model studies of typical hydropower reservoirs on mountain rivers. These reports provide valuable case studies though it must be remembered that to prove the viability of the method for general application will require good field data, and possibly mathematical and physical modelling.

In the light of these case studies and with availability of more reliable field data Ackers and Thompson have been able to state that sediment flushing by the use of large bottom outlets can effectively extend the life of reservoirs and can preserve some live storage permanently in cases where, without flushing, virtually all the available storage would be lost within decades. It is in reservoirs where the storage ratio of volume to mean annual flow is less than 0.5 that attention has to be given to flushing techniques. Ackers and Thompson define reservoirs with these ratios as having half lives of less than 100 years, Figure 3. Half life is the time it takes to lose half the useful storage volume.

It is interesting to note that Kabell recommends that on purely economic grounds (in Zimbabwe) no reservoir should be constructed if the design half life is less than 20 years. To put it another way he recommends that all dams in Zimbabwe should be built to provide a minimum storage ratio of 0.10.

One of the much quoted examples of success in flushing a reservoir is the case reported by Duquennois (1956) of the Iril Emda reservoir in Algeria. He claims to be able to maintain the reservoir indefinitely at 80% of its initial capacity. Without the technique of flushing, 50% of the reservoir capacity would be lost in about 40 years. Over the three years 1953 to 1956, 45% of the total solids arriving at the reservoir were removed by the technique adopted.

Fan Jiahua in the UNESCO report gives many examples of how flushing has been achieved in Chinese reservoirs. The technique adopted on the Heisonglin, Honglingjin and Sanmenxia reservoirs was to use the flood season flows to flush as much sediment as possible from the reservoir basin. The water level is lowered during the flood season by operating the bottom outlets in a controlled fashion. This results in flows of high sediment concentration being discharged through the dam and scouring deposits from previous years. This technique of 'storing the clear water and discharging muddy water' has been used successfully on many medium and small reservoirs in China as summarized by Zang et al (1976). The muddy water is usually diverted downstream and used for 'warping', a technique of depositing fertile sediments across farm land to increase yields. This mode of operation is suitable for reservoirs where the sediment is fine and much of the annual sediment load is discharged in a relatively short period at high concentrations. So that the operation can be timed correctly, the technique requires good organisation, and a knowledge of sediment concentration and flow. The UNESCO report quotes an example from Sanmenxia reservoir on the Yellow river in China. Some figures will assist in indicating the magnitude of the problem.

TABLE 1: Sanmenxia reservoir

Annual runoff	$43.2 \times 10^9 m^3$ of which 60% occurs during the flood season, July to October
annual sediment discharge	1.6×10^9 tonnes
Average annual sediment concentration	37.8kg m^3
Maximum sediment concentration	933kg m^3

Over an 18 month period, in 1960 to 1962, 1.8×10^9 tonnes of sediment where deposited in the reservoir basin. After 1962, the reservoir operation was changed by lowering the water level during the flood season. This had some benefit in reducing the amount of deposition. However with the addition of bottom outlets and tunnels the discharge capacity of the dam was increased during the 1970's so that it is now possible to discharge nearly all the sediment flowing into the reservoir and still retain the storage purpose by impounding water during the dry season. Table 2 shows how the quantity of sediment in the outflow has been increased thus minimizing the deposition within the reservoir.

TABLE 2: Sediment outflow at Sanmenxia reservoir

PERIOD	OPERATION	SEDIMENT QUANTITY IN OUTFLOW 10^9 tonne	OUTFLOW/ INFLOW %
September 1960 -March 1962	Storing	0.11	6.8
April 1962 -July 1962	Flushing using 12 openings	3.39	58.0
July 1962 -June 1970	as above plus 2 tunnels and 4 penstocks	7.38	82.5
July 1970 -October 1973	as above plus 8 diversion outlets	5.93	105.0
November 1973 -October 1978	- ditto -	6.68	100.0

Sanmenxia is a large reservoir (capacity not given) on a large river with reasonable records of flow and sediment discharge. The sediment which is mainly silt and clay is derived from loess soils, the composition of which is given by Fan et al (1980) as 6% sand (0.5 - 0.05mm), 80% silt (0.05 - 0.002mm), 14% clay (0.002mm). This material is suitable for deposition on agricultural land without any disadvantages. The 'warping' of this material is seen as a major factor in increasing agricultural production.

Reports of the flushing technique on smaller reservoirs are also given in the UNESCO report and in Zang et al. It is not always possible to operate the reservoir to flush deposits from the reservoir basin each year because of operational requirements and demands upon the water stored.

Jowett (1984) describes the flushing of the Mangahao reservoirs in New Zealand. From 1924 to 1958, 59% of the capacity was silted up so in 1969 when the situation was serious a low level diversion tunnel was used to flush one of the reservoirs. Within one month 70% of the accumulated sediment had been flushed (estimated at 800 000m^3). The costs of this operation where high, debris had to be hauled away and the downstream river bed was affected by excessive sediment deposits reducing fish spawning grounds. The power station is now closed for three weeks during sediment flushing reducing power generation by 4% (4GWh per year). Jowett points out that the technique can be enhanced if reasonably sized bottom outlets are installed at the construction time making sure that proper abrasion resistant linings are used. These points are also noted by Bhargava et al (1987) in their report on sedimentation of dams in the Indian Himalayas, and by Dawans et al, (1982) in Switzerland and Rienossl and Schnelle (1982) in Austria. Care must also be taken to avoid environmental problems downstream during the flushing period due to high discharges and high sediment loads damaging structures and the river ecology.

From the literature available and the reports given it is clear that flushing is a technique that can be used, sometimes very effectively in maintaining reservoir storage. However to be successful the technique must be carefully planned and anticipated at the design stage as Ackers and Thompson warn. These points of allowing for the flushing of sediment and taking the cost of such action into the capital budget of the projects are emphasised by studies in China by Shih and Shih (1980), in Japan by Takasu (1982) and in Taiwan by Hwang (1985). Techniques to mathematically predict the performance of reservoirs with or without flushing allowance are now available as given by

Bettess and White (1984). Mathematical models, as summarised by Bettess (1988), and physical modelling, examples of which are given by Mukhamedov (1981) and Jaggi and Kashyap (1981), can now assist the planners and designers of future reservoirs.

Flushing techniques can be used on all sorts and sizes of reservoirs however the technique is probably not required on reservoirs with half lives in excess of 100 years. Reservoirs having a half life of less than 100 years (usually more like 50 years) are probably the sites where the technique is most beneficial. On reservoirs with small storage volumes the loss of valuable water may not permit flushing. The successful flushings of Santo Domingo reservoir in Venezuela as reported by Krumdieck and Chamot (1979) requires the complete loss of stored water. This is possible because the power station is used only to satisfy peak power demands. On a reservoir used for irrigation in a semi-arid region it will probably not be possible to use the water for flushing particularly if the inflow of water is highly variable as is often the case on ephemeral rivers.

There is, therefore, an argument, in some cases, for the mechanical removal of sediment from reservoir basins. This point is considered in the next section.

5.3 Mechanical methods - dredging

In general the use of dredging to restore lost storage is an expensive method and is infrequently resorted to. Chow considers that hydraulic dredging provides the most economical methods for fine-grained submerged material, and it is these methods that are considered in this section. In 1943 Brown considered that the cost of dredging was too high and that because dredging machines could not be easily moved from site to site only large reservoirs could be contemplated. As has been seen from earlier sections it is probably not necessary to remove sediment from large reservoirs anyway. With the advent of small dredgers and as new sites for reservoirs become rarer the value of using small dredgers should increase.

Fan Jiahua in the UNESCO report gives five situations when dredging is undertaken.

(a) when flushing is not successful,

(b) when building a bypass channel is impossible,

(c) when it is not possible to use water for flushing,

(d) when the dam is irreplaceable with no possibility of raising the dam height, and

(e) when the energy consumed in flushing (or the loss of power generation) is uneconomic for reducing the rate of silting.

Bolton (1979) points out that engineers in Algeria used to assess whether dredging was justified by comparing the cost of restoring a given capacity each year with the cost of providing storage for an equivalent volume by building a replacement structure (the annual cost being based on the projected life of the reservoir). If the cost of dredging did not exceed the cost of replacement by more than a factor of 2.3 dredging was considered worthwhile.

Several cases of dredging have been reported from Japan and Austria. Kobilka and Hauch (1982) have estimated that the cost of gravel dredging in hydropower plant ponds on the Danube is economically reasonable. In Japan, when the deposits are of sand and gravel the dredging of material is not too costly. On the Sakuma reservoir, Okada and Baba (1982) report that the sediment removed (10m annually) is of good quality quartz sand, highly suitable as fine aggregate for concrete. Suryono also considers the dredging of sand from the Lesti river upstream of Karangkates reservoir as being feasible as the material is of good quality for concrete.

Most of the literature available on dredging concerns the use of large offshore and estuary dredging machines, however a paper by Scheuerlein (1986) reminds us that the application of dredging technology to the clearance of silted reservoirs is far from being sufficiently adapted to the particular conditions found in these reservoirs. Scheuerlein lists the main objectives of a reservoir dredging system as ;

(a) minimization of pollution in the working area,

(b) high capacity at large working depths,

(c) economically feasible costs,

(d) water consumption must be kept as low as possible, and

(e) the equipment must be capable of being dismantled and transported over land.

Scheuerlein goes on to consider the various forms of dredger and recommends consideration of an under water bucket-wheel dredger because it is economical in the use of water. Special dredging techniques such as jet pumps (Fig 4) air lift pumps (Fig 5) and pneumatic pumps (Fig 6) are thought to be worth further research. Scheuerlein believes that those special techniques offer possibilities for reservoir dredging but that "a real break-through is still missing!". Hopefully the dredging industry should feel challenged to find a capable, efficient and economic way to solve the reservoir dredging problem.

Clark (1983) gives a summary of a comprehensive survey to identify and characterise portable dredgers in the USA. The survey revealed a wide range of portable dredger capabilities and design features. Dredging depths range from 3m in smaller, one-piece units to over 18m for larger, modular-built dredgers. Production rates range from 15 to $1400\text{m}^3\text{hr}^{-1}$ with a wide range of cutter mechanisms such as cutterheads, ladders with chain cutters, bucket wheels, wide horizontal cutters, twin rotating vertical cutters, open suction dustpans and jet pumps. The degree of portability varies greatly from one dredger to another and many portable dredgers can be transported in one piece on flat-bed trailers.

The definition of portable is the one used by Clark. "A dredge can be considered portable if it can be easily moved from one jobsite to the next over existing roadways. If a dredge must be dismantled for transport, it should be constructed for that purpose so dismantling and reassembly can be done easily and quickly."

Portability is important for reservoir dredging because it allows for the capital costs of purchasing a dredger to be shared between projects. One small dredger may be able to service five or six reservoirs in a region over several years if it can be moved easily between sites.

The number of small reservoirs, the very ones that are often severely affected by sedimentation, is often underestimated. For example there are many more than 2 million small reservoirs (less than 62000m^3 capacity) in the USA, according to Hadley (1980). In Zimbabwe there are many hundreds of small reservoirs whose aggregate value is probably greater than the few large dams in the country. Other countries like Tanzania, as reported by Christiansson (1981), Lesotho as reported by Chakela (1981), and India all have small reservoirs for rural water supply and irrigation. The reservoirs are very often constructed with minimal design information. However just because they are small and not prestigious does not mean that they are unimportant in development terms. The sedimentation of a small reservoir supplying water to a town and small irrigation scheme can have a devastating effect on the lives and prosperity of many people. The use of a portable dredger <u>may</u> have great benefits in these cases.

Several portable cutter-suction dredges have been brought to the attention of Hydraulics Research. Details have been given to provide typical examples. Mention of trade names does not constitute an endorsement or approval of any particular system. Further information can be obtained from the manufacturer or their authorised agents.

<u>Mud Cat - Horizontal Auger Dredge</u>, manufactured by Mud Cat Division, National Car Rental System Inc, PO Box 16247, St Louis Park, Minnesota 55416, USA. This system uses a horizontal auger cutter, Figure 7. The cutter knives dislodge material and the spiral auger drives the material to a pump suction intake. Various machines are offered with digging depths from 3m to 8m drawing 0.6m and producing between 45 to 155m^{3}hr^{-1}. The main centrifugal dredge pump and

cutter assembly require between 150kW to 260kW of power from a diesel engine. The Harris group of companies in the UK have considerable experience of using Mud Cat machines on small reservoirs, lakes, canals and sludge ponds. The dredger winches itself along a cable strung across the lake dredging in both directions. A driven helical cutter (the auger) feeds dredgings to the suction pump which can then discharge the spoil as far as 2000m from the site. The Mud Cat is fitted with cutter head shields to minimise turbidity around the machine. One man can operate the system with another in attendance. Prices are around US$150 000.

Mini Dredge - VMI, manufactured by VMI Inc 4310, N Martin, Bethany, Oklahoma 73008, USA. This system is very similar to the Mud Cat, producing between 115 to 150m^3hr^{-1} from a 125kW to 160kW diesel powered centrifugal pump. The Mini Dredge works down to 4.5m drawing 0.5m. Prices range from US$120 000 to US$300 000.

Both the Mud Cat and Mini Dredge are portable and it is possible to transport them with little modification. Maximum lengths are 14.5m, maximum widths are 2.75m, weights vary from 5.5 tonnes to 11.4 tonnes.

The principle of the jet pump is to accelerate a primary fluid, usually water, to a high velocity jet which creates a suction which acts on the surrounding sediment and draws it into the discharge tube, Figure 4. The advantage of the method is the absence of movable parts exposed to the sediment/water mixture as is the case in conventional pumps. This gives the promise of lower maintenance costs and simpler operation. Wakefield (1972) and (1986) demonstrates the advantage of jet pump dredging over conventional dredgers. The consulting and development engineers Wakefield and Imberg have improved the understanding of how jet pumps work and how they can be made to function efficiently. Their designs now form the basis for the dredgers operated by Reservoir Desilting International Ltd and Alluvial Mining & Shaft Sinking Co Ltd.

The RDIL Muck Duck, manufactured and operated by Reservoir Desilting International Ltd, Vine Lane, Hillingdon, UB10 OBX, UK is a self propelled portable catamaran pontoon dredge employing the jet pump principle. Details are given in Fig 8 of the dredging depth and output. Normally the delivery of the jet pump will only reach about 0.5km from the dredging site but this can be increased with an additional centrifugal booster pump. The usual staffing arrangements are one operator and an assistant, however in some situations it is possible to operate the dredger unmanned. As is common with all dredgers the manufacturers prefer to design the machine to suit a particular job. However a typical small, fully portable Muck Duck would cost US$240 000 to work on a reservoir like Tokol sabo dam. This would be powered by a diesel engine requiring between 95 and 260kW of power to deliver 100 to 400 tonnes hr^{-1}. An example like Tokol would therefore take 15 weeks (5 days of 10 hours each per week) to clear.

The Amrod remote dredging system and Diver operated dredge from Alluvial Mining & Shaft Sinking Co Ltd, 2 High Pavement, Basildon, SS14 1EA, UK are special applications of the jet pump principle. These machines can operate down to 300m, (the remote system), and are therefore used mainly in connection with off-shore problems. However the principles of ease of use, low maintenance costs, exact control over dredging are fairly clear to see. These machines could prove to be particularly useful in dredging operations in deep water near to the dam face.

Solids in the size range 100 to 250mm can be easily handled by the system. Because these are special machines, and in the case of the remote system require sophisticated support vessels, the cost is not quoted here.

It is clear from a brief examination of the market that small, portable, dredgers with reasonable production rates and modest power requirements could be used on many small to medium sized reservoirs throughout the world. Capital investment will probably be in the region of US$250 000 for one dredger through transportation, labour, fuel and ancillary equipment costs will have to be added.

5.4 Mechanical methods - digging

The physical removal of deposited material by means of excavators or even by hand is a fairly expensive and slow technique to reclaim storage. The development of local sand extraction industries at the upstream end of reservoirs can assist in removing significant quantities of material however the volumes of material deposited are often greater than can be removed for building purposes.

Removal of volcanic sands from the head waters of Karangkates reservoir (Indonesia) up until the construction of Sengguruh dam was done by hand. This provided an income for the local population but health risks due to exposure to water-borne parasites could be a problem if this technique was recommended in a wide number of locations. The use of bulldozers to move sediments in the reservoir basin to assist in flushing has been reported by Krumdieck and Chamot and the Swiss National Committee on Large dams.

5.5 Mechanical Methods - siphoning

Siphon dredging used for desilting reservoirs differs from ordinary dredging, as described in section 5.3, by using the hydraulic head difference between the upstream and downstream water levels at the dam as the source of motive power. Both Brown and the UNESCO report quote examples of siphon dredging. An example, quoted by UNESCO, in China on the Tianjiawan reservoir considers that the method has the following advantages:

(a) low cost of dredging,
(b) the siphon dredger can be easily moved, and
(c) the water is not wasted, the water sediment mixture being used for warping.

The only major disadvantage is the blocking of the pipe line with organic debris which may prove difficult to remove. A siphon device installed on the Rioumajou dam in France operates automatically carrying up to 15kg of sediment in a flow of $1m^3s^{-1}$ in a 44m pipe, 400 to 500mm in diameter. The UNESCO reports say that the device operates with remarkable efficiency and its cost was amortized within one year.

Siphon dredging is obviously a low cost solution and should be considered for the removal of small sized sediments near to the dam if the discharge of sediment laden water is permitted downstream. The technique is most successful when that quantity of water released for dredging purposes is required downstream anyway.

6 SEDIMENT DISPOSAL

No method of sediment removal from a reservoir basin can be contemplated without consideration of where and when the spoil is to be disposed. This section briefly outlines some of the points that should be considered.

Embi (1986) considers that the most natural solution to the problem of where to dispose of excavated sediment would be to return it to the river. After all the problem was created by the dam obstructing the natural process of sediment transport to the sea. However, as has been shown by Jowett, the discharge of sediment downstream when the power of the river has been reduced can cause excessive and damaging deposits of sediment which only have to be removed again (at a cost). There is some fear that the trapping of sediment in a dam may increase the degradation (lowering of the bed levels) downstream in the river with a resulting problem of scouring around bridges and structures. Therefore the release of some sediment could be beneficial. This has to be balanced by the change in flow regime (usually less variation of flow) introduced by the reservoir operations.

If the sedimentation is caused by excessive soil erosion then an ideal solution would be to return the sediment to the fields but this is virtually impossible in most cases.

On large impoundments it may not even be necessary to remove sediment but if it is required then, to minimize the transport distances, spoil dumping in the dead storage area could be considered. The use of mechanical methods on large reservoirs is not thought to be the best solution when compared against flushing or designing the reservoir with sufficient capacity.

On smaller reservoirs, with half lives of 50 years or less then dredging down to the minimum operating level should be feasible. The deposition of spoil in suitable areas around the reservoir so that material can be used for construction or agriculture is the best solution for small reservoirs. The discharge of material over or through the dam is the usual situation. Whilst the costs of doing this might be low the costs of sediment removal further downstream from other reservoirs, ports, irrigation schemes and so on should also be considered.

If sediment is to be released downstream of the dam then timing may be critical. For example large sediment concentrations at a time of low flow may damage fish habitats and endanger downstream supplies. The discharge of sediment in higher flow may avoid sediment deposition but the additional water may cause a greater risk to flooding.

As a simple rule it may be best to consider the disposal problem with regard to the size of the reservoir. On large reservoirs (half life over 100 years) use the nearby storage available in the dead water zone. On medium sized reservoirs (half life 20 to 100 years) use a combination of methods, deposit in the dead storage, discharge fines through the dam and remove coarse material for construction. On small reservoirs (half life less than 20 years) all sediment above the minimum operating level will have to be removed on a regular basis, once every few years. Stream size in general will not usually permit discharge downstream so nearby storage areas, land reclamations, etc, should be contemplated, along with sediment removal for construction. Any large scale development of sand winning will require an infrastructure of suitable roads which in itself may cause increased urban development and agriculture in an already erosion sensitive drainage basin.

7 ECONOMIC ASPECTS

As was mentioned in the introduction of this report the economic aspects of reservoir sedimentation need to be discussed if the benefits of reservoir desilting are to be assessed. The costs of carrying out reservoir desilting operations can be calculated and included in either the annual maintenance budget or in the capital works of the dam construction. The cost of not doing any desilting can be calculated from a fairly simple analysis of the sediment yield and the benefits to be accrued from the project. If a dam has been built to provide hydropower then it should be an easy matter to calculate the generating capacity lost due to sedimentation. Reservoirs constructed for irrigation, particularly small scale irrigation, in semi arid areas (eg Zimbabwe) are often severely affected by sediment. Loss of reservoir storage in these cases can be related to a reduction in the area of land cultivated and a reduction in the yield of crops. The following example of Mapanzure irrigation scheme supplied by Gozho reservoir in Zimbabwe can be used to demonstrate the loss of irrigated land, (HR data files have been used to provide this information).

TABLE 3: Gozho reservoir

Latitude 20°23'S
Longitude 30°51'E
Capacity = $1.3 \times 10^6 m^3$
Mean annual runoff (MAR) = $4.3 \times 10^6 m^3$
Capacity/MAR = 0.3
Catchment area = $43 km^2$
Sediment yield = 410 tonnes/km^2/year (1975 to 1982
Mapanzure Irrigated area = 43 ha

Over a 20 year life span for the small holder irrigation scheme loss of storage due to sedimentation has been calculated to be 15000m^3 per year. This amount of water on an annual basis is sufficient to irrigate 2ha each year, which would reduce the effective irrigation area to 3ha in 20 years.

If we accept the assumption that farm incomes in Zimbabwe on small-holder schemes are US $800/ha/annum and assuming that sediment yields and farm incomes remain static over 20 years then the loss of income from irrigation due to sedimentation would be approximately US$336 000.

The effect of applying a discount rate to the lost income over a twenty year flow of benefits is to reduce the impact of the lost income. Whilst this may be accepted as valid for calculating returns on capital invested in the engineering works it involves a cost to "socio - economic development" of which the client should be made aware. Where suitable dam sites and irrigable land are, or are soon to become a constraint and where regional devlopment is an objective, sustainability may supercede capital as the scarce commodity. If the first ten years of the life of this reservoir are considered at the rate of siltation given and discounting future benefits at 10% the present value of that income is approximately US$164 900.

The cost of small holder irrigation development is given in Zimbabwe as US$5 000/ha which for this 43ha scheme would total US$215 000. The costs exceed the benefits over a ten year period.

Without siltation however the present value of benefits would be US$344 000. So that investment in desilting equipment up to US$129 000 would produce a break even at 10 years. The life of the scheme infrastructure is given as 20 years so a further ten year flow of benefits would accrue (although subject then to the siltation rate given above), giving an additional present value of US$125 159.

More thought needs to be given to the economic considerations at the design stage of small dam smallholder irrigation projects to determine the economic benefit of including dredging capability particularly in the light of the relative ease with which capital costs financing is accessible to poor countries and the difficulties encountered in recurrent cost financing.

A more rigorous economic analysis should be undertaken which should allow for opportunity costs, varying farm incomes and pricing policy for power and water. The simple analysis does indicate that in many instances the introduction of desilting devices at the design stage of a dam could be economically justified and that the use of a portable dredger to serve several small reservoirs where flushing is not possible could have a economic benefit.

The use of modelling techniques to predict sedimentation behaviour of a proposal reservoir and to test desilting techniques may be justified at the design stage. With the increase of power in small computers it will soon be very easy to run simulation programs in design offices, however the data requirements to predict future sedimentation with confidence should not be ignored. The collection of good quality field data to use in simulations for design purposes will be an expensive and lengthy exercise. The expense, though, should be judged against the costs of not understanding how the proposed reservoir will behave. Without that knowledge the chances of the reservoir being silted up and difficult to reclaim are much higher. The costs of field data collection and survey should therefore be taken into account at the pre-feasibility stage and viewed as a necessity.

8 CONCLUSIONS

Sedimentation of reservoirs is likely to continue to be a problem for the operators and beneficiaries of reservoirs. As the suitable sites for dams are used up so more attention must be given to reclaiming or maintaining storage for existing reservoirs.

The literature examined for this report revealed a wide range of techniques and solutions to the problem. It is difficult to generalise because each reservoir and drainage basin has some unique features. We can, though, learn from the practice of others and think about the problem of sediment removal at the design stage. Design for sedimentation rather than allow it to become a surprise after several years of operation.

No one technique will be successful. Much of the literature stresses the importance of soil conservation, and preventing material reaching the reservoir. This is a long term strategy and can be supplemented by considering flushing or operational techniques on large and medium sized reservoirs (over $10 \times 10^6 m^3$ capacity) provided adequate facilities are provided during construction. On small reservoirs, which usually can ill afford to lose water through flushing, dredging techniques using small portable dredgers could be feasible. To justify this economically will require a more rigorous approach to quantifying the benefits of reclaiming storage. Disposal of spoil and the transport of the dredger from one site to another must be taken into account before planning dredging.

Mention was made earlier of doing nothing, that is letting the reservoir fill with sediment. This is certainly a possibility for reservoirs with half lives of many hundreds of years, in excess of the design life of the structure. It may seem sensible to do this, in some cases, based on present economic thinking. To do nothing though implies ignoring the overall cause of sedimentation and not appreciating the value of soil and water for future generations.

The development of techniques to reclaim and maintain reservoir storage needs to proceed by research efforts aimed at understanding the processes of sedimentation, the design of suitable systems and the impact of desilting on downstream communities. It is anticipated that reservoir desilting will become a necessity over the next 50 years as the volume of all sizes of reservoirs is more fully realised. Construction of new dams and reservoirs will and should continue. As pointed out by Rapp et al (1973) even a short-lived reservoir may be economically justified in areas where the need for water is pressing. The construction plan should include a carefully made prognosis of the expected rate of sedimentation and the life of the reservoir and should include a plan for control of sediment.

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FIGURES

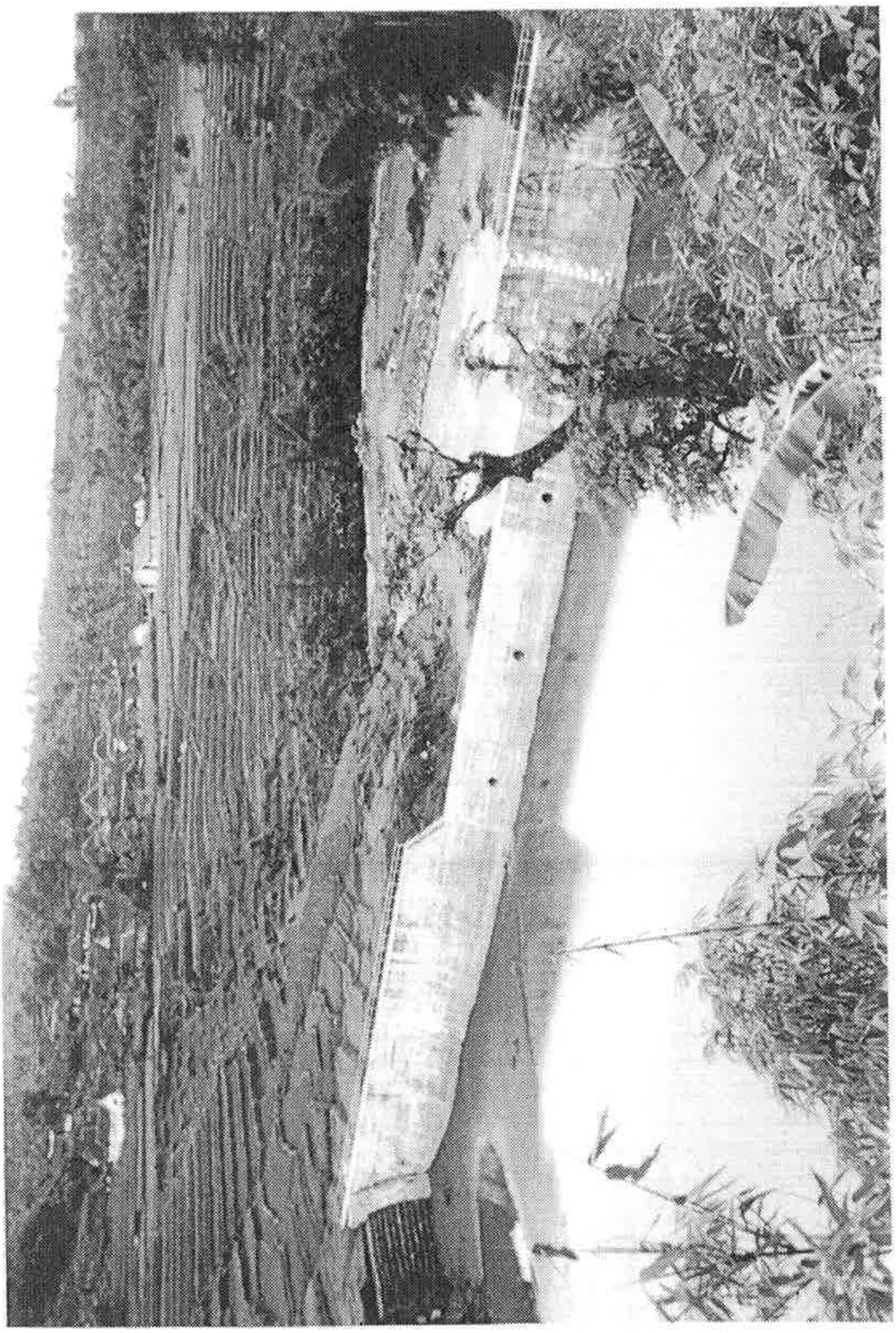

Fig 1   Tokol Sabo dam   March 1976

Fig 2   Tokol Sabo dam   February 1984

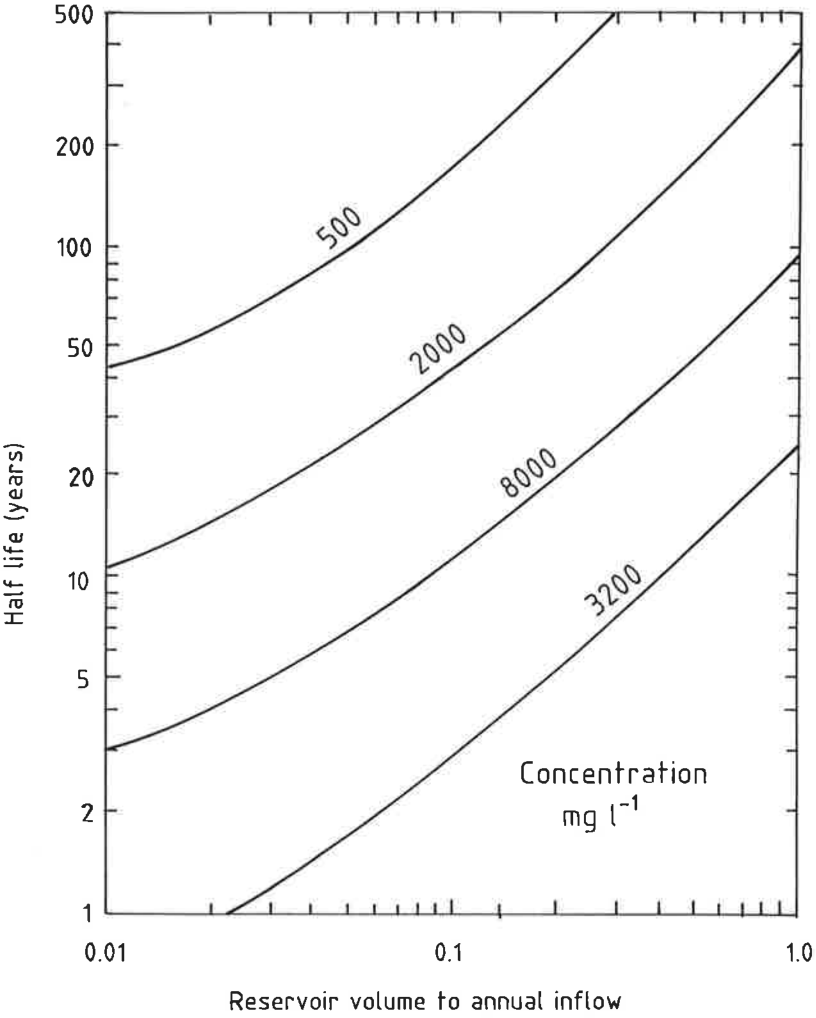

Fig 3 Reservoir half life relatioships after Ackers and Thompson (1985)

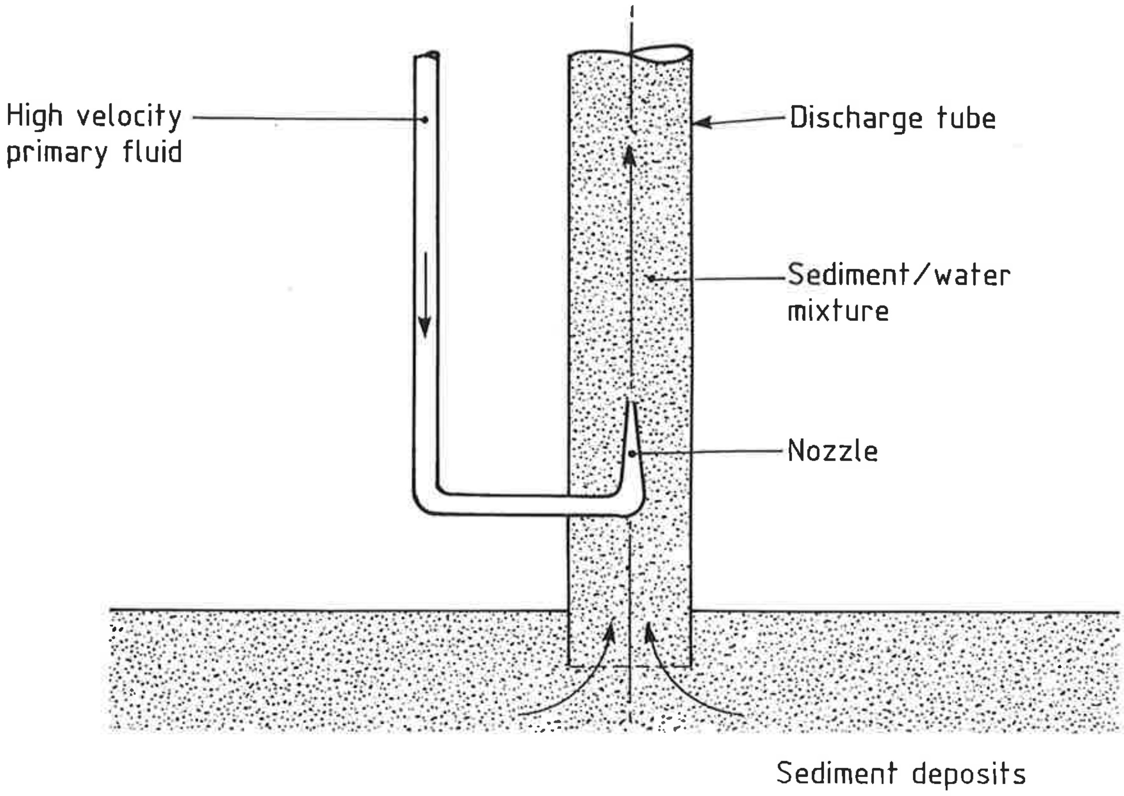

Fig 4 Jet pump dredging (working principle)
after Scheuerlein (1986)

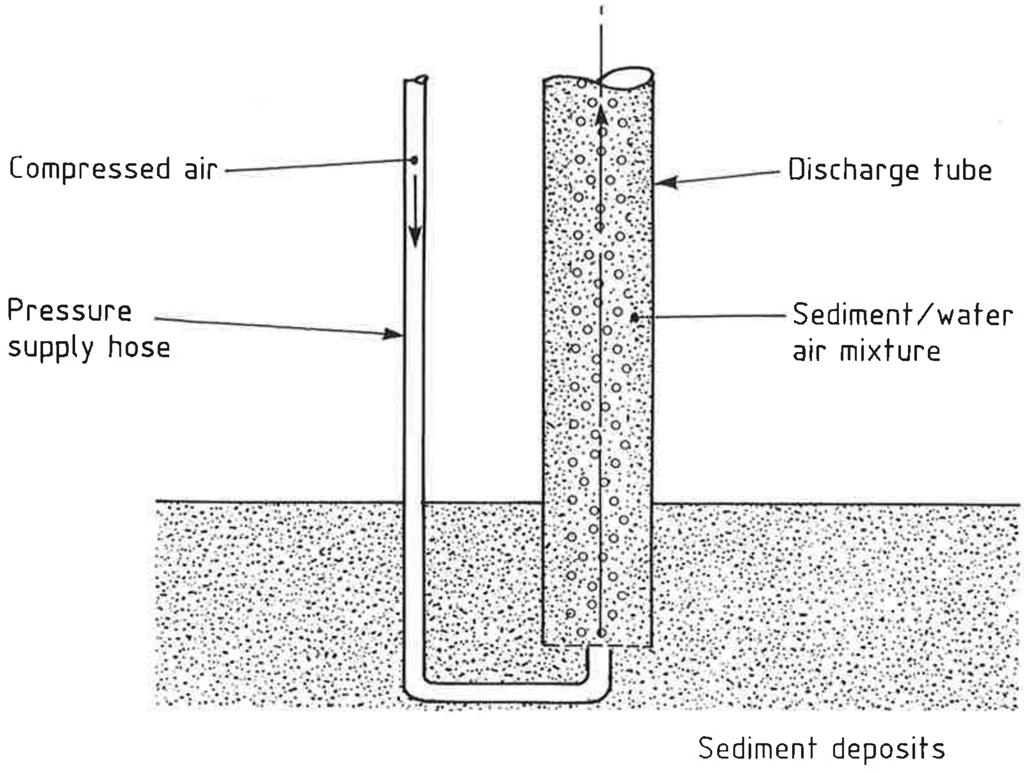

Fig 5 Air-lift pump dredging (working principle) after Scheuerlein (1986)

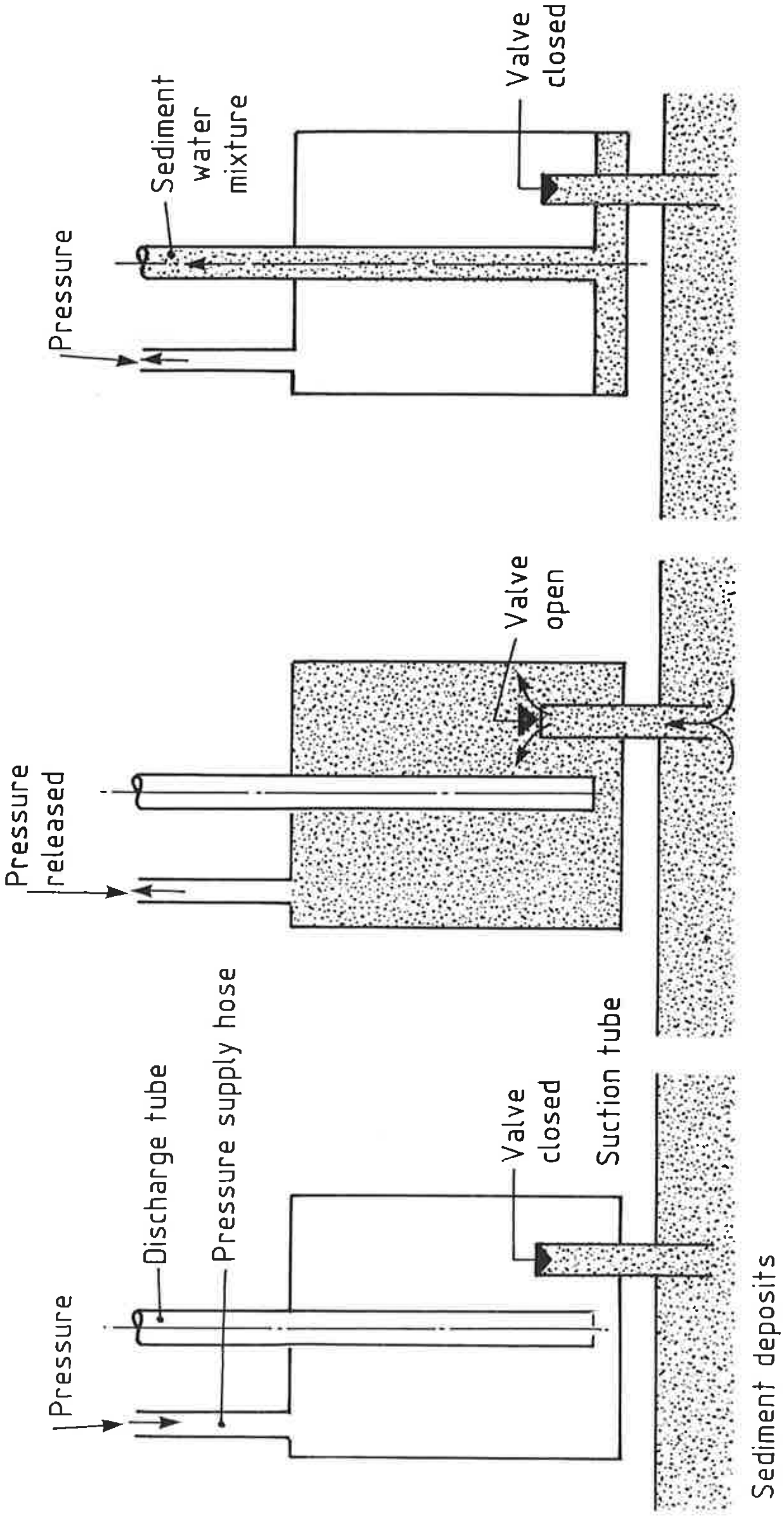

Fig 6 Pneumatic pump dredging (working principle) after Scheuerlein (1986)

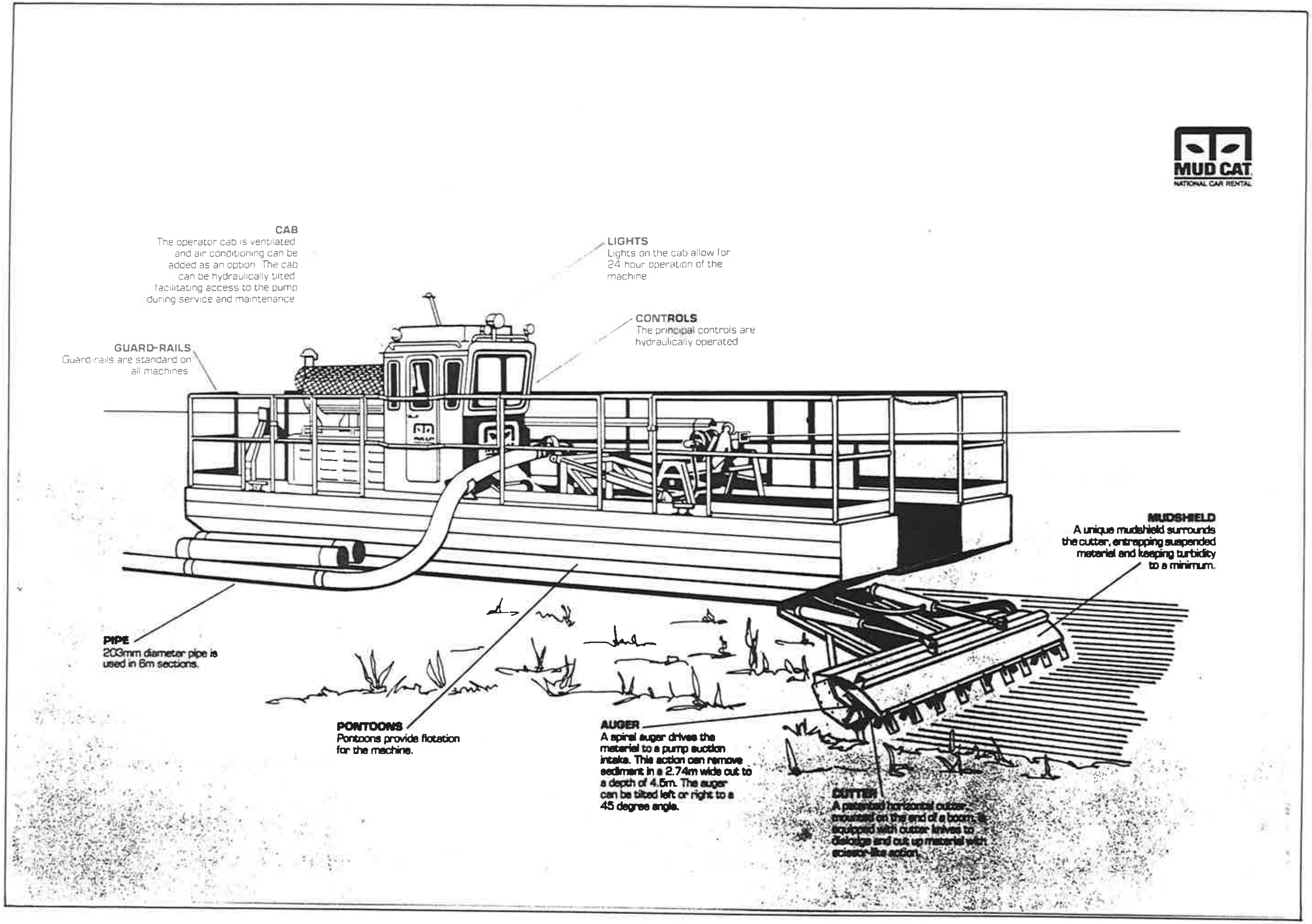

Fig 7 Mud Cat portable dredger

THE RDIL DREDGE

The RDIL Muck Duck is a self propelled portable catamaran pontoon dredge employing the jet pump principle. It has been designed with mobility in mind and will fit into container space for shipping.

The dredge is constructed in three sections consisting of a forward, central and rear pontoon arrangement. The central section is the basic dredge and can be operated independently if conditions permit. The forward pontoon section allows dredging to greater depths and a rear pontoon comprises a centrifugal booster permitting discharge to greater distances or to similar distance at increased rates.

The valid output range is 50 to 200t/h of dry solids at dredge depths between 0.8m and 30m, and at distances between 50m and 1km (greater distances can be achieved by the use of additional booster pumps).

Materials which can be handled extends from slimes, tailings and compact silt to gravel up to 125mm in size.

Vital Statistics

Length	Forward Section = 6m Central Section = 14.3m Rear Section = 4m
Width	Forward Section = 2.55m Central Section = 2.55m (for transit) 4.75m (working) Rear Section = 4m (working)
Draught	900mm
Dredge Depth	Central Section only = 6m Central & Forward Sections = 10m
Discharge Pipe	Normally 250mm
Engines	SAME. 1056PT. Diesels, turbo charged, air cooled
Weight	Forward Section = 4t Central Section = 14.5t Rear Section = 6t

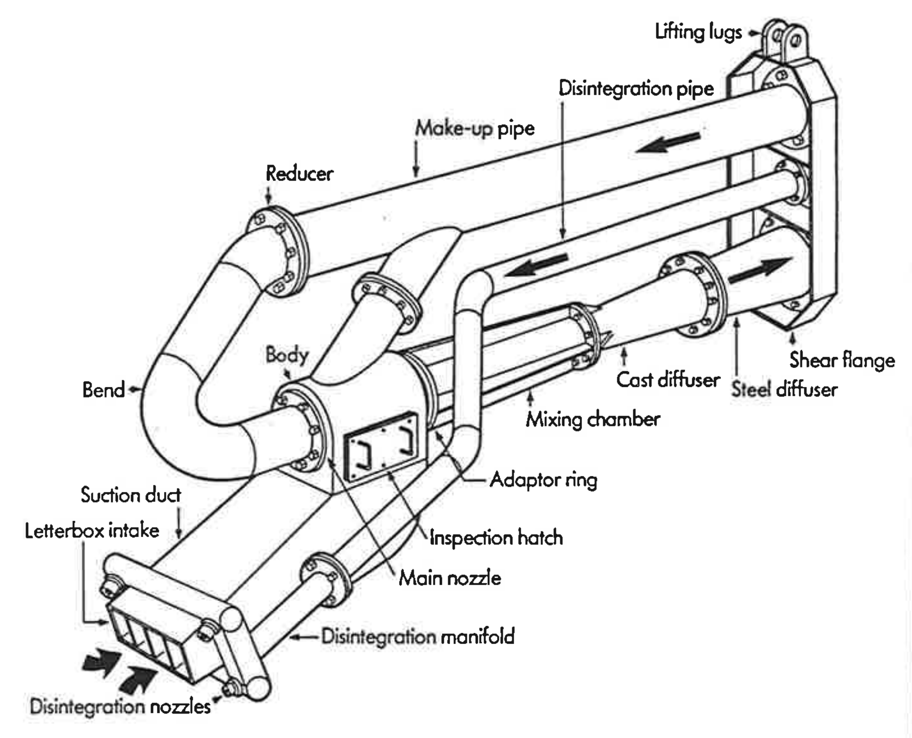

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Fig 8 The RDIL 'Muck Duck' dredge

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