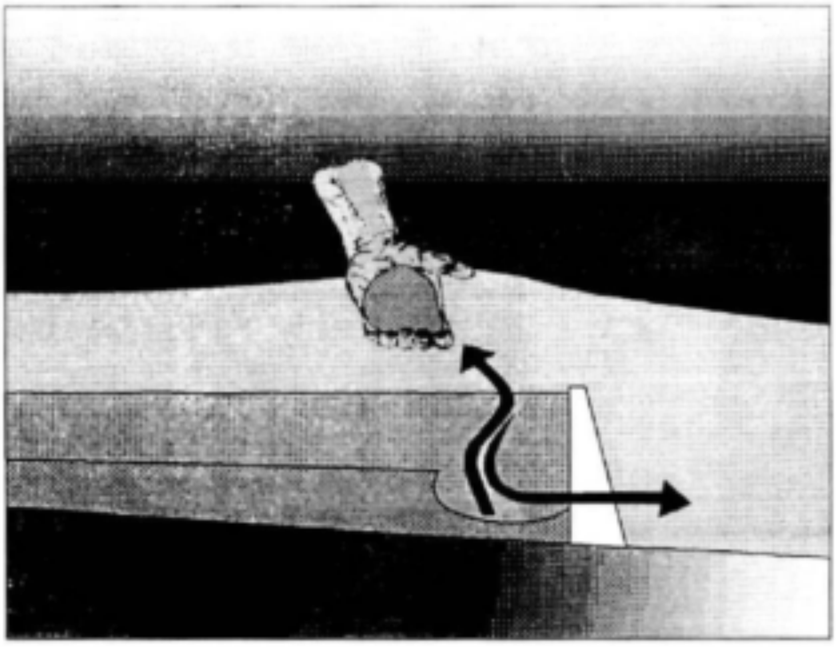
Dealing with Reservoir Sedimentation – Dredging

GR Basson • A Rooseboom

TT 110/99

Water Research Commission

Dealing with Reservoir Sedimentation - Dredging



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SUMMARY

Sedimentation generally limits the life span of reservoirs. The replacement of lost storage capacity is a world wide problem and the need therefore exists to limit reservoir sedimentation as much as possible.

In 1992 it was envisaged that this study would be undertaken to:

- evaluate reservoir sedimentation theory and to make contributions where possible
- define and evaluate the most important measures to control reservoir sedimentation with the emphasis on engineering methods at the reservoir
- evaluate the impact of the implementation of engineering or operational measures on reservoir sedimentation, at existing/future reservoirs on the long-term viability and sustainable use of reservoirs.

This document is an addendum to the main study report: *Dealing with reservoir sedimentation* (Basson and Rooseboom, 1997). It must be emphasised that dredging of reservoirs should be regarded as only one of several available techniques to manage reservoir sedimentation.

Reservoir dredging is being carried out world-wide, but mostly on a small scale localized at intakes, or storage dredging in small reservoirs. The cost of dredging is generally higher than the creation of additional/new storage, but technical developments in the dredging industry have narrowed this gap to a point where dredging has to be considered as a major technique for controlling sedimentation. This is especially true in semi-arid to arid regions where catchment or sediment control methods cannot be implemented successfully. Limited suitable new dam sites, socio-economic considerations when raising a dam, and environmental concerns related to the construction of especially medium-scale to large-scale dams, are all factors favouring reservoir dredging.

Dredging equipment suitable for reservoir dredging is evaluated in this report, including conventional (mechanical and hydraulic) and specialised dredging techniques. Case histories have indicated that the selection of the correct dredging equipment for especially reservoir dredging is essential. Boundary conditions such as consolidated clay necessitate the use of a cutter. The dredging industry is highly specialised and it is difficult to recommend a specific dredger for general reservoir dredging application.

The cutter-suction and bucket-wheel dredgers with floating pipeline do, however, meet most of the requirements for reservoir dredging and should be considered in dredging depths of less than 30 m. For deeper applications, specialised grab or fluidization-pump systems are available.

Siphon dredging systems with a cutterhead could result in a considerable cost saving by eliminating the use of pumps. These systems are, however, limited by the available head, required transport distance, limitations on water loss and environmental concern with downstream disposal.

Case studies of dredging carried out in Southern Africa and on international reservoir dredging projects are discussed in this report.

A number of South African reservoirs where severe sedimentation has occurred, have been used in an economic analysis to determine whether the unit costs of dredging could compete with conventional measures to increase reservoir capacity, such as raising of the dam. The results of the analyses are shown in **Table 1**. It is clear that at many reservoirs significant relative increases in water yields could be achieved through dredging. The estimated unit costs of dredging were however, only in the case of Prinsrivier Dam found to be lower than alternative measures to increase the reservoir capacity.

Some key findings of the dredging economic analysis are:

- Although difficult to generalize, the required dredging unit costs need to be in the order of less than R1,50/m^3 sediment excavated.

- To obtain the same yield benefit, a much smaller volume can be dredged compared to a raised dam with additional storage created.

- Dredging of all the sediment is not necessary and the required volume is determined by the water demand, run-off reservoir basin characteristics, volume of sediment, etc.

- At some reservoirs a dead storage zone for sedimentation has been provided with the lowest water release valves located above this zone. Dredging of the dead storage zone can therefore not be considered because the water cannot be utilized. It is recommended that the lowest valves are installed close to the original river bed level.

- The general assumption in water resources planning that sedimentation fills the dead storage zone with a horizontal surface level, should be analysed in more detail for existing reservoirs and for the final designs of new dams, to evaluate the impact of loss of live storage due to sedimentation. Allowance in future for sedimentation of reservoirs can still be made, but the design of a dead storage zone specifically for sedimentation should be discarded.

- The use of electric power instead of diesel power should seriously be considered in any dredging project, because it can more than halve the unit dredging costs.

- The cost of disposal should not be underestimated as it could easily make up 20 % of the total cost of a dredging project.

Table 1: Dredging costs

Reservoir	Sediment to be dredged (million m³)	Water yield increase (million m³/a)	Dredged yield/current yield ratio	Required cost of non-dredging option (1994) (R/m³ storage capacity)	Estimated obtainable dredging cost (1994) (R/m³ sediment)
Floriskraal	17	3	1,50		
Grassridge	44	5	2,50		
Hazelmere	6	2	1,08		
Gariep	480	60	1,03		
Kommandodrif	16,5	1,8	1,56		
Krugersdrift	12	4	1,33	0,75 (raised)	
Lake Arthur	15	5,8	3,32		
Lake Arthur	7,5	4	2,60		4,63*
Darlington	143	20	1,63		
Darlington	30	9	1,28		
Pongolapoort	39	4	1,01		
Prinsrivier	3,44	0,92	3,88	7,00 (raised)	3,75**
Prinsrivier	1,28	0,80	3,50	7,00 (raised)	3,98**
Vaal	174	35	1,04	0,70 (LHWP)	
VanRyneveldspas	34	5	3,50	0,55 (boreholes)	
VanRyneveldspas	16	4	3,00	0,55 (boreholes)	2,15**
Driel	5	1	1,00		

Notes: * Diesel power dredging

** Electric power dredging

Typical dredging unit costs (actual and estimated) for Southern African reservoirs are indicated in **Figure 1**. These costs should only be used as a rough indication because each project has its own specific boundary conditions. The unit costs of dredging given in Table 1 and Figure 1 include the cost of disposal. (Please note that all costs mentioned in the report has a base date of 1994, unless specified differently).

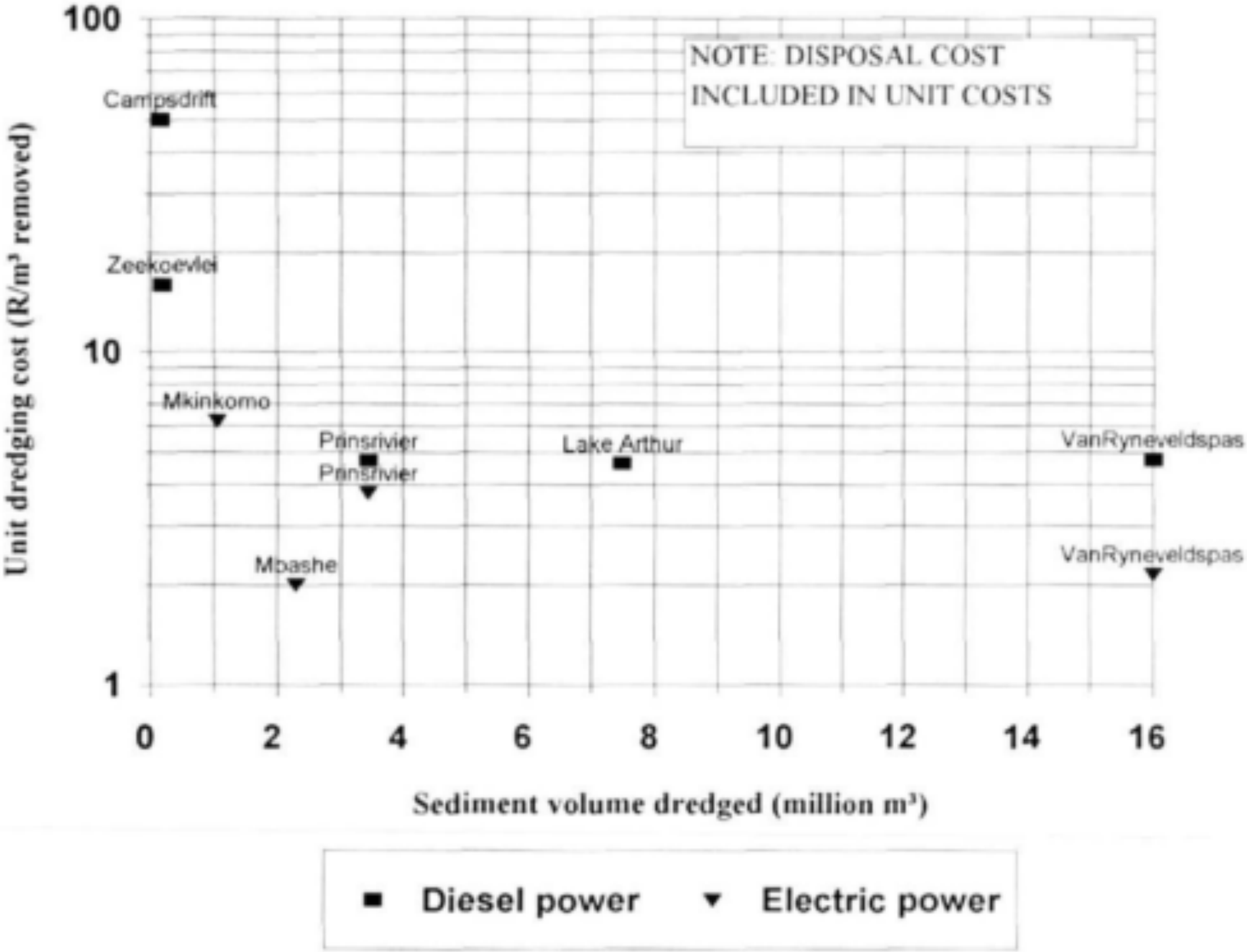

Figure 1: Dredging unit costs

The beneficial uses of dredged sediment have been investigated. Clay briquettes made of sediment from Darlington Dam indicate that it is possible to manufacture bricks from the sediment. However, transport distances to building sites could be a limiting factor. The possible use of sediment for agricultural purposes should be discarded because of the physical characteristics of the sediment: too coarse or too fine (uniform) due to the sorting process of reservoir sedimentation.

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Mr H Maaren	Water Research Commission (Chairman)
Mr D S van der Merwe	Water Research Commission
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Prof A H M Görgens	University of Stellenbosch
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APPENDIX A: INVESTIGATION OF THE POSSIBLE AGRICULTURAL USE OF DREDGED SEDIMENT

1. INTRODUCTION

1.1 Reservoir Sedimentation - The Problem

During the past decades a great number of dams have been constructed in river systems to create storage capacity for power generation, irrigation, drinking water supply and flow regulation. Independent of the purpose of water resources schemes, they clearly have one thing in common - the fact that they always constitute an artificial interruption in the hydro-morphological river regime. The practice of reservoir operation teaches that such interference leads to sedimentation of reservoirs. As a result reservoir sedimentation is one of the main threats to reservoir management regarding operational efficiency and effective lifetime. Typical problems are the reduction of live storage and water yield/hydropower, the abrasion at hydropower plants, clogging of bottom intakes, and forces exerted on the dam by the sediment.

Having in mind the relatively high capital costs of a reservoir, it is imperative for reservoir management to develop and implement strategies to control reservoir sedimentation in an economically viable way.

This study, sponsored by the South African Water Research Commission, evaluates the available techniques to control reservoir sedimentation as part of a world-wide combined research effort to co-ordinate knowledge on this subject. This report forms an addendum to a main study report: "Dealing with Reservoir Sedimentation" (Basson and Rooseboom, 1997).

1.2 Reservoir Sedimentation Management Techniques

There are numerous ways of managing sedimentation:

a) minimize entry of sediment into a reservoir by

- watershed erosion control
- upstream trapping of sediment (debris dams or vegetation)
- bypassing of high sediment loads

b) minimize reservoir sedimentation by

- sluicing: passing of sediment-laden flood through the reservoir by partial drawdown of the water level
- turbidity current venting

c) remove accumulated sediment deposits by

- flushing by complete water level drawdown during rainy season
- excavation by dredging or conventional mechanical equipment

d) accept reservoir sedimentation, and

- maintain long-term storage by raising the dam
- abandon the sedimented reservoir and construct a new reservoir or water transfer scheme elsewhere in the river system.

The technical, economical and environmental feasibility of the above measures depends on a great number of factors:

- availability of suitable bottom sluicing facilities
- surplus water available for flushing
- characteristics of the sediment and reservoir basin
- purpose of storage and water demand
- consequences of flushing/dredging sediment disposal
- consequences of control measures interfering with the main reservoir operation
- environmental impact
- institutional-political limitations.

Generally, dredging is an expensive means of restoring the storage capacity of a reservoir, and it should only be considered if the use of alternative control strategies is not possible. (Bruk, 1985). The cost of raising a dam or of constructing a new dam is generally believed to be lower per unit volume storage than the unit dredging costs.

Most of the control measures have been implemented and tested at reservoirs. Dredging has largely been limited to the removal of sediment which has accumulated in front of intakes, or to recovery of lost storage in small reservoirs. Although dredging equipment developed for general coastal dredging is generally suitable for reservoir dredging, a number of specific boundary conditions, and specifically high unit costs, limited dredging as an economical solution.

In South Africa sedimentation is controlled at a few small reservoirs by flushing during high-flow periods. Due to the country's semi-arid to arid climate, however, water losses by sedimentation control strategies are not acceptable and management have had to accept reservoir sedimentation in most cases.

1.3 Control of Reservoir Sedimentation with Dredging

The excavation of deposited sediment in a reservoir is one of the methods to regain lost storage due to sedimentation. In this context excavation in nearly all cases involves dredging, being the excavation of soil material from the underwater. Dredging is a highly specialised technology and is mostly used in ports, waterways and mining. Dredging, however, also takes place on a routine basis in many reservoirs all over the world.

In the development and operation of water resources many variables play a role in the decision support system. One of the major factors is the economic feasibility of a project. The cost of dredging reservoirs has been relatively high compared to the provision of new storage or alternative sediment control methods in most countries where it has been implemented. A more scientific approach in recent years in the dredging industry can, however, possibly reduce costs and provide an economically feasible method of ensuring a long reservoir life.

Most of the problems encountered in reservoir dredging - large depth, consolidated sediment, debris and disposal limitations - have been experienced at dredging operations elsewhere and a great deal of knowledge gained is readily available for reservoir dredging. The dredging industry is highly specialised, and each project has its own purposely designed dredging equipment, taking into account soil properties, water depth, environment and logistical constraints. The same applies to reservoir dredging, where recently developed techniques could lower unit costs to an acceptable level.

To date dredging of reservoirs in South Africa has been on a limited scale, only in small reservoirs, due to the high cost of dredging compared to the construction of new or enlarged storage. Historical quotations for dredging on a large scale in South African reservoirs were generally more than 10 times the unit cost of new storage. These quotations, however, included high mobilization costs from overseas, no detailed field surveys were carried out and therefore the unit dredging costs offered posed a low risk to the contractor. In recent years local dredging contractors have been established in South Africa on a larger scale than in the past, with links with international specialists.

The purpose of this report is to assess techniques for reservoir dredging and the specific boundary conditions involved. World-wide reservoir dredging case studies will be discussed, as well as the local Southern African experience. The main objective of the report, however, is to evaluate the economic feasibility of the dredging of specific South African reservoirs compared to alternative options for the control of sedimentation. From this preliminary evaluation, three representative reservoirs are selected and a detailed financial cost analysis carried out, taking into account site specific conditions such as pumping distances, disposal sites, sediment characteristics and dredging depths.

A brief overview of the history of dredging and general available dredging equipment and their applications is presented, together with reservoir specific equipment and new developments. Specific items such as the disposal and possible uses of dredging material and environmental concerns associated with the dredging of reservoirs are also discussed.

This report is written for water resources planners and managers with the aim of providing a general background of available technology to cope with the problems of reservoir sedimentation. A review of reservoir dredging practices world-wide, as well as in South Africa, with specific emphasis on the economical aspects, will help the decision-maker in the selection of alternative sediment control methods. The dredging contractor will, however, also learn from case histories and the specific dredging problems encountered in the dredging of reservoirs.

2. HISTORY OF DREDGING

The term "dredging" refers to those methods of displacing soil which are characterized by excavation "in the wet" and disposal in stream or onto the shore. (Linssen and Oosterbaan, 1975). The development of dredging equipment is closely linked with the successive stages of development of human technology: hand power, the lever, the wheel, mechanical power and automation. Dredging is an ancient art but a relatively new science. Although work on primitive dredging can be traced back several thousand years, it is only relatively recently that the art has been transformed into a science covering the design of dredgers and dredging techniques.

The art of dredging began along the Nile, Euphrates, Tigris, and Indus rivers many thousands of years ago. (Gower, 1968). The early forms of dredging were carried out by primitive methods with spades and baskets. Canal dredging in Sumeria and Egypt (400 B.C.) and in Babylon under the direction of Nebuchadnezzar (600 B.C.) has been recorded. Agitation dredging was also used in early times. Tree trunks weighted by stones were dragged behind a boat on the Indus River to stir the mud into suspension. The suspended material was then carried downstream by the river current. The scraper dredger relying on this principle was first used in Zeeland in 1475 A.D. In the Netherlands a new basic dredging tool was developed during the Middle Ages known as the "bag and spoon". This spade and basket was an efficient tool operated by two men.

The horse-driven "mud mill" was developed towards the end of the sixteenth century in Delft, Holland, over a period of more than two centuries. The mill, activated by a revolving chain, scooped up the mud onto a chute **(Figure 2.1)**.

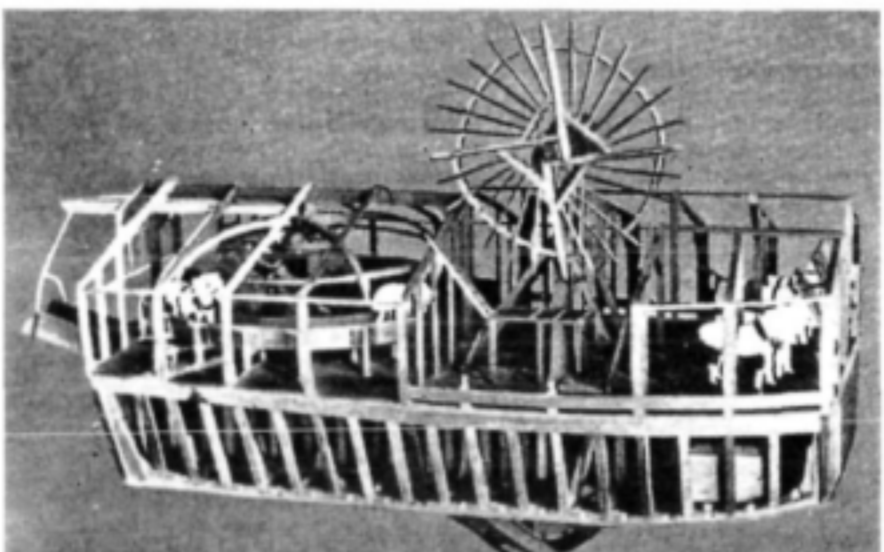


Figure 2.1: Mud Mill

The need to dredge harbours and ship channels quickly developed in England in the second part of the sixteenth century. The first known offshore mining operation was off the Essex coast in England when bisulphide of iron was dredged from the sea bed.

A grab dredger (**Figure 2.2**) was developed in the sixteenth century both in Italy and Holland. The main problem in the field of dredging, however, was the lack of sufficient energy. Development of a steam engine by James Watt in the eighteenth century finally gave the long-needed energy to propel ships and dredgers, and the development of a centrifugal pump by Le Demour in 1732 gave birth to modern dredgers.

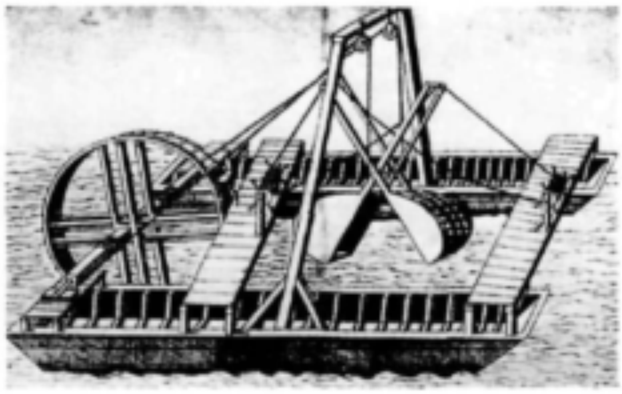


Figure 2.2: Grab dredge (Lorini, 1597)

Bazin(1867) presented the idea of a suction dredger in 1867. His design, which incorporated a rotating harrow under the bow of a ship and suction pipes under the stern, was applied in the dredging of the Suez canal. Lebby(1855) conceived the first hydraulic hopper dredger which operated in 1855 (**Figure 2.3**).

The period between 1890 and 1930 can be characterized as one of consolidation. Due to a lack of major capital dredging projects in Europe the activities were restricted to maintenance dredging. It was in these times of recession that dredging companies became aware of the importance of the properties of the soil in relation to the production capacities of their equipment.

In the 1950s dredgers developed gradually. Certain types of equipment had become accepted in particular regions: In Western Europe non-propelled suction dredgers and bucket dredgers with barges and pump-ashore units were most commonly used, while in the UK much grab dredging was carried out. In the USA cutter-suction dredgers, dippers and suction hopper dredgers carried out the bulk of the work.

Figure 2.3: First hydraulic dredger

Since 1960 a more scientific dredging approach was followed, eg.:

- electronic measuring devices led to the optimization and automatization of dredging
- a new approach to soil mechanics resulted in dynamic soil mechanics
- survey methods and equipment were developed to obtain accurate hydrographic sounding and positioning
- hydro-geological scanning methods were developed to obtain detailed information on *in situ* sediment characteristics.

Modern dredging covers the fields of hydraulic engineering, soil mechanics, mechanical engineering and industrial engineering. The dredging industry is now characterized by a wide range of enterprises, varying from local contractors to large companies operating all over the world. The diversity of jobs to be carried out by dredging have expanded enormously, leading to a high level of specialization.

Dredging equipment and techniques have become highly specialised due to the nature of work to be accomplished eg.:

- Reclamation of low-lying areas
- Deepening of water courses/harbours to be accessible to navigation under various conditions such as currents, winds, etc.
- Dredging of drainage/irrigation canals
- Dredging in reservoirs at hydropower intakes
- Environmental dredging to remove contaminated material
- Dredging for marine minerals: nearshore and offshore in deep areas

- Dredging of reservoirs to recover lost storage due to sedimentation and related problems such as disposal, deep dredging, clayey and consolidated material
- Beach nourishment by dredging in the nearshore region
- Landfill projects - airports, artificial islands
- Land-based dredging such as dredging open-cast coal mines

The dredging industry has the characteristic of high capital-intensity in common with other industries. Labour has become very important in the dredging industry both for highly qualified personnel and the lower ranks. In certain cases the employment of local labour is recommended and requires intensive on-the-job training.

Many types of equipment are used in dredging and can be classified into two broad categories: mechanically or hydraulically operated. The greatest improvements during the last 30 years have been in the dredgers operating on the hydraulic principle. These modern dredgers are more efficient, fully instrumented and partially or fully automated which results in a lower cost of dredging.

3. DREDGING EQUIPMENT

In this chapter a distinction is made between conventional and specialised dredging equipment.

3.1 Conventional Dredgers

Dredgers can be classified as either mechanically or hydraulically operating as illustrated in **Figure 3.1**.

3.1.1 Mechanical Dredgers

The main advantage of mechanical dredgers lies in their ability to operate in restricted locations and to remove material at low sediment-water ratios. On the other hand they are all characterized by their inability to transport dredged material over long distances, by their lack of self-propulsion, and relatively low production rates. The dragline, dipper and bucket-ladder dredgers also cause excessive turbidity in the water.

The mechanical dredger is not only used for removing coarse material such as sands and gravels deposited at the head of a reservoir where the water depth is shallow, but also in localised areas such as at hydropower intakes, sometimes at great depths.

a) Grapple/Grab

The grab dredger (**Figure 3.2**) is usually derrick mounted on a barge and equipped with a clamshell bucket. The grab dredger breaks the cohesion and excavates the sediment in a single procedure. The excavated sediment is usually transported in barges. In some applications a dredger pump is installed directly above the shovel with a pipeline to transport the sediment accumulated in the shovel (Rokosch, 1992).

It works best in soft underwater deposits. Large dredging depths are possible from 30 m to 150 m. In cohesive clays difficulties may be encountered in emptying the bucket.

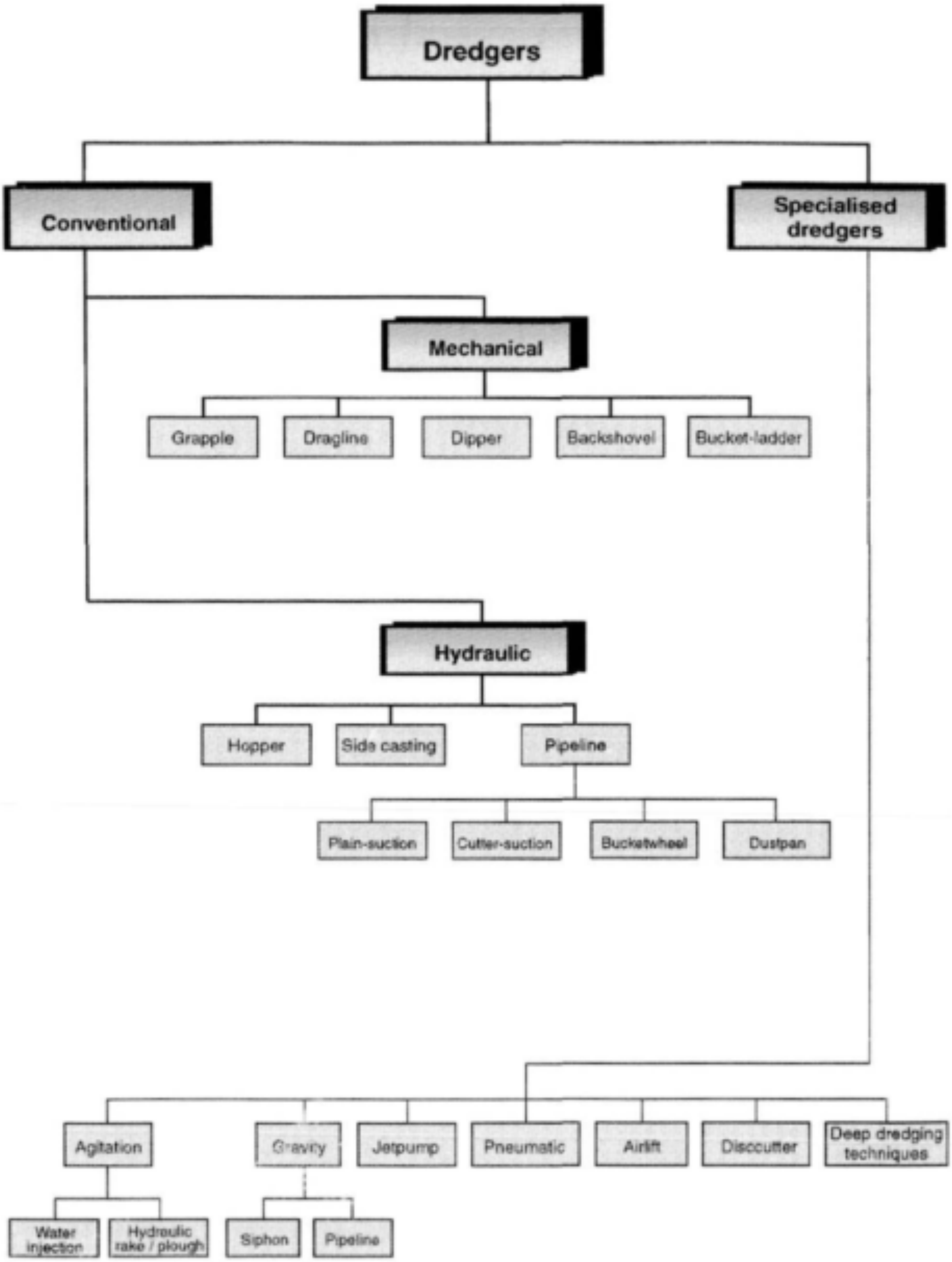


Figure 3.1: Classification of dredgers: Conventional and specialised

Figure 3.2: Grab dredger

b) **Dragline**

The dragline system (**Figure 3.3**) consists of a steel bucket suspended by cable from a moveable crane. Large dredging depths are possible.

Figure 3.3: Dragline dredger (San Lameer)

c) **Dipper/Back-shovel**

The dipper dredger (**Figure 3.4**) is the floating counterpart of the familiar land-based mechanically excavating shovel. It has a shovel with the opening either towards the back (back hoe) or to the front. It works best in hard compact sediment or rock. The maximum dredging depth is 20 m and dredging is restricted to non-cohesive sediment.

d) **Bucket-ladder**

The bucket-ladder dredger (**Figure 3.5**) has a chain of buckets with a continuous work cycle. The top of the chain is thrust into the underwater deposit so that each bucket digs its own load and carries it to the surface. This dredger is expensive, but the continuous process results in higher production rates than for grapple or dipper dredgers. The efficiency in highly cohesive sediment is, however, low. The maximum dredging depth is generally 12 m, but some can work to 30 m depths (Wittke, 1970).

Figure 3.4: Dipper dredger

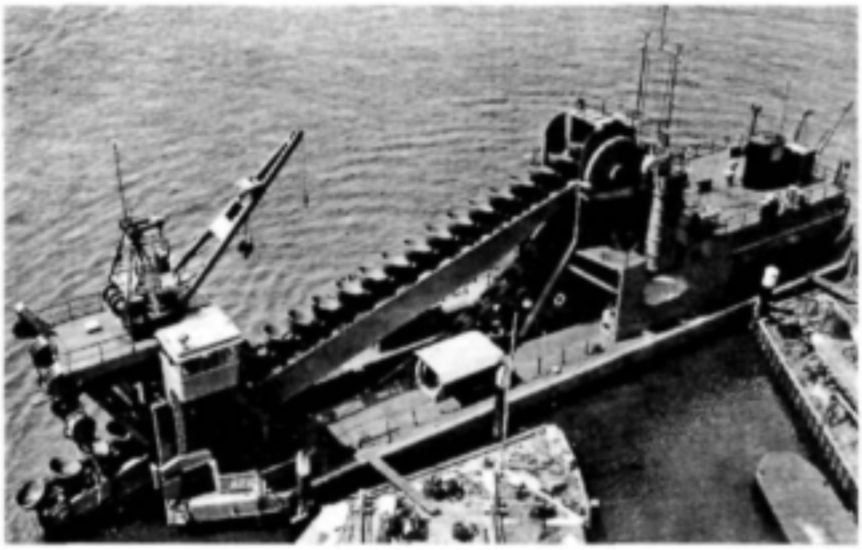


Figure 3.5: Bucket-ladder dredger

3.1.2 Hydraulic dredgers

By hydraulic dredging is meant a system in which liquid plays a part throughout all phases of the process: in the breaking of the cohesion, excavation and transport in a pipeline.

Hydraulic dredgers are self-contained units which handle both phases of the dredging system: they excavate the material and dispose of it either by pumping through a floating pipeline to a placement area, or by storing it in hoppers which can be subsequently emptied over the disposal area. These dredgers are more efficient, versatile and economic to operate because of this continuous, self-contained digging and disposal principle of operation.

In a hydraulic dredger the material to be removed is first loosened and mixed with water by cutter heads or by agitation with water jets and then pumped as a fluid.

Hydraulic dredgers can be grouped into the following main groups:

a) Hopper

A trailing suction hopper dredger (**Figure 3.6**) is a self-propelled dredging vessel that excavates the sediment via one or two suction mouths (**Figure 3.7**) and pumps it into its own hopper via pipelines. As soon as the hopper is full the dredger sails to the relocation site, where the dredged material is discharged either via its bottom doors or by pump.

Figure 3.6: Trailing-suction hopper dredger

The draghead configuration varies according to the type of material. The trailing suction hopper dredger is extensively used in river channels and port maintenance, in all but hard material. The maximum dredging depth is 20 m, but 40 m is possible with a submerged pump on the drag-arm.

Figure 3.7: Hopper drag head

b) Cutter-suction (Figure 3.8)

The rotating cutter cuts the sediment, which is discharged by the dredger pump via a floating and shore pipeline to the disposal area. The cutter is capable of vertical and horizontal movement by raising or lowering the cutter ladder and by moving the vessel across the cut by cables and spuds. The dredger rotates around the working spud which is located at the stern, resting in the sediment. The front is winched from one side of the sweep to the other by using two anchors.

Cutter-suction dredgers are most well known, efficient, reliable and versatile. An important development was the installation of a submerged dredger pump on the ladder of the dredge, thereby increasing the concentration of slurry in the pipe and making deep dredging possible.

The cutter-suction dredger can effectively dig and pump all types of alluvial and compacted deposit such as clay. Rock, coral and limestone can also be dredged. The maximum dredging depth is in the order of 30 m without a submerged pump.

Cutters are used with and without teeth depending on the hardness and compactness of the material to be dredged. Several types of cutter design are used (**Figure 3.9**).

The transportable cutterhead pipeline dredger is of specific interest to reservoir dredging. In recent years many dredgers even larger than 500 mm (discharge pipe diameter) have been designed in the portable range. These dredgers can be dismantled and transported by truck or ship to where they are required.

Especially for dredging on inland water, a much lighter superstructure consisting of floats can be utilized. The same safety aspects as for seagoing dredgers are not required, resulting in capital cost reductions.

In deep dredging (depths >30 m) conventional cutter-suction methods will be unsuitable for reservoir dredging due to limited suction capacity which would lower the solid content ratio and the associated cavitation problems.

The cutter-suction dredger is capable of handling cohesive and consolidated sediment and works with a water-sediment ratio of 4:1 or even 3:1 under favourable conditions.

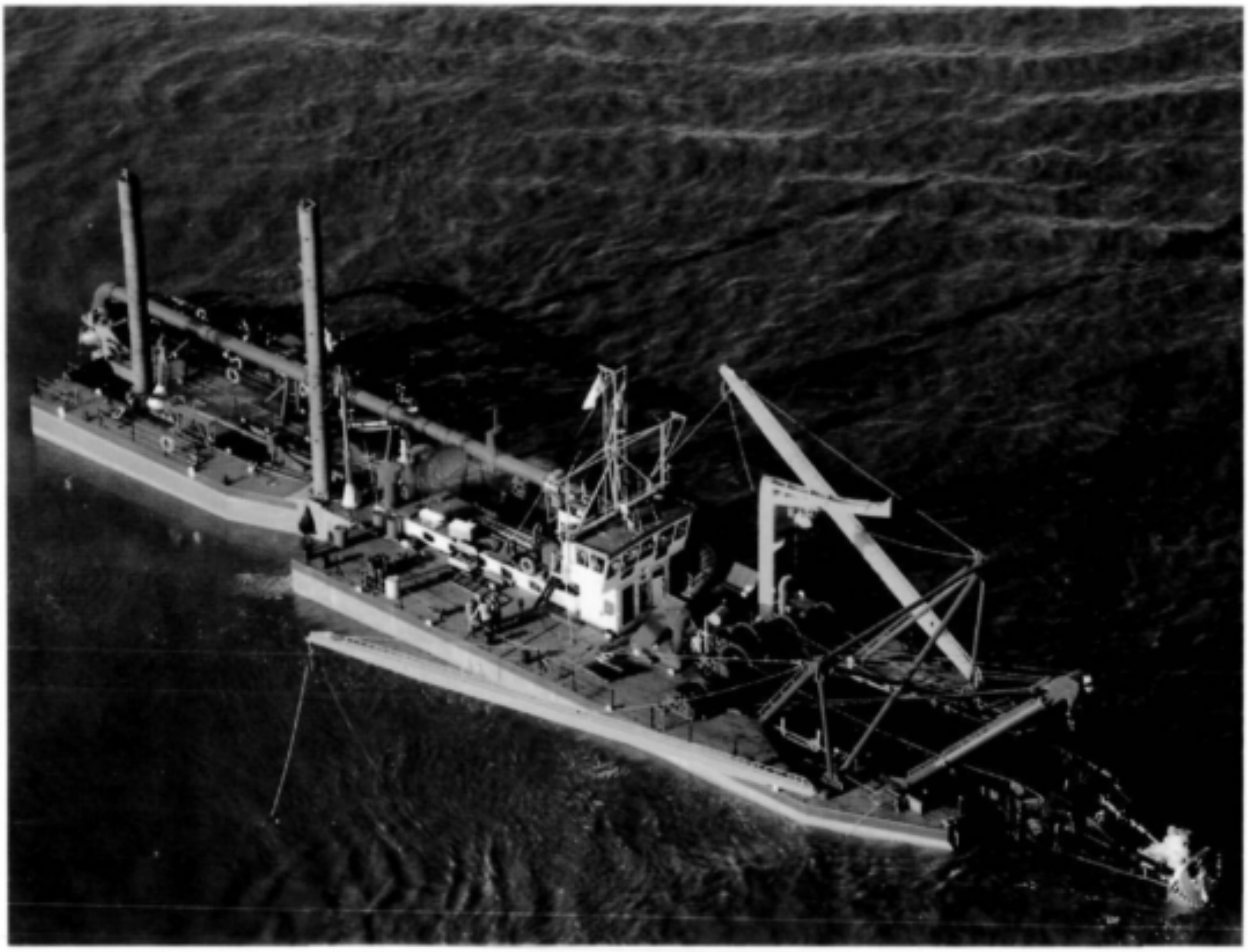


Figure 3.8: Cutter suction dredger

Figure 3.9: Cutter-head

c) **Bucket-wheel**

The bucket-wheel dredger (**Figure 3.10**) has a rotating wheel with bottomless buckets. Soil is cut and directed into the interior of the wheel and conveyed into the suction line. The dredger is suitable for the removal of thick layers of sediment (bulk dredging) and strongly cohesive sediments such as clay.

Figure 3.10: Bucket-wheel dredger

Bucket-wheel dredgers have been extensively used in open-cast mining under aquatic conditions. A comprehensive range of sophisticated bucket wheel dredgers from 150 to 1 500 m^3/h exists. Water-sediment ratios of 3:1, or even 2:1 under favourable conditions, can be achieved (Scheuerlein, 1987).

d) **Plain suction/dustpan**

The dustpan dredger (**Figure 3.11**) is a stationary suction dredger that is usually moved by means of anchor wires. It has a wide flat suction mouth which is suitable for the removal of thin layers of sediment. When dredging in sand and consolidated silt, water jets are used to break the cohesion.

The dredger works like a large vacuum cleaner with the dustpan head (without a cutter) as wide as the dredge. It is suitable for high-volume, soft material dredging.

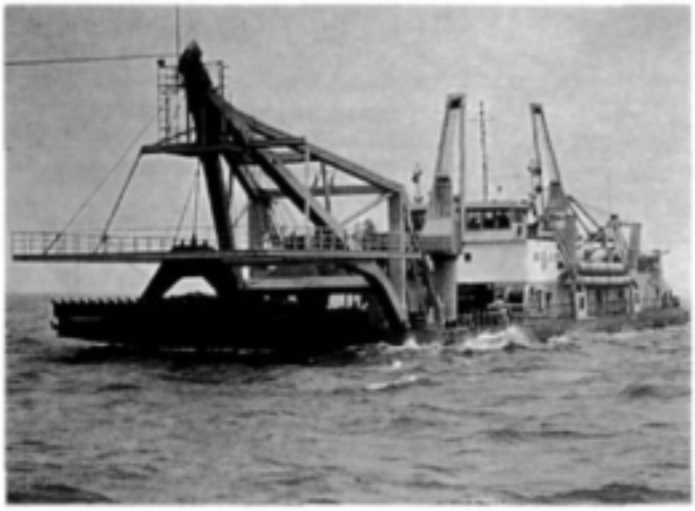


Figure 3.11: Dustpan dredger

3.2 Specialised Dredging Equipment

3.2.1 General

Several unique aspects of reservoir dredging and other dredging operations have prompted dredger designers to come up with new ideas to solve problems such as deep dredging depths, consolidated clay-silt sediment, etc. Low-cost dredging techniques have also been developed, mainly for general maintenance dredging, but some techniques also apply to reservoir dredging. The specialised techniques/equipment discussed are:

- Water injection
- Jet pump
- Air lift pumps
- Pneumatic pumps
- Siphon dredging
- Deep dredgers
- Underwater rotary hoe
- Walking dredgers
- Disc bottom cutter
- Ploughs
- Permanent dredger installations

3.2.2 Water injection

The water injection dredging technique induces a density current by injecting water into the bed sediment. The density current transports the sediment to the dam where it can be flushed out through bottom gates. It should be possible to reduce flushing water losses by adopting an intermittent operation, thereby allowing some consolidation (Estourgie, 1988). Instead of flushing, the movement of sediment from live storage to dead storage space (designed for sedimentation) could be carried out. Water injection dredging should provide a low-cost option compared to most conventional techniques, but there may be some complications, for instance:

- control/monitoring of the density current is difficult
- the reservoir basin characteristics may not be suitable for the development of a density current
- induced turbidity and nutrients released from the sediments may cause environmental concern
- highly consolidated clay-silt sediment may not be easily fluidized and a mechanical loosening of material is required.

The combination of water injection with flushing and lateral erosion (Xia Maiding, 1989) looks promising. Estourgie (1988), reported that the water injection dredging technique has been successfully used in many ports with varying sediment characteristics. Some details of these projects are indicated in **Table 3.1**. The highest production obtained was in silt. Although the projects in **Table 3.1** are not representative of reservoir conditions, field results look promising for application in reservoirs.

Table 3.1: Water injection project information

Location	Material	Production (m^3/h)
Epon harbour, the Netherlands	Dense fine sand, 10 % silt of low permeability	800 (160 000 m^3) Density current concentration of sand and silt: 20 000 mg/ℓ
Shipping lane, the Netherlands	Clay and consolidated silt: max shear strength of 25 kPa. (Normally in maintenance dredging < 5 kPa)	800 (15 000 m^3)
Ferny harbour, the Netherlands	Silt	1 500 (20 000 m^3)
Westbuitenhaven, the Netherlands	Loose silt	1 500 - 3 000 (500 000 m^3)

During water injection dredging, water is injected into the sediment creating a water-sediment mixture with fluid properties and an extremely low viscosity. During the 1980s a water injection dredger was constructed in the Netherlands, Jetsed, and extensive *in situ* measurements were taken to ascertain conditions during the process, such as soil properties, turbidity, dispersion of the sediment, current velocities and working methods (Estourgie, 1988). Jetsed has a 14 m wide jet pipe hanging just above the bed and a pumping capacity of 12 000 m^3/h **(Figure 3.12)**.

Figure 3.12: Water injection dredger Jetsed

Tests showed that in silt the determining factors for jet penetration are its *in situ* density, viscosity and permeability, and the jet characteristics: jet diameter, exit velocity of water, pipe velocity and surface distance from the pipe. Field results indicated that very little turbidity is induced outside the turbidity current. The induced turbidity currents had varying thicknesses from 1 to 3 metres.

The use of water jets at the suction pipe for disintegration and fluidization of sediment is most suitable if the sediment is permeable and cohesionless (Wakefield, 1992). Nevertheless, it may still be used for impermeable sediment such as mud and fine silt provided cohesion is not high. The water jets cause fluidization of the sediment for easy suction and transport.

Water jets use more power than does a cutter, but capital cost is much lower due to less structural loads induced by water jets.

Experience with water jet disintegration in reservoirs showed that clay layers cannot be disintegrated effectively, with the resultant lumps of sediment causing blockage of pipelines.

3.2.3 Jet pump

The jet pump is a system which uses the kinetic energy of pumped clean water to entrain sediment-laden water. The motive power of a jet pump is a high velocity jet of water, entrainment occurring in a suction chamber, energy sharing in a mixing chamber, followed by pressure recovery in a diffuser **(Figure 3.13)** (Wakefield, 1992).

The main characteristics of the jet pump system are:

- Sediment acquisition is extremely constant. By avoiding the fluctuations which are inevitable with a simple suction pipe, the average output may be tripled.

- The excavation of sand and gravel is possible from great depths: 50 to 70 m.

- The installation of a jet pump on the dredger head of a hydraulic dredger will improve production, especially in deep dredging.

- A major benefit is that the driving pump need not have coarse material pass through it, thereby reducing maintenance.

- The jet pump has a low efficiency, rarely over 25 % (Sheng, 1983). In some cases however, the overall system efficiency may be greater if a jet pump is used. By matching jet pumps and centrifugal pumps in series, dredging can be carried out at minimum power. The application is elimination of cavitation in deep dredging, but even more important is the reduced unit cost of dredging due to the combination of pump characteristics.

- The jet pump is capable of discharge up to 200 m above water level in one stage, but as the head increases, the system efficiency becomes more related to the hydraulic efficiency and the power consumption is no longer acceptable (Wakefield, 1993).

- Jet pump maintenance is minimal, the lifetime of wearing parts varying from four months for the most abrasive materials to five years. If a centrifugal booster pump is used in combination with a jet pump, its wear and tear is greatly reduced by the constancy of flow, resulting in life increases of up to 200 % (Wakefield,1993).

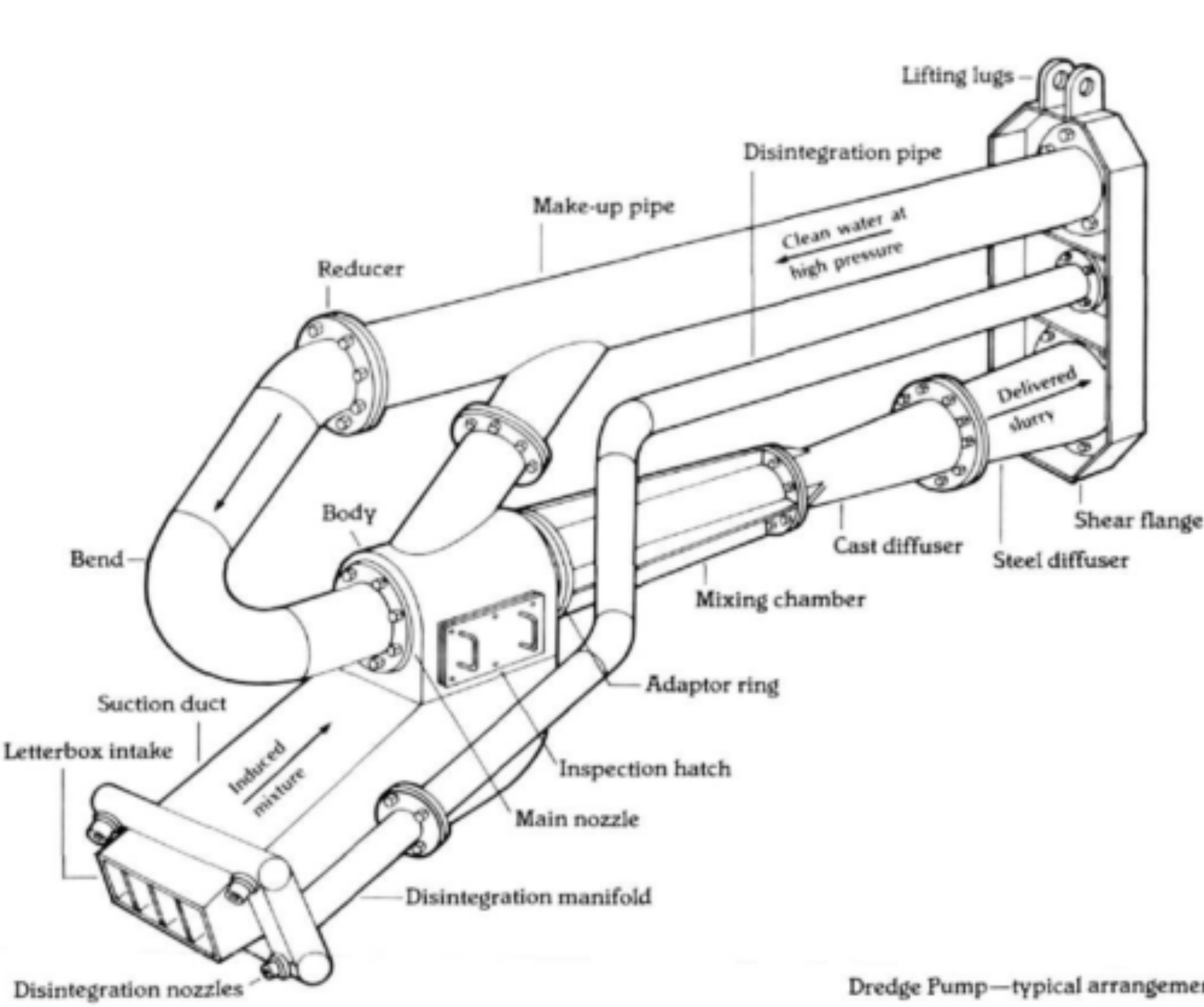


Figure 3.13: Jet pump working principle

Blockage of the suction can be resolved by backflushing, but normally choking is rare owing to low suction velocity at high concentration. During backfilling the primary flow from the jet is continuous down the discharge pipeline, keeping everything moving and progressively reducing the average concentration in the pipeline, until the concentration of sediment in the pipeline is low enough for shutdown, if required, without the danger of sinking a sediment-laden pipeline.

In Japan a set of five small to large jet-ejector dredgers ranging in depth capacity from 50 m to 100 m was manufactured in 1963. These dredgers had been in service for several years in Osaka and other ports, dredging sand, with agitation by water injection.

3.2.4 Air lift pump

The air lift pump consists of a pipe into which pressurized air is injected (**Figure 3.14**). It is one of the simplest methods of hydraulic lifting and works like a vacuum cleaner (Van Oostrum, 1990). Air under pressure is let into the suction pipe and the lower density of the water-air mixture inside the pipe relative to the water outside, lifts the mixture, carrying solids in suspension. This method is applied at great depths, even over 100 m. The system has been used world-wide for mining and the cleaning of sands and lakes (India).

The pump efficiency is usually only between 25 % and 50 % (Sheng, 1983). The Z & J compressed air dredger has a rotary head with a cutting appliance and spraying device which agitates the sediment. In case of blockage of the suction pipe by debris, reversal of the waterflow is possible.

Z & J (Zimmermann & Jansen, GmbH, Germany) developed a compressed-air dredger in 1970 which is used primarily for the recovery of sand and gravel from great depths (120 m). In order to dredge mud and very fine materials, Z & J designed a hydraulically-driven rotating head with a cutting appliance at the lower end of the conveyance tube. The slurry mixture thus obtained contains up to 50 % solids. The dredging device has operated successfully in the case of firm and solid layers of material such as clay and silt. A maximum production of 300 m^3/h has been reached (Sheuerlein, 1988).

The air lift pump has been used in China since 1976. The main advantage of this dredger is the relatively high efficiency of excavating sediment: 50 - 80 % sediment in volume. The abrasion of machine parts is limited and the cost is generally low. In the Wanjiayon reservoir, Chanxi Province, a unit dredging cost of 0,6 yuan/m^3 was obtained.

The air lift pump consumes a large amount of energy at substantial depth, has a high water consumption and cannot handle cohesive sediment (Roovers, 1989).

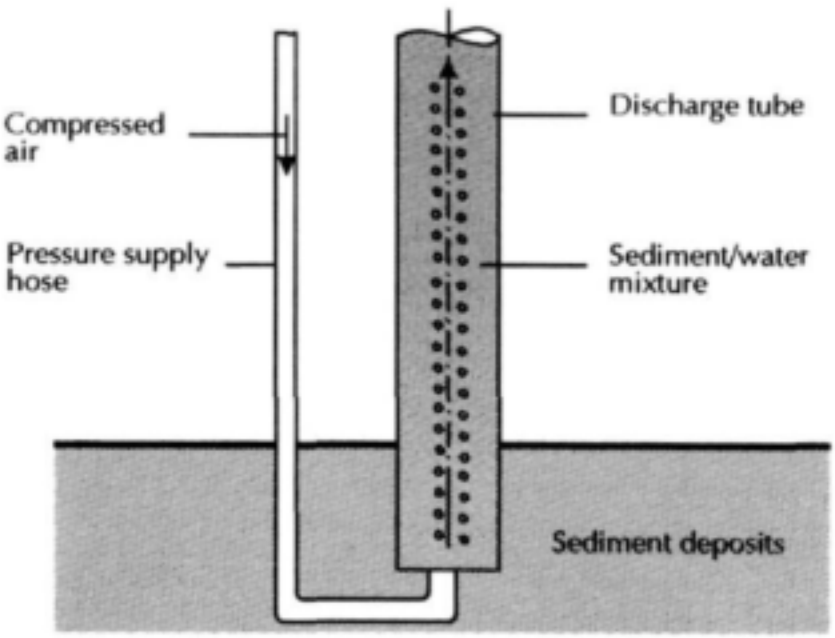


Figure 3.14: Air lift dredging pump

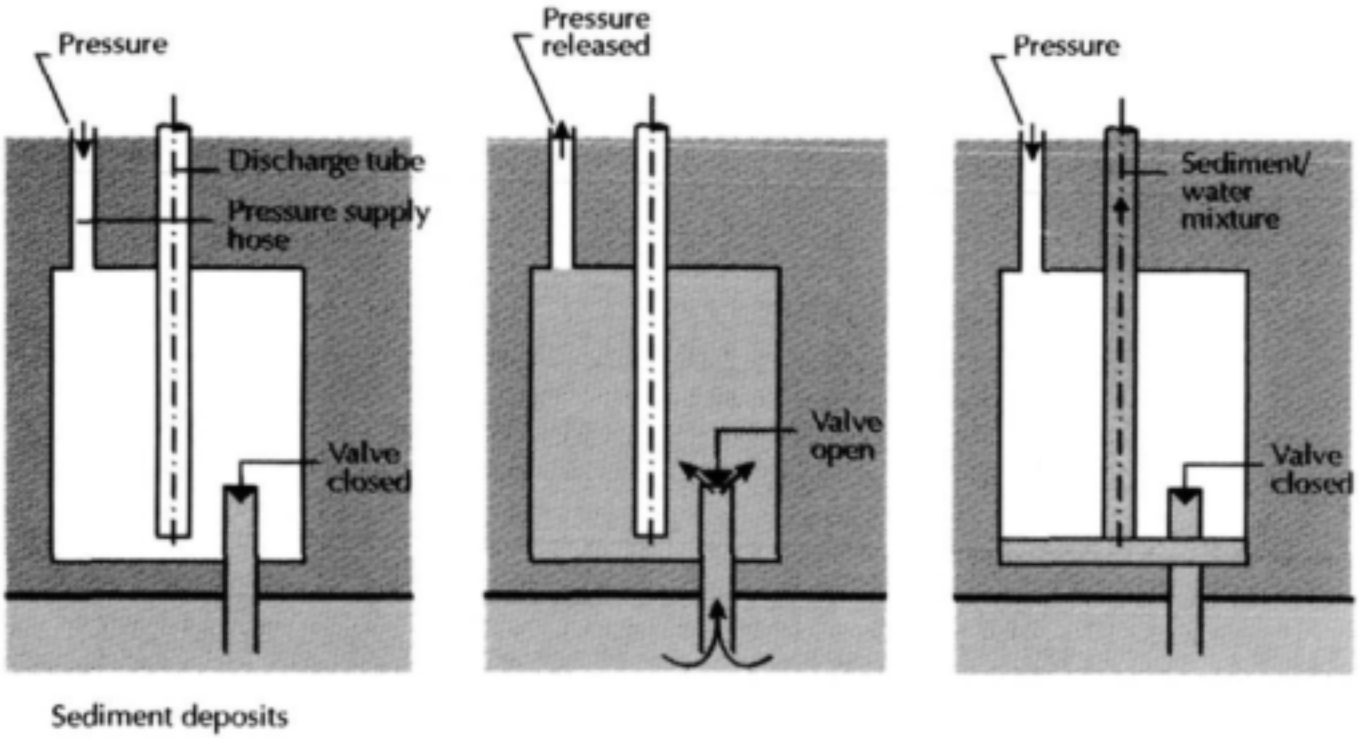


Figure 3.15: Pneumatic dredging pump

3.2.5 Pneumatic pump

A pneumatic pump consists of a tank with a system of valves and is operated by filling the tank with water sediment due to pressure difference, emptying the pump by pumping compressed air into the tank, and lastly releasing pressure to repeat the process **(Figure 3.15)**. The advantages of this system are that there are no dredging depth limit, it is suitable for dredging polluted materials since it does not disturb the bed, and there is practically no wear since there are no mechanisms in contact with the dredged material (apart from the valves); the water-sediment ratio is also lower than for conventional dredging equipment.

In dredging depths over 20 m the energy consumption of the air pump is high. In the Oozer pump the suction capability is improved by maintaining negative pressure in the tank, by using a vacuum pump. The pneumatic pump is free from cavitation problems and moves sediment in higher concentrations than centrifugal pumps. Consolidated clay and debris in the sediment make the use of a pneumatic pump undesirable (Scheuerlein, 1988).

The EPI pump (EPI Pneuma systems SPA, Italy) consists of three tanks to allow a continuous sediment discharge. The EPI pump also has a shovel installed to the cylinder of the pump in order to dredge semi-hard or hard materials.

It has been used in:

a) the Ofima reservoir at Palagnedra (Switzerland) for hard bottom material with dredging depths up to 51 m

b) the Gibraltar Lake, California, USA, to eliminate material deposited on the bottom of the lake: mud, sand, gravel, up to depths of 48 m

c) the SAIPEM SPA of ENI Group (Italy) burying sealine project, working in depths up to 100 m

d) Shihmen reservoir, Taiwan, with dredging depth up to 80 m. In both the Gibaltar and Shimen reservoirs, units with a capacity of 600 m^3/h were used. The water-sediment ratio achieved averaged 1:1, with the sediment consisting of clayey silt and clay.

Another system, the Oozer (Japanese) uses one tank only, with a vacuum pump. Its range of working depth, capacity and water/sediment ratio is similar to the EPI system.

3.2.6 Siphon dredging

Siphon dredging (also called hydro-aspirator) (**Figure 3.16**) in a reservoir makes use of the hydraulic head of the stored water in a reservoir to aid in the transport of dredged sediment through a floating or submerged pipeline linked to an outlet at the dam or discharging over the dam. This principle has been practised in Italy and China and resulted in reduced dredging costs. A relatively new approach, referred to as a Sediment Evacuation Pipeline System (SEPS) (Hotchkiss, 1992), is similar to a siphon system. The system consists of a pipeline, either flexible or fixed, linked to a low level outlet at the dam and the suction end at a sediment source. Unlike with a siphon, the SEPS requires no priming and is not subject to low pressures. Pipeline sediment concentrations by volume vary up to 8 % (Eftekharzadek and Laurren, 1990), which means that a relatively low sediment-water ratio compared to conventional dredging and water losses, especially in semi-arid areas could be unacceptably high.

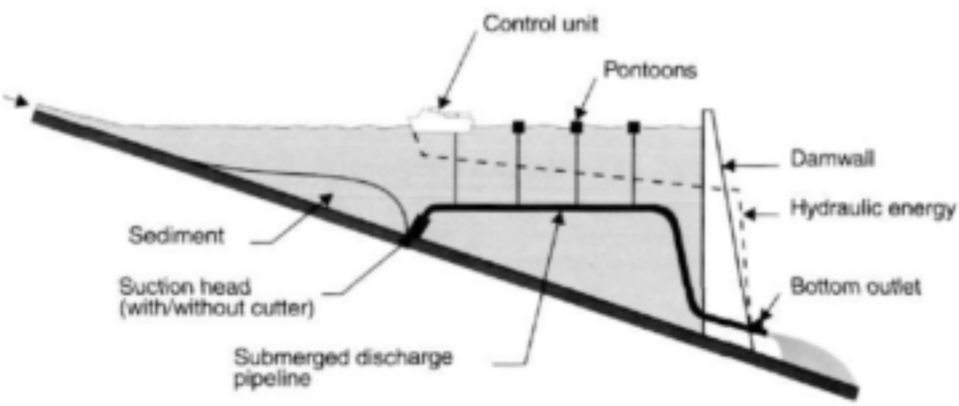


Figure 3.16: Siphon dredging

The use of the available hydraulic head is not new. As early as 1892 - 1894, such a system was used by Jandin to remove 1,4 million m^3 of sediment from the Djidiouia reservoir in Algeria (Fan, 1983). The system consisted of a 61 cm diameter pipeline, 1,6 km in length with a moveable pontoon to manoeuvre the suction end. Pipe discharge was about 1,5 m^3/s. A company in Italy has used the concept to remove sediment from reservoirs. The method was initially applied in Lake Sassogattono and Lake Molato in the 1960s. Subsequently the method has been used in the Abato Alonia project, Italy, to prohibit the free discharge of dredged material in the river downstream of a dam. Details of the Molato and Alonia Lake dredging are given in **Chapter 5**. In Italy booster pumps along the pipeline were in some cases added when the hydraulic head was insufficient.

In the design of a conventional dredging discharge pipeline system, sediment characteristics and other factors require that extremely high discharge velocities are used, in the order of 4 to 5 m/s. This is to prevent blockage of the pipeline which could result in serious production delays and ultimately loss of a complete pipeline. With siphon dredging these high velocities are only obtainable under specific boundary conditions: high dam walls and full storage, and relatively short discharge pipelines. The selection of a suitable pipe diameter based on pipeline length and available water head is presented in **Figure 3.17** (Geolidro, 1990) and was used in the siphon dredging of Italian reservoirs. Typical maximum and mean productions (with the aid of a cutter) obtained in Italy are shown in **Figure 3.17**.

The main features of the siphon dredger are:

- Low cost: capital and running.
- Discharged water can be used for irrigation and the system can be operated when required, having a permanent reservoir installation.
- The sediment-water ratio obtained in the Geolidro (Italy) system varied from 1:2 for clay, to 1:3 to 4 for sand and gravel.

In practice, where the sediment contains a high percentage of consolidated clay, the use of a gravity system such as siphon dredging without a cutter at the suction end will result in low production rates. Agitation by water jets or air will not solve the problem and large blocks of clayey sediment could block the pipeline.

Siphon dredgers operating at a number of reservoirs in the semi-arid regions of China have the following advantages:

- Low unit cost of dredging.
- The water sediment mixture discharged is used for irrigation and serves as fertilizer.
- The siphon dredger is easily manoeuvred.

Problems experienced are:

- flexible joints in pipeline provide high flow resistance, resulting in large head losses
- at high concentration discharge, blockage of the pipeline may occur due to low velocities and abnormal pressure distributions.

Downstream river disposal could cause undesirable environmental effects and must be carefully evaluated at each project. In Switzerland, for example, the induced turbidity is limited by law to 4 % by mass. Downstream disposal could, however, also have a positive effect on the river system by improving the sediment imbalance caused by the dam. If other reservoirs exist downstream of the dredged one, disposal into the river will only mean a displacement of the sedimentation problem and disposal sites in areas next to the river will have to be investigated.

In Atkinson reservoir, Nebraska, USA, a flexible pipe was installed, leading over the top of the dam and discharging downstream (Hotchkiss, 1993). With this experimental system it is hoped to optimize siphoning with a permanent, unsupervised installation.

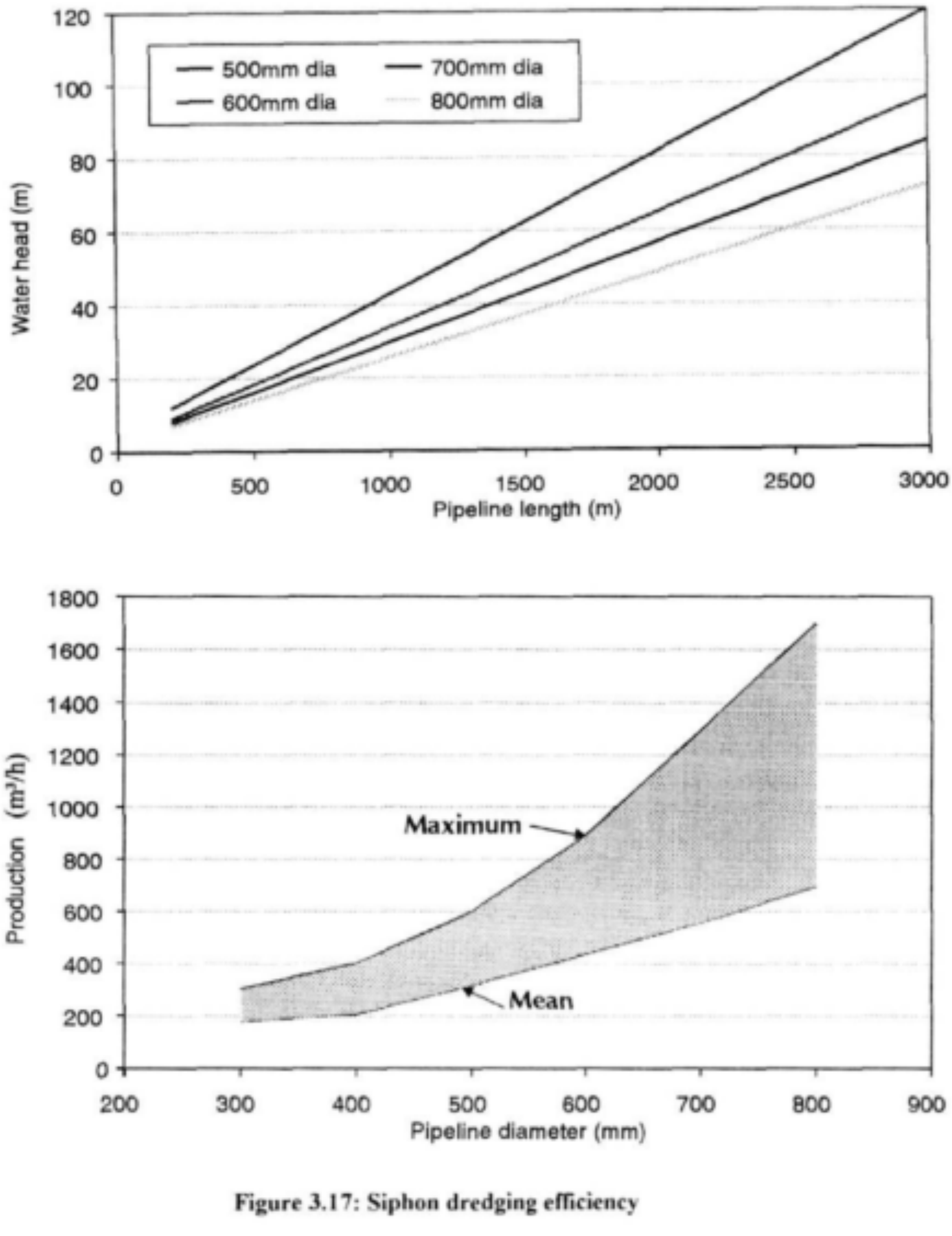


Figure 3.17: Siphon dredging efficiency

3.2.7 Deep dredgers

Conventional dredging equipment can easily handle dredging depths of up to 30 m. In deeper reservoirs deep dredging equipment (**Figure 3.18**) have been developed and used for the specific boundary conditions (see the discussion on specific projects in Chapter 5 for details of case studies).

Although it is difficult to generalize, a silt-tight remote-controlled grab system is probably the best solution for the removal of sediment in localized areas in deep reservoirs. The benefits are:

- Dredging depth is unlimited.
- The system can remove any kind of sediment, including debris.
- Water consumption is minimized by excavating material *in situ*.
- No turbidity is created.

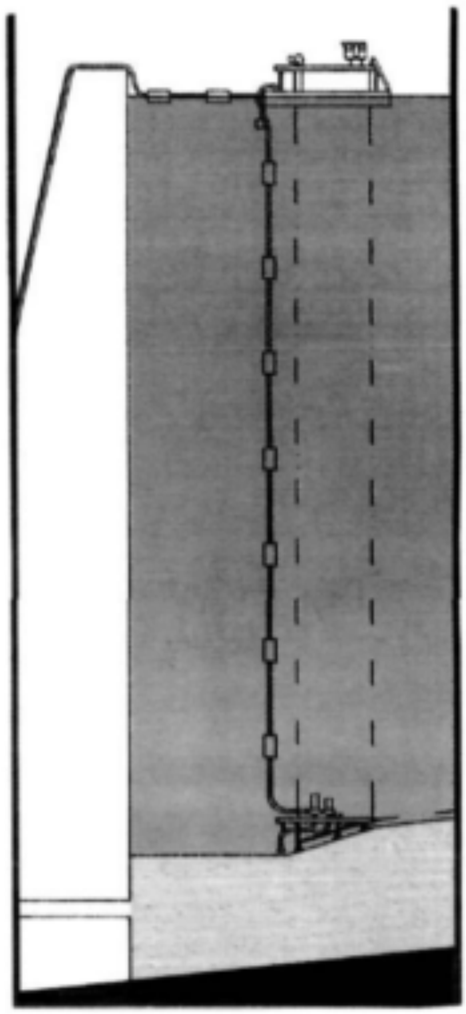


Figure 3.18: Deep dredging

Although high hoist velocities of 90 m/min and a descent velocity of 135 m/min are designed (Deepdredger TIJL-3) (Roovers, 1989), the process is still not continuous, and theoretically higher production rates can be achieved by pumping. Features such as computer-aided depth positioning under variable water level conditions, help to minimize deep dredging costs.

3.2.8 Underwater rotary hoe

The underwater rotary hoe is a new technique based on excavation techniques used in mining and tunnel construction. The material picked up by the hoe is carried on as a solid mass by means of an Archimedean screw, then, in adding a little water, the consistency of the material is adjusted to the requirements of a pump similar to those used in conventional dredging technology. No suction is required and consequently no water is required for the excavation process. The main advantages are high excavation rates at low water consumption, and avoiding pollution of the working area. (Sheuerlein, 1987).

Equipment based on this principle was developed by Hinteregger & Söhne (Austria), and has been used under laboratory conditions and in a small-scale pilot project, achieving water sediment ratios up to 1,5:1. Large-scale application will give final proof of its application.

3.2.9 Walking dredger

Two types of walking dredger have been developed for small-scale dredging work, eg.

a) The crawl-cat has four hydraulic spuds for vertical movement, each spud having a crawler for forward movement (**Figure 3.19**). A swinging cutter ladder, which is moved by means of hydraulic cylinders, is attached to the front of the pontoon. Normal maximum dredging depth is 5 to 6 m.

b) The roll-cat has 4 drum wheels, with a dredging depth of 3 m.

The main advantages of these dredgers are that no cables and spuds are required for positioning and therefore no down-time during forward movement of the dredger is required (Van Dee, 1984). The soil-bearing ability must be high enough to allow the use of a walking dredger.

Figure 3.19: Walking dredger - Crawlcat

3.2.10 Disc bottom cutter

The disc bottom cutter (**Figure 3.20**) is a special cutter head used in a cutter-suction dredger which rests horizontally on the sediment. The sediment is loosened by rotating vertical blades and the dredged material sucked into a pump. This type of dredger is used for strongly consolidated silt and sand. A disc bottom cutter has been used in the dredging of Zeekoevlei, discussed in **Chapter 5**.

Figure 3.20: Disc bottom cutter

3.2.11 Ploughs

Ploughs are used as low-cost dredging devices for the movement of material close to its *in situ* density over distances of up to a few hundred metres, for movement over short distances for localized levelling, and the placement of material into suspension to allow removal by density current or river flow (Mohammed, 1994). In reservoir application a plough could be pulled by boat or by cable system from land. **Figure 3.21** schematically indicates the use of a plough for agitation.

3.2.12 Permanent dredging installations

The use of a system of fixed silt pumps (submersible or with suction pipes in the sediment) may be considered in reservoir dredging in a sediment trap. This type of installation has been tried out both in Holland and Belgium in coastal applications (De Vlieger, 1991). Tests led to the conclusion that the "influence radius" of the pumping installation is limited, because the sediment processes a certain internal friction which causes it to adopt a certain "equilibrium slope", preventing the gravitational flux towards the suction mouth.

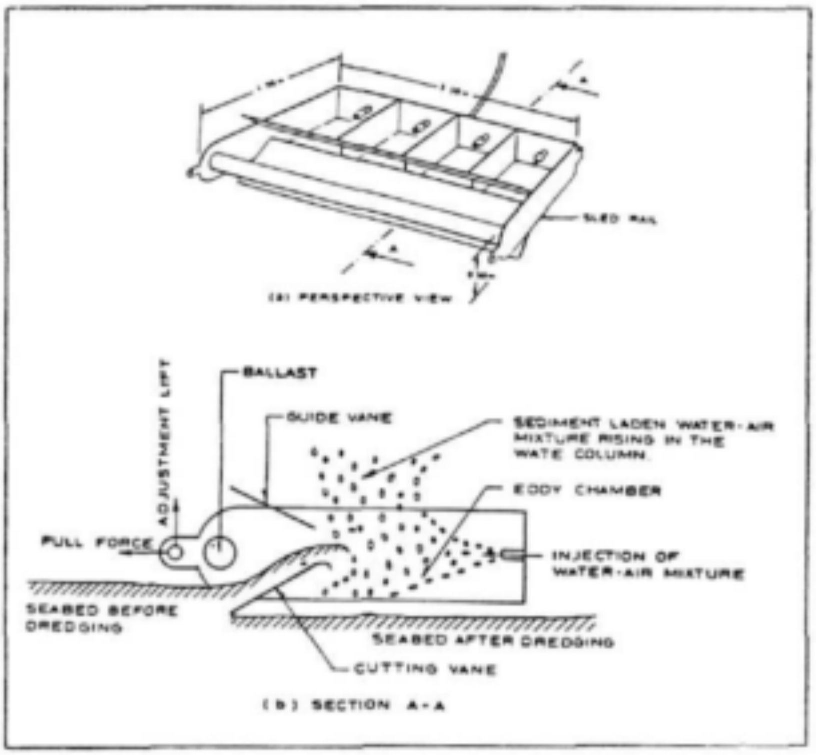
3.3 Suitable Dredging Equipment for Reservoir Dredging

Although each project has its own unique boundary conditions, it is generally accepted that for reservoir dredging in depths of less than 30 m, especially with consolidated clay, the cutter-suction or bucket-wheel dredgers should be utilized for large-scale bulk dredging projects.

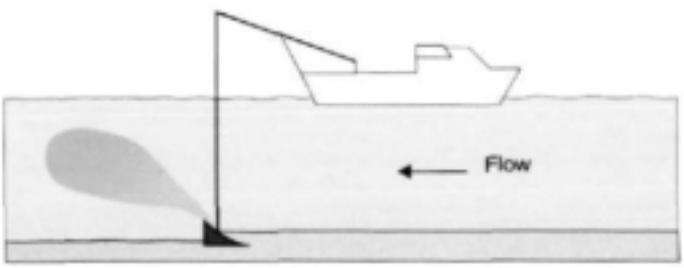
At greater depths, the grab dredger could be used for localized dredging. Under suitable conditions, siphon dredging will also provide a cheap dredging solution.

Selection of suitable reservoir dredging does not only involve selection of the dredger, but also of a sediment transportation and disposal system. The boundary conditions in reservoir dredging, selection of dredging and transportation equipment, and means of disposal, are discussed in **Chapter 4**.

Boat and plough dredging system



Plough with water injection agitation



Plough operation

Figure 3.21: Ploughs

4. FACTORS INFLUENCING THE SELECTION OF DREDGING EQUIPMENT FOR RESERVOIR DREDGING

4.1 General

Any dredging operation consists of:

- excavation of the sediment;
- transportation of the dredged sediment; and
- disposal.

The selection of dredging equipment is highly project specific and depends on a number of boundary conditions. Reservoir dredging boundary conditions are discussed in this chapter, together with the selection of appropriate dredging systems: excavation, transportation and disposal.

4.2 Reservoir Dredging Boundary Conditions

The cost of dredging differs from project to project, depending on specific boundary conditions. The boundary conditions which determine the type of equipment, method of operation, disposal, production and ultimately the costs, are:

- **Sediment characteristics**
  a) Geotechnical properties of the material
  b) Total volume of material to be dredged: localized or bulk dredging
  c) Geometry and location of material: layer thickness
  d) Quantity and nature of impurities: trees, construction and other debris, etc.
  e) Presence of hazardous materials for staff or equipment

- **Hydraulic and hydrological conditions**
  a) Water required for hydropower or irrigation may be limiting on dredging
  b) Current/waves: Flood conditions could limit dredging to the dry season
  c) Water levels: variable due to variable inflows and dam operation
  d) Depth of dredging
  e) Available hydraulic head for siphon dredging

- **Water quality conditions**
  a) Sediment/nutrient dynamics
  b) Algal/turbidity dynamics
  c) Fe, Mn and heavy metal dynamics

- **Meteorological conditions**
  - a) Rainfall
  - b) Temperature
  - c) Humidity
  - d) Wind velocity
  - e) Visibility

- **Environmental considerations**
  - a) Turbidity
  - b) Dissolved oxygen, etc.

- **General site information**
  - a) Accessibility of reservoir: limitations on weight and dimensions for road transport
  - b) Availability of labour and materials
  - c) Operational restrictions: night operation, public holidays
  - d) Availability of electric power
  - e) Restrictions on dredged material transport and placement
  - f) Environmental restriction, i.e. turbidity

Some of the major boundary conditions and their impact on the dredging operation are discussed below:

4.2.1 Sediment constraints

Sediments carried by a river will settle in a reservoir as soon as velocity and turbulence have decreased sufficiently. Consequently the upstream section of the reservoir will take most of the coarser material, while the finer sediment is deposited closer to the dam. The upper zone of the live storage is subject to drying, consolidation and cracking when exposed during low operating water levels. The fine material, which usually remains submerged, consolidates considerably over years due to the thickness and water depth. The finer sediment closer to the dam consists mostly of silt and clay with a highly cohesive nature. (Breusers et al., 1982).

The sediment encountered in reservoirs usually contains silt and clay, with very little coarse material, except in the upper reaches of the reservoir. Compared to port silt, the density is relatively high, 1100 to 1700 kg/m^3, with cohesions higher than 10 kPa (Basson and Rooseboom, 1997). Neither plain hydraulic suction nor jetting offers feasible means of dislodging the sediment. Experience has shown that the sediment has to be mechanically disintegrated before hydraulic transport.

The consolidated fine sediment remains stable at steep faces during excavation, something not normally encountered in coastal dredging, with the result that dredging with the usual cutter-suction dredger can only be done layer by layer, because of the danger of collapse when dredging at depth (Korver, 1988). The typical excavation characteristics of dredgers in different soil types are presented in **Table 4.1**.

Table 4.1: General characteristics of dredgers in different soil types

Rock/soil type	Excavation characteristics							Suitability of pipeline transport	Often observed bulk density before excavation
	Grab	Dipper	Bucket-Ladder	Plain Suction/ Dustpan	Cutter-Suction	Trailing Suction Hopper	Bucket-Wheel		
Boulders	Difficult, but large units cope	Fair	Very slow	NA	NA	NA	NA	NA	NA
Cobbles or cobbles with gravel	Fair	Fair	Fair	Difficult	Difficult	Difficult	Fair	Poor	NA
Gravel	Fair	Easy	Fair	Difficult to fair	Fair	Difficult to fair	Fair	Fair	1,75 - 2,2
Sandy gravel	Fair to easy	Easy	Fair to easy	Difficult to fair	Fair to easy	Fair to easy	Fair to easy	Fair to good	2,0 - 2,3
Medium sand Fine sand Extra fine sand Silty fine sand	Easy	Easy but low production	Easy	Easy	Easy	Fair to easy	Easy	Good Very good	1,7 - 2,3
Cemented fine sand	Difficult	Fair	Fair	NA	Easy to fair	Difficult	Easy	Bad to good	1,7 - 2,3
Silt	Fair	NA	Easy	Difficult to fair	Easy	Fair to easy	Easy	Very good	1,6 - 2,0
Firm or stiff gravelly or sandy clays	Difficult to fair	Fair	Difficult to fair	NA	Difficult to fair	NA	Fair	Only possible after disintegra-tion	1,8 - 2,4
Soft silty clays (ie alluvial clay)	Easy	NA	Fair to easy	NA	Easy	Fair	Easy	Fair	1,2 - 1,8
Firm or stiff silty clays	Fair	Fair to easy	Easy	NA	Fair to easy	Difficult to fair	Easy	Only possible after disintegra-tion	1,5 - 2,1
Peats	Easy	NA	Easy	NA	Easy if no gas encoun-tered	Fair	Easy	Very good	0,9 - 1,7

NA = Not applicable

Note: This table only gives a rough indication and should be used with caution. The qualifications used (bad, poor, fair, easy, very good, etc.) are meant to show the degree of suitability but should not be related to the output or unit cost of production.

The total volume of sediment to be dredged and the required production rate have a major influence on the selection of dredging equipment and the unit dredging cost. With large-scale bulk dredging in excess of say 5 million m^3, the costs of disposal and mobilization constitute a relatively small portion of the total cost, and the unit dredging cost is therefore much lower than with small-scale dredging projects (say less than 1 million m^3).

The thickness of deposited sediment is important in reservoir dredging. Although millions of cubic metres of sediment could be deposited in a reservoir, it could be distributed over a wide area in the reservoir, in a thin layer of sediment. Dredging under such conditions where the availability is poor will lead to high dredging costs because the dredger has to be moved frequently.

The presence of debris in the sediment or plants, root systems of reeds, etc. could lead to slowing of the dredging operation due to blockage of the cutter and/or the suction pipe. The root systems of especially reeds are quite extensive and should not be underestimated. The only dredgers that can handle debris are bucket, grab and dipper dredgers.

When dredging reservoir sediment which is polluted, special care must be taken in the dredging process as well as disposal of the material. It is however a misconception that all reservoir sediment is contaminated. It is estimated that about 90 % of sediment dredged from lakes is not contaminated. Turbidity should however be kept low when dredging contaminated sediment.

4.2.2 Hydraulic/hydrological constraints

The loss of water from reservoirs in semi-arid areas due to dredging is of major concern. Since the sediment-water ratio with conventional dredging methods is normally in the order of 1:4, dredging and disposal downstream of a reservoir could cause severe water losses and create a critical hydrological condition for the dam. The problem is in some cases solved when riparian irrigators can use the sediment-water discharge as part of the normal irrigation release. This could limit dredging to only periods with irrigation releases or at high storage levels.

Placement of sediment does not have to be downstream, however, but can be contained in dykes around the reservoir just above the full supply level. Normally this area also limits development because it is in the flood zone. Flood flow velocities through a reservoir are normally low enough to prevent damage to the dykes. After deposition in the disposal area, clean water is returned to the reservoir.

New dredging development reduces the volume of make-up water required for the dredging process e.g. dredger heads that can excavate with a low water consumption (Rosenbrand, 1991). Blockages of the discharge pipeline may, however, be a problem.

Variable water levels and depth of dredging are two aspects of reservoir dredging that go hand in hand. If a conventional cutter-suction dredger with say a maximum dredging depth of 30 m is used, the dredging operation can be moved seasonally along the reservoir to keep within the dredger depth capacity. A probabilistic water resources model could be used to predict water levels in the reservoir which will also help in selecting the correct dredger.

If dredging depths exceed the normal depth working range of conventional dredgers, deep dredgers have to be considered. In recent years the development of equipment has made dredging to depths exceeding 100 m possible.

4.2.3 General reservoir dredging constraints

Transportability of the dredging equipment between reservoirs by road is in most cases a necessity with reservoir dredging. This implies that the dredger must be dismountable which is normally not a problem with reservoir dredgers which do not need the same superstructures as self-contained ocean-going dredgers.

Electric power instead of conventional diesel power could bring about a major cost reduction. Electric power is normally supplied by overhead lines on the bank, with a floating line to the dredger which could be attached to the floating pipeline. Special precautions have to be taken with the safety aspects of the electric power supply. Electric power is often used at hydro-electric power generation reservoirs and is recommended for use at any large-scale dredging operation.

Apart from the excavation of the sediment, transportation and disposal of the sediment are of major importance.

4.3 Transportation of Dredged Material to the Disposal Site

Various systems for the transport of dredged material exist, and it is possible to distinguish between pipeline transport (**Figure 4.1**) and mechanical transport: barges, trucks, conveyer belts, cable bucket conveyers.

Pipelines pose the most attractive solution for both low-density and high-density transport. In reservoir dredging, flexible floating pipelines are used with cutter-suction dredgers. Steel or HDPE pipe sections are used, with flexible joints and the pipe suspended by floats. Combinations of floating and fixed shore pipelines can also be used. Pipe diameters normally vary from 0,3 m to 0,8 m, depending on the sediment characteristics, pumping distance, etc. Pipeline lengths of 2 to 4 km have been used in reservoir dredging. Normally booster pumpstations along these long pipelines are required to give sufficient head. In the Netherlands a temporary pipeline of 18 km with 10 pumping units has been used to discharge dredged material (Breusers et al., 1982).

The design velocities for these discharge pipelines are in the order of 3 to 5 m/s, to limit possible blockage of the pipeline. The high velocities cause highly abrasive action in especially flexible joints.

Figure 4.1: Floating discharge pipeline at Mkinkomo reservoir, Swaziland

When mechanical dredgers are used much less water is contained in the excavated sediment, which makes the use of barges or floating conveyer belts a necessity. A special positive displacement pump can, however, also be used to pump the sediment at high densities. A concrete pump was used to pump 20 000 m^3 sediment over a distance of 1 540 m with a 125 mm diameter pipe at a reservoir in Germany. Loading shovels excavated the sediment which was subsequently sieved (50 mm) and pumped with the injection of small amounts of water. The average sediment content pumped varied from 50 to 54 per cent.

In transport from the dredger to shore, the dredger manoeuvrability has to be maintained, while shifting of the transport system must be simple and its workability good. In most cases reservoir conditions rule out the use of floating conveyer belts or cable conveyer systems. Barge transportation is a well-known traditional method and could be successfully used with mechanical dredging equipment, especially when dredging coarse sediment in the upper reaches of the reservoir. Double handling of the sediment and low production rates could lead to high unit costs, however.

On land, transport by conveyer belt is possible, but applicability depends largely on capital cost and expected lifetime (Korver, 1988). Trucks can be used for transport depending on distance and cost.

4.4 Disposal

Dredged reservoir sediment can be disposed of in several ways:

4.4.1 Directly downstream of dam

This is one of the cheapest methods of disposal, but high sediment concentrations could cause environmental concerns if not properly managed. In many countries the maximum allowable induced concentration in the downstream river is limited by legislation, for example, in Switzerland the concentration limit is 4 % by volume (Pralong, 1986). In most Third World countries no legislation exists to limit induced turbidity, but environmental concern will definitely require a thorough study of each project.

If properly managed, discharge of dredged sediment to the downstream river could be beneficial to the environment by restoring the sediment imbalance caused by the dam.

The dredging discharge could be used as part of the normal irrigation water demand, thereby minimizing water losses caused by dredging. If the downstream irrigators have weirs on the river, sediment releases from the main reservoir will however fill these weirs within a short period and it will only be during a high flow period that some of the weir sediment could be flushed out to obtain the original regime.

When siphon dredging is considered downstream disposal is the only option, but dredged sediment could also be contained in disposal areas along the river. If downstream dams exist and sediment is disposed directly downstream the sedimentation problem will only be transferred to another location.

When dredging is carried out under low flow conditions, downstream disposal could result in settling of most of the sediment directly downstream of the dam which will only be washed away under flood conditions. This situation could, however, be beneficial to the environment by limiting turbidity during low flow conditions, while at high flows the river will only transport sediment according to its equilibrium transport characteristics.

4.4.2 In the dead storage zone

Many reservoirs have dead storage zones, which are volumes of water below the lowest outlet which were created by topographical outlet limitations and/or allowance for sedimentation during the design phase of a dam. The dead storage zone can be used to dispose of sediment, but a minimum volume of water should normally be maintained for the preservation of aquatic life. Dredging therefore takes place in the live storage sediment and it is transported and disposed of in the dead storage. Silt screens should be used in the disposal area to limit excessive turbidity and the release of nutrients in the sediment which could lead to eutrophic conditions.

Artificial islands may also be created by the dredged material, but the volume of water in the live storage area taken up by the island should be analysed in terms of water yield/hydropower benefit. Disposal in the dead storage zone is not a long-term solution to the sedimentation problem.

4.4.3 Next to the dam basin

By using containment dikes, it is possible to dispose directly next to the dam basin, above full supply level. With this approach the disposal area will become temporarily unsuitable as a habitat for animals and birds, but within a short period of time, particularly in warm climates, the area should quickly revegetate and regain productivity. Dikes allow the retention of effluent until it attains suitable quality to be released back to the reservoir. Apart from additional evaporative losses, no major water losses are incurred using this disposal method. The topography and recreational use of the dam may cause limited sites for disposal, and consequently larger transport distances and higher costs.

By constructing dikes with say maximum heights of 3 m, disposal in layers of 0,5 to 1,0 m in depth to allow drying, the use of a drainage system, and revegetation with natural flora, the environment will not be harmed. In some cases (Mkinkomo reservoir, Swaziland), the disposed sediment is used for land reclamation next to the reservoir (**Figure 4.2**).

In cases where land ownership is a problem, the area between full supply and the high flood levels could be used, or even just below full supply level in the live storage zone. Dikes should, however, be designed in such a way that they are protected against the wave action, and the wetting and drying caused by rising and falling reservoir water levels.

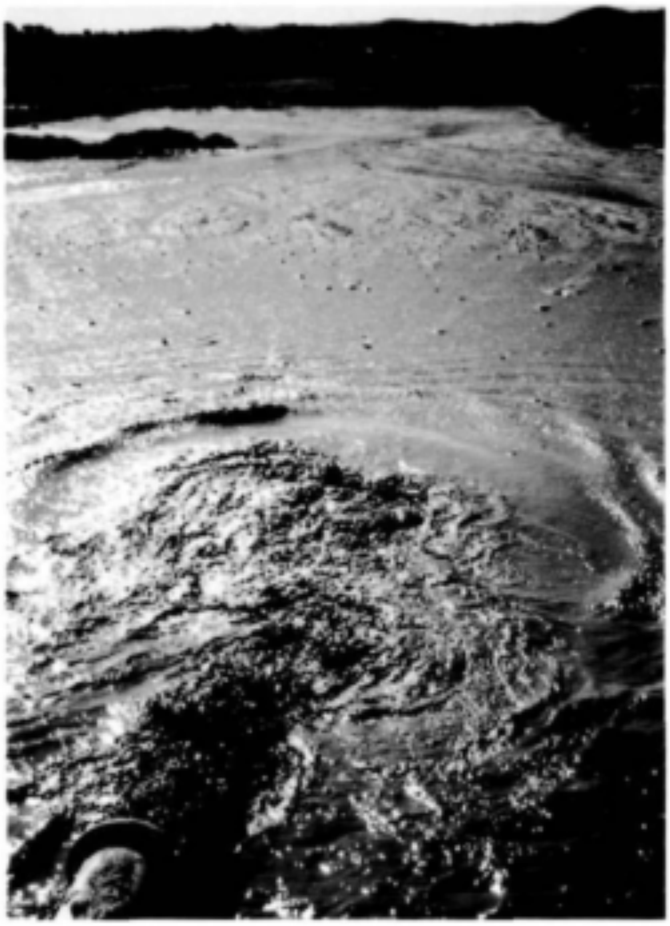


Figure 4.2: Disposal site (Mkinkomo)

Because of bulking of excavated sediment, initially up to 2 or 3 times the *in situ* volume, and the slow settling velocities, the silt dam areas must have sufficient volume and surface area to allow for quick drying. It is possible to accelerate dewatering of the deposits. Breusers et al.(1982), discussed a possible procedure for reservoir sediment disposal: Dikes can be constructed from suitable dredged sediment and subsequently filled with the disposed sediment to a depth of 1 m, and the surface water drained. The layer is then allowed to dry, a crust forms and cracks appear on the surface (**Figure 4.3**). To improve drainage and increase the surface area, an amphirol can be used in the fresh mud. The amphirol is an amphibious vehicle supported by two counter-rotating cylinders to which a spiral blade has been attached (**Figure 4.4**). Further furrowing might be accomplished by the use of disc wheels. Once natural plant growth starts in the highly nutrient-rich sediment, the deeper layers are dewatered by evapotranspiration (**Figure 4.5**). After 6 months to 1 year, depending on the climate, the mud has been converted into clay and a new layer of sediment can be placed on top of the former one (**Figure 4.6**). This can be repeated several times and in the end one is left with a site suitable for agriculture or other land uses.

Figure 4.3: Disposal site after 3 months (Mkinkomo)

Figure 4.4: Amphyrol

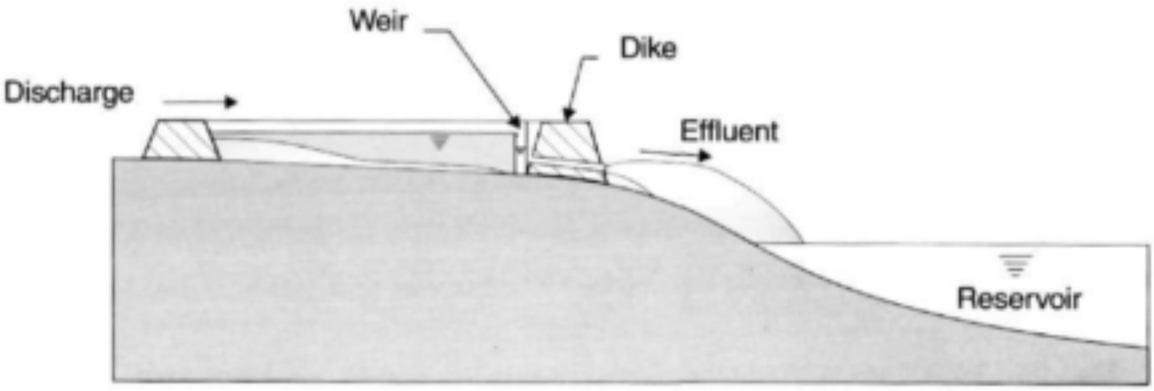


Figure 4.5 Cross-section through disposal area

Figure 4.6: Disposal site after 6 months (Mkinkomo)

4.4.4 Areas downstream of the dam

If suitable open areas are available, sediment can be discharged in contained areas next to the river, downstream of the dam. Unlike with deposition next to the reservoir basin, water will be lost downstream. If irrigation or compensation water has to be released in any case the dredged water could be utilized for this purpose, thereby limiting losses.

4.4.5 Off-site disposal

Roovers (1989) proposed a system of quick dewatering to reduce the volume of dredged material when the sediment is to be disposed of at off-site spoil areas by truck. Instead of using a diked area at the dam with its associated long drying time, hydrocyclones and a belt filter process can be used.

5. RESERVOIR DREDGING - INTERNATIONAL EXPERIENCE

5.1 General

Dredging of reservoirs is carried out on a routine basis in many countries all over the world. The purpose of this chapter is to discuss some of the case histories and hopefully to learn from the historical experience with regard to the problems encountered with new technology applied, consolidated clay, deep dredging, the cost of dredging, disposal, environmental aspects, etc. General conclusions about the feasibility of dredging should not be drawn from the information provided, because each dredging project is to a certain degree unique. Very few technical details have actually been published on field reservoir dredging, probably due to the fierce competition amongst contractors in the dredging industry.

5.2 Chinese Experience

China experiences a highly variable climate with rainfall of less than 200 mm in the north to more than 2 000 mm in the south. Where surplus water is available the reservoir sedimentation problem is resolved by sluicing and flushing of incoming and/or deposited sediment. In the semi-arid region, however, sedimentation is to a large extent being controlled by dredging.

5.2.1 The <u>**Xuanwei reservoir**</u> is a small (small in terms of Chinese reservoirs) lake-type reservoir built on the Panlang River in the Yunnan Province. It has a mean annual run-off of 220 million m^3 and annual incoming sediment load of 200 000 m^3. By 1980 the dam had lost half its storage due to sedimentation, but since then dredging with one dredger was undertaken to maintain the remaining storage capacity. The average efficiency of removing sediment has been 120 000 to 193 400 m^3 /a.

5.2.2 The <u>**Shuichaozi reservoir**</u>, Kuengming Province, China, had an original storage capacity of 9,58 million m^3, designed for power generation. The MAR and mean annual sediment load is 608 million m^3 and 1,9 million tons respectively. After 7 years of operation (1959 to 1966), 5,1 million m^3 of storage was lost by sedimentation. Although a new reservoir was constructed upstream in 1966, the loss of storage increased to 8,21 million m^3 (86 %) by 1981. With the original capacity comprising only 1,6 % of the MAR, a logical sediment control method seems to be flood flushing. No sluice facilities were, however, installed and dredging was the only way of preventing total loss of the reservoir function.

Two TYP-250 type dredgers have been used since 1979 dredging 1 to 3 km from the dam. The sediment consists of fine clay and silt. The average dredged discharge concentration obtained was 220,36 kg/m^3, with a production of 242,4 t/h.

5.2.3 In the **Tianjiawan reservoir** (original capacity 9,42 million m^3), Shanxi Province, China, a siphon dredger (also called hydro-aspirator) is used, consisting of a barge made up of six steel floats and a floating pipeline of 229 m, 550 mm in diameter, connected to the dam outlet. The siphon dredger was installed in 1975 after the reservoir lost 40 % of its storage due to sedimentation and the lack of flushing water. The sediment deposits are composed of fine grains with a median diameter of 0,006 - 0,008 mm and a dry density of 0,8 - 1,27 t/m^3, with most of the sediment close to the dam, an ideal condition for siphon dredging. The annual run-off is 3,95 million m^3 and the annual sediment inflow is 250 000 m^3.

In 1977 the annual run-off and sediment load were 4,16 million m^3 and 298 000 m^3 respectively. Water used for removing sediment amounted to 2,05 million m^3 and 320 000 m^3 of sediment was dredged. An average concentration of 190 kg/m^3 was obtained during 695 hours of operation. All the water and sediment released were used for irrigation. The production rate was 460 m^3 /h at an average unit cost of 0,045 yuan/m^3. A sediment-water ratio of 15,6 % by volume was obtained. A suction head of dustpan shape and nozzles were first used but a rotating cutter was later attached. The total head of the project is 17,4 m but the effective head is only 7,9 m.

Followed by the experience gained in the Tianjiawan reservoir, siphon dredgers have been widely used in several small-sized reservoirs in the arid and semi-arid regions in the north and north western parts of China, such as:

- the Xiaohuasan reservoir, Shanxi province
- the Hongqui reservoir, Qinhuai province
- the Xintiau reservoir, Gansu province.

5.3 The United States Experience

In the USA it is estimated that $ 50 million is spent annually on reservoir dredging (Crowder, 1987) at a cost of approximately $ 2/m^3. Most of these dredging projects involve relatively small-scale dredging operations and also include dredging for environmental purposes.

5.3.1 Lake Herman, South Dakota, USA

Lake Herman is a natural lake used for recreation. Due to sedimentation the average depth of the lake is 1,7 m, with sediment approximately 2 m deep. Dredging of 47 860 m^3 of sediment was carried out during the summers of 1970, 1971 and 1972. The silt was transported via a pipeline to a silt deposit area next to the lake. The average water depth was increased from 1,7 m to 3,4 m. No significant changes in the levels of organisms or nutrients were observed. Water returning from the deposition area to the lake, was lower in nutrients than the water in the lake.

A hydraulic cutter-suction dredger was used, with a floating discharge pipeline. The sediment-water ratio obtained was 18 %. The dredging showed that not only could the depth be regained, but also that the nutrients in sediments could be efficiently removed.

5.3.2 White Tail Creek project, USA

Although on a very small scale, this project (Hotchkiss, 1992) illustrates the possible use of a submerged pipeline siphoning device. At a trout farm, sedimentation of a weir disrupted the farming operation and a dragline was required to remove sand for about 2 hours per week. In 1990 a siphoning system was installed, consisting of a 150 mm diameter uPVC pipe with slots cut into the top of the pipe 2,54 cm x 50 cm long. The slotted area is bigger than the pipe flow area and several slots are therefore covered with cut-off light-weight plastic pipe and moved once or twice a day. Other characteristics of the scheme include:

-	pipeline discharge:	0,05 m^3/s
-	pipeline length:	110 m
-	available head:	1,3 m
-	maximum design sediment load:	140 000 kg/d
-	maximum design sediment concentration:	5,3 % by weight
-	observed maximum input to system:	4 800 kg/d
-	observed sediment concentration:	0,06 % per weight

The low sediment-water ratio obtained is not acceptable for general application of the system on a larger scale.

5.4 Billings Lake Hydropower Reservoir, Sao Paulo, Brazil

A somewhat unique sedimentation situation developed in Billings Lake. The lake is located on a watershed and is mainly fed by water pumped into the lake by the Pedreiro pumping station with a maximum capacity of 380 m^3/s, at the 25 m high Rio Grande Dam. The pumped water contains fine sediment which deposited and blocked the discharge outlet from the pumps.

Dredging was carried out in 1990 by a contractor for Eletro Paulo. Channels were dredged in the deposited sediment by cutter-suction dredger and the excavated material was transported by floating pipeline away from the outlet and deposited into the lake. The dredging was considered feasible (Eletro Paulo,1990). No dredging would mean loss of hydropower and an increased rate of upstream flooding.

5.5 Roseires Dam, Sudan

The Roseires Dam is located on the Blue Nile, near the Ethiopian border and provides irrigation water and water for the generation of electricity which supplies approximately 80 % of the Blue Nile grid area. During the rainy season large quantities of tree trunks, sediment and other debris are deposited near the intake of the hydropower station. Dredging has to be carried out during this period to prevent the silt and debris from partially or completely blocking the water intakes to the power station.

Dredging started in 1984 with two clamshell dredgers. A dredging programme with management and training under Dutch bilateral aid was executed until 1986. Every year from November to July, when current velocities permitted working with floating equipment, the area in front of the intakes was dredged. During the flood season, when high current velocities prevent safe navigation on the reservoir, the intakes are kept free by dredging part of the silt deposit directly in front of the intakes by means of a dredger pump suspended from a clamshell dredger.

Figure 5.1: Grab dredger - Roseires Dam intake dredging

Dredging experience at Roseires Dam indicated that merely keeping the inlet open can be a major task, resulting in high dredging cost per cubic metre. No dredging would result in the loss of the dam's function (Demas, 1991).

5.6 Reservoir Dredging in Switzerland

5.6.1 Lausanne Dam, Switzerland

Dredging of the Lausanne Dam involved the excavation of sediment 180 m deep to clear the water intake (Pralong, 1986). A total quantity of 17 000 m^3 sediment was removed at a cost of \$ 11,70/m^3 during a period of six weeks. Despite the relatively high cost per cubic metre, the dredging was considered successful. No dredging could have resulted in total loss of the reservoir's function.

5.6.2 Palagnedra Dam, Switzerland

The Palagnedra reservoir, which is part of the Maggia power plant, has been subject to quick sedimentation which would have limited power generation if dredging was not carried out.

Evaluation of different solutions for clearing the lake bottom led to the development of a dredger with a floating pipeline (350 m) connected to a valve at the dam, and capable of dredging to depths of 50 m. The dredger consists of a dredger head suspended from the dredger by cable with its own underwater pumps to provide the suction and transportation of dredged material via a 350 mm diameter pipeline to the surface, as well as water injection to loosen the sediment **(Figure 5.2)**. At the surface a discharge pump on the dredger pumps the material to the dam where it is discharged downstream. The dredger capacity is 120 000 m^3/a, corresponding to 1½ times the mean annual sedimentation, considering that the dredging is limited to two flood periods of two months each.

Experiments on the effects of discharging silt downstream of the dam have shown that this will have no adverse effects on the quality of the water (Liechti and Haeberli, 1970).

5.7 Shihmen reservoir, Taiwan

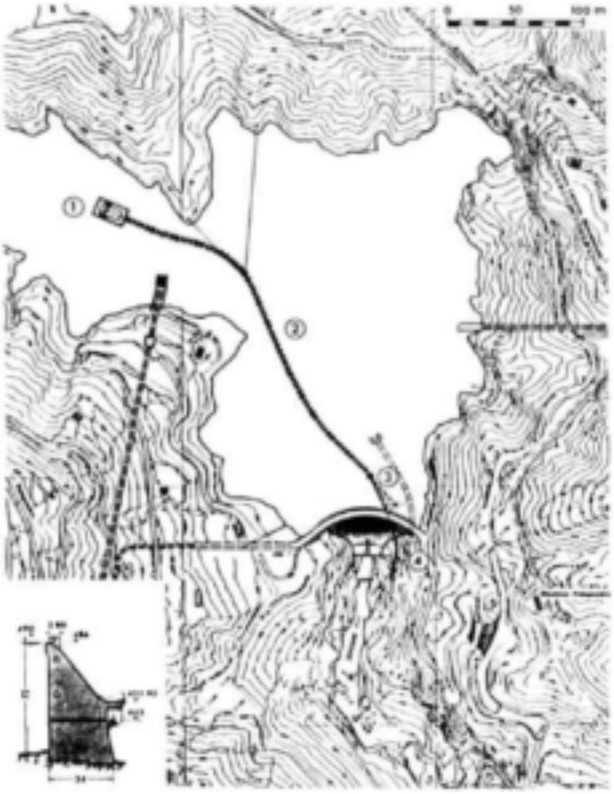
Continuous maintenance dredging was considered effective in the Shihmen reservoir. A hydraulic dredger was used to remove sediment from a depth of 80 m. The annual sediment removal was estimated to be between 300 000 and 600 000 m^3, while the economic life of the dredger was estimated to be 10 years (Wu, 1986).

5.8 Reservoir Dredging in Italy

5.8.1 Molato Lake, Piacenza, Italy

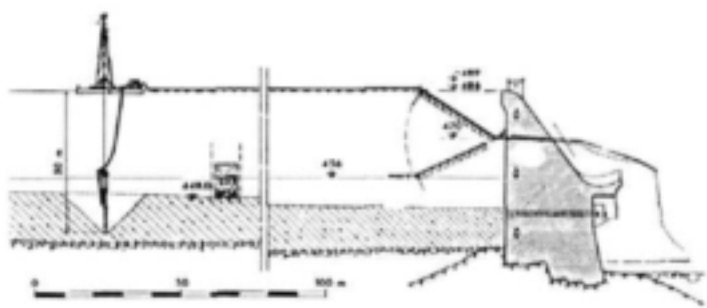
The sediment at the dam reached a thickness of 8 m to 10 m and obstructed the two main bottom outlets and the powerhouse intake. Sediment removal had a double aim: to recover the useful capacity and to free the bottom outlets.

The dredging involved a cutter-suction dredger with a flexible submerged pipeline linked to the dam to discharge sediment downstream. Although the sediment was cut with a normal cutter no pump was used to provide suction and discharge. Instead, the hydraulic head of the reservoir was used. A booster pump was, however, employed in cases of insufficient hydraulic head, such as when a long pipeline would be used.

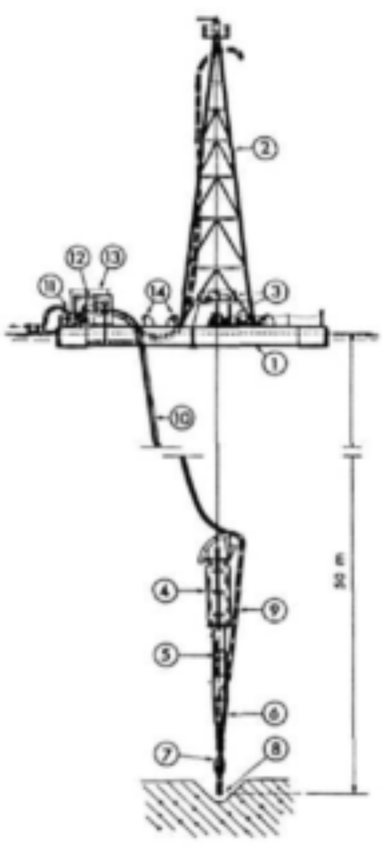


Legend of reservoir operation

1 Dredger (maximum depth capacity : 50 m)
2 Floating pipeline (350 mm dia; 350 m length)
3 Mobile element linked to dam
4 Discharge pipe through dam and valves



Longitudinal section of dredging operation (Above)



Vertical section of the dredger (left)

1 Pontoon	*8 Suction head*
2 Frame,height 26 m	*9 Upward pipe, 350 mm dia*
3 Lifting winch	*10 Flexible pipe*
4 Float	*11 Discharge pump*
5 2 pumps	*12 Cabin*
6 2 pressure water pipes	*13 Transformer*
7 Hydro-ejector	*14 Anchoring winches*

Figure 5.2: Palagnedra reservoir dredging

5.8.2 Alonia Lake, Potenza, Italy

The initial live storage capacity of this reservoir was 22,8 million m^3. Due to sedimentation however, 375 000 m^3/year was lost. Dredging up to 1974 removed 5,2 million m^3 of sediment up to 1 500 metres from the dam. The same dredging principle as described for the Molato lake, was employed.

Design criteria provided by the contractor (Geolidro, 1990) indicated production rates for hydraulic head, pipeline lengths and pipe diameter. Mean and maximum sediment removal rates are provided in **Figure 3.17**. At high dams, with limited lengths of pipeline required, the cost (1990) could be approximately \$0.17/m^3 of sediment dredged, which is much lower than conventional dredging methods. Water loss depends on the sediment characteristics: for clay 2 m^3 of water per 1 m^3 of sediment while for sand-gravel 3 to 4 m^3 of water per m^3 of sediment. Disposal downstream could, however, pose environmental concerns which are addressed in **Chapter 4**.

5.9 The Algerian Experience (Bellouni, 1984, Balachir, 1980, In Bruk, 1985)

Dredging has been carried out in a number of reservoirs in Algeria during the irrigation periods to recover lost capacity. A suction and force dredger with rotating cutterhead was used. A sediment-water ratio of 1:5 was obtained, but when plugging occurred in the floating pipeline the ratio increased to 1:9. The dredger production was approximately 340 000 m^3/month.

The dredging procedure involved excavation from the dam to the upstream end to open a channel in the deposits, to facilitate the movement of density currents towards the bottom outlets. Dredging undertaken between 1957 and 1968 is summarized below:

Dam	Year	Sediment dredged (million m^3)
Cheurfas	1958 - 1961	10
Sig	1962 - 1964	1
Fergang	1965 - 1966	3
Hamiz	1967 - 1968	1,2

During 5,5 months of dredging in Hamiz reservoir, 2 300 hours of effective dredging were recorded, while 730 hours of stoppage occurred during the operation. The main causes of stoppage were mechanical incidents, plugging of pipelines (25 % of the time), changes of location, and changes in discharge pipe lengths. In this case a production rate of 76 % of the nominal dredger capacity was achieved, slightly more than the roughly 70 % availability which is normally allowed for in dredging.

The method of siphoning sediment deposits was first suggested by Jandin (Brown, 1944) in the last century. The method was used from 1892 to 1894 in the Djidiouia reservoir where 1,4 million m^3 of silt and clay were removed. Most of the sediment was, however, thought to be unconsolidated, only 498 000 m^3 was previously accumulated sediment. The reservoir had an original capacity of 2,4 million m^3. Jandin's equipment consisted of a flexible pipe, 61 cm in diameter, capable of discharging 1,53 m^3/s under normal operating conditions. The average content of sediment in the inflow was only 3 %, with a maximum concentration of 7 % during flood flows. The pipeline was connected to an opening at the base of the dam and could be moved around the reservoir within a radius of 1,6 km. What made this method different from other simple siphon pipe systems, or the use of a siphon for transport while using a conventional cutterhead to disintegrate the sediment (Geolidro, 1990), was the use of a turbine near the mouth of the pipe actuated by the pipeline flow, coupled to a wheeled chopping instrument near the intake end of the pipe. This chopping instrument was designed to agitate the sediment.

5.10 **Austria** (Kobilka and Hauck , 1982)

In Austria a chain of hydro-electric power stations on the Danube River was constructed from 1957 to 1968. At the Ybbs-Persenbeug power station reservoir, sedimentation in the upper reaches caused flood risk and navigational problems. During the first four years of operation, 800 000 m^3 of sediment was deposited in the 76 million m^3 reservoir. The same problem occurred at the upstream power station with a storage capacity of 54 million m^3. During years with floods up to 400 000 m^3 of sediment was deposited. These gravel deposits were periodically removed by dredging which was considered economically viable since the dredged material could be used for construction purposes elsewhere.

The problems encountered in Austria are not unlike the recent investigation in South Africa where the sedimentation in a series of possible reservoirs on the Vaal and Caledon rivers to facilitate upstream pumping, was analysed.

5.11 Reservoir Dredging in Japan

5.11.1 Akiba Dam, Japan

The Akiba Dam, 34 million m^3 in capacity, 84 m high, was constructed in 1958 for power generation. Annual removal of 400 000 m^3 of sediment is required to maintain the original river bed and is obtained by:

- dredging of 150 000 m^3 /a of silts and clay up to 4,5 km from the dam, and disposal upstream of the dam, to be released with flood discharges

- dredging of 200 000 m^3/a of well-graded sediment 4,5 km to 8,2 km from the dam, used for concrete aggregates

- excavation of 50 000 m^3/a of gravel upstream 8,2 km from the dam by dry mechanical equipment, of which some is used as concrete aggregate.

5.11.2 Sakuma Dam, Japan (Murakami, 1979)

The Sakuma Dam had an original capacity of 330 million m^3, is 155 m high, and is used for power generation. A volume of 73 million m^3 of sediment accumulated in the reservoir during its first 24 years of operation since 1956, equalling a rate of 3 million m^3/a.

Approximately 0,3 million m^3/a is dredged in the upper reaches to counter river bed aggradation. The coarse material is used as fine aggregate for concrete (Bruk, 1985), and road construction.

Only the upper reaches, 22 to 30 km from the dam, were dredged. Two dredgers were used to dredge and haul 750 m^3/d to the disposal site 5 km from the dam, making one round trip per day. The number of working days is limited by reservoir operation for power generation and flushing to 270 d/a.

A combination of flushing, watershed erosion dams and dredging of the coarser sediment in the upper reaches of the dam is practised to reduce sedimentation of the reservoir.

5.11.3 Miwa reservoir, Japan

The Miwa reservoir, with an original capacity of 37 million m^3, with a dam 69,1 m high, was constructed in 1959 for flood control, irrigation and power generation. In 1972, 9,5 million m^3 of storage capacity had been lost due to sedimentation.

Dredging began in 1965 and 2,3 million m^3 had been excavated by 1974. The dredged sediment was used as concrete aggregate (Bruk, 1985).

5.12 Rioumajou Dam, France (Evrard, 1980)

A hydraulic siphon device was installed at Rioumajou Dam to clear the water intake and sluice from sediment. The siphon straddles the 21 m high dam, with the 450 mm diameter, 20 m long upstream pipe located near the inlet. The discharge is 1 m^3/s with a sediment-carrying capacity of 15 kg. The siphon device operates with remarkable efficiency and its cost was recovered almost within one year.

5.13 **Deep Dredging** (Newman, 1992)

Dredging had to be carried out at a hydropower intake at a 120 m high dam, with water depths ranging from 110 m to 55 m . The sediment consisted of clay (27 %), 67 % silt and thick mud. The required production per annum was 500 000 m^3 of sediment at 150 m^3/h, while the dredged area covered a strip 500 m from the wall, 400 m wide. Furthermore the equipment had to be electrically powered and transportable.

Existing deep dredgers used in mining were first investigated. The soft silty sediment precluded the use of a remotely operated tracked vehicle with bottom stationed pumps, which would have sunk into the soft silt. Similar jet pumps mounted in flotation buoys hovering above the work site would have resulted in the suction head picking holes in the silt. Grabs and centrifugal pumps hung over the dam were tried but tended to create holes. This was because the silt, although soft, was still too stiff to flow into the hole created by the suction tube.

The dredging solution adopted consists of a surface pontoon, from which the dredging is controlled, an 800 m long floating power cable, a 550 m long floating pipeline which discharges sediment over the crest of the dam, and a submerged dredging unit (**Figure 5.3**). The 18 m x 18 m steel frame submerged unit has 3 pumps:

- A water pump supplies the fluidizing jets.
- A primary jet venturi pump picks up the silt and ensures complete disintegration of the sediment.
- A centrifugal pump discharges silt to the surface to a booster pump on the pontoon.

Blockage of the suction pipe is solved by using the jet pump in reverse flush mode. The dredging module contains multiple fluidizing heads on three levels. The module is operated by lowering it at a rate of 5 cm/min to a maximum depth of 4 m into the silt. The whole system (pontoon and dredger module) can be moved progressively forward through the silt, again at about 5 cm/min. The system is capable of production rates of up to 750 m^3/h. No indication of the unit cost of dredging or actual production rates was given.

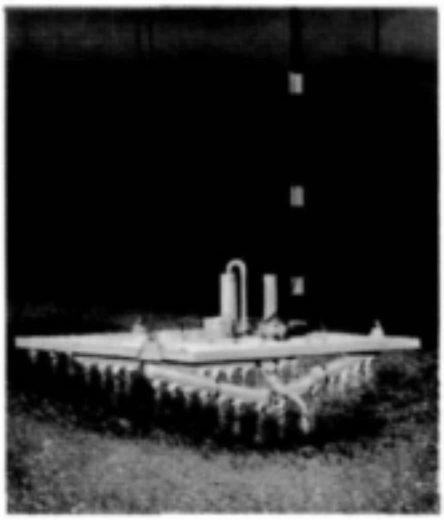


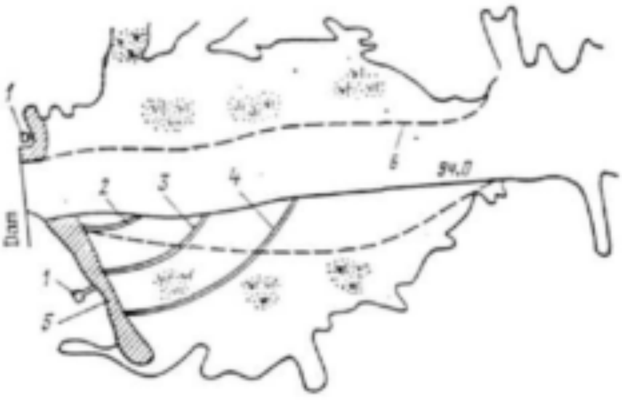
Figure 5.3: Tailored intake dredging suspended jetting suction unit

5.14 Chiryurt reservoir, Russia (Vorobev et.al., 1989)

The Chiryurt reservoir was constructed in 1961. Sedimentation reduced its live storage from 9 million m^3 to 1,5 million m^3 by 1968. After conducting a series of flushings it was, however, possible to remove the deposited sediment. Two hydropower reservoirs, the Chirkey and Miatla plants, were constructed upstream in 1978 and 1988 respectively, which reduced the sedimentation at Chiryurt reservoir.

Since 1985 the sediment has been removed by dredger in combination with hydraulic flushing. Dredging was carried out at the irrigation intake (260 000 m^3) and at the right bank intake (130 000 m^3). The dredging cost was 387 000 rubles, too high for general excavation in the reservoir basin.

To increase the effectiveness of removing sediments, the management of the cascade of Sulale hydro-electric stations developed and tested a method of combined removal by dredging and hydraulic flushing. Pilot channels, curvilinear in plan, 10-20 m in width were to be cut as indicated in **Figure 5.4**. The dredged channels increase the storage volume, reduce the water level and subsequently lead to increased velocities in the dredged channels under sluicing conditions. The curvilinear shape of the channel also increases the erodibility of the concave part of the sediment.



Schematic diagram of the location of the cuts in the Chiryurt reservoir: 1) intake works; 2) pilot channel of the first phase; 3) pilot channel of the second phase; 4) pilot channel of the third phase; 5) zone of cleaning by the dredge; 6) boundary of the reed beds.

Figure 5.4: Combined dredging - flushing operation

One cut, 180 m in length, 2,5 to 3,5 m deep and with a volume of 25 000 m^3 , was dredged. Two hydraulic sluicings were carried out; the first by lowering the normal pool level by 1 m for 9 days and a second by lowering the pool by 2 m for 26 days. Surplus water was used which resulted in maximum concentrations of 0,75 g/ℓ at 600 m^3/s (201 000 m^3 sediment removed) and 1 g/ℓ at 550 m^3/s (740 000 m^3), for the first and second flushings respectively.

Changes in the direction of the velocities in the flow in the region of the cut led to gradual erosion of the left bank deposits above the cut and to the erosion of the island, widening the inlet of the channel by 10 m .

This combination of sediment removal techniques could be useful under specific conditions to remove overbank deposits.

6. DREDGING IN SOUTHERN AFRICA

6.1 General

Dredging has been carried out for many years in ports, beach nourishment projects, marinas and in the mining industry in South Africa. A number of reservoirs have also been dredged. While most of the ports and major coastal projects are dredged by government in South Africa, numerous small harbour, marina and environmental dredgings have been carried out by private contractors in recent years.

Although dredging has been with us for many years, isolation to some extent due to political reasons, led to the use of relatively outdated equipment on projects not always suited to the available equipment. This resulted in excessively high unit dredging costs ranging from R2 to R30/m^3 of sediment removed.

The Department of Water Affairs and Forestry (DWAF) has been approached by several European dredging companies with proposals to dredge reservoirs during the 1980s. Although field visits to some reservoirs were undertaken, the total water resources picture of the country was never considered and costing of possible dredging was on a very general basis. Thus, obtained costs for dredging were in the order of R4 to R12/m^3, much higher than the alternatives such as the raising of a dam. These quotations were therefore never followed up by the DWAF. Dredging on a small scale by private contractors have, however, been carried out in a number of reservoirs and inland projects, although some at high cost.

Dredging has been carried out in Zeekoevlei (Cape Town), Campsdrift canal (Pietermaritzburg), Hermanus estuary, Richards Bay harbour and mining (Richards Bay Minerals), mining at Luderitz, Collywobbles reservoir in the former Transkei, Mkinkomo reservoir in Swaziland, sandmining at Mgeni River mouth and Caledon River, Mgeni canalization, Koeberg (Cape Town), Marina Martinique, Saldanha Bay, San Lameer Lake, Club Mykonos, Vaal River (bridge construction), and at several mines.

Technical details of the dredging carried out at some of the above projects are discussed in the remainder of this chapter. The actual cost of historical dredging is discussed in **Chapter 7**. These projects include:

- Collywobbles (Mbashe), Transkei
- Mkinkomo reservoir, Swaziland
- Campsdrift canal, Pietermaritzburg
- Zeekoevlei, Western Cape

- Canalization of Mgeni River, Durban
- San Lameer Lake, KwaZulu Natal

6.2 Dredging Case Studies

6.2.1 Mbashe weir (Collywobbles), Eastern Cape (Rooseboom, 1993)

The first large-scale reservoir dredging in South Africa to recover lost storage was carried out in the Collywobbles reservoir (also known as Mbashe), in the former Transkei. Collywobbles had an original storage capacity of 8,8 million m^3 and was designed for hydro-power generation. Severe sedimentation prompted the owner of the dam to adopt dredging as a method of controlling the sedimentation after the use of a low level outlet proved to be insufficient to flush deposited sediment. **Figure 6.1** shows sediment removal after flushing, with the dredger in the foreground.

Figure 6.1: Mbashe (Collywobbles) reservoir dredging

Investigation of the sediment load and characteristics in 1986 led to the recommendations that both a small (200 t/h) dredger and a large (1 200 t/h) dredger should be purchased. The small dredger was to be used for removing sediment within a radius of 250 m of the penstock inlet and the large dredger to regain sufficient storage capacity within the reservoir (Rooseboom, 1993).

Whilst the smaller dredger did manage to keep the penstock area clear, practical problems were encountered with its operation especially when the dam was overflowing. It required five full-time employees to operate this dredger. As it had to operate during periods when the dam was not spilling, it used storage water which was lost for power generation.

The larger dredger, with a design capacity of 750 t/h (4 million m^3 sediment per year), was used from 1986 to 1989, and was sized to enable the removal of the estimated annual sediment inflow of 2,3 million m^3 by operating the dredger during periods when the Mbashe River inflow exceeded generation requirements. During such periods of excess river inflow no cost was assigned to the water required for the operation of the dredger. In addition, the installed capacity of the Mbashe hydro-station exceeded the total Transkei electrical load in 1986, and the energy required for the dredging operations could be provided by the hydro-station at no additional cost. This was achieved by using a floating power cable.

Figure 6.2: Mbashe dredger (jet pump technology)

The dredger was operated by the Transkei Electricity Supply Corporation (Tescor) between August 1986 and April 1989. Tescor achieved only 16 % (800 000 m^3/a) of the maximum rated dredger output of 5 million m^3 sediment/a during this period due to a number of reasons:

a) The clay content of the sediment was much higher than originally predicted, giving it a cohesive nature.

b) The dredger, a jetpump system with waterjets for agitation, had to be modified by adding a horizontal drum agitator to cope with the cohesive clay sediments. Sediment-water ratios obtained were, however, still low.

c) Mechanical failure of major dredger components was one of the main reasons for the low dredging output. Mechanical components from different countries used in building up the dredger proved to be incompatible.

d) Difficult operating conditions. The dredger could not operate properly under flood and high wind conditions. Under low inflow conditions the limited quantity of stored water had to be used both for power generation and dredging.

The nominal dredger ratings were:

Average sediment discharge	: 750 t/h
Average pumping water discharge	: 2 520 m^3/h (0,7 m^3/s)

With the average dry density of silt, 1,3 t/m^3, the average rated volume of sediment removed per hour was 577 m^3. The rated sediment-water ratio is therefore 1:3,3 (23 %) which seems realistic with an upper limit of 25 % sediment (ratio 1:3).

Although the nominal annual dredger rating is 5 million m^3 sediment/a (say 52 weeks @ 975 m^3/h @ 5 days/week @ 20 h/d), a design average annual rating of 70 % of the maximum rating is normally accepted due to availability, in this case equalling 3,4 million m^3/a. The realistic average annual dredging rate achieved by Tescor is therefore 23 % of the design rating, which is still extremely low.

When dredging started, a concern was that discharged sediment might build up downstream of the dam. This did not materialize and no ecological problems were identified which could be attributed directly to dredging. In the case of Collywobbles the discharge flows to the Indian Ocean about 30 km away, with very little development along the river

At the start of dredging operations a minimum storage of 1,5 million m^3 was required, but during the course of dredging the electricity tariff scheme changed and resulted in a minimum required storage of 1,0 million m^3. It was therefore decided to discontinue dredging in 1989 because it was felt that by reconstructing the sluice gate at the dam, this minimum storage capacity could be maintained by flushing.

The unit dredging cost determined for the Collywobbles reservoir is approximately R2/m^3 (1993 escalated). Details of how this cost was determined are given in **Chapter 7.3.1**.

6.2.2 Mkinkomo reservoir, Swaziland

The case of Mkinkomo reservoir (Friede, 1994 and Haskoning, 1988) illustrates the scope of a dredging project to restore lost reservoir capacity.

The relatively small Mkinkomo reservoir (8 m high dam) located on the Lusushwana River, came into operation in 1963 (**Figure 6.3**). By 1987, the deposition of river sediment had reduced the original capacity of about 3,2 million m^3 to about 0,8 million m^3. The sedimentation resulted in a large quantity of suspended solids entering the hydro canal, leading to the Edwaleni and Maguduza power stations. Excessive wear on the turbines of these power stations occurred, despite continuous dredging of the Edwaleni headpond, located just upstream of the penstock to the Edwaleni power station.

The regime of the Lusushwana River changed after 1984, when the upstream Lupohlo-Ezulwini hydro-electric scheme with a capacity of 20 million m^3 came into operation. The Lupohlo reservoir permits the operation of the Edwaleni and Maguduza power stations at a higher load factor and also during periods of lower river flow. The operation of the Mkinkomo reservoir is integrated into the whole hydropower system and functions more as a short-term buffer than a storage facility. The sedimentation reduced its power-peaking capacity.

The feasibility study (Haskoning, 1988) indicated that a cutter-suction dredger should be used to remove 2,5 million m^3 of sediment, with transportation by floating and shore-based pipeline and placing of the dredged material in confined disposal basins downstream of the dam along the main stream.

The costs and benefits of dredging were estimated, based on repeat dredging after 12 years, which was calculated as the optimum period.

The costs consist of:

- backlog dredging, duration 1½ years
- loss of power due to water loss during the dredging process.

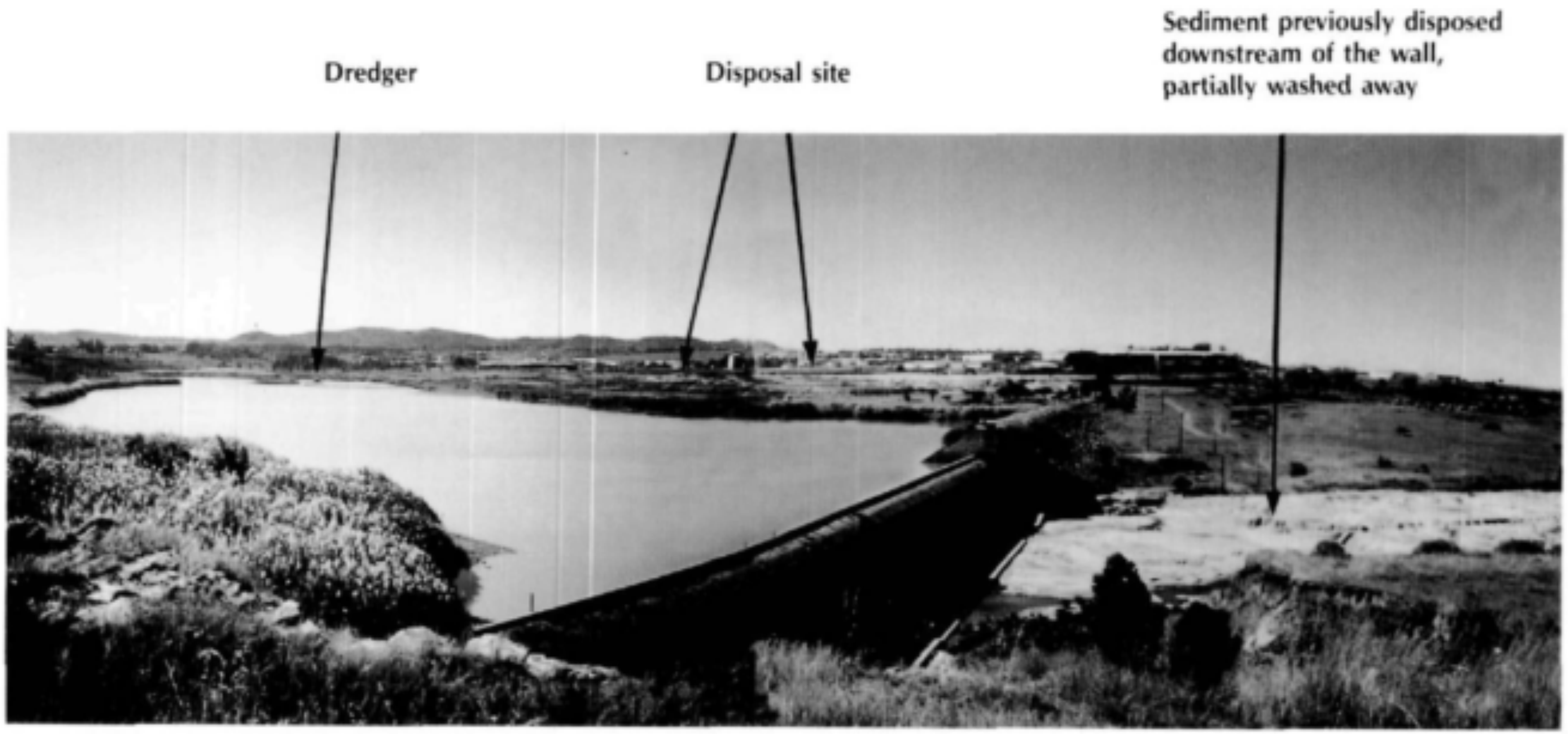


Figure 6.3: Mkinkomo Dam - Swaziland

The benefits were the avoidance of:

- regular cleaning of the outlet by divers
- power loss during the outlet cleaning
- dredging of the headpond
- power loss due to reduced reservoir capacity and related spillages.

During the design phase of the project the land designated as disposal area could not be made available due to problems of landownership. Another approach was used which involved storing the dredged material by building a sediment-retaining dam about 6 km downstream of the dam. The estimated cost for the retaining dam was no higher than the anticipated costs for the construction of the disposal basins on the sloping area along the river.

It was also calculated that it was feasible to build a sediment trapping dam upstream of the Mkinkomo reservoir once it was dredged.

In 1991 tenders for the dredging of Mkinkomo were received. Although the dredging cost was approximately R4,00/m^3, this excluded the cost of the civil works of the disposal dam, etc. The relatively high tender prices forced the owner of the dam to resort to an alternative dredging approach. A RSA-based dredging contractor was approached in 1993 to use a cutter-suction dredger with disposal by floating pipeline, directly downstream of the dam. A volume of 250 000 m^3 of sediment was dredged at a unit cost of R4,50/m^3. During this period of dredging there was little or no river flow downstream of the dam and disposed sediment was left directly downstream of the dam. The clayey material caused concern to both environmentalists and riparian irrigators. Fortunately the sediment was washed away during the rainy season. Instead of downstream disposal, slimes dams were constructed next to the reservoir and dredged sediment is currently disposed of into these dams. The dredged material is used for land reclamation.

A total of 700 000 m^3 has been dredged since 1993 and it is estimated that a further 350 000 m^3 still had to be dredged. The dredger and disposal site are shown in **Figure 6.4**.

The cutter-suction dredger used is ideal for the consolidated clayey sediment. A production rate of 180 to 200 m^3/h under favourable conditions is achieved. Earlier dredging using water jets showed that clay layers in the sediment could be undercut and the layer eventually broken down, but the clay blocks proved to be difficult to transport by pipeline. The same problem was experienced at the Collywobbles reservoir, Transkei.

Cutter-suction dredger

Cutter-head

Disposal site next to reservoir basin

Figure 6.4: Mkinkomo reservoir dredging - Swaziland

The maximum dredging depth is 8 m. A 300 mm diameter floating pipeline, 320 m in length, is being used with the dredger. The client, the Swaziland Electricity Board (SEB) provided an overhead power supply on land, as well as a floating power cable which is linked to the floating pipeline. Electric power results in a significant cost saving.

Few major problems have been experienced since dredging started. Only blockages by debris in the suction pipe have occurred, but these could be rectified quickly by raising the cutterhead and clearing it. The discharge pipeline flow is maintained by jetpump under these circumstances. A 24-hour operation is maintained. The dredger is manoeuvred by spuds and land-anchored cables. Discharge pipeline velocities of 3 m/s ensure that no settlement will occur, but as an extra precaution clean water is pumped every 3 hours to flush the pipeline.

The use of conventional equipment on the disposal site proved to be more expensive than expected. Fortunately most of the sediment is sandy and free-draining which facilitates handling. The dredged sediment is disposed of by land-based pipeline with two discharge ends in order to discharge alternately in newly constructed diked areas. With the 24-hour operation of the dredger, it is quite a formidable task to keep ahead with the construction of new diked areas, whilst minimising the unnecessary use of equipment and movement of material. It is foreseen that the disposed material will be built up to a maximum height of 7 m and will be left for 3 years before it will be used as industrial site. The cost of disposal is estimated at R1,20/m^3.

The SEB foresees that dredging will probably have to be repeated in 8 years' time, and although this is highly expensive (at a current (1994) unit rate of R6,20/m^3), no alternative exists.

6.2.3 Campsdrift canal

The City of Pietermaritzburg canalized a portion of the Msunduze River in order to make available additional land for industrial development and to create a recreational facility. A sedimentation basin was constructed at the upstream end of the canal, which could be drained after major storms to facilitate removal of silt deposits by excavators and trucks. It had been estimated that 80 % of the annual incoming sediment load of 100 000 m^3 could be trapped in this way.

In September 1987 the canal experienced a flood which filled the sedimentation basin with silt to capacity and deposited large quantities of sediment in the main canal. Prior to this flood, sediment from the sedimentation basin and canal had been removed with excavators and rough-terrain dump trucks, with disposal on the canal banks in allocated areas.

In March 1988 a significant flash flood deposited more sediment into the canal system and in July 1988 a contractor was appointed to remove 95 000 m^3 from the sedimentation basin with dry excavation methods previously used. The sedimentation basin has fairly coarse sediment which is relatively free draining. One problem using dry mechanical methods to remove the sediment is that it has to be carried out in a short time span during the low flow season. Prior to the sediment removal the use of either a cutter-suction or jet pump type dredger was investigated, but it proved to be more expensive than the use of conventional equipment. The dredging option included a dredger, a permanently installed buried pipeline, and suitable slimes dams to be constructed to give landfill depths of about 1,5 m, while drainage/drying times of about 6 months were anticipated.

The main canal was cleared of silt twice during the dry season by mechanical excavators. It was necessary to dewater the area to be excavated by forming drainage channels along the length of the canal bed on both sides of the canal. Large submersible pumps were employed to assist in draining the body of sediment to be excavated and it took four months to remove 88 000 m^3 via numerous ramps cut into the left bank of the canal. Draining of the canal meant total loss of the recreational facility for four months.

In 1990 a total of 275 000 m^3 was dredged from the main canal by cutter-suction dredger, and disposed along the banks in allocated areas by pipeline. The maximum pipeline length used was approximately 1 500 m. (See **Figure 6.5**.)

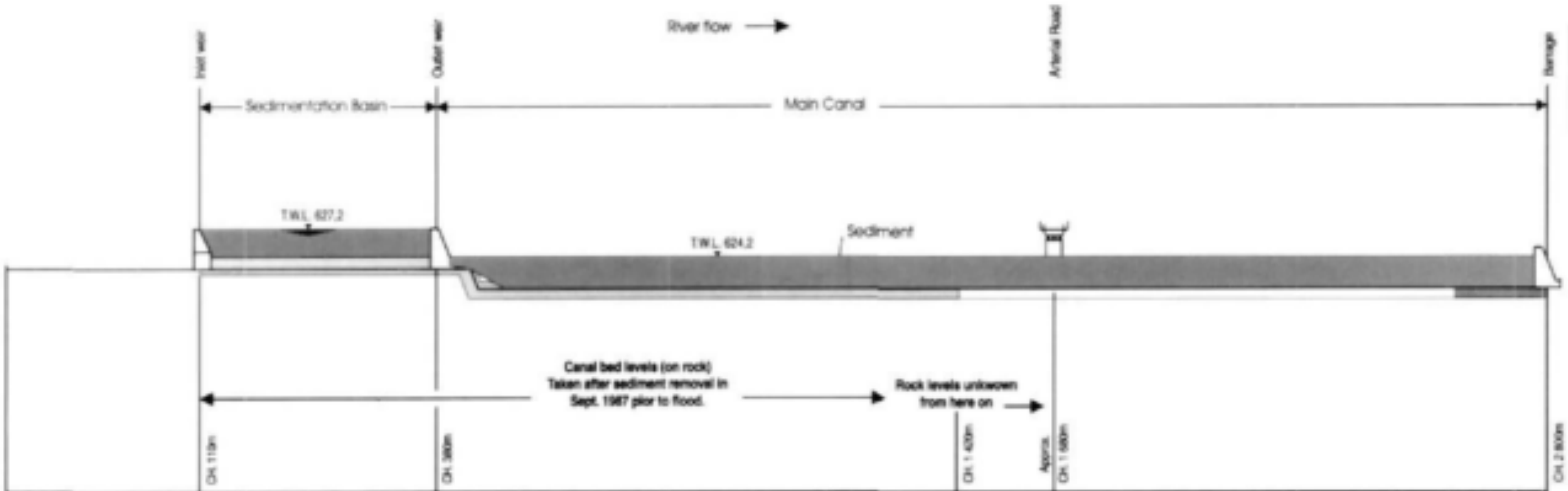
The future approach by the City of Pietermaritzburg will be to use conventional equipment to remove sediment from the sedimentation basin, and dredging in the main canal with disposal along the banks in allocated areas from where the dried sediment is removed to off-site spoil areas within a 10 km radius. The unit cost of the sediment removal, as discussed in **Chapter 7**, is extremely high.

6.2.4 **Zeekoevlei** (Anon, 1982), Western Cape

During 1982 dredging of approximately 200 000 m^3 of silt and sand was carried out in the Zeekoevlei. A disc bottom cutterhead instead of a crown cutterhead was selected because of lower induced turbidity. The head consisted of a number of cutting blades fitted between a bottom plate and top ring with the suction head inside the cutterhead. The higher number of cutting blades than the crown cutter also worked as a safeguard against obstacles.

The dredging carried out at Zeekoevlei is generally termed environmental dredging today. Transportation of the sediment was by 400 mm diameter steel pipe, 1 700 m in length. The disposal site was a diked reclamation area.

The unit cost of dredging and disposal, escalated to 1994 value, was in the order of R16/m^3 of sediment removed.



Prior to Sept. 1987 flood	28 700m³ sediment removed (June - Sept. 1987) Excavation to rock by conventional equipment	88 200m³ sediment removed (June 1987 - Sept. 1987) Excavation to rock by conventional equipment	Estimated 27 000m³ in this area (Aug 1987) No sediment removed
After Sept. 1987 flood	86 200m³ sediment deposited Detailed survey (Feb. 1988) No sediment removed	150 000m³ sediment in this area (Oct. 1987) No sediment removed	Unknown deposition No sediment removed
After Mar. 1988 flood	95 200m³ sediment removed (1988) ± 25 000m³ sediment removed (1990) ± 10 000 m³ sediment removed (1991)	183 000m³ sediment in this area (August 1988)	Estimated 130 000m³ in this area (August 1988)
	Excavation to rock by conventional equipment	Sediment removed from here ± 280 000m³ by dredging (1990)	

Figure 6.5: Campsdrift canal sediment removal

6.2.5 Canalization of Mgeni River, Durban

Dredging near the Mgeni River mouth from 1981 to 1984 was carried out by a Belgian contractor with a cutter-suction dredger. The project had the following boundary conditions and characteristics:

- Volume dredged: 4,15 million m^3
- Material: Silt and coarse sand
- Availability: 15 755 h effective dredging/(7 x 24 hours per week x 146 weeks) = 64,2 %
- Production: 263 m^3/h

  Of 8 800 hours of delays, 4 600 hours were due to blockages of the pump and cutter
- Transportation was by 200 m floating pipeline and 3 000 m shore pipeline (450 mm diameter)
- The average dredging unit cost achieved was 2 USD (1984), which is extremely high when converted to a 1994 value.

6.2.6 San Lameer

The San Lameer recreational lake had to be dredged in 1987 after high flows filled it with sediment. The average depth was only 0,3 m , instead of the required 1,0 m depth, and special precautions had to be taken during the project to protect the ecologically sensitive river banks. In 1987/88 tenders for the project were asked, but the quoted R1,6 million (escalated to 1994 cost) was considered too high. After discussions a smaller dredger was contracted at R750 000 (1994 cost). Disposal was by pipeline at sea. The low production of the dredger, together with problems with reeds, resulted in only 20 % of the project being completed when it was decided that draglines and conventional equipment for transport would be required to keep within the budget (**Figure 6.6**). The final project cost was approximately R950 000 (1994).

The lesson learned from this project is that the selection of the appropriate dredging equipment for a project is very important. During the project the boundary conditions for the environment had to be changed to keep costs down.

Figure 6.6: San Lameer dredging operation

7. COST OF DREDGING

7.1 General

The use of dredging as a method to control reservoir sedimentation has often been discarded due to the associated historically high unit costs. Despite the relatively high costs, dredging of reservoirs has been, and is, practised throughout the world. Local Southern African experience showed, however, that dredging costs could be in the same order as alternative methods to deal with reservoir sedimentation, such as the construction of new reservoirs or raising of a dam.

Traditionally, the dredging cost expressed as a unit cost per cubic metre of sediment removed, was related directly to the capital cost of say, raising a dam expressed as a unit cost (R/m^3), or in some cases to a present value unit cost, calculated over a 45-year period. Typical historical unit costs of constructing new storage range from approximately 10 c/m^3 of storage to 50 c/m^3 (1994). These relatively low costs are, however, rising due to reasons such as:

(a) limited ideal dam sites
(b) rising labour costs
(c) dam safety aspects in raising dams
(d) environmental concerns
(e) socio-economic issues.

Typical costs of reservoirs (DWAF, 1994) in South Africa, escalated to 1994 values, are indicated in **Table 7.1**.

Table 7.1: Historical South African reservoir construction unit costs

Dam	River	Constructed	Capacity (million m^3)	Unit cost (1994) (R/m^3 storage capacity)
Zaaihoek	Slang	1987	193	0,71
Inanda	Mgeni	1989	256	0,94
Knellpoort	Rietspruit	1989	137	0,14
Wolwedans	Groot Brak	1990	24	2,44
Driekoppies	Lomati	1994	251	2,00
Woodstock	Tugela	1982	383	0,21

It is not quite clear how these reservoir unit costs were calculated, but it might be that some of the overhead costs which normally form part of private contractor contract prices, were not included in these government constructed dams.

The Driekoppies Dam with a full supply capacity of 251 million m^3, presently under construction, is a recent example of where the capital cost is in the order of R500 million, thereby resulting in a direct calculated unit cost of close to R2,00/m^3 of storage capacity.

On the other hand, dredging has a much wider range of related unit costs, ranging from R1,00 to R30,00 per m^3 of sediment removed. The cost of dredging is highly site-specific dependent on a number of boundary conditions (see **Chapter 4**). Typical high volume (> 20 000 m^3) mining dredging in coastal areas is in the order of R1,50/m^3, and it is believed that this unit cost can also be obtained in reservoir dredging in South Africa. For smaller general dredging projects typical unit costs are higher, in the order of > R4,00/m^3.

In reservoir dredging the cost of dredging should, however, not be expressed and compared to alternative methods in terms of a unit cost per m^3 of sediment removed, but rather in terms of the yield or hydropower benefit (or other gains). This approach is necessary because compared to the construction of additional storage or the raising of a dam, dredging gives a much higher yield benefit for the same capacity created or dredged. This is especially true in the semi-arid to arid regions of our country. By raising a dam the additional storage created usually has basin characteristics which increase evaporative losses, while with dredging it is possible to make use of the original narrower valley bottom, with a much better capacity-yield relationship. In deep deposits of sediment, sometimes up to 20 m deep (Prins River Dam, Welbedacht Dam), dredging of a "reservoir" within the deposits will create additional storage, with no increase in water surface area and evaporation.

A further advantage of the dredging of reservoirs is that costs can be distributed over a number of years, resulting in a lower present unit cost of dredging than with capital investment, such as with the raising of a reservoir. When a dam is raised (or a new dam constructed) it is necessary to allow for future sedimentation, say 30 to 45 years ahead. The storage created initially therefore has a higher yield than is immediately required. With dredging, however, it is only necessary to dredge to obtain a capacity and associated yield to supply the demand at a required assurance. Dredging costs can therefore be kept to a minimum and by delaying dredging as long as possible, a lower present unit cost of dredging can be obtained.

Dredging of a reservoir will normally be carried out to regain the required yield, which will involve high volume dredging over a number of years. In order to maintain the required water demand, "continuous" maintenance dredging will be required to cope with annual sedimentation. The unit cost of this dredging could be lower than the initial dredging because the sediment to be removed is less consolidated, and by using dredging in combination with other control methods such as flushing or agitation dredging and density currents, further cost reductions could be achieved.

The cost of disposal should not be underestimated and it could easily constitute 20 % to 40 % of the total unit dredging cost (Korver, 1988). In the case of Mkinkomo reservoir, Swaziland, disposal costs are R1,20/m^3 of sediment dredged, nearly 20 % of the total unit cost.

The unit cost of dredging can be reduced by:

- Limited capital cost. A dredger for protected waters can be much simpler in construction than a seagoing vessel and usually is constructed of a number of pontoons. In South Africa the approach to build dredgers locally with importation of major components such as pumps and cutter, has resulted in major capital cost savings (Mkinkomo). Incompatibility of equipment could, however, lead to mechanical failure (Collywobbles).

- Using electric power instead of diesel power. When nearby power supply is available, a floating power cable could be utilized. This could result in a major unit cost reduction.

- Working longer hours. Because of the relatively large capital cost of a dredger, working hours of 20 hours per day, for say 6 days per week, are often adopted.

- Minimizing manning. Manning on reservoir dredgers can be substantially eliminated because of monitoring equipment which automatizes the dredging operation to a large extent.

- Keeping establishment cost down. The ease of transporting a reservoir dredger by road and reassembling on site ensures low establishment costs. The mobilization cost of international contractors to South Africa is, however, high.

- Ensuring high availability (the ratio of the time for which the plant is in actual working condition to the time required to be in operation). Availability is affected by factors such as starting up and shutting down, repositioning, pipeline moving and blockages, etc. The use of suitable dredging equipment for a particular project will ensure high availability. In mining dredging, availability in the order of 95 % is obtainable. The same should apply in reservoir dredging.

- High volumes to be dredged. On small dredging projects the cost of establishment and disposal can easily outweigh the actual dredging cost, resulting in high unit costs. In large-scale reservoir dredging, the total unit cost can be more related to the dredging cost.

7.2 Example of Reservoir Dredging Costing

It is not possible to give a general estimate of costs for dredging reservoirs (or any dredging project), because the cost level of dredging depends on the site-specific boundary conditions.

Nevertheless, in this section a cost estimate is given for a more or less standard solution for dredging a reservoir with conventional methods (Brabben, 1988), to indicate the various cost elements and their sensitivity.

Table 7.2 gives a breakdown of the estimated dredging cost for a project with these conditions. Crew and labour costs are an important item. Labour costs vary greatly between countries and therefore have a direct effect on dredging costs. Many countries do not have skilled dredging personnel available, which necessitates the employment of expatriates.

Fuel costs are estimated at 15 % of the total cost. This cost could be reduced if electricity were used as power, or if siphon dredging were used.

The disposal cost of dredged material depends very much on local conditions. In this case it has been assumed that one hydraulic crane is required to build spoil retaining dikes during the whole period while the dredging is in progress.

The mobilization estimate is based on mobilization from overseas and includes making the dredger fully operational. When dredging is of a more permanent basis, the mobilization cost is minimal.

The main boundary conditions in this example are:

- Cutter-suction dredger (0,4 m diameter suction pipe)
- Dredging depth <15 m
- Volume to be dredged: 2 million m^3
- Mainly fine sediment: <0,070 mm
- Transportation by 1 km floating pipeline and 4 km shore pipeline, elevation difference 30 m (down)
- Placement in diked disposal areas
- No significant delay due to debris
- Power on pump: 610 kW
- Power on cutter: 110 kW
- Auxiliary power: 100 kW
- Dredger cost: $1 250 000
- Discount factor: 1.1

- Lifetime: 15 years
- Annuity: 0,13147
- Utilization: 45 weeks/a
- Operation gross: 144 h/week = 6 x 24 h
- Operation nett: 120 h/week = 6 x 20 h
- Production: 27 000 m^3/week = 225 m^3/h

Table 7.2: Breakdown of dredging cost for a typical international dredging project

Item description				Cost/week	% Total
Depreciation and interest		$1 250 000 @	0,56 %/week	$6 939	9,3
Maintenance and repair		$1 250 000 @	0,30 %/week	$3 750	5,0
Fuel and lubricants				$11 163	15,0
Crew and labour:		7 @ 144 hr/w @ $15/h		$15 120	20,3
Pipeline:	Floating	1 000 m @ $3/m/week		$3 000	4,0
	Shore	4 000 m @ $0,5/m/week		$2 000	2,7
Disposal:	Hydraulic crane	$80/hr @ 120 h/w		$9 600	12,9
	Miscellaneous			$1 000	1,3
Insurance of dredger:		2 %/year @ $1 250 000 @ 45 weeks/a		$556	0,7
Subtotal				$53 128	71,2
General costs 10 % of subtotal				$5 313	7,1
Mobilization/Demobilization				$1 200 000	21,7
Cost per m^3 (excluding mobilization)				$2,16	
Cost per m^3 (including mobilization)				$2,76	

7.3 Historical Cost of Reservoir Dredging in South Africa

A number of case studies exist of reservoir dredging in South Africa (as described in **Chapter 6**), of which costs are known. Usually the unit dredging costs have been on the high side due to a number of reasons:

a) Reservoir dredging, especially problems with consolidated clay, is a relatively new field in dredging world-wide, resulting in the incorrect choice of dredging techniques, related low production rates and high unit costs.

b) South Africa has been isolated from the rest of the world until recently, resulting in a lack of technical expertise and equipment. Fortunately the situation has changed during the past two years, resulting in the establishment of co-operation between national and international dredging organizations. Smaller dredgers are also being manufactured under licence by local contractors.

c) In the past, quotations for reservoir dredging have been obtained from a number of mainly European contractors. These estimates were usually R6,00/m^3 of sediment removed and higher, due to limited knowledge of local conditions, high mobilization cost, etc. The competition between local contractors, the development of new techniques, and a better knowledge of local conditions could reduce dredging cost estimates to an acceptable level to be considered by water resource planners and operators.

A few case studies in Southern Africa can be used to best illustrate the historical cost of dredging.

7.3.1 Collywobbles, Transkei

Background on the dredging of Collywobbles reservoir on the Mbashe River, Transkei, is presented in **Chapter 6**. The dredging cost components considered (Rooseboom, 1993) comprise:

a) Capital cost
b) Cost relating to staffing, operating and normal maintenance of the dredger
c) Cost equating the value of the water discharged by the dredger, and the energy utilized by the dredger.

Capital cost

The cost of the dredger was R3,76 million (1987). The poor dredger output resulted in a ten-year lifespan being adopted.

The residual value of the dredger is unknown. When the dredger was advertised for sale during 1992 little serious interest was attracted and it is assumed that the dredger will have no residual value at the end of the period of depreciation. The interest paid during the loan period was capitalized and the dredger was depreciated at a uniform annual rate. The loan value was R3,379 million (1986 R) for a period of 15 years at 13 % p.a.

Operating and maintenance costs

In 1986 initial estimates of annual costs (excluding the value of water discharged and electricity utilized) were R393 700 (escalated to 1993 R). Following two years of operation, Tescor developed an accurate record of historical operation, maintenance, breakdown and repair costs. The 1989 dredger operating and maintenance costs (escalated to 1993 R) were R630 000/a.

Water and energy costs

The cost to Tescor of dredging of the water discharged and the electricity utilized varied according to the rate of flow into the Mbashe weir and the electrical load on the Tescor network at the time of dredger operation.

The minimum present-day cost, assuming that Eskom's tariff A structure applies, coincides with the Mbashe weir spilling more than 0,7 m^3/s. During this condition only the energy and power cost, calculated at the tariff A, applies.

The maximum present-day cost occurs when the Mbashe weir is not overflowing. During this condition both the equivalent cost of the energy and power which could have been generated by the water discharged by the dredger, and the energy and power utilized by the dredger are relevant.

Calculation of specific dredging costs

The specific cost of dredging was considered to comprise the three separate components, namely capital, operating and energy costs. The average annual availability of the dredger is expressed as a percentage and defines the actual annual sediment volume discharged in proportion to that which could have been achieved had the dredger been operating at nominal capacity continually throughout the year.

The specific dredger costs were calculated for the following availabilities:

16 % (800 000 m^3/a), which was achieved by Tescor
40 % (2 000 000 m^3/a), the minimum annual output required
70 % (3 500 000 m^3/a), the design availability
100 % (5 000 000 m^3/a), the maximum achievable working 6 days/week
@ ±16 hours per day

The total annual capital cost of the dredger is independent of the volume of sediment actually dredged in a particular year. The capital component of the specific cost for the varying dredger availabilities is determined by dividing the total annual capital cost by the corresponding annual dredger output. The specific component of the operating and maintenance costs is calculated by a similar method, while specific costs related to the water discharged and electricity utilized by the dredger are calculated for both the minimum and maximum cost scenarios. Specific dredging costs are indicated in **Table 7.3**.

Table 7.3: Specific dredging costs for Collywobbles (1993 R/m³)

Availability (%)	Capital cost	O & M cost	Water/Energy cost		Total cost
			Minimum	Maximum	
16	0,99	0,78		0,32	**2,09***
	0,99	0,78	0,18		**1,95***
40	0,40	0,31		0,32	1,03
	0,40	0,31	0,18		0,89
70	0,23	0,18		0,32	0,73
	0,23	0,18	0,18		0,59
100	0,16	0,13		0,32	0,61
	0,16	0,13	0,18		0,47

Note: * = Achieved

Comparative dredging costs (1993 escalated cost)

The original (1986) estimate of dredging cost was R0,29/m³ (1993 escalated) based on 63 % availability, and assuming zero water and energy costs. The equivalent **Table 7.3** total cost is R0,46.

A quoted contract dredging rate of R1,60/m³ (1993 escalated) was independent of the availability achieved by the contractor, but excluded a lump sum prepayment for establishment (negotiable) cost.

The unit dredging cost determined for the Collywobbles reservoir proved to be approximately R2,00/m³. It is believed (Rooseboom, 1993) that this figure could have been brought down by more efficient operation. Better initial sediment characteristics determination and selection of technically suitable dredging equipment could have reduced the operational costs. Unit costs of dredging of even less than R1,00/m³ of sediment removed are theoretically possible.

7.3.2 Mkinkomo reservoir, Swaziland

Initial dredging in 1993, with disposal directly downstream of the dam, was at a unit rate of R4,50/m³ (250 000 m³). This included mobilization, land and waterbased powerlines and the dredging, and excluded disposal (no cost) and electricity costs.

Disposal next to the reservoir basin for land reclamation proved to be more expensive due mainly to the use of mechanical earthmoving equipment. The dredging cost was in the order of R5,00/m³ of sediment removed, while the disposal cost was R1,20/m³ of dredged sediment, bringing the total unit cost (1994) to R6,20/m³.

7.3.3 Campsdrift canal

The excavation and disposal of sediment from the Campsdrift canal as discussed in **Chapter 6** proved to be highly expensive in terms of unit costs. This is mainly because of the high cost of construction of slimes dams and the additional use of conventional equipment to dispose sediment up to 10 km from the canal.

A cost estimate carried out in 1989 for a cutter-suction dredger was:

-	Establishment and removal from site	R 210 000
-	Removal of ± 150 000 m^3 sediment from main canal @ R3,50/m^3 (including all equipment necessary to pump to slimes dams up to 1,5 km from dredger)	R 525 000
-	Formation of 7 slimes dams	R1 050 000
	Total cost (1989)	R1 785 000
	Unit dredging cost (excavation, transport and disposal)	R 11,90

In 1990, 275 000 m^3 of sediment was dredged at a cost of approximately R14/m^3.

The removal of sediment by conventional plant to off-site spoil was priced (1989) at R15,70/m^3, assuming a maximum haul distance of 10 km . This results in a total cost of approximately R50/m^3 of sediment removed, escalated to 1994 prices.

8. ECONOMIC YIELD/DREDGING ANALYSIS OF SELECTED SOUTH AFRICAN RESERVOIRS

8.1 General

In this study, because of the importance of cost, the approach followed was to determine the required unit cost of dredging for a number of reservoirs by evaluating alternative methods of increasing the yield, such as raising of the dam, new storage and/or groundwater use.

Following the initial economic evaluation, three reservoirs were selected where dredging seems viable and a detailed cost analysis was carried out incorporating field data, to establish dredging costs with the specific site boundary conditions taken into account. The dredging cost analyses of specific dams involved the selection of appropriate conventional dredging equipment. The costing of possible non-conventional dredger usage, such as siphon dredging, was addressed separately.

Steps followed in the economic analysis of reservoir dredging, are:

a) From the DWAF listed surveyed reservoirs (DWAF, 1994) select reservoirs with the highest sedimentation in terms of percentage of original storage capacity and volume of sediment compared to other reservoirs in South Africa (Refer to **Table 8.1, Figures 8.3** and **8.4**). This DWAF list only contains the larger DWAF reservoirs where regular basin surveys are carried out and a number of privately owned and small dams are not listed which might have worse sedimentation characteristics (such as Collywobbles, Transkei).

b) For the do-nothing scenario, determine the current yield and assurance of supply, using the Water Resources Yield Model (WRYM), developed on the Vaal River Study by the DWAF.

c) Determine the year 2023 (30-year) yield with future sedimentation.

d) If the water demand predicted for the next 30 years exceeds the yield from the dam (determined in (b) and (c), analyse dredging.

Table 8.1: Selected reservoirs for dredging analysis

Dam	River	Construction date	Last survey date	Last survey FSC (million m3)	Sediment volume (1994) (million m3)	% Sediment of original FSC
Albasini	Levubu	1952	1975	25.7	4.1	13.8
Allemanskraal	Sand	1960	1989	179.3	40.2	18.3
Amersfoort	Skulpspruit	1971	1983	1.0	0.2	16.7
Bethulie	Bethuliespruit	1921	1979	2.0	4.6	69.7
Boegoeberg	Orange	1931	1983	20.4	14.3	41.2
Bon Accord	Apies	1925	1980	4.4	1.3	22.8
Bulshoek	Olifants	1922	1980	6.3	1.0	13.7
Calitzdorp	Nels	1917	1981	4.8	1.0	17.2
Clanwilliam	Olifants	1935	1980	124.1	9.8	7.3
Darlington	Sondags	1922	1990	187.8	139.9	42.7
Doringrivier	Doring	1969	1984	19.6	3.9	16.6
Driel	Tugela	1974	1986	10.4	5.0	32.5
Egmont	Witspruit	1938	1972	9.7	3.5	26.5
Elandsdrift	Great Fish	1973	1981	9.7	2.5	20.5
Erfenis	Vet	1959	1987	212.2	23.1	9.8
Floriskraal	Buffels	1957	1992	50.3	16.8	25.0
Gamkapoort	Gamka	1969	1981	44.8	10.1	18.4
Gariep	Orange	1971	1991	5342.9	545.9	9.3
Glen Alpine	Mogalakwena	1967	1991	20.0	2.9	12.7
Grassridge	Great Brak	1924	1984	49.6	41.2	45.4
Hartebeespoort	Crocodile	1923	1990	195.1	20.0	9.3
Hazelmere	Mdloti	1975	1987	17.5	6.1	25.8
Kalkfontein	Riet	1938	1990	318.8	36.6	10.3
Kammanassie	Kammanassie	1923	1981	35.9	3.6	9.1
Keerom	Nuy	1954	1981	7.4	0.9	10.8
Kommandodrift	Tarka	1956	1985	58.8	14.7	20.0
Koppies	Renoster	1911	1978	40.7	12.0	22.8
Krommenellenboog	Little Marico	1955	1983	9.4	2.3	19.7
Krugersdrift	Modder	1970	1989	73.2	12.4	14.5
Lake Arthur	tarka	1924	1985	29.3	75.8	72.1
Leeu Gamka	Leeu	1959	1981	14.2	7.8	35.5
Maden	Buffalo	1909	1981	0.3	0.1	25.0
Marico Bosveld	Great Marico	1933	1991	27.0	3.2	10.6
Phalaborwa	Olifants	1966	1990	3.0	6.0	66.7
Pietersfontein	Keisies	1968	1981	2.1	0.6	22.2
Pongolapoort	Phongola	1973	1984	2445.3	55.0	2.2
Poortjie	Blaasbalk	1925	1981	5.4	2.0	27.0
Prinsrivier	Prins	1916	1981	2.3	5.3	69.7
Roodepoort (Cornelia)	Leeu	1896	1992	0.9	1.0	52.6
Rooiberg	Hartbees	1935	1983	3.7	3.5	48.6
Stompdrift	Olifants	1965	1981	55.3	6.4	10.4
Vaal	Vaal	1938	1986	2536.0	210.0	7.6
Vaalhartz	Vaal	1936	1991	48.7	41.6	46.1
VanRyneveldspas	Sondags	1925	1978	47.4	31.4	39.8
Welbedacht	Caledon	1973	1998	14.0	99.8	87.7
Weltevrede	Leeu	1907	1992	1.8	1.1	37.9
Wentzel	Harts	1934	1979	5.1	1.3	20.3
Windsor	Klip	1950	1986	0.8	3.8	82.6
Xonxa	Wit Kei	1974	1986	135.1	22.5	14.3

Note: selected dams for economic dredging analysis shown in italic

e) For the dredging scenario, alter the current area-volume relationship by removing just enough sediment normally in the deepest part of the basin for maximum yield benefit to obtain the required yield. This would normally require large volumes of bulk dredging over a few years at the beginning of the analysis period of say 30 to 45 years. The cost of maintenance dredging to remove annual sedimentation and to supply the growth in demand was also included in the analysis (Refer to **Figures 8.1** and **8.2**).

f) Compare the yield benefit obtained by dredging to that of raising (or alternative storage/sources of water). Normally this means an increase in reservoir capacity at the beginning of the analysis period, which can supply in the future demand (or comparable yield obtained by dredging) by taking into account future sedimentation. The same yield benefit for dredging and the alternative must be obtained to make the costs directly comparable.

g) In the economic analysis dredging versus raising cost (or other alternatives) are compared over a 45-year period. Net present value costs (NPV) are determined for various real discount rates, from 2 to 10 %. (2,75 % is the 1994 rate for the Lesotho Highlands scheme). Dredging unit costs for various costs per m^3 of sediment removed are determined as indicated in **Figures 8.1 and 8.2**.

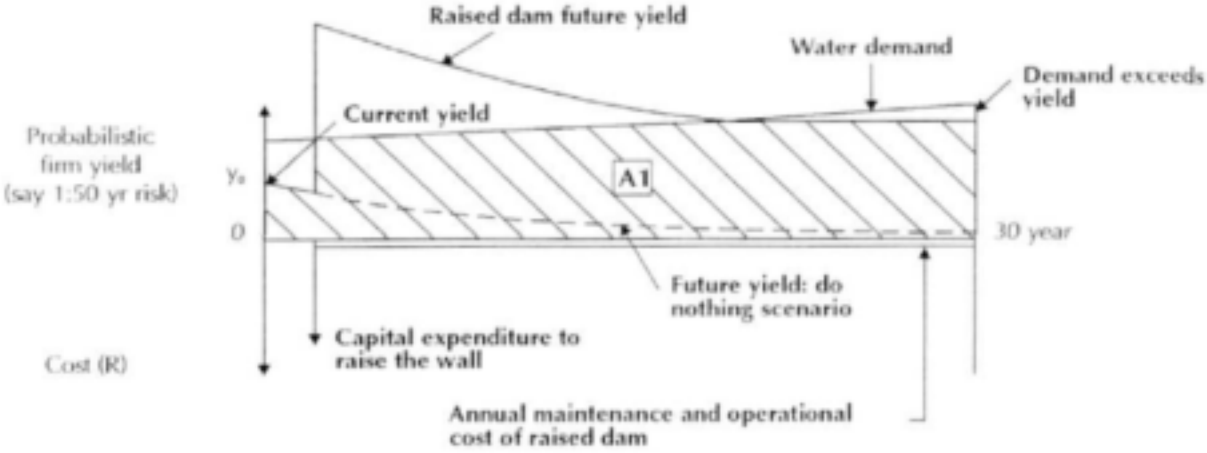
h) Dredging water losses were not considered because it was assumed that disposal would be upstream of the dam, along the reservoir basin and above full supply level, or in the dead storage zone.

It should be noted that only directly cost-related aspects were considered in the analyses. In reality, environmental, socio-economic and other factors may also play an important role in deciding on a method of dealing with reservoir sedimentation.

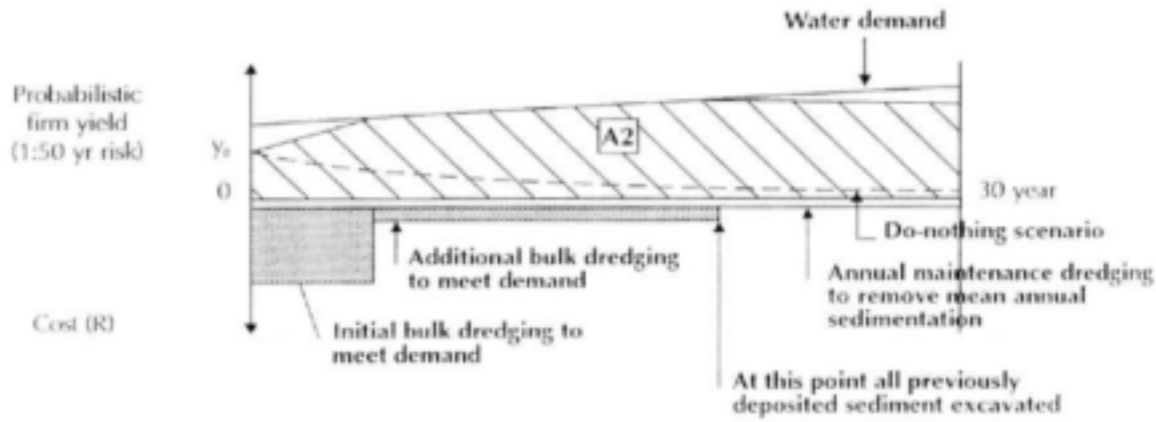
The economic analyses of 23 selected reservoirs are discussed in the remainder of this chapter. The positions of these reservoirs are indicated in **Figure 8.5**.

Some of the terminology used in the yield analysis needs to be defined:

- Historical firm yield: A firm yield of a reservoir based on the historical hydrological record which has been adjusted to the current development level.
- Probabilistic yield: A firm yield based on stochastically generated flow records and an assurance of supply of the water demand, at current development level.
- FSC: Reservoir full supply capacity.



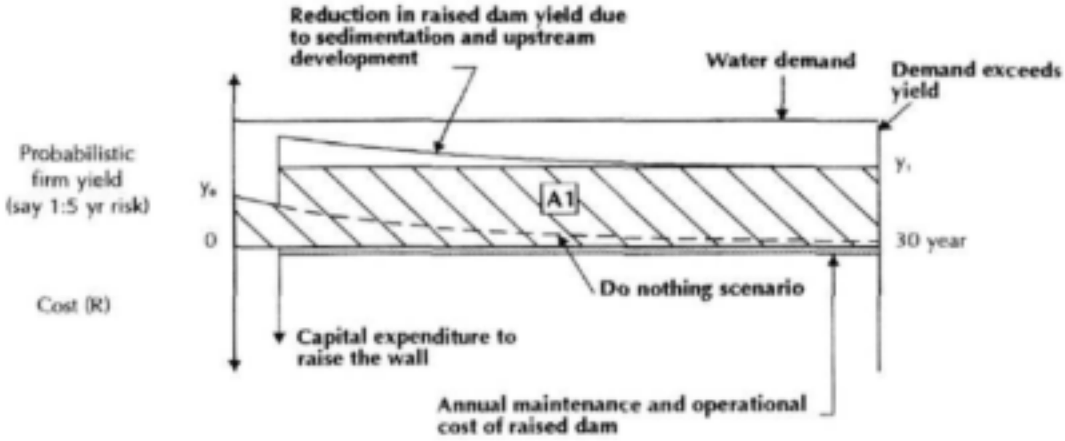
Conventional alternative: Raised dam



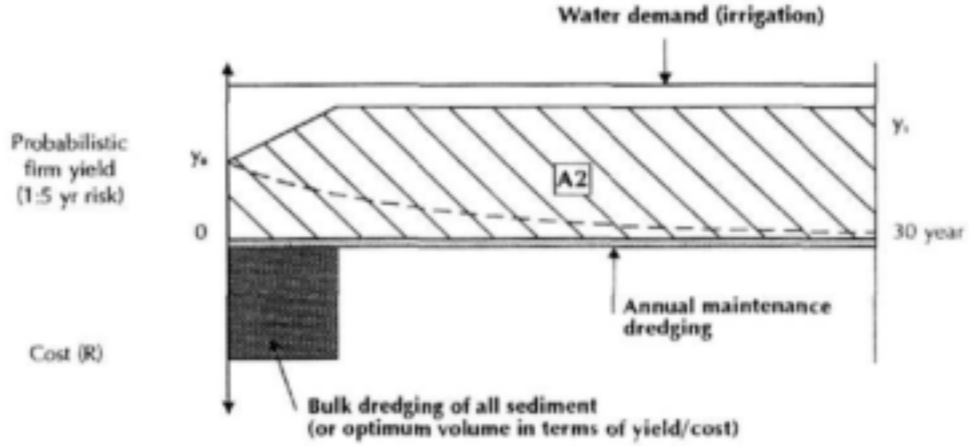
Dredging: Yield can meet demand

Notes:
- Area A1 should equal area A2 in order to directly compare cost.
- When demand exceeds yield it could be due to dam not raised enough, all sediment dredged, etc.
- With a raised dam, the initial yield will be higher than the demand. Both domestic and irrigation users need to plan for the long term and therefore the higher yield will result in a higher assurance of supply of the required demand.
  For some irrigation use, a higher assurance of supply could lead to higher crop production, but this was not considered in this study

Figure 8.1: Economic dredging analysis - methodology: yield can meet demand

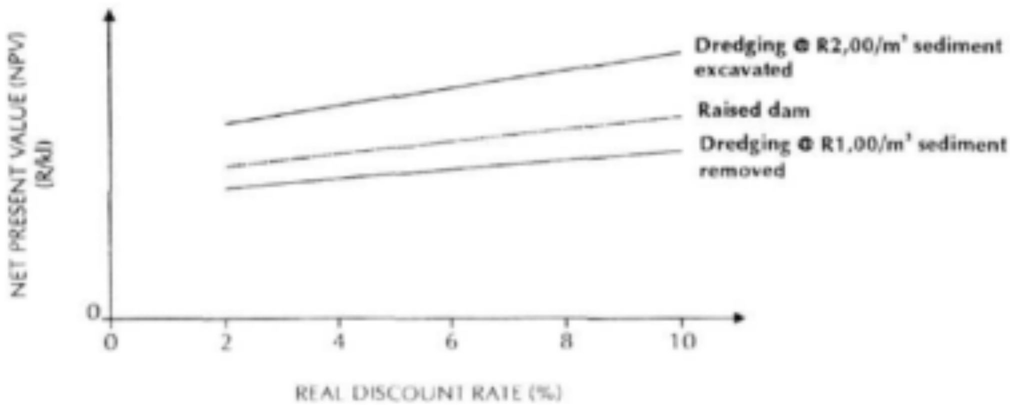


Conventional alternative: Raised dam



Note: Yield (y1) of dredging should equal yield (y1) in raised dam option

Dredging: Demand always > yield (typical irrigation)



Net Present Value (NPV) of raising and alternative scheme cost

Figure 8.2: Economic dredging yield analysis - methodology: Demand > yield, and NPV calculation

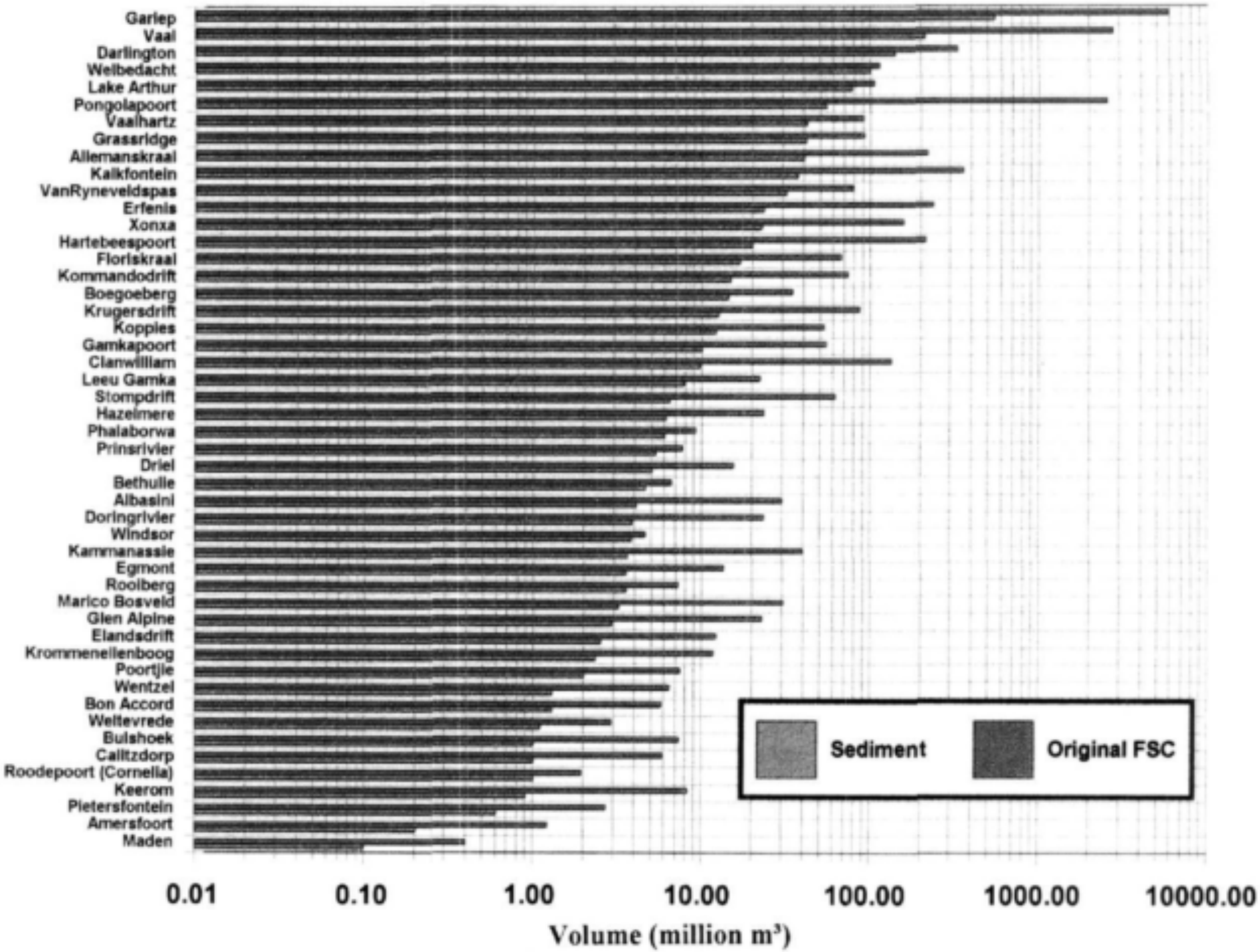


Figure 8.3: Selected reservoirs: sediment versus original FSC

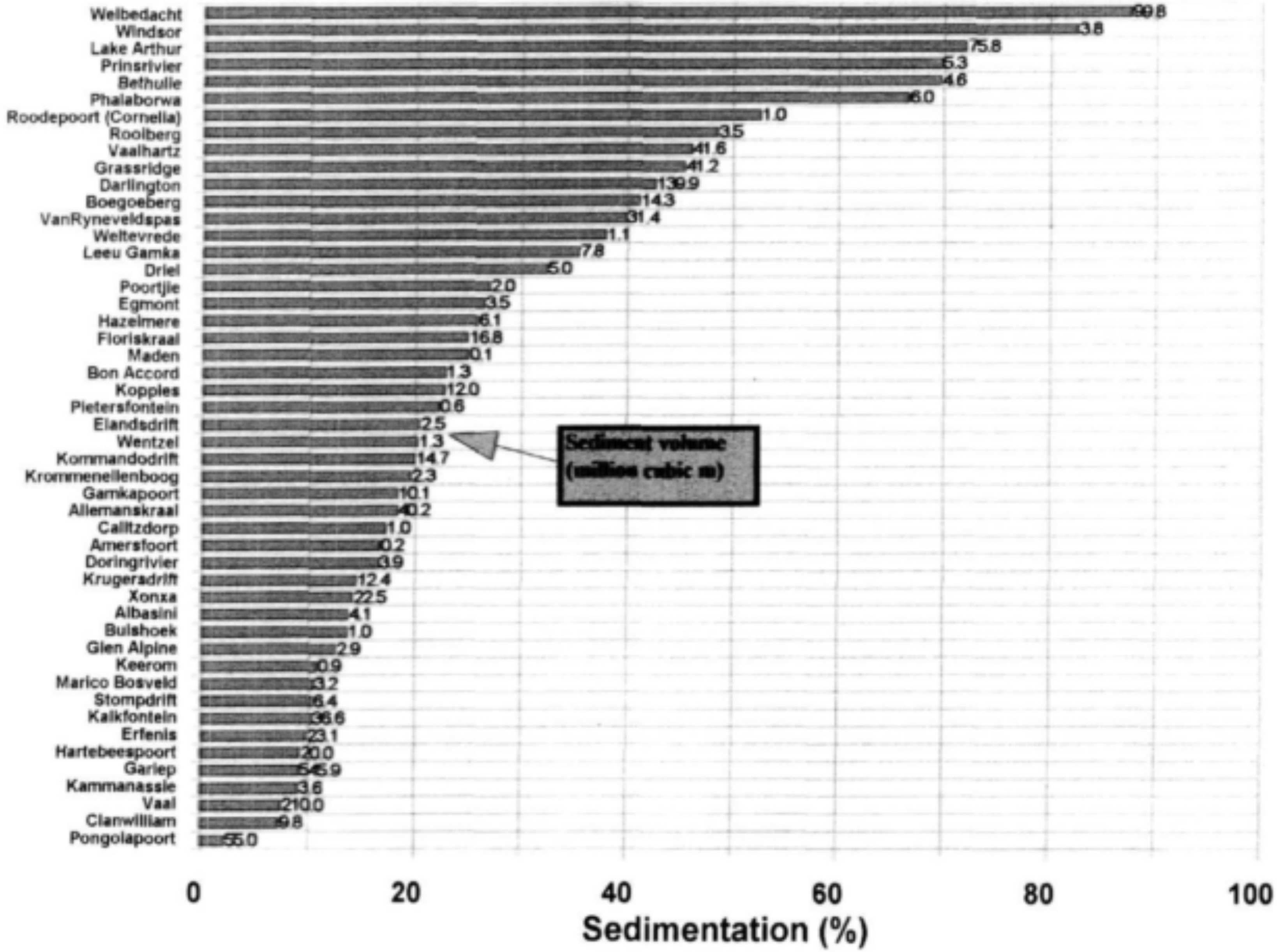


Figure 8.4: Selected reservoirs: sediment as % of original FSC

1. Albasini Dam
2. Allemanskraal Dam
3. Boegoeberg Dam
4. Bon Accord Dam
5. Driel Barrage
6. Erfenis Dam
7. Floriskraal Dam
8. Grassridge Dam
9. Hartbeespoort Dam
10. HazelmereDam
11. Gariep Dam
12. Kalkfontein Dam
13. Kommandodrift Dam
14. Koppies Dam
15. Krugersdrift Dam
16. Lake Arthur
17. Darlington Dam
18. Pongolapoort Dam
19. Prinsrivier Dam
20. Vaal Dam
21. Vaalhartz Dam
22. VanRyneveldspas Dam
23. Welbedacht Dam

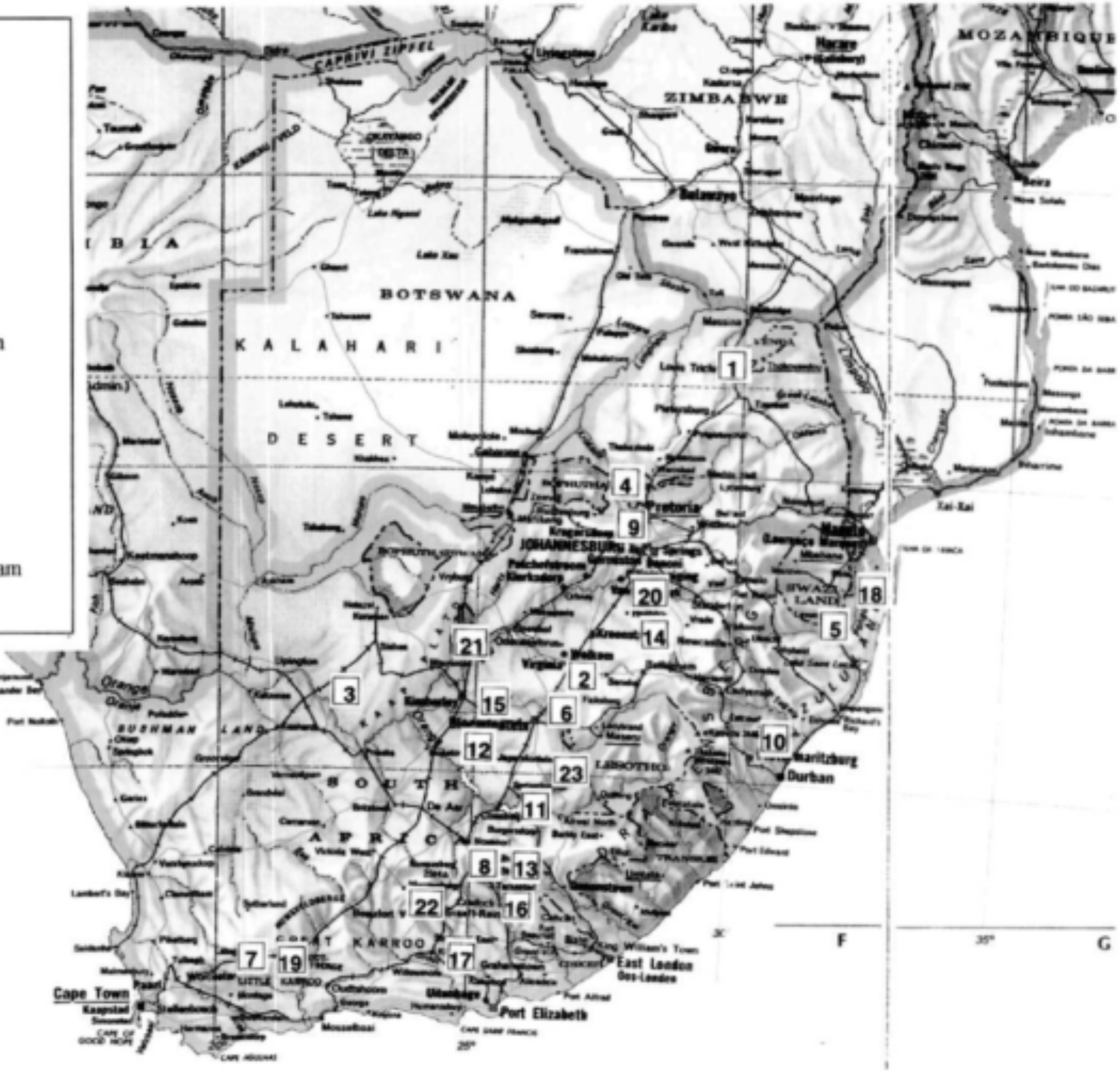


Figure 8.5: Economic dredging analysis: selected reservoir positions

8.2 Economic - Dredging Analysis of Selected Reservoirs

8.2.1 Albasini Dam

a) General (Figure 8.6)

Albasini Dam on the Levubu River was constructed in 1952, and had an original FSC of 29,5 million m^3. Sedimentation reduced the capacity to 25,6 million m^3 (1975 survey). Further sedimentation after 1975 will have occurred but unfortunately no basin surveys have been carried out. The Northern Province has, however, experienced a severe drought since 1983, and it is doubtful whether sedimentation at the same rate as before 1975 occurred. Overgrazing and the recent drought could lead to significant sedimentation in future, however.

b) Water demand

Irrigation and domestic users in Louis Trichardt have been supplied from the dam. During the drought, however, users had to rely on groundwater. Based on the historical reservoir water releases when no restrictions were imposed, the water demand is in the order of 9 million m^3/a.

c) Yield analysis

- Current situation

The current situation was analysed based on the 1975 basin survey, and the hydrology and system were obtained from the DWAF (Swart, 1993).

The analysis indicated that the current demand can be supplied at an assurance of better than a 1 in 20 year risk of failure.

- Dredging analysis

Dredging of all the sediment was analysed. The yield results are:

Description	FSC (million m^3)	Historical firm yield (million m^3/a)	Probabilistic yield (million m^3/a)			
			1:10 yr	1:20 yr	1:50 yr	1:100 yr
Current situation (1975 survey)	25,6	5,8	12,1	10,3	7,8	6,7
Dredging of all sediment	29,5	6,1	12,4	10,8	8,0	6,9
Yield benefit	-	0,3	0,3	0,5	0,2	0,2

Figure 8.6: Albasini Dam

The dredging yield benefit is in the order of 0,3 million m^3/a.

d) Economic analysis

No economic analysis was carried out due to the small yield increase by dredging, and because the current demand is supplied at an acceptable assurance taking into account that groundwater has been developed as alternative supply.

e) Key results

Although the Albasini Dam has lost more than 13 % of its storage capacity, the capacity is still large in relation to the run-off and therefore dredging gives a relatively small yield benefit.

8.2.2 Allemanskraal Dam

a) General (Figure 8.7)

Allemanskraal Dam was constructed in 1960 mainly for irrigation. Sedimentation has reduced the original full supply capacity of 220 million m^3 by 20 % to the current 176 million m^3.

b) Water demand

The current demand is 47,44 million m^3.

c) Yield analysis

- Current situation

The current historical firm yield is 49 million m^3 and it is estimated that future sedimentation will reduce the yield to 48 million m^3. The current firm yield approximately equals the water demand.

Figure 8.7: Allemanskraal Dam

- Dredging analysis

If all sediment is dredged (43 million m^3), a historical firm yield of 52 million m^3/a could be obtained, not much more than the current yield (3 million m^3/a). The reason for this is that a dead storage zone for sedimentation was provided in the reservoir and water cannot be abstracted/released from this zone.

d) **Economic analysis**

No economic analysis was carried out because the available yield equals the demand.

e) **Key results**

The water demands and available yield seem to be in balance at Allemanskraal Dam. The provision of a dead storage zone without bottom valves to be able to abstract from this zone, results in a low dredging benefit. With dredging to be considered as an option in future sedimentation control, it is recommended that bottom release facilities are provided at a reservoir.

8.2.3 Boegoeberg Dam

a) **General (Figure 8.8)**

Boegoeberg Dam is situated downstream of Vanderkloof Dam on the Orange River. The dam was constructed in 1931 and had an original FSC of 34,66 million m^3. Sedimentation has reduced the capacity by nearly 15 million m^3 and the last basin survey indicated a FSC of 20,4 million m^3 (1983). This capacity might be much less now after the floods in 1988.

b) **Water demand**

The dam is currently being used as diversion weir and has to be kept at a high water level to supply the irrigation canal. Increasing the reservoir capacity would therefore not create a large yield increase because of the large dead storage of the irrigation canal supply. Furthermore, most of the run-off of the Orange River system is generated in the east while Boegoeberg Dam is situated in an arid region. No economic-yield analysis was therefore carried out for Boegoeberg Dam. (During 1996 it was established in the Orange River Replanning Study, that a larger Boegoeberg reservoir would help in the low flow operation of the lower Orange River to limit spillage from the system).

Figure 8.8: Boegoeberg Dam

8.2.4 Bon Accord Dam

a) **General (Figure 8.9)**

Bon Accord Dam was constructed in 1925 with an original FSC of 6,3 million m^3 (at current full supply level). In 1937 the spillway was lowered and the FSC as surveyed in 1980 is 4,3 million m^3.

b) **Yield analysis**

A recent yield analysis carried out by the DWAF indicated that the yield from the dam is sufficient to meet the irrigation demands. Therefore no dredging-economic analysis was carried out.

8.2.5 Driel Barrage

a) **General (Figure 8.10)**

Driel Barrage was constructed in 1974 as part of the Tugela-Vaal transfer scheme. Sedimentation caused a reduction of 4,9 million m^3 capacity by 1983 (original FSC = 15 million m^3), and increasing demands led to the construction of Woodstock Dam upstream of Driel Barrage in 1982. After the construction of Woodstock Dam, sedimentation has reduced to 0,08 million m^3 (1983 to 1986). At least 32 per cent of the original FSC in Driel has been lost to sedimentation.

Figure 8.9: Bon Accord Dam

Figure 8.10: Driel Barrage

b) **Yield analysis**

- Current situation

The Vaal-Bloemhof system was analysed and the historical firm yield is 2 294 million m^3/a.

- Dredging analysis

If 5 million m^3 of sediment is dredged from Driel, the additional system yield is only 1 million m^3/a.

c) **Key results**

Dredging of Driel Barrage will result in a yield increase of 1 million m^3/a, which is relatively too small to consider viable.

8.2.6 Erfenis Dam

a) **General (Figure 8.11)**

Erfenis Dam was constructed in 1959 with an original full supply capacity of 235 million m^3. Sedimentation however, reduced the capacity by 10,5 % (25 million m^3) and the current (1994) FSC is estimated at 210 million m^3.

b) **Water demand**

The current water demand (mainly irrigation) is estimated at 60,5 million m^3/a.

c) **Yield analysis**

- Current situation

The yield analysis of the current situation indicates:

Description	Historical firm yield (million m^3/a)	Probabilistic yield (1:50 years) (million m^3/a)
Do nothing - 1994	43	61
Do nothing - 2023	42	-

Nothing has to be done because the demand can be supplied at a high assurance.

- Dredging analysis

If all sediment is dredged, the historical firm yield is 46 million m^3/a, which is only slightly more than the current yield.

d) **Economic analysis**

No economic analysis was carried out because the demand can be supplied with current conditions.

e) **Key results**

Although the reservoir has lost 10,5% of its capacity due to sedimentation, the available yield is sufficient. This case illustrates that just because there is sediment in the reservoir does not mean it has to be removed.

Figure 8.11: Erfenis Dam

8.2.7 Floriskraal Dam

a) General (Figures 8.12, 8.13 and 8.14)

Floriskraal Dam was constructed in 1957, had an original FSC of 67 million m^3 and has lost 17 million m^3 of storage capacity due to sedimentation.

b) Water demand

The dam was constructed for irrigation development and based on the historical use the current demand is 20 million m^3/a.

c) Yield analysis

- Current situation

The 1 in 5-year risk of failure yield from the dam is 12 million m^3/a, much less than the demand, and the irrigators will therefore have to rely strongly on the use of groundwater.

- Dredging analysis

Dredging of all the sediment (17 million m^3) was analysed. The yield analysis results are:

Description	FSC (million m^3)	Historical firm yield (million m^3/a)	Probabilistic yield (million m^3/a)			
			1:5 yr	1:10 yr	1:20 yr	1:50 yr
Current situation	50	6	12,0	10,8	8,3	7,2
Dredge all sediment	67	9	14,0	12,8	10,7	9,4
Yield benefit	-	3	2,0	2,0	2,4	2,2

The increased yield by dredging is in the order of 2,0 million m^3/a for 17 million m^3 of sediment excavated. It should be noted, however, that dredging of a much smaller volume will result in nearly the same yield benefit.

d) Economic analysis

An economic dredging analysis was not carried out for Floriskraal Dam because the yield benefit was considered too small.

Figure 8.12: Floriskraal Dam

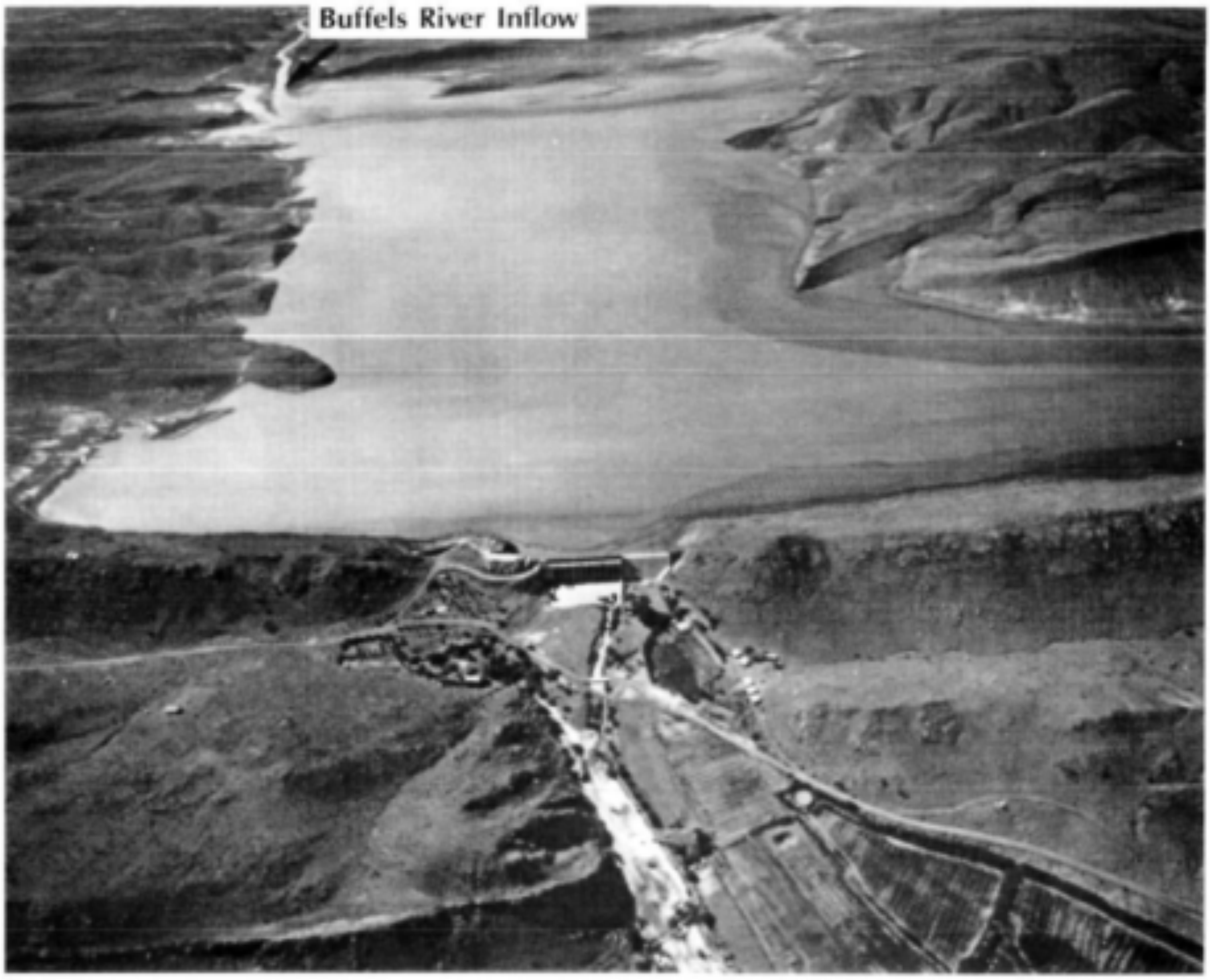
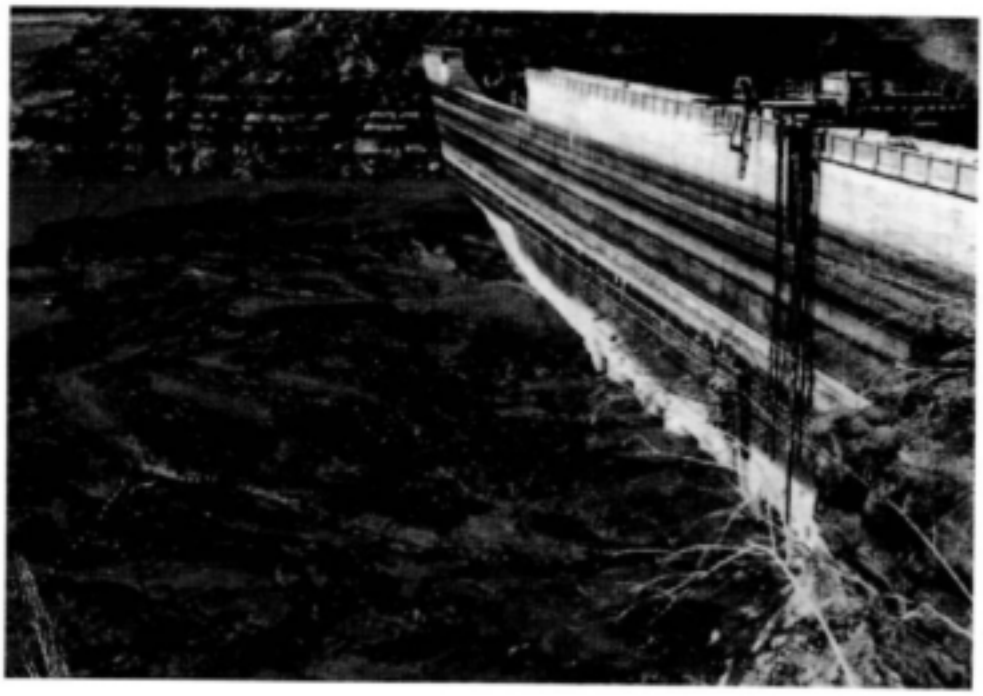


Figure 8.13: Floriskraal reservoir



Sedimentation at dam - 1993

Original reservoir basin

Figure 8.14: Floriskraal reservoir sedimentation

e) **Key results**

Dredging of Floriskraal Dam yields only a relatively small increase in yield because the current reservoir capacity is much larger than the MAR.

8.2.8 Grassridge Dam

a) ***General (Figure 8.15)***

Grassridge Dam was constructed in 1924 for irrigation purposes. The original (raised) capacity of 91 million m³ has been reduced due to sedimentation to the current FSC of 47 million m³. The mean annual sedimentation is roughly 0,69 million m³/a.

b) **Water demand**

The irrigation demand is approximately 50 million m³/a, most of which is supplied from the Gariep reservoir.

c) **Yield analysis**

The current situation and dredging of all the sediment were analysed:

Description	FSC (million m³)	Historical firm yield *(million m³/a)*	Probabilistic yield (million m³/a)			
			1:10 yr	1:20 yr	1:50 yr	1:100 yr
Current	47	2	7	6,5	3,8	2,9
Dredge all sediment	91	7	12,5	12	9	7,5
Yield increase	-	5	5,5	5,5	5,2	4,6

It should be noted that much less sediment can be dredged with almost the same yield benefit indicated above.

d) **Economic analysis (Figure 8.16)**

Dredging at a unit cost of R2,00/m³ will result in a NPV of R0,8/ℓ at a discount rate of 2,75 %.

e) **Key results**

Dredging of Grassridge Dam will increase the yield by 5,5 million m³/a. Currently sufficient water is available from the Orange River system.

Figure 8.15: Grassridge Dam

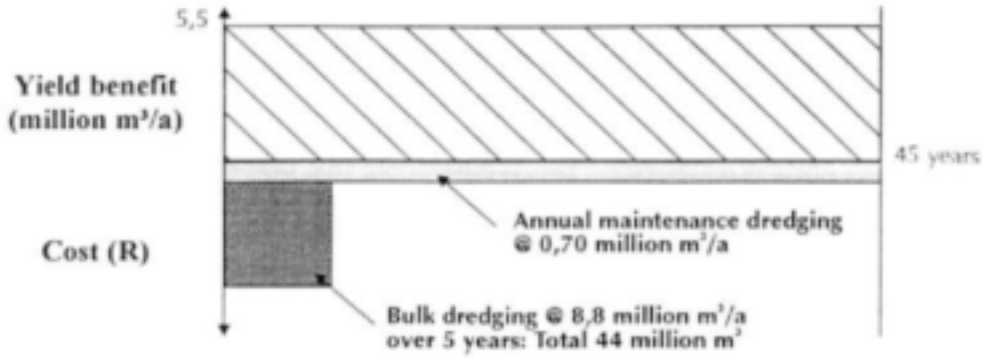
8.2.9 Hartbeespoort Dam

a) General (Figure 8.17)

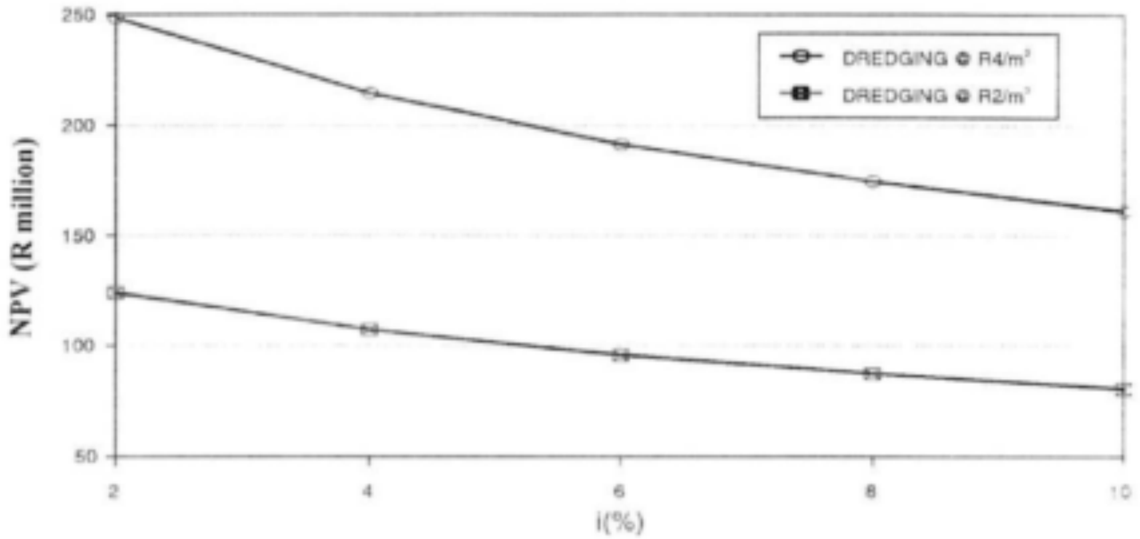
Hartbeespoort Dam on the Crocodile River was constructed in 1923 on the Crocodile River. The dam was raised in 1970, and has a current FSC of 195 million m^3. Sedimentation has reduced the capacity by approximately 20 million m^3.

b) Yield analysis

A recent yield analysis study by the DWAF indicated that the increasing return flows from the Gauteng area will in future cause an increase in yield and therefore additional supplies are not currently required. No economic-dredging analysis was therefore carried out.



Proposed dredging:



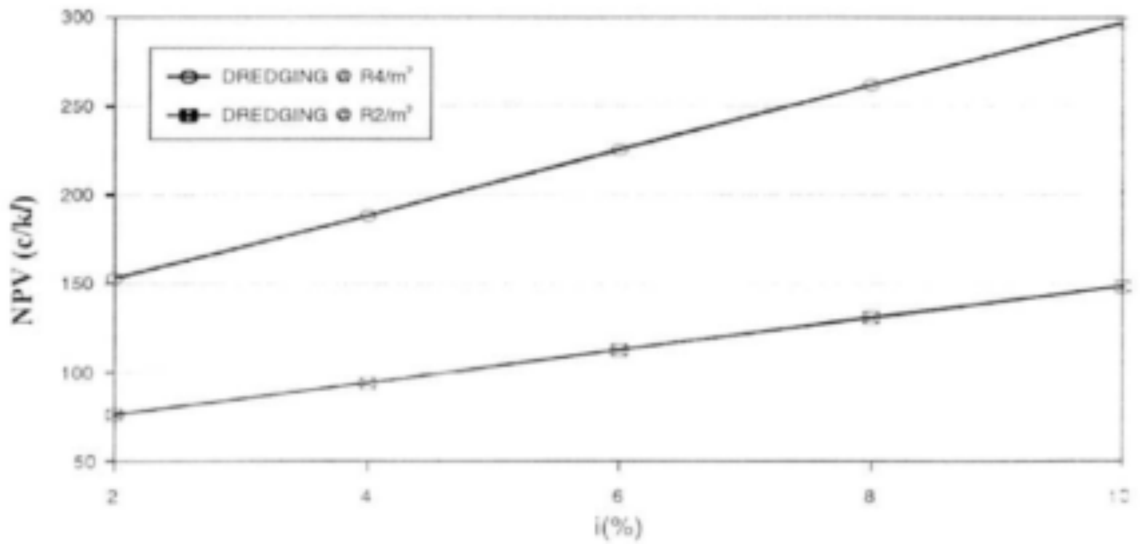


Figure 8.16: Economic dredging analysis: Grassridge Dam

Figure 8.17: Hartbeespoort Dam

8.2.10 Hazelmere Dam

a) General (Figure 8.18)

Hazelmere Dam on the Mdloti River was constructed in 1975. Sedimentation reduced the original FSC of 23,5 million m^3 by 25 % (6 million m^3) to the current 17,5 million m^3.

b) Water demand

The main water use is irrigation, but domestic use could increase in the near future. The current demand is approximately 20 million m^3/a, but future demands could exceed 30 million m^3/a within a few years.

Dam and basin

Flood of 1987

Figure 8.18: Hazelmere Dam

c) **Yield analysis**

- Current situation

Yields of the current situation and in 30 years time are as follows:

Description	Historical firm yield (million m^3/a)	Probabilistic yield (1:100 years) (million m^3/a)
Current situation - 1994	23	28
Do nothing - 2023	22	-

- Dredging analysis

If all sediment (6,05 million m^3) is dredged, the historical firm yield for the current condition is 25 million m^3/a, a yield increase of 2 million m^3/a.

- Alternative - raised dam

The option to raise the dam has been part of the original design and can be accomplished by the installation of crest gates. The historical firm yield for a raised dam is 31 million m^3/a (benefit: + 8 million m^3/a) and for a 1 in 100 year assurance, 35 million m^3/a (benefit: + 12 million m^3/a).

d) **Key results**

Although 25 % of the original FSC has been lost due to sedimentation, the yield benefit by dredging is only 2 million m^3/a, much less than a yield obtainable by raising the wall.

In the short-term with current demands, the reservoir yield is sufficient to supply the demand at an acceptable risk of assurance.

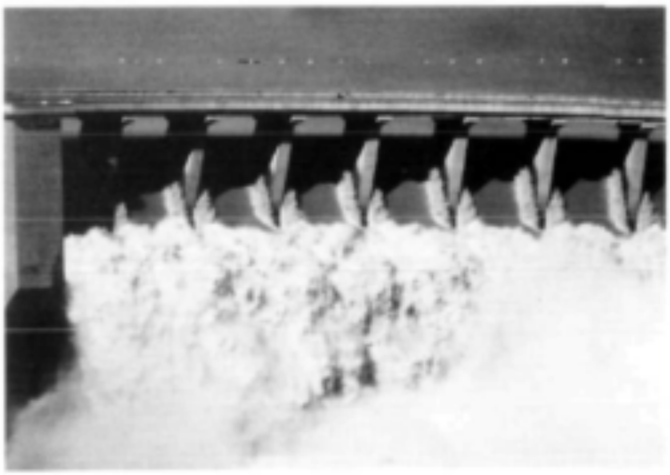
8.2.11 Gariep Dam

a) **General (Figure 8.19)**

Gariep Dam was constructed in 1971 and is the largest reservoir in South Africa. The original FSC of 5 889 million m^3 has been reduced to 5 343 million m^3 by 1991 (basin survey), a reduction of 546 million m^3 (9,3 % original capacity).

Aerial view of reservoir

Reservoir in flood - 120 % full



Sedimentation in upper reaches - Bethulie Bridge (1993)

Figure 8.19: Gariep Dam

b) **Water demand**

In the current situation system analysed the available yield still exceeds demand. A recent analysis by DWAF, however, indicates future shortfalls in the yield, especially at the Orange River Mouth with the phasing-in of the Lesotho Highlands scheme and increased demands.

c) **Yield analysis**

- Current situation

A system without phase 1A of the Lesotho Highlands scheme was analysed to determine a system yield at the river mouth. A historical firm yield of 3840 million m^3/a was obtained.

- Dredging analysis

The Eastern Cape Orange-Fish tunnel intake elevation was considered the minimum operating level in the reservoir in both the current situation and dredging analyses. Dredging of all sediment above this minimum operating level was considered, resulting in a total volume of 480 million m^3 of sediment to be dredged. The historical firm yield with the reservoir live storage dredged to its original capacity is 3900 million m^3/a, a yield benefit of 60 million m^3/a.

- Alternative source

No alternative source was considered because the current system yield exceeds the water demand.

d) **Economic analysis**

Dredging of all sediment above the Orange-Fish tunnel intake was considered. Bulk dredging over 15 years and annual maintenance dredging of 27 million m^3/a were analysed. The annual sedimentation is extremely high with related high dredging NPV.

e) **Key results**

The Orange River System currently has enough water to supply its demands. It is only in future when development upstream of Gariep Dam can lead to failure of supply mainly on the lower Orange River and Eastern Cape. Gariep Dam has lost nearly 10 % of its original capacity in 20 years, of which 88 % is in the live storage above the Orange-Fish tunnel intake. The high annual sedimentation leads to a high NPV of dredging. A system yield increase of 60 million m^3/a can be obtained by dredging all sediment in the reservoir at a level above the Orange-Fish tunnel intake.

8.2.12 Kalkfontein Dam

a) General (Figure 8.20)

Kalkfontein Dam on the Riet River was constructed in 1938, mainly for irrigation use. The original FSC of 355 million m^3 has been reduced by 10 % to the current 318 million m^3.

b) Water demand

The current water demand is 56,36 million m^3/a.

c) Yield analysis

- Current situation

  A yield analysis carried out by the DWAF indicated that the demand can be supplied at a risk of failure of 1 in 6 years. This risk was acceptable for the area and therefore nothing has to be done to augment the current yield.

d) Key result

The current demand can be supplied at an acceptable assurance.

8.2.13 Kommandodrift Dam

a) General (Figure 8.21)

Kommandodrift Dam on the Tarka River was constructed in 1956 to support irrigation upstream and downstream of Lake Arthur. Sedimentation has reduced the original FSC of 73,5 million m^3 by 16,5 million m^3 to the current 57 million m^3.

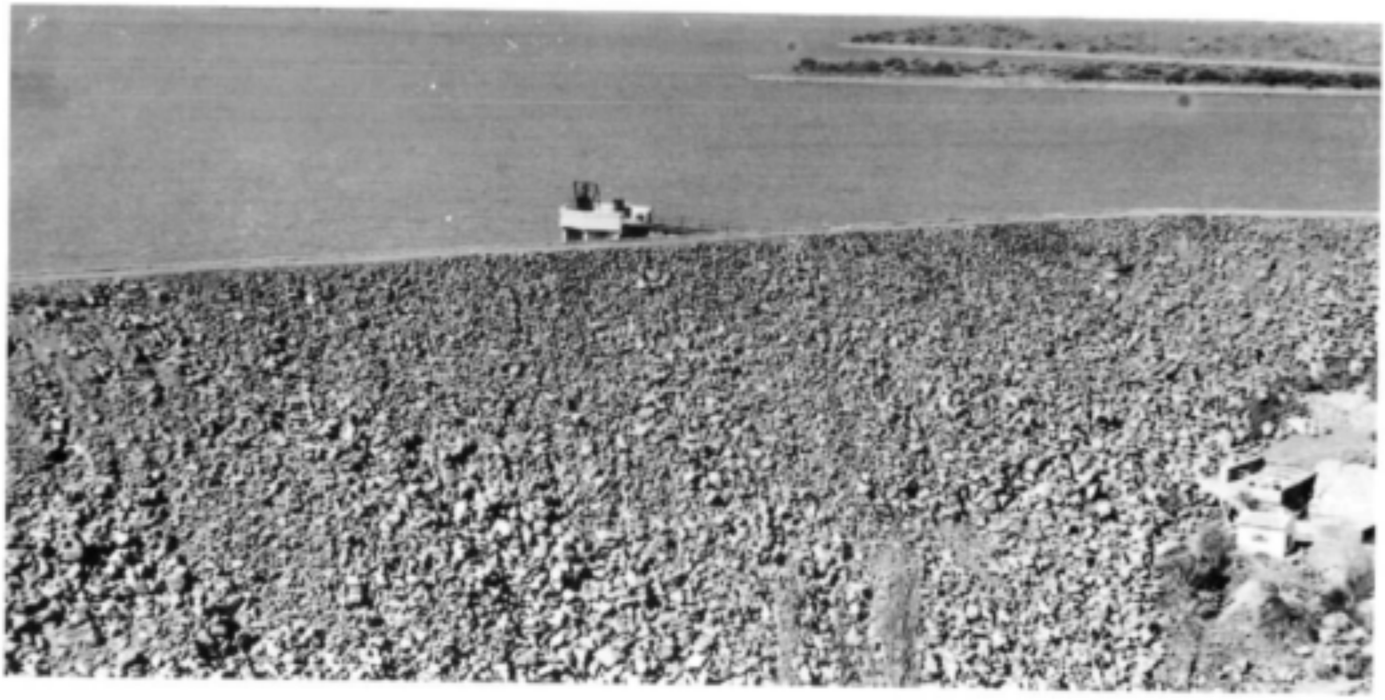


Figure 8.20: Kalkfontein Dam

Figure 8.21: Kommandodrift Dam

b) **Water demand**

Although previously the reservoir was used to support irrigation downstream of Lake Arthur as well, a transfer scheme from the Great Fish River recently constructed now supports most of the irrigation downstream of Lake Arthur. The current area of irrigation supported by Kommandodrift Dam is 705 ha, with a demand of 9,5 million m^3/a.

c) **Yield analysis**

- Current situation

The current demand has a risk of failure of 1 in 10 years. Future sedimentation could, however, cause failure of supply.

- Dredging analysis

Dredging of all the sediment was considered. The yield analysis results are:

Description	FSC (million m^3)	Historical firm yield (million m^3/a)	Probabilistic yield (million m^3/a)			
			1:10 yr	1:20 yr	1:50 yr	1:100 yr
Current situation	57	3,2	10,0	8,8	6,5	5,0
Dredging all sediment (16,5 million m^3)	73,5	5,0	13,2	12,5	9,0	8,0
Yield increase	-	1,8	3,7	3,7	2,5	3,0

d) **Economic analysis (Figure 8.22)**

Although the yield benefit of dredging is relatively small, the assurance of supply will be considerably improved.

In the economic analysis only a NPV for dredging was determined, because the current demand can be supplied from the reservoir at an acceptable assurance. For the initial bulk dredging, 3,3 million m^3/a for 5 years was assumed, as well as annual dredging of 0,51 million m^3/a.

e) **Key results**

Kommandodrift Dam currently supplies the irrigation demand at a risk of failure of 1 in 10 years which is acceptable. Future sedimentation might, however, reduce the yield, and dredging (just enough to supply the demand) should then be considered together with other alternatives.

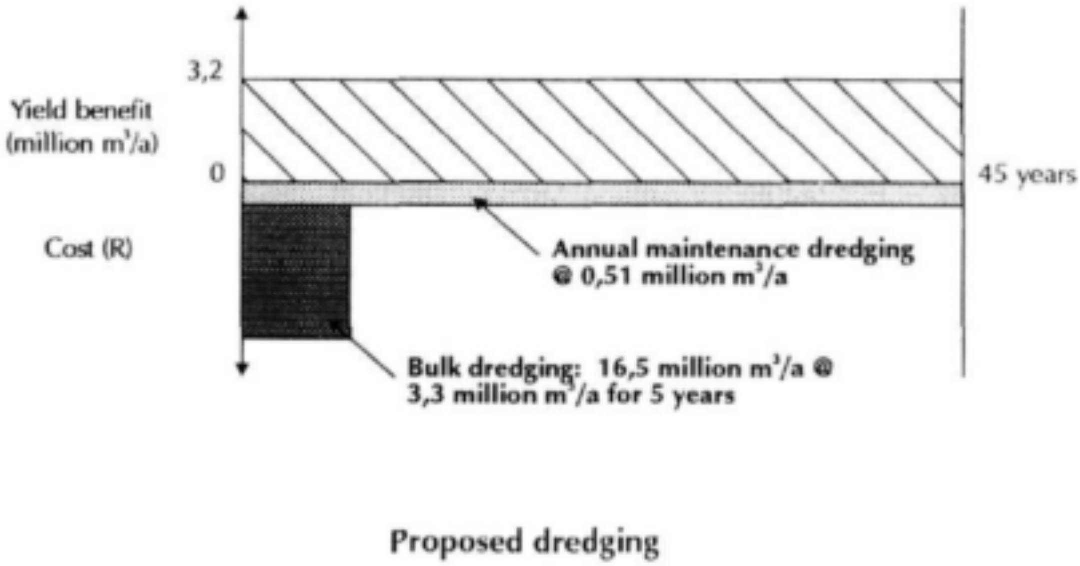


Figure 8.22 Economic dredging analysis: Kommandodrift Dam

8.2.14 Koppies Dam

a) General (Figure 8.23)

Koppies Dam was constructed in 1911, and raised in 1925, 1954 and 1969. The original FSC (raised) of 66 million m^3 has been reduced by 47 % (31 million m^3) to the current FSC of 35 million m^3.

b) Water demand

The current water demand is 18,6 million m^3/a with little future growth. The main use is for irrigation with some domestic use.

c) **Yield analysis**

- <u>Current situation</u>

Yields for the current situation are as follows:

Description	Historical firm yield *(million m³/a)*	Probabilistic yield (1:20 years) (million m³/a)
Do nothing - 1994	12	21
Do nothing - 2023	10	-

The current firm yield (1:20 years) exceeds the demand.

Figure 8.23: Koppies Dam

d) **Key results**

The current yield is sufficient to supply the irrigation at a risk of failure of ± 1 in 30 years.

8.2.15 Krugersdrift Dam

a) **General (Figure 8.24)**

Krugersdrift Dam on the Modder River was constructed in 1970 with an original capacity of 85 million m^3. Sedimentation reduced the capacity by 12 million m^3 (1970 to 1989), 15 % of the original full supply capacity.

Figure 8.24: Krugersdrift Dam

b) **Water demand**

The current irrigation water demand is 41 million m^3/a.

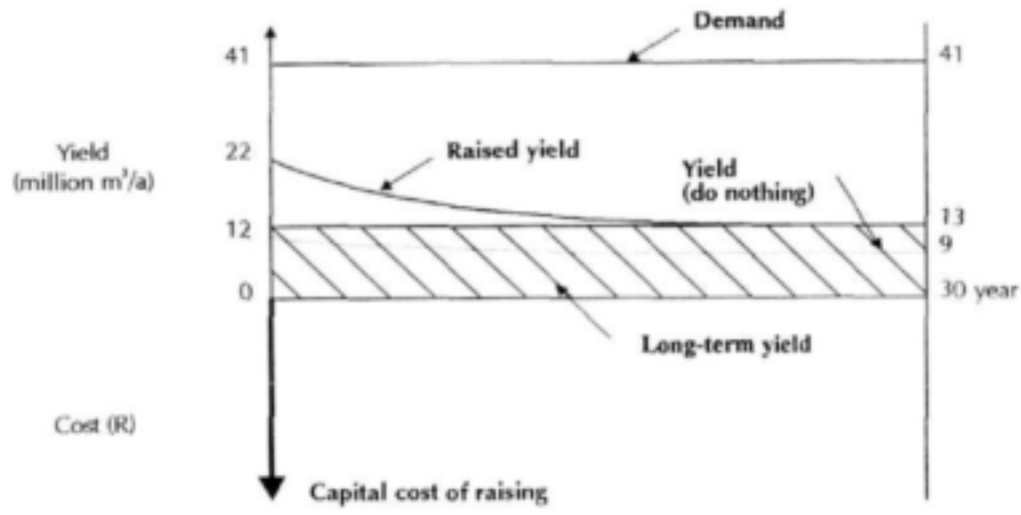
c) **Yield analysis (Figure 8.25)**

- Current situation

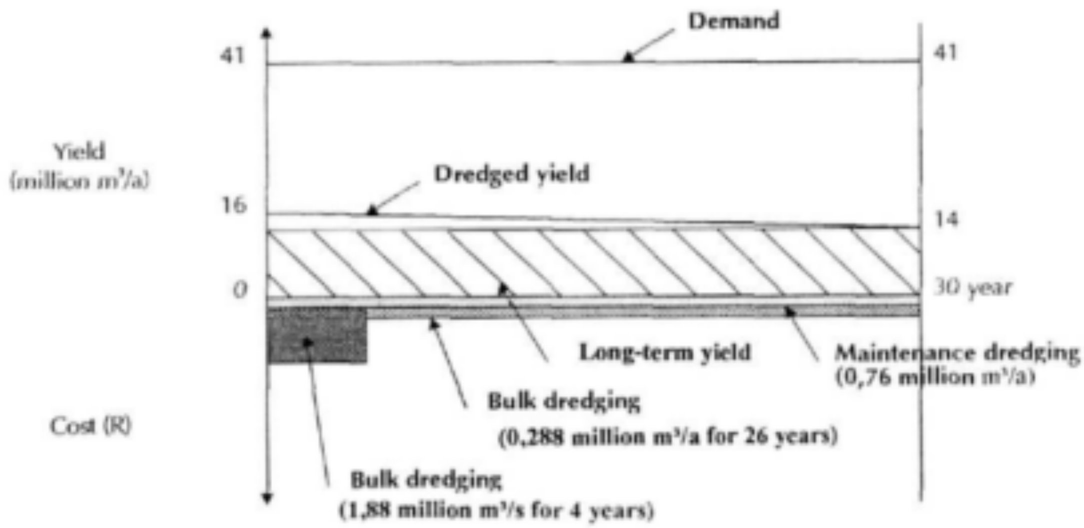
The current historical firm yield equals 12 million m^3/a, while the 1 in 5 year risk of failure firm yield is 24 million m^3/a. It is clear that the water demand exceeds the available yield by far. If nothing is done, future sedimentation will diminish the historical firm yield to 9 million m^3/a.

- Dredging analysis

If all the sediment is dredged the historical firm yield will increase to 16 million m^3/a (1994) and 14 million m^3/a (2023) respectively. For the current situation, dredging of 12 million m^3 of sediment will result in a 4 million m^3/a yield increase.



Dam raising



Dredging

Note: Dredging and raising have approximately the same long-term yield benefit. Bulk dredging is carried out over 30 years to obtain a constant yield benefit for comparison purposes.

Figure 8.25: Economic dredging analysis options: Krugersdrift Dam

- Alternative - raised dam

The dam can be raised and it will result in the following historical firm yields:

1994 : 22 million m^3/a
2023 : 13 million m^3/a

Although the initial benefit of raising the dam is much more than the dredging option, sedimentation and evaporative losses will decrease the yield in 30 years time to less than the dredged yield.

d) **Economic analysis (Figures 8.25 and 8.26)**

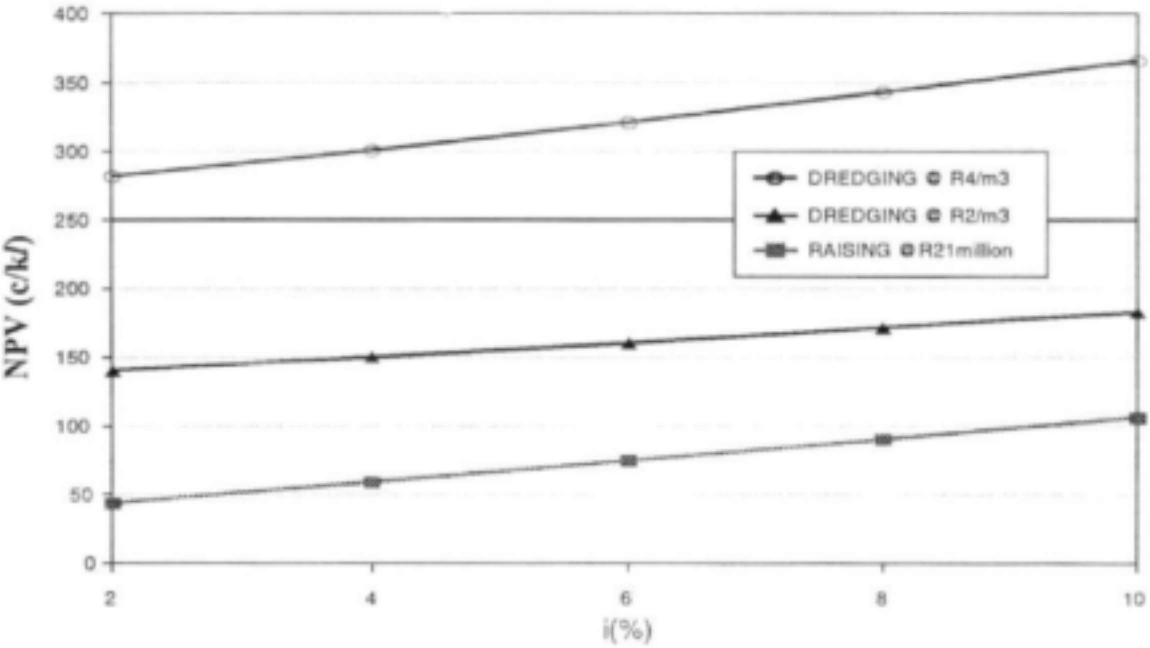
In order to have comparable yield benefits, initial bulk dredging has to be carried out over a 4-year period at a rate of 1,88 million m^3/a, and for the remainder of the analysis period 0,29 million m^3/a has to be excavated. Dredging of 0,76 million m^3/a also has to be carried out to cope with on-going sedimentation. Both raising and dredging of the reservoir have approximately the same long-term yield benefit.

The cost of raising the dam, previously calculated by the DWAF, is in the order of R21 million. Dredging therefore has to be carried out at less than R0,75/m^3 in order to be cheaper than raising the dam.

e) **Key results**

The yield analyses indicate that the initial benefit of raising the dam will in the long-term be reduced to the same order as a firm yield obtained by dredging. The unit cost of dredging of R0,75/m^3 required is very low and would be difficult to achieve.

Something has to be done to augment the Krugersdrift reservoir yield or the irrigation area should be reduced. Currently the irrigators are supplied at a very high risk of failure.



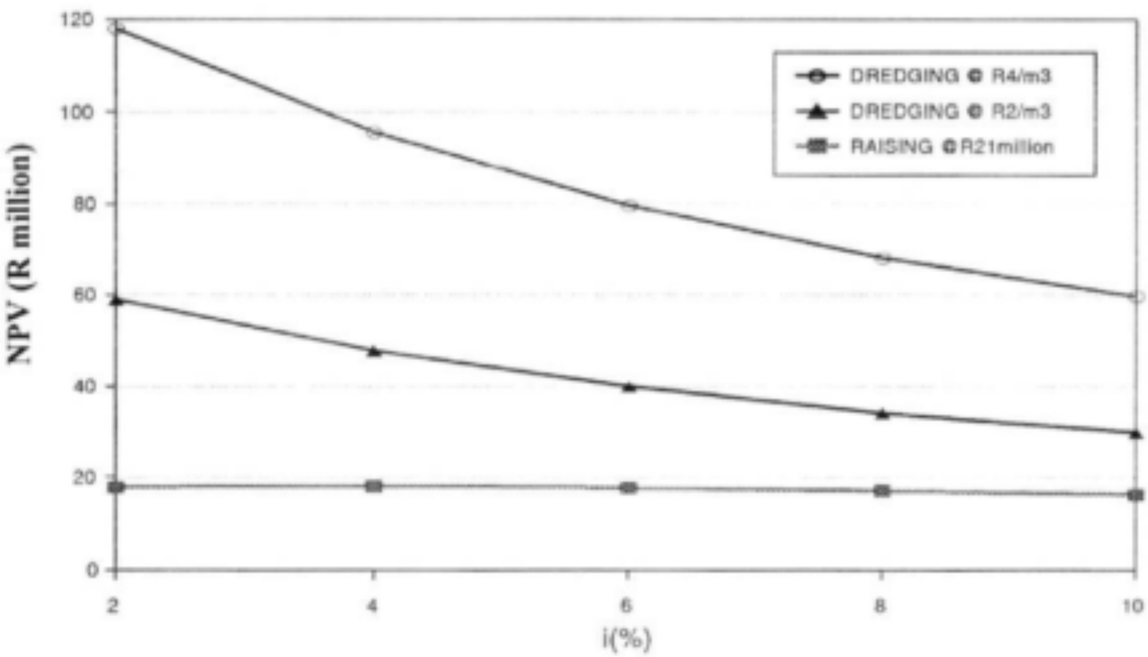


Figure 8.26: Economic dredging analysis: Krugersdrift Dam

8.2.16 Lake Arthur

a) General (Figure 8.27)

Lake Arthur was constructed in 1924. Sedimentation reduced the yield and the dam had to be raised in 1939 and 1945. The original FSC (raised) was 107 million m^3 and the current FSC is only 28 million m^3. In 1956 Kommandodrift Dam was constructed upstream of Lake Arthur and the sedimentation regime of Lake Arthur changed considerably: From 1924 to 1985 1,24 million m^3/a capacity was lost by sedimentation, while from 1958 to 1985 the sedimentation was at only 0,1 million m^3/a.

b) Water demand

Until recently the water demand (irrigation) was 25,65 million m^3/a which was supplied by both Kommandodrift and Lake Arthur. A canal from the Great Fish River now supplies most of Lake Arthur's demand and Kommandodrift Dam only has to support irrigation upstream of Lake Arthur. The current irrigation demand from Lake Arthur therefore is 2,43 million m^3/a (180 ha).

c) Yield analysis

- <u>Current situation</u>

  A yield analysis was carried out for a system with both Kommandodrift and Lake Arthur. Lake Arthur is, however, not supported by Kommandodrift Dam.

Lake Arthur has crest gates which the Dam Safety Office found unsafe to use. Apparently they should be left open and later removed. Yields with and without these gates were determined. When the crest gates are ignored the demand can be supplied at a risk of failure of 1 in 50 years.

Dam

Spillway in flood

Valve for irrigation releases
- First opening of season scoured sediment from the reservoir

Figure 8.27: Lake Arthur

Dredging analysis

Although 79 million m^3 of sediment has been deposited in the reservoir, dredging of all the sediment would create a reservoir too big for the available run-off. Two smaller dredged volumes were therefore considered as shown in the following table:

Description	FSC (million m^3)	Historical firm yield (million m^3/a)	Probabilistic yield (million m^3/a)			
			1:10 yr	1:20 yr	1:50 yr	1:100 yr
Current with crest gates	28	2,5	5,0	4,2	3,5	3,1
Current without crest gates	10	1,8	4,5	3,5	2,5	2,2
Dredge 15 million m^3 (with gates)	43	8,3	11,0	9,3	8,2	7,7
Dredge 7,5 million m^3 (with gates)	35,5	6,5	9,0	7,8	7,0	6,4

Although the two dredging option volumes differ by 100 %, the yields only differ by approximately 20 %. The 7,5 million m^3 of dredging yield benefit is in the order of 4 million m^3/a.

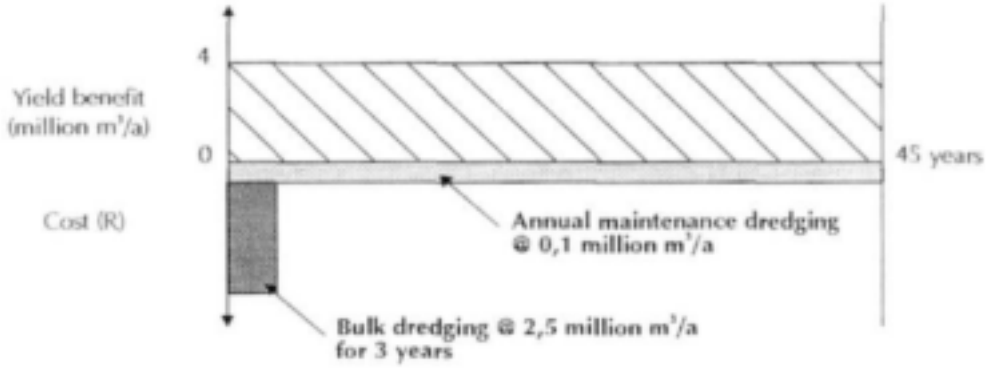
- Alternative

A canal from the Great Fish River was recently constructed at a cost of R7,5 million.

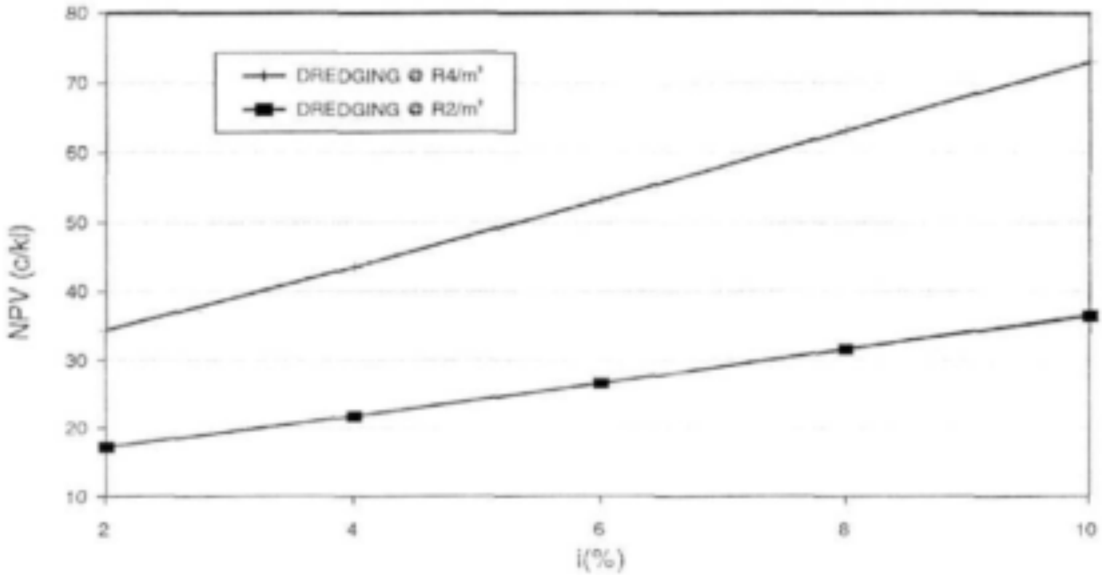
d) **Economic analysis (Figure 8.28)**

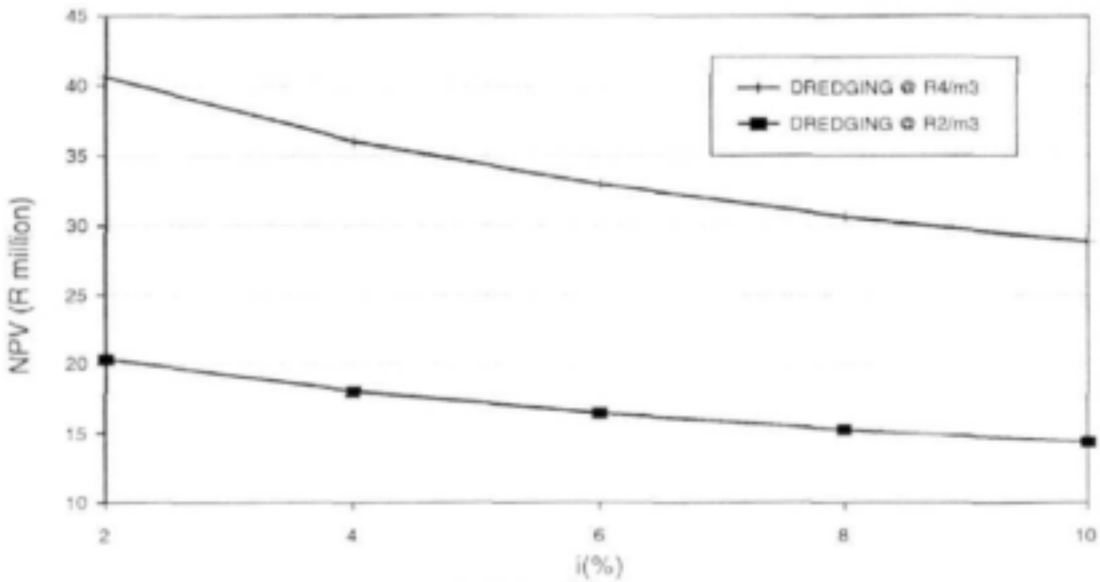
In the economic analysis the cost of dredging cannot be directly compared with the cost of the recently constructed diversion canal because is does not include the historical cost of the Orange-Fish River project and the canal supports a much higher demand than the dredged reservoir can.

Dredging of 2,5 million m^3/a for 3 years and annual dredging of 0,1 million m^3/a were analysed. The NPV of dredging at a dredging cost of R4,00/m^3 is in the order of R0,38/m^3.



Proposed dredging:





NPV Dredging cost

Figure 8.28: Economic dredging analysis: Lake Arthur

c) **Key results**

Although most of the Lake Arthur traditional irrigation supply area is now supplied by transfers from the Great Fish River, dredging of the reservoir was analysed because it is representative of other old reservoirs. The dredging-yield results indicated:

- a relatively small volume of sediment (in this case 7,5 million m^3) can be dredged with almost the same yield benefit as much higher dredging volumes. This is of course site-specific and related to the mean annual run-off, evaporation, reservoir basin shape, etc.

- The construction of Kommandodrift Dam upstream of Lake Arthur reduced the sedimentation considerably, resulting in relatively low NPV dredging cost.

8.2.17 Darlington Dam

a) **General (Figure 8.29)**

Darlington Dam was constructed in 1922 on the Sondags River. The dam was raised twice, in 1935 and 1952. Sedimentation has reduced the original capacity by 140 million m^3 in 68 years (2 million m^3/a). The current FSC is estimated at 185 million m^3.

b) **Water demand**

The current demand is much more than the Darlington reservoir yield and most water is transferred from Gariep Dam to Grassridge to Elandsdrift to De Mistkraal Dam and finally to Darlington Dam by a system of canals and rivers. The water is used mainly for irrigation.

c) **Yield analysis (Figure 8.30)**

- Current situation

  The yield analysis was carried out to see if it is possible to utilize more of the Darlington Dam catchment run-off by dredging it. No transfer of Oranje water was considered.

Figure 8.29: Darlington Dam

- Dredging analysis

Three dredging options were considered: dredging all sediment, dredging 30 million m^3 in the area at the dam, and dredging (arbitrary selection) 30 million m^3 of sediment in a canal extending upstream from the dam. The reason for the canal was to investigate the possibility of using it for sluicing to remove annual sedimentation. The yield analysis results are:

Description	FSC (million m^3)	Historical firm yield (million m^3/a)	Probabilistic yield (million m^3/a)				
			1:5 yr	1:10 yr	1:20 yr	1:50 yr	1:100 yr
Current situation	185	32	60	55	52	42	37
Dredge all sediment	328	52	-	-	-	-	-
Dredge 30 million m^3 at dam	215	40	-	-	-	-	-
Dredge 30 million m^3 in canal	215	41	70	65	60	52	45

The yield benefit obtainable by dredging is 20 million m^3/a. If 30 million m^3 is dredged, the yield benefit would be in the order of 10 million m^3/a which is actually a high yield increase for the volume of sediment removed. This is because evaporative losses are minimized during critical periods by dredging.

- Alternative source

In the case of Darlington Dam, water is transferred from Gariep Dam and recent DWAF analysis indicated that the Orange system has enough water at least until the completion of phase 1B of the Lesotho Highlands Scheme to supply the Eastern Cape.

d) **Economic analysis**

Bulk dredging of 6 million m^3/a for 5 years, and annual dredging of 2 million m^3/a were considered in the economic analysis. **Figure 8.30** shows that if dredging (30 million m^3) is carried out at a unit cost of R2,00/m^3, a net present value of R0,65/kℓ is obtained which should be compared to possible future alternative schemes.

e) **Key results**

Darlington Dam currently does not require additional yield since water is augmented from the Orange River. A dredging-yield analysis indicated that up to 20 million m^3/a could be gained by removal of the sediment.

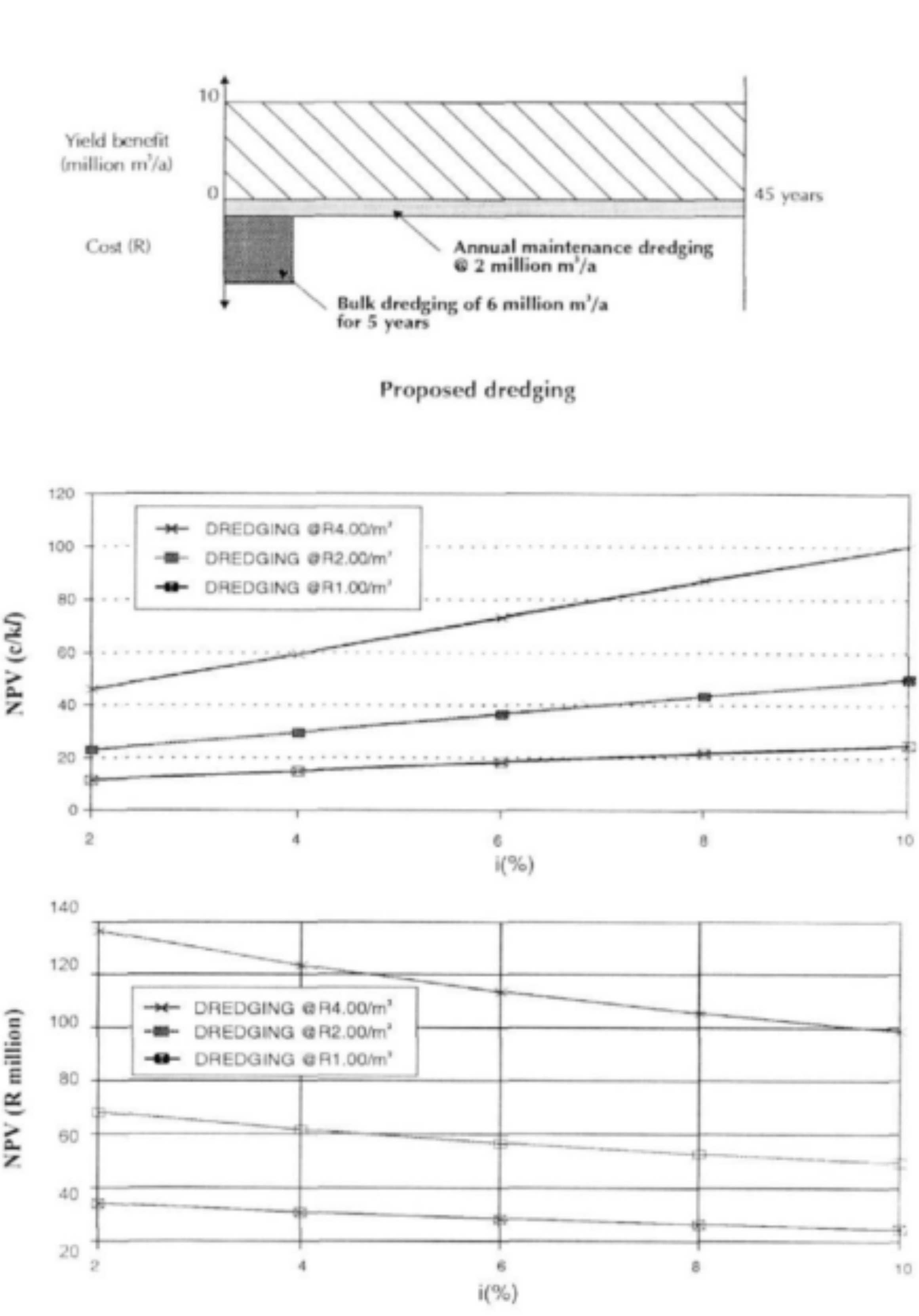


Figure 8.30: Economic dredging analysis: Darlington Dam

8.2.18 Pongolapoort Dam

a) General (Figure 8.31)

Pongolapoort Dam, the third largest dam in South Africa, was constructed in 1973 with an original FSC of 2 500 million m³. By 1984 (last survey after Damoina flood) sedimentation had however reduced the capacity by 56 million m³.

Figure 8.31: Pongolapoort Dam

b) Water demand

The current water demands are:

User	Demand (million m³/a)
Mozambique	64
Swaziland	4,5
Domestic	31
Irrigation	410
Environment	± 250

c) **Yield analysis**

- Current situation

The yield of the irrigation water use was analysed. A physical constraint in the system is that the irrigation canal is at a relatively high level, at a minimum operating level of close to 250 million m^3 storage.

The yield analysis indicated that the current irrigation demand can be supplied at a high assurance of a 1 in 50 year risk of failure. The system and hydrology used in the analysis were obtained from the DWAF (Stassen, 1993).

- Dredging analysis

Due to the high level of the irrigation canal, dredging of sediment in the live storage (for irrigation), will entail 39 million m^3 of the 56 million m^3 (1984 survey) sediment in the reservoir.

The irrigation yield results are:

Description	FSC (million m^3)	Historical firm yield (million m^3/a)	Probabilistic firm yield (million m^3/a)			
			1:10 yr	1:20 yr	1:50 yr	1:100 yr
Current situation	2 445	351	490	450	410	382
Dredging of 39 million m^3	2 484	355	490	450	410	390
Yield benefit	-	4	-*	-*	-*	8

* negligible

The dredging yield benefit is very small.

d) **Economic analysis**

No economic analysis was carried out because the current irrigation demand can be supplied at a high assurance.

e) **Key results**

Dredging of Pongolapoort Dam cannot be considered due to the relatively small yield benefit. This small yield benefit can be ascribed to:

- the high level of the irrigation canal and most of the sediment being in the upper live storage zone

- the reservoir has only experienced a small percentage (2,2 %) (1984) capacity reduction due to sedimentation.

8.2.19 Prinsrivier Dam (Ladismith)

a) General (Figure 8.32)

Prinsrivier Dam was constructed in 1916 with an original full supply capacity of 4,34 million m^3 to support irrigation development of 361 ha. Sedimentation of the reservoir resulted in loss of the required yield and the dam had to be raised twice, in 1962 and 1985, to improve the situation. Major storm events contributed most to the loss of capacity and it was specifically the 1981 flood which reduced the capacity by over 1 million m^3. Before the 1981 flood the yield from the dam was less than the required irrigation demand, and the situation was even worse after the flood. The raising of the dam in 1985 did not solve the problem completely, because the current capacity of ±2,3 million m^3 is less than what is required and evaporation losses are high due to the raised dam basin characteristics. Although the raising of the dam (1985) was partially subsidized by Government, the raised capacity was limited by what the irrigators could afford to pay.

The annual sedimentation is estimated at 0,073 million m^3/a and it will not be long before the current reduced irrigation area of 180 ha will have to be reduced even further in order to farm at an acceptable assurance of water supply.

Figure 8.32: Prinsrivier Dam

b) **Water demand**

Currently lucerne (for milk production), citrus and vineyards are irrigated. The historical water releases and a theoretical demand based on crop requirements and water losses were analysed for the 180 ha currently irrigated:

Description	Demand (million m^3/a)
Crop requirement and losses	2,40
Recorded releases (1985 - 1991)	1,54
Recorded releases (1989 - 1991)	1,86
Recorded releases - DWAF complete record	1,54

The irrigation season is from September to April with little irrigation in February.

The actual current water demand is between 1,54 and 1,9 million m^3/a.

c) **Yield analysis**

- Current situation

A long recorded inflow record is available: 1916 to 1989. Yields for the current capacity, dredged dams and a raised dam were analysed. The current situation yield proved to be insufficient: 0,75 million m^3/a at a risk of failure of 1 in 5 years.

- Dredging analysis

If all the sediment is dredged, the resultant full supply capacity would be 7,6 million m^3, which would mean a capacity of twice the mean annual run-off. In semi-arid climates, capacity - MAR ratios of 2:1 are acceptable, but with larger capacities the incremental yield benefit is diminishing. The yields for different dredged capacities were therefore analysed in order to obtain the required demand. For irrigation of mostly lucerne a 1 in 5 year risk of failure of supply should be acceptable, especially in this case where some of the water can be supplied by groundwater under drought conditions. Two dredged volumes are indicated due to the uncertainty as to the actual water demand. The yield analysis results are indicated in **Table 8.2**.

- Alternative - raise dam

Yield analysis results indicated that evaporative losses dominate with further raising of the dam and it is not possible to obtain the required demand. New storage upstream or downstream of the existing dam or combinations with the existing or raised dam were also investigated, but all resulted in available yields less than the required, or what can be obtained by dredging. A raised dam, with a raising of 12 m, was used in the analysis, because this seems to give the optimum yield benefit.

Table 8.2: Prinsrivier Dam yield analysis

Description	FSC (million m^3)	Water yield (million m^3/a)	
		Historical analysis	Probabilistic 1:5 yr
Current situation	2,30	0,32	0,75
a) Dredge 3,53 million m^3 sediment	5,83	1,24	1,70
b) Dredge 1,20 million m^3 sediment	3,50	1,12	1,58
Raise dam by 12 m	7,00	0,70	1,27

d) **Economic analysis (Figure 8.33)**

Two dredging options were considered:

(a) bulk dredging of 0,43 million m^3/a for 8 years and annual maintenance dredging of 0,073 million m^3/a; and

(b) bulk dredging of 0,32 million m^3/a for 4 years and annual maintenance dredging of 0,073 million m^3/a.

Relatively long bulk dredging periods were used because water availability limits annual dredging volumes.

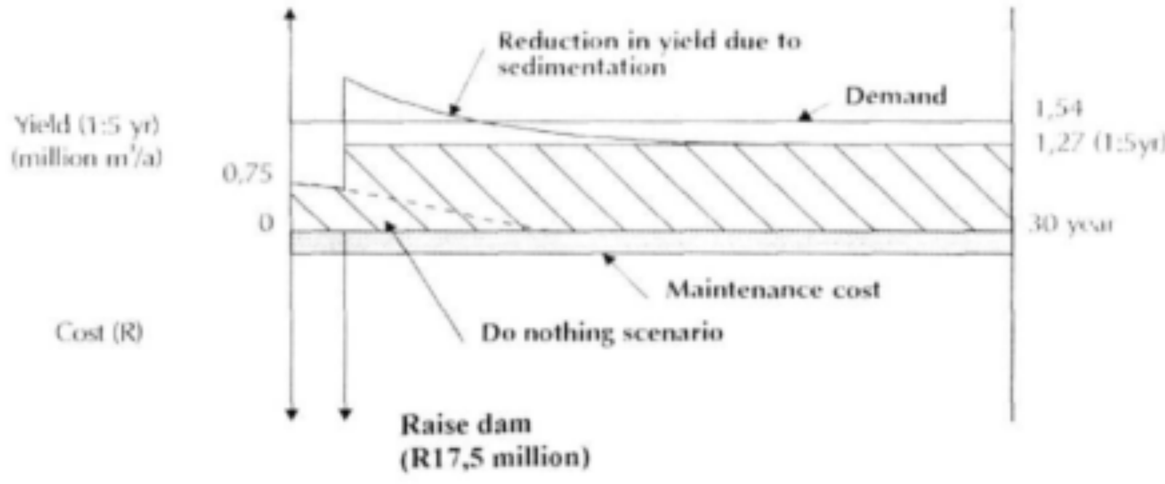
Although the raising of the dam cannot give the same yield as either of the dredging options, the raising unit cost is best compared with option (b) dredging. The raised dam cost is estimated at R17,5 million. The cost analysis results are indicated in **Figure 8.34**. Dredging unit costs as high as R7,00/m^3 (option B) of sediment excavated are cheaper than raising the dam! If dredging option A is carried out, the required irrigation demand will be supplied, and at a dredging unit cost of approximately R5,50/m^3 it will still be less expensive than the unit cost of raising the dam.

c) **Key results**

The yield results for Prinsrivier Dam, illustrate the severity of evaporative losses from a reservoir basin of which the capacity has been considerably reduced through sedimentation. Further raisings or new dams cannot yield the required irrigation demand and it would seem that dredging is the only alternative available to provide a long-term storage capacity. Even if the dam is raised a third time, it would be at a higher unit cost than that which could possibly be achieved by dredging. Dredging has the advantage of creating a large increase in capacity by excavating through 15 m deep sediment in the main basin, while keeping the evaporation area as small as possible during hydrologically critical periods.

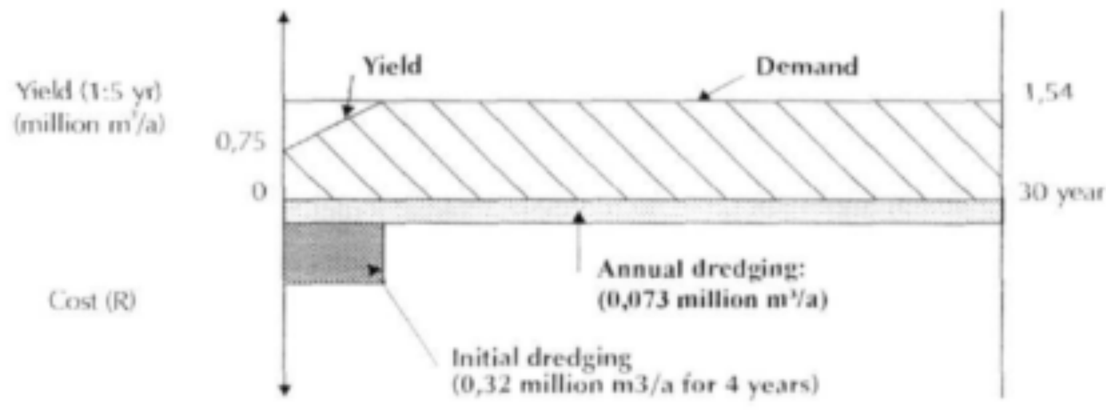
Due to the favourable dredging unit cost situation at Prinsrivier Dam, this dam was selected as one of three for which a detailed dredging cost analysis was carried out, taking into account all boundary conditions. Of specific importance in this case is disposal of the sediment which has to be downstream of the dam.

Although it might be possible to prove that dredging is cheaper than raising the dam, it will still involve millions of rand which in this case will have to be paid by 8 irrigators. Although the writing-off of 8 irrigation farms and the dam, canal and other infrastructure is an option, as many as 50 people who have been dependent on the irrigation for generations, will be affected. The Prinsrivier irrigation scheme is perhaps insignificantly small in the South African context, but there are many other small reservoirs which have suffered the same fate with associated financial, socio-economical and other implications.



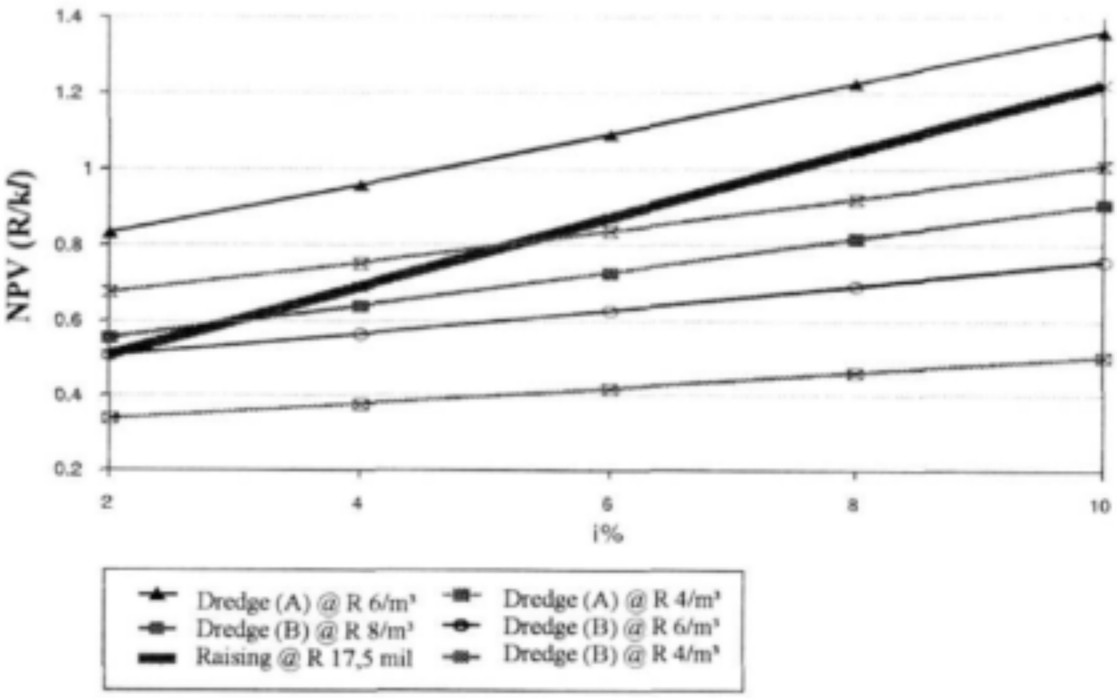
Raising the dam

Note: In this case the yield benefits are not the same because the demand cannot be supplied by a raised dam or alternative storage.



Dredging option B

Figure 8.33: Economic dredging analysis options: Prinsrivier Dam



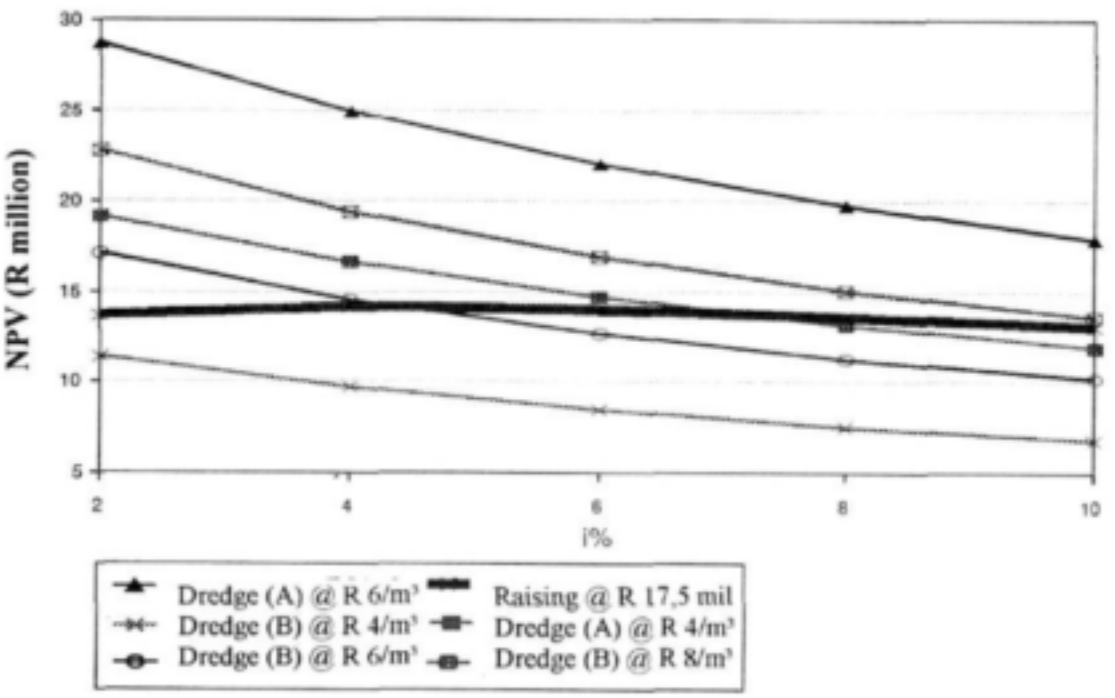


Figure 8.34: Economic dredging analysis: Prinsrivier Dam

8.2.20 Vaal Dam

a) General (Figure 8.35)

Vaal Dam is a very important component in the supply of water for domestic, industrial and irrigation use in the Gauteng Province, as well as along the Vaal River. The dam was constructed in 1936 and due to the ever-increasing demand, had to be raised in 1952, 1956 and 1985. The current FSC is 2 577 million m^3. The Vaal System has been augmented for many years by pumped transfers from mainly KwaZulu-Natal, and recently phase 1A of the Lesotho Highlands Water Project is also augmenting the system.

It is estimated that 230 million m^3 (9 % of the "original" (raised) capacity) has been lost due to sedimentation.

b) Water demand

The current system water demand exceeds 2 000 million m^3/a.

c) Yield analysis

- Current situation

  Because the incremental yield benefit of dredging is of interest, only the Vaal Dam subsystem was used in the yield analysis. At present, the Rand Water Board minimum operating level of Vaal Dam has to be at a storage above 10 % of the FSC, which results in a historical firm yield of 933 million m^3/a for the current development level.

- Dredging analysis

  If the volume below the minimum operating level (10 % FSC) is assumed to be dead storage, it can be used for disposal of sediment excavated in the reservoir live storage. If all the sediment is dredged from the live storage, 174 million m^3 of sediment has to be excavated (option A).

Figure 8.35: Vaal Dam

The actual original dead storage of the reservoir is, however, 58 million m^3. Disposal of 39 million m^3 of sediment in the dead storage zone and the rest just below the full supply level (172 million m^3), can be considered. Although disposal above full supply level is possible, land ownership problems will be experienced especially where recreational development around the reservoir has taken place. With option B a total volume of 211 million m^3 has to be dredged.

The dredging yield results are as follows:

Description	**Historic firm yield (million m^3/a)**	**Yield increase (million m^3)**
Current situation	933	-
Dredging option A	968	+ 35
Dredging option B	954	+ 21

- <u>Alternative - Lesotho Highlands water</u>

The cost of dredging has to be compared to the unit cost of water imported from the Lesotho Highlands, which is currently (1994) R0,46/m^3 (DWAF) for the phase 1A and 1B scheme. Future schemes will probably be at an even higher unit cost than the Lesotho Highlands water.

d) **Economic analysis**

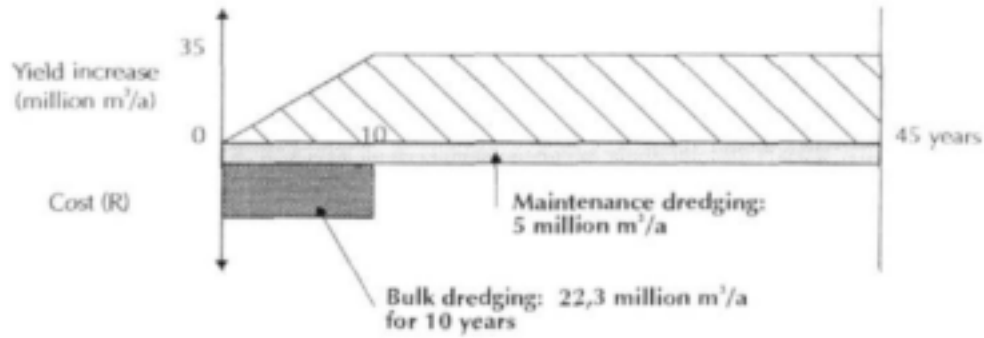
The initial bulk dredging of option A dredging is proposed to be carried out over 10 years at a rate of 22,4 million m^3/a which includes the annual sedimentation dredging of 5 million m^3.

If dredging is compared to the Lesotho water cost **(Figure 8.36)**, it is clear that if dredging could be carried out at a unit cost of less than R1,30/m^3 of sediment removed, the increase in yield, although relatively small, will be cheaper than Lesotho imported water.

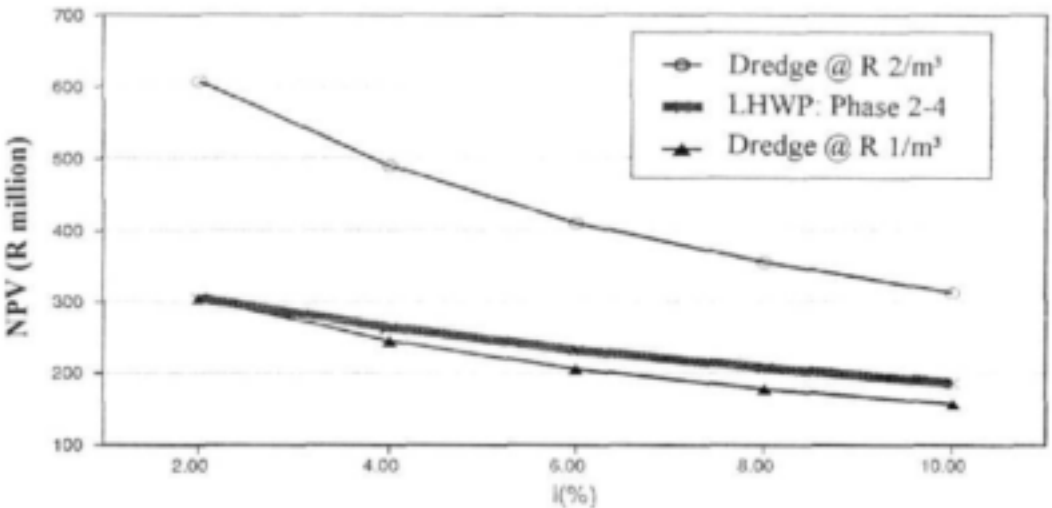
e) **Key results**

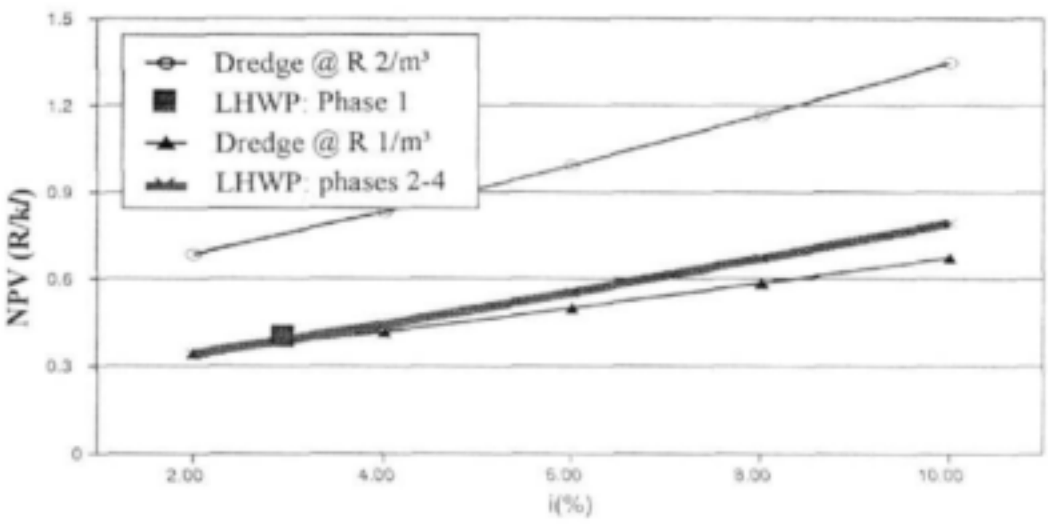
Dredging in Vaal Dam could be carried out by considering the current minimum operating level as dead storage, and by disposal in this zone dredging unit costs could be reduced (no disposal cost) considerably. In practice, however, the 10 % dead storage zone could be utilized by river releases and pumping to purification plants downstream of the dam during drought conditions, and it is therefore doubtful whether it will be considered as dead storage.

Even if disposal could be in the dead storage zone, (option A), pumping distances could become excessively long with related high dredging cost. Nevertheless, the increase in yield of 35 million m^3 (option A), is quite high and with large-scale dredging operation, a unit dredging cost of close to R1,30/m^3 could possibly be achieved. It should also be noted that by optimising the dredged volume-yield benefit, much less sediment could be dredged for almost the same yield increase.



Dredging





Dredging versus Lesotho Highlands water cost

Figure 8.36: Economic dredging analysis: Vaal Dam

8.2.21 Vaalharts weir

a) General (Figure 8.37)

The Vaalharts weir was constructed in 1938, and raised once in 1967. Currently the weir is used as diversion only and it has very little natural run-off entering the reservoir downstream of Bloemhof Dam. Sedimentation has reduced the capacity by nearly 42 million m^3, and the current capacity is in the order of 48,7 million m^3 (1991 survey).

Because the reservoir is still large in relation to its incremental catchment run-off, dredging will not have a high yield benefit. The Bloemhof and Vaal dams upstream of the Vaalharts weir also utilise their run-off optimally and water has to be imported to supply the current demands of the Vaal River system. An economic-dredging analysis was therefore not carried out for the Vaalharts weir.

Figure 8.37: Vaalharts weir

8.2.22 VanRyneveldspas Dam

a) General (Figures 8.38 and 8.39)

VanRyneveldspas Dam was constructed in 1925 to supply Graaff-Reinet, but mainly to support irrigation. The reservoir has lost 34 million m^3 of its original capacity of 76 million m^3 due to sedimentation, at an average rate of 0,55 million m^3/a.

b) Water demand

Based on historical supplies, the Graaff-Reinet water demand is 4 million m^3/a. During the recent drought in the Eastern Cape the dam was empty and groundwater had to be used. The groundwater resource has a (developed) yield of 45 ℓ/s continuously. The annual water quota use of water by Graaff-Reinet is 3,285 million m^3.

The irrigation demand is approximately 13,5 million m^3/a for ±1 000 ha irrigated. If the total irrigation area is developed (± 3 000 ha), the demand would be in the order of 40 million m^3/a. Due to many years of drought and low assurance of supply, irrigation has become a secondary income to farmers in the area. The actual irrigated area and demand vary according to rainfall, river flow, water level in the reservoir, and when in the season a decision on irrigation use is made.

c) Yield analysis

- <u>Current situation</u>

The reservoir is operated by releasing irrigation and domestic water until a storage volume of 3,337 million m^3 is reached. If the water level drops below the level, only Graaff-Reinet has the right to use the water and irrigation releases are discontinued.

The yield analysis was first carried out without considering a minimum storage for domestic use.

Figure 8.38: VanRyneveldspas Dam: view from right bank

Figure 8.39: VanRyneveldspas Dam

- Dredging analysis

Two dredging options were considered - excavation of all the sediment (34 million m^3) and dredging of 16 million m^3 of sediment.

The yield analyses results are as follows (no allowance for minimum storage for domestic use):

Description	FSC (million m^3)	Historical firm yield (million m^3/a)	Probabilistic yield (million m^3/a)			
			1:10 yr	1:20 yr	1:50 yr	1:100 yr
Current 1994, no MOL	42,0	2,0	11,0	8,5	4,7	3,5
Do nothing 2023, no MOL	36,0	1,9	-	-		
Dredge all sediment	76,0	7,0	12,5	12,5	9,0	7,0
Dredge 500 m wide strip	58,0	6,0	13,0	12,0	8,5	6,5

Dredging of 16 million m^3 of sediment, gives almost the same yield as excavating all sediment from the reservoir. The yield benefit for irrigation at an assurance of supply of say 1 in 10 years, is only 2 to 4 million m^3/a. Dredging will therefore not significantly improve the risk of failure in yield to the irrigators. The risk of failure at high assurance (1 in 50 years) is decreased significantly, however. The yield benefit of dredging doubles the yield at a risk of failure of 1 in 50 years. It would therefore seem that dredging could be meaningful if the dredged volume is mainly used for domestic supply.

Another system was therefore analysed with a 6,5 million m^3 of storage reserved for domestic use and 16 million m^3 of sediment removed, with yields calculated specifically for Graaff-Reinet:

Description	FSC (million m^3)	Historical firm yield (million m^3/a)	Probabilistic yield (million m^3/a)			
			1:10 yr	1:20 yr	1:50 yr	1:100 yr
- Current with 3,3 million m^3 reserved storage	42,0	-	2,2	1,7	1,0	0,6
- Dredged with 6,5 million m^3 reserved storage	58,0	-	6,0	5,4	3,0	2,4

The current situation shows clearly that only about 1,0 million m^3/a can be supplied from the reservoir at a risk of failure of 1 in 50 years which is realistic for domestic supply. By dredging, the domestic demand of 4 million m^3/a can be supplied at a reasonable risk of failure of 1 in 30 years and any shortfalls can be supplied by groundwater.

- Alternative - groundwater

The current groundwater sources have to be developed further to obtain a yield comparable to the dredging option.

d) **Economic analysis (Figures 8.40 and 8.41)**

For the initial bulk dredging 4 million m^3/a has to be removed for 4 years with annual dredging of 0,58 million m^3.

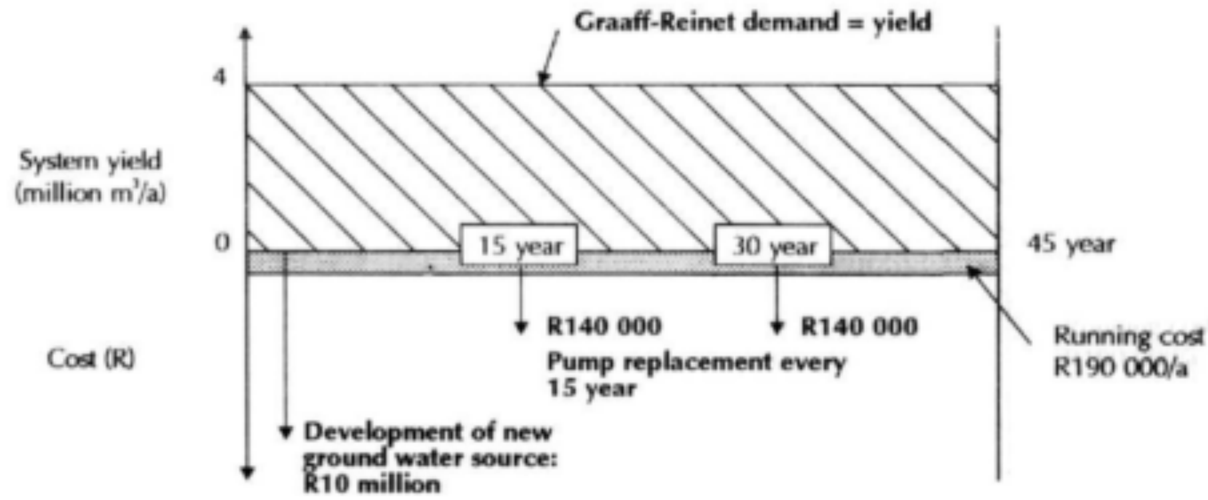
It is estimated that the further development of the groundwater source will be in the order of R10 million m^3 with running costs of R190 000 m^3/a.

e) **Key results**

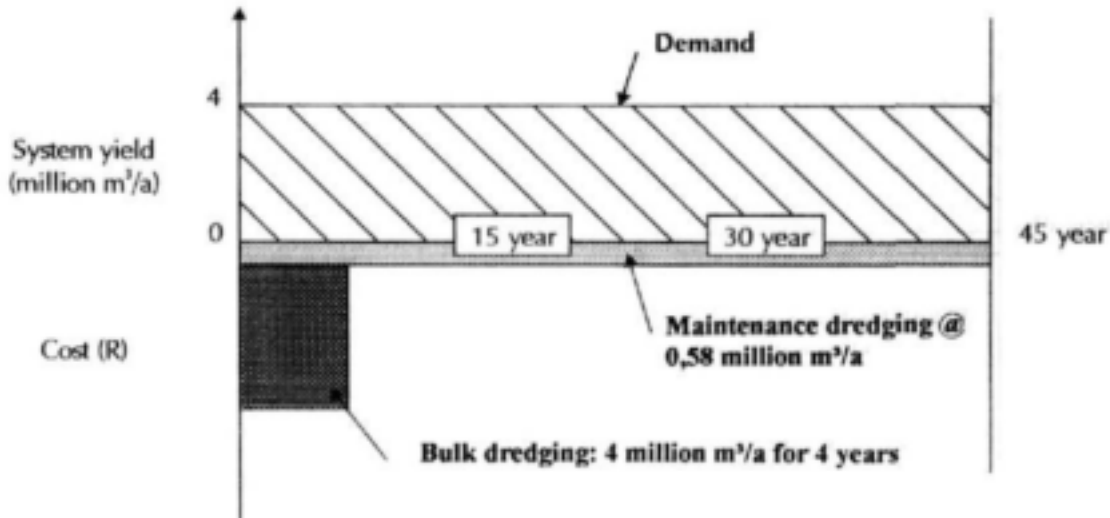
Dredging of VanRyneveldspas Dam can be carried out and if sufficient minimum storage is reserved for Graaff-Reinet use, the town will be supplied at a high assurance, while the irrigation supply will not be affected. The yield results indicate that water users such as domestic, who require a high assurance, will benefit most from the dredging of VanRyneveldspas Dam.

The further development of groundwater as alternative source seems at this stage to be economically more viable than dredging, but the following should be considered:

- The dredged volume of 16 million m^3 could be further reduced.
- The reserved storage of 6,5 million m^3 for domestic use should be optimized.
- It is uncertain at what assurance of supply the groundwater can be utilized.
- An alternative to groundwater development is transfer of water from Somerset East. This option has previously been investigated, and its capital cost will definitely exceed the cost of developing groundwater.

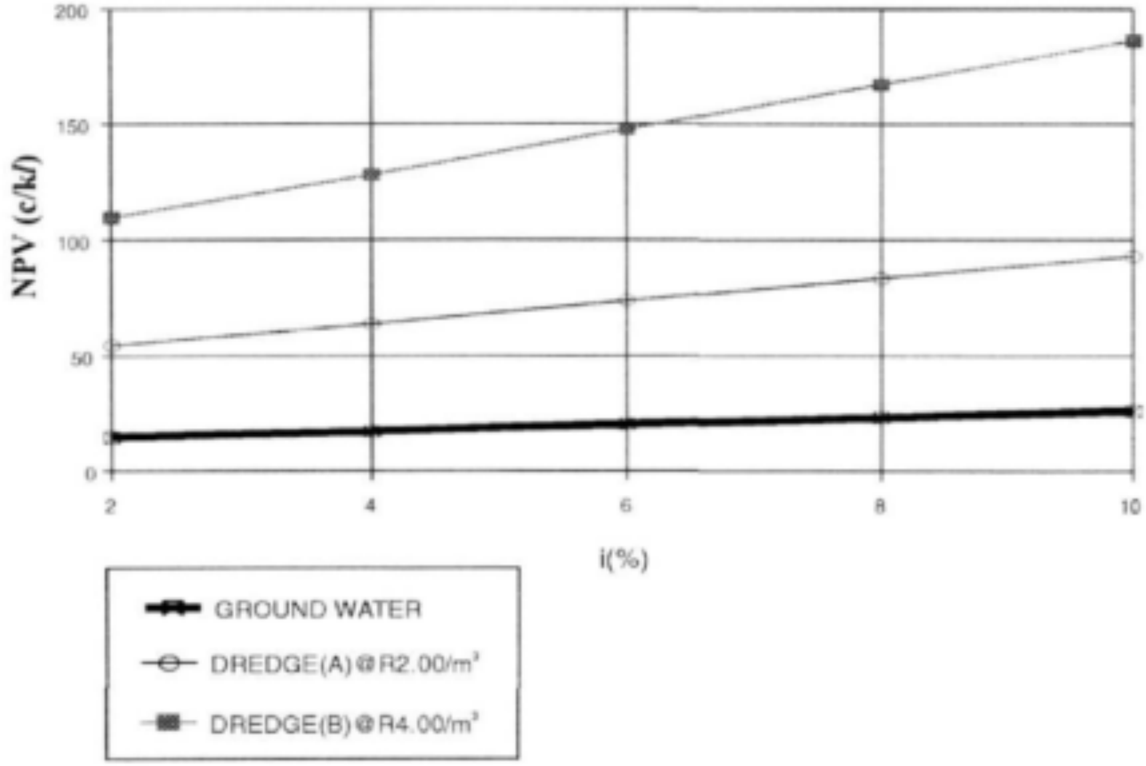


No dredging: Reservoir and Groundwater



Dredging

Figure 8.40: Economic dredging analysis options: VanRyneveldspas Dam



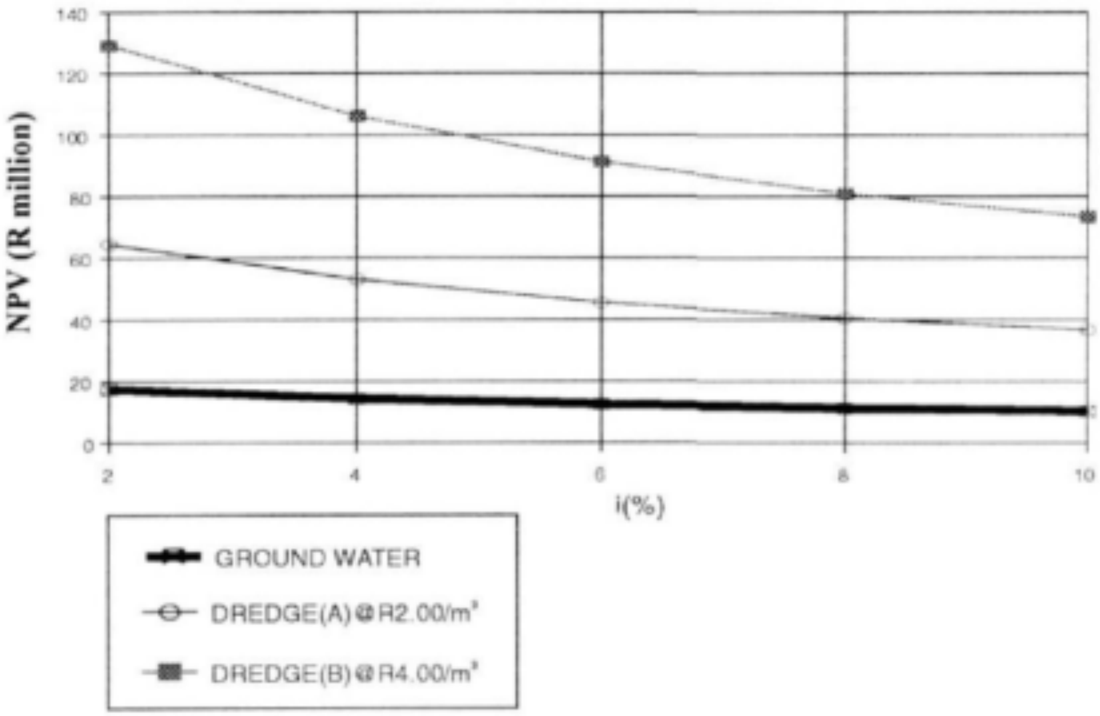


Figure 8.41: Economic dredging analysis: VanRyneveldspas Dam

8.2.23 Welbedacht Dam (Wepener)

a) General (Figure 8.42)

Welbedacht Dam was constructed on the Caledon River in 1973, as main water source of Bloemfontein, and later of Botshabelo. Most of its original full supply capacity of 113,8 million m^3 was, however, quickly lost due to sedimentation and in 1991 only 17 million m^3 of storage volume remained. A change of operational procedures by flushing the reservoir, however, improved the situation slightly to give a current (1998) full supply capacity of approximately 14 million m^3 (88 % of original capacity lost due to sedimentation).

A sedimentation analysis carried out during the 1980s to determine the long-term equilibrium capacity of the reservoir (Rooseboom, 1986), indicated that at best a 10 million m^3 of capacity will remain if flushing is practised.

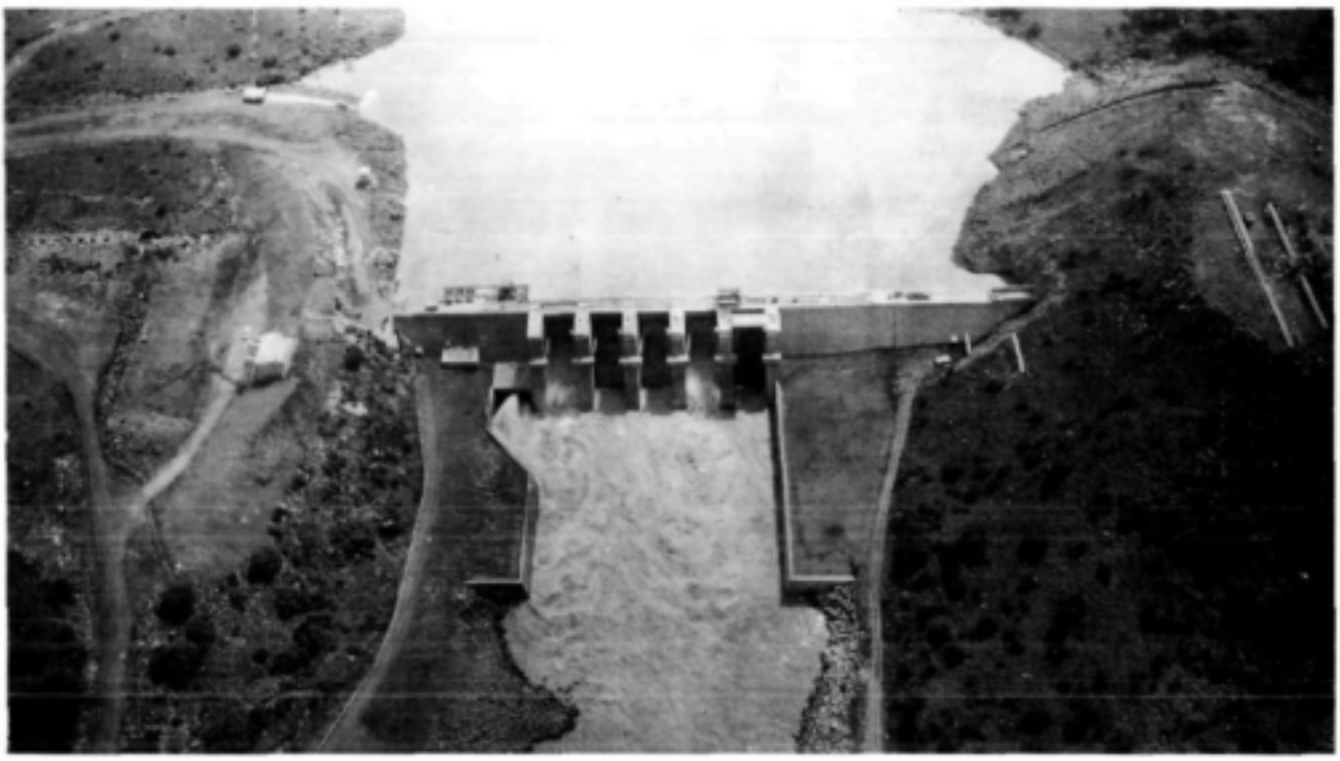


Figure 8.42: Welbedacht Dam

b) **Water demand**

The water demands of the Greater Bloemfontein system were obtained from a recent DWAF water resources study. The current (1994) Bloemfontein demand is 42 million m^3/a while in 30 years' time it is estimated to be 97 million m^3/a.

In 1989, Knelpoort Dam was constructed on the Rietspruit, a tributary of the Caledon River, and a pump station in the Welbedacht Dam basin. This was done to create additional storage with which the Welbedacht Dam yield could be supplemented, and it provides for off-channel storage and relatively low sedimentation rates, although at high pumping cost. Knelpoort Dam also forms part of a pump transfer scheme to the Modder River, the so-called Novo transfer scheme, which augments the Welbedacht Dam to Bloemfontein supply. **(Figure 8.43)**

c) **Yield analysis**

- Current situation

  Previous analyses by DWAF have indicated that the bottleneck in the Bloemfontein supply system is the Welbedacht Dam to Bloemfontein supply pipeline and not the diminishing water yield of Welbedacht Dam caused by sedimentation. In fact, the analyses indicate that no pumping to Knelpoort Dam is actually required because the water demands can be readily supplied (at an acceptable assurance). The historical firm yield for the current development level is 51 million m^3/a, which is more than the current demand of 42 million m^3/a.

- Future, year 2023 situation

  In 30 years' time, the Novo transfer scheme will have been commissioned. It would be possible to supply the future demand by doing nothing to the sedimentation in Welbedacht Dam, and rather supplementing through the Novo transfer scheme, than increasing the existing Bloemfontein pipeline capacity which will be more expensive than the Novo scheme. The current Bloemfontein pipeline capacity used in the analysis is 150 Mℓ/d.

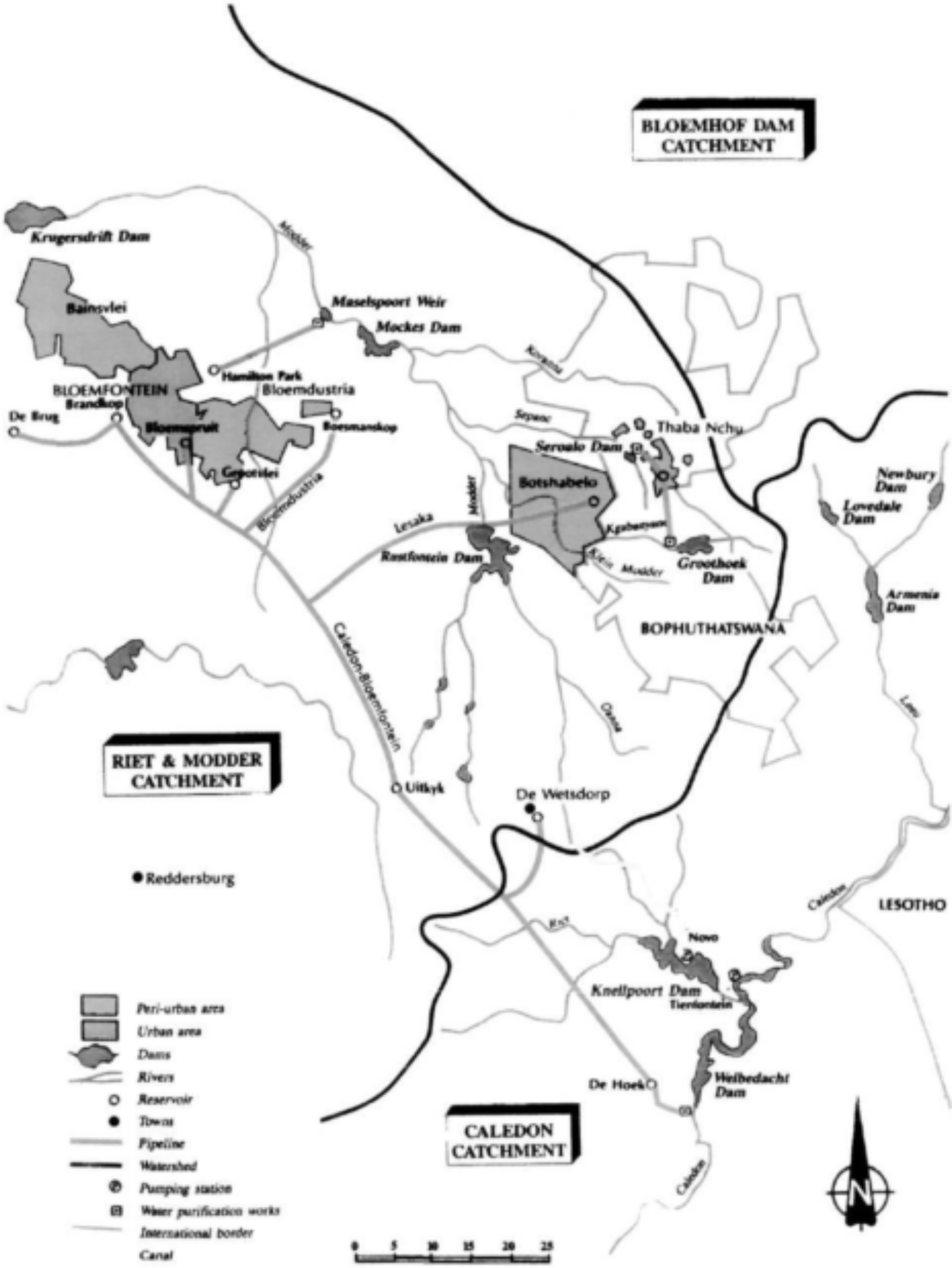


Figure 8.43: Layout of the Welbedacht-Novo-Bloemfontein scheme

- Dredging analysis

If this analysis was carried out before the construction of the Knelpoort Dam transfer scheme, dredging of Welbedacht Dam and increased pipe capacity from Welbedacht Dam to Bloemfontein could be compared in terms of cost to the Tienfontein-Knelpoort Dam - Novo transfer scheme. With the Novo scheme now phased for commissioning by 1998 (or later), dredging of Welbedacht reservoir can mainly be evaluated in terms of the Tienfontein pumping cost reduction it will yield. The ideal dredged Welbedacht reservoir capacity should therefore be determined to minimize Knelpoort Dam augmentation to Welbedacht Dam. The Welbedacht reservoir purification plant and Bloemfontein pipeline will then be run at maximum capacity by utilizing the dredged Welbedacht Dam yield.

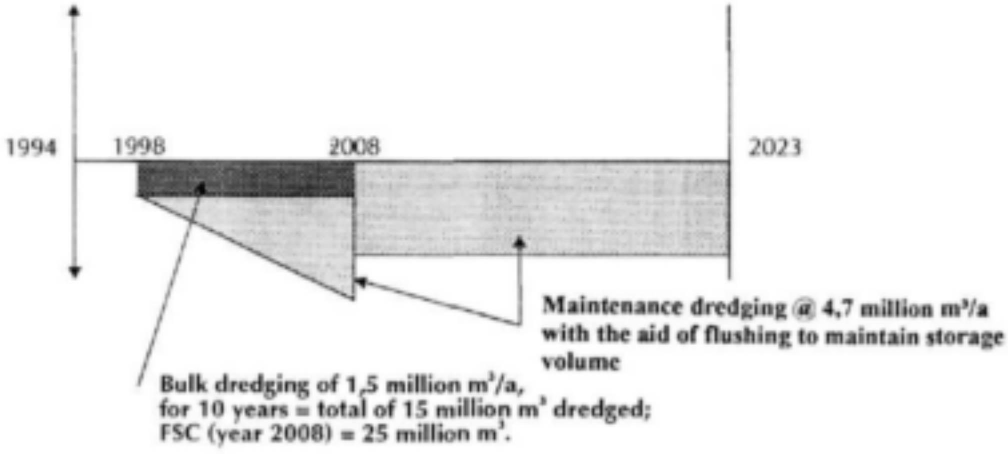
The "optimum" dredged full supply capacity of Welbedacht Dam was determined by analysing different Welbedacht Dam capacities and required Knelpoort Dam rule curve levels for the year 2008 and 2023, the results of which are indicated in **Figure 8.44**. A dredged full supply capacity of about 25 million m^3 in Welbedacht Dam seems to be the limit above which relatively little benefit in terms of Tienfontein pumping cost will be obtained.

d) **Economic analysis**

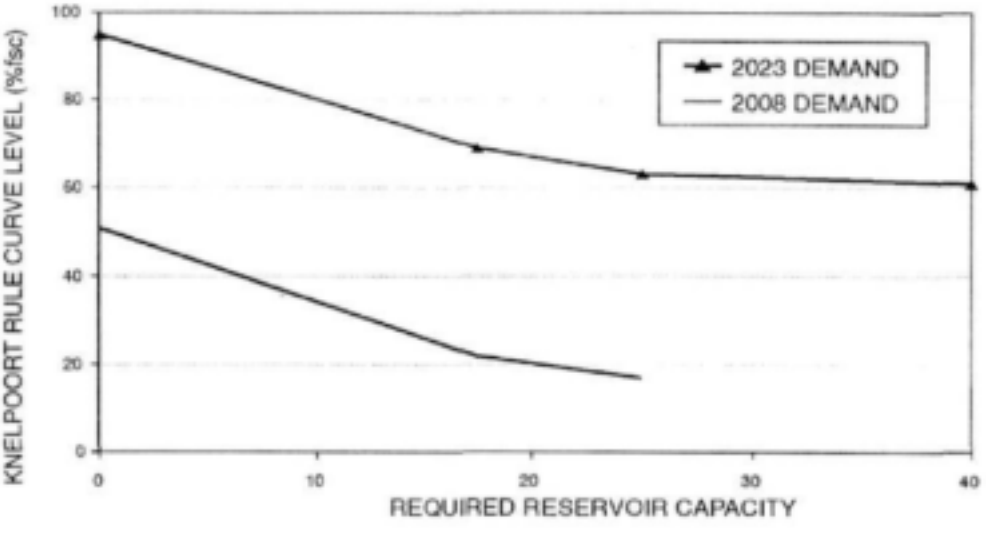
The pumping costs at Tienfontein, Welbedacht Dam, Maselspoort and in future, Novo, could be affected by dredging Welbedacht Dam. The pumping costs at these pump stations were therefore considered in the cost analysis for situations with and without dredging, as indicated in **Figure 8.45**.

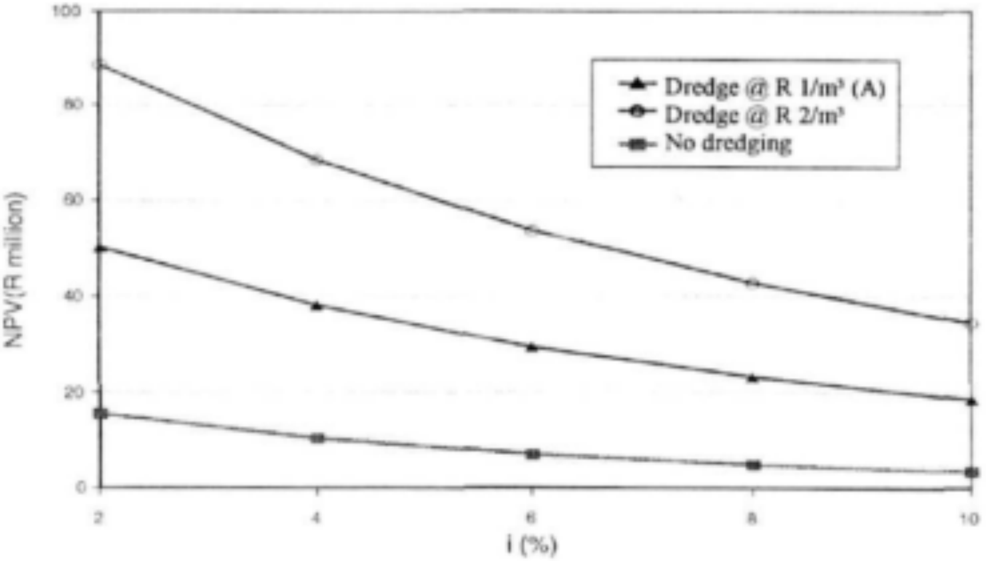
Due to the fact that the current yield exceeds the demand, nothing has to be done until 1998 when Novo has to be phased in. In the dredging option, 1,5 million m^3/a has to be excavated from 1998 to 2007, as well as annual sedimentation of 4,7 million m^3 from 1998 to the year 2023. The "optimum" dredged capacity of 25 million m^3 (15 million m^3 dredged) in Welbedacht Dam is therefore reached in 15 years' time when it will be required by the rising future water demands.

The yield analysis results of a system without dredging and with Welbedacht Dam dredging for each of the system pump stations (mean annual pumping in million m^3/a) are indicated in **Figure 8.45**. It would seem that only the Tienfontein pump station will seriously be affected by dredging, and because all other expenses are mutual, dredging cost should be lower than the difference in Tienfontein pumping costs with and without dredging.



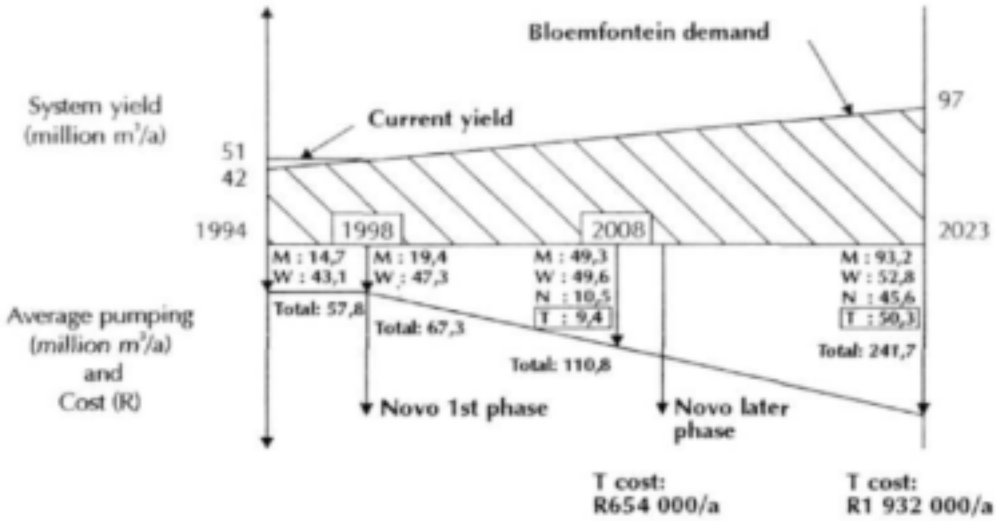
Proposed reservoir dredging





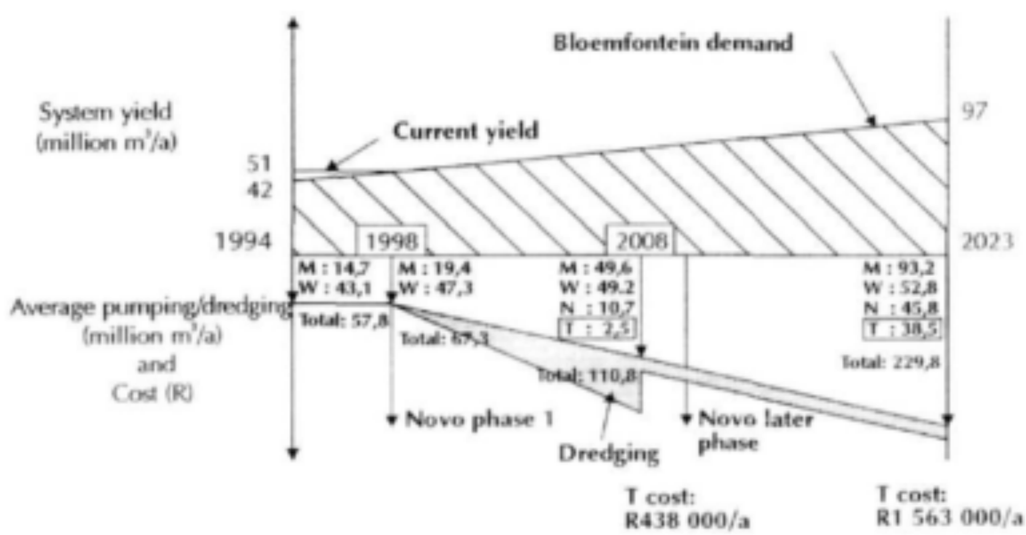
Required reservoir dredging

Figure 8.44: Proposed dredging: Welbedacht Dam



NO DREDGING

M	:	Maselspoort mean annual pumping (million m³/a)
W	:	Welbedacht mean annual pumping (million m³/a)
N	:	Novo mean annual pumping (million m³/a)
T	:	Tienfontein mean annual pumping (million m³/a)



Dredging

Figure 8.45: Economic dredging analysis: Welbedacht Dam

Figure 8.44 shows the net present values of a scheme with dredging versus no dredging. Dredging has to be carried out at a unit rate of less than 20 c/m^3 to be cheaper than the alternative: no dredging.

In the dredging yield analysis, a dredged canal with approximately equal dimensions to the 1991 scoured channel in the reservoir was used, with the idea that flushing can be used for removal of annual sedimentation, and dredging only for the bulk dredging of 15 million m^3 of sediment, from 1998 to 2007.

e) **Key results**

In the case of Welbedacht Dam it is not the reservoir yield, but the pipeline capacity to Bloemfontein which is limiting the system yield. Knelpoort Dam and Tienfontein pump station have been constructed and the lowest future cost development will be the Novo transfer scheme. Dredging of Welbedacht Dam will therefore only limit the pumping of water to Knelpoort Dam which will be used to augment Welbedacht Dam yield. The economic analysis indicates that for dredging to be comparable to pumping cost saving, a unit dredging rate of about R0,10 m^3 is required. The main factors which affect the required dredging cost are:

- no capital expenditure can be saved by dredging;
- annual sedimentation is high (4,7 million m^3/a), with related high annual dredging cost.

The small capacity of Welbedacht reservoir in relation to the run-off (1 % MAR), should make the practise of bulk initial dredging and flushing possible. Flood flushing has been practised since 1991 and although the floods were less than the 1 in 5-year flood and only for durations of a few hours, results obtained look promising. One problem with the combined use of dredging and flushing is the high level of the sluice gates (15 m) above the original bed level.

Combined use of dredging and flushing (with the current high outlets at the dam) could have the following benefits:

- Reduced pumping cost at Tienfontein
- Reduced turbidity at Welbedacht Dam with decreased water treatment costs
- Possible lower flood levels at the Wepener Road Bridge and in Wepener.

8.3 Summary of Results

The results of the dredging economic analyses are summarised in **Table 8.3**. It is clear that at many reservoirs significant relative increases in water yields could be achieved through dredging. The estimated unit costs of dredging, were, however only in the case of Prinsrivier Dam found to be lower than alternative measures to increase the reservoir capacity (See details in Chapter 9).

Table 8.3 Summary of estimated dredging yield and costs

Reservoir	Sediment to be dredged (million m³)	Water yield increase (million m³/a)	Dredged yield/current yield ratio	Required cost of non-dredging option (1994) (R/m³ storage capacity)	Estimated obtainable dredging cost (1994) * (R/m³ sediment)
Floriskraal	17	3	1,50		
Grassridge	44	5	2,50		
Hazelmere	6	2	1,08		
Gariep	480	60	1,03		
Kommandodrif	16,5	1,8	1,56		
Krugersdrift	12	4	1,33	0,75 (raised)	
Lake Arthur	15	5,8	3,32		
Lake Arthur	7,5	4	2,60		4,63**
Darlington	143	20	1,63		
Darlington	30	9	1,28		
Pongolapoort	39	4	1,01		
Prinsrivier	3,44	0,92	3,88	7,00 (raised)	3,75***
Prinsrivier	1,28	0,80	3,50	7,00 (raised)	3,98***
Vaal	174	35	1,04	0,70 (LHWP)	
VanRyneveldspas	34	5	3,50	0,55 (boreholes)	
VanRyneveldspas	16	4	3,00	0,55 (boreholes)	2,15***
Driel	5	1	1,00		

Notes:
- * Data from Chapter 9
- ** Diesel power dredging
- *** Electric power dredging

The relationship between the volume of sediment dredged and the water yield benefit as found at the reservoirs analysed in this study, is indicated in **Figure 8.46**. Yield benefits are often much higher than with conventional means of increasing the storage capacity (such as raising the dam), due to the deep basin with limited evaporation which can be created by dredging.

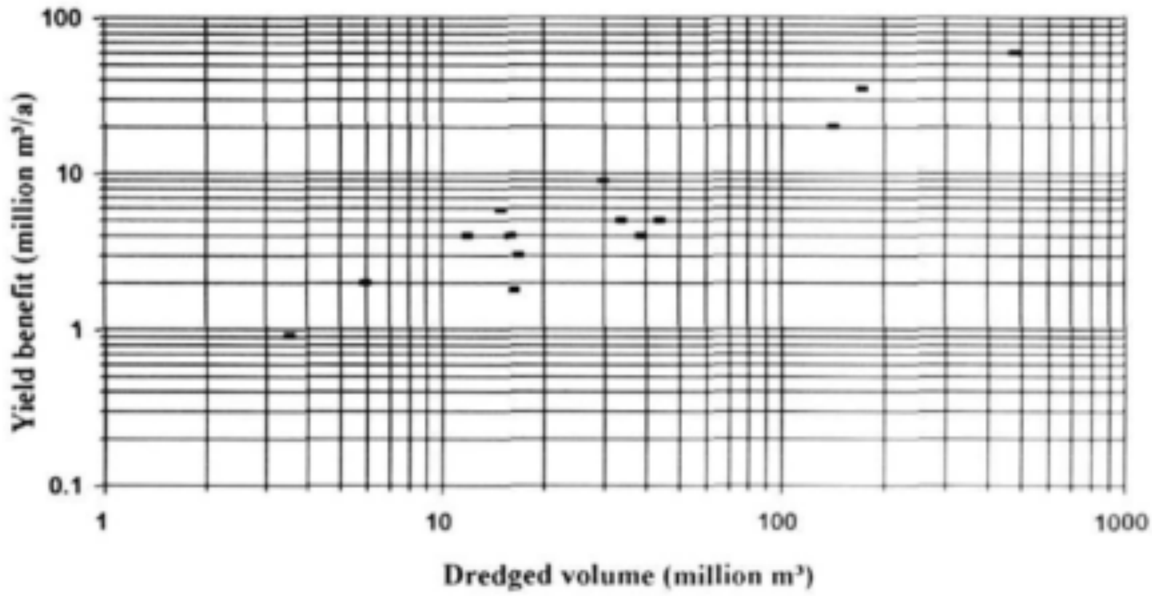


Figure 8.46: Dredging volume versus water yield benefit

9. DREDGING COST ANALYSIS OF THREE SELECTED RESERVOIRS IN SOUTH AFRICA

9.1 Selection of Three Reservoirs for Detailed Dredging Cost Analysis

Three representative reservoirs were selected for a detailed dredging cost analysis, based on the following parameters:

- Yield analysis results.
- Water demand currently exceeding water yield.
- Significant sedimentation caused reduction in yields.
- Insufficient sluice gates and/or surplus run-off make flushing impossible.
- Alternative schemes are relatively expensive - in the case of Lake Arthur an alternative scheme has already been implemented recently, where actual cost figures can be used.
- The dredging should be representative of general South African conditions, covering both small (Prinsrivier) to medium-sized reservoirs, with varying sediment properties, pumping distances and volumes of sediment varying from 1,3 to 16 million m^3 in the bulk initial dredging.
- Watershed management options are not practical in terms of significant yield reduction due to the high variance in flow conditions in the semi-arid to arid Karoo area where the mean annual rainfall is in many places less then 200 mm.

9.2 Detailed Dredging Cost Analysis of Three Selected Reservoirs

The South African based contractor, Gendredge, provided cost estimates for dredging of three reservoirs: VanRyneveldspas Dam at Graaff-Reinet, Lake Arthur at Cradock and Prinsrivier Dam at Ladismith.

9.2.1 VanRyneveldspas Dam (Figure 9.1)

a) Boundary conditions

The following boundary conditions exist at VanRyneveldspas Dam:

- 16,0 million m^3 of sediment has to be dredged initially from the dam upstream to form a channel (300 m wide) in the deepest part of the original reservoir basin. A channel versus all the dredging at the dam was considered in the yield analysis, but no significant differences were found. Dredging of a channel will, however, reduce pumping distances during the dredging operation.

Figure 9.1: VanRyneveldspas Dam: Dredging and disposal proposal

- The sediment contains mainly clay and silt fractions, with some sand further upstream of the dam. The density of the sediment varies from 850 to 1 600 kg/m^3, with an average of 1 200 kg/m^3.

- No suitable disposal for the sediment could be found downstream of the dam in the river, or off-channel storage due to the town of Graaff-Reinet being situated in this area. Land disposal contained in dikes next to the reservoir seems to be a solution which also limits water losses.

- Nearby power transmission lines can be used as an alternative power supply.

b) Proposed solution for VanRyneveldspas Dam

Gendredge proposed a bucket-wheel dredger for dredging near the dam, while for dredging in the upper reaches of the dam a cutter-suction dredger was considered. Three disposal sites around the dam, with maximum pumping distances of 3,5 km are proposed. The proposed dredging period is 4 years.

Cost estimates are:

- Dredger: Bucket-wheel:	Capital cost:	R17,5 million	
	Optimal production:	750 m^3/h	
- Mobilization :			R640 000
- Dredging cost/m^3, including pipeline and auxiliary equipment, and disposal site (Diesel-powered):			R4,76
- Dredging cost/m^3, including pipeline and auxiliary equipment, and disposal site (Electric-powered):			R2,15
- Demobilization :			R460 000

Total cost for 16,0 million m^3 of sediment dredged:	Diesel power	R76,16 million
	Electric power	R34,40 million

9.2.2 Prinsrivier Dam (Figure 9.2)

a) Boundary conditions

The following boundary conditions for dredging exist at Prinsrivier Dam:

- From the yield analysis results two volumes to be dredged were to be considered : Option A : 3,44 million m^3 and option B : 1,28 million m^3.

- The proposed dredging periods for options A and B are 8 and 4 years respectively, based on minimizing water losses. Disposal of the sediment can only be in the valley downstream of the main wall of the reservoir due to the mountainous area. The estimated periods of initial dredging were based on the assumption that water discharged during the dredging could be utilized for irrigation. The upstream end of an irrigation canal is situated on the river downstream of the dam, as previously used and can be commissioned again.

- A secondary road downstream of the dam should not be influenced by the disposal.

- The dredging should be in the main basin, in the deepest part of the original reservoir.

- The sediment has a maximum depth of 15 m, consists of clay and silt, and is highly consolidated.

b) Proposed solution for Prinsrivier Dam

Gendredge proposed a cutter-suction dredger, with a maximum rated dredging depth of 28 m. Minimum unit dredging costs will be achieved in 2 years for option A and in 1 year for option B. This might be problematic if not enough water is available and/or if not enough storage is created at the disposal site. Nevertheless, the final dredging operation will be a compromise between minimum water loss for irrigation, available water and minimum cost. The cost estimates for both shorter and longer dredging periods are provided:

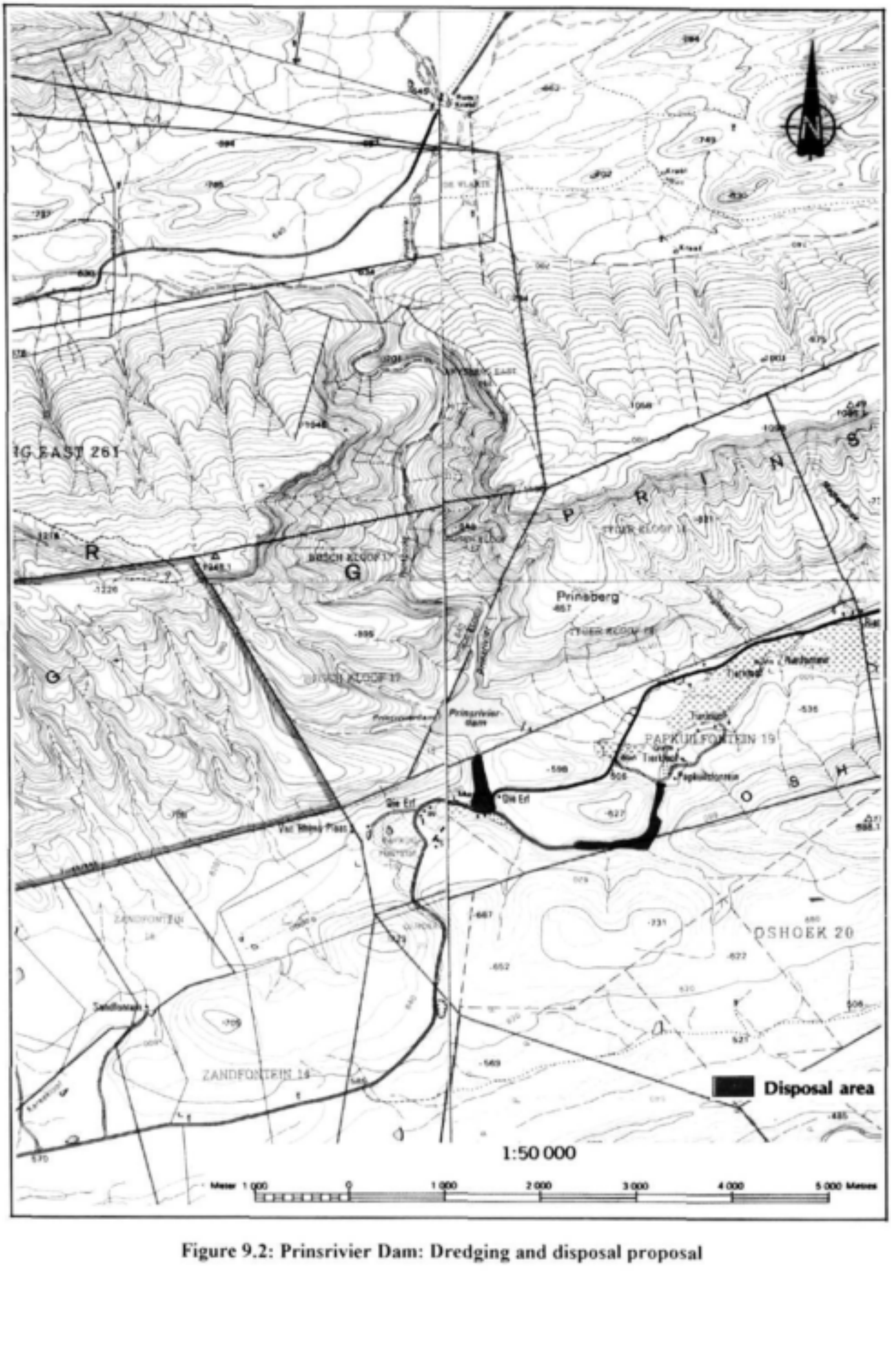


Figure 9.2: Prinsrivier Dam: Dredging and disposal proposal

- Dredger: Cutter-suction:	Capital cost:	R9,0 million	
	Optimal production:	350 m^3/h (80 m^3/h)*	
- Mobilization (Options A and B)			R300 000
- Dredging cost/m^3, including pipeline of 1,5 km and auxiliary equipment:			
Option A	(Diesel-powered)		R4,72 (± R5,70) *
	(Electric-powered)		R3,76
Option B	(Diesel-powered)		R5,00 (± R6,50) *
	(Electric-powered)		-
- Demobilization (Options A and B)			R250 000
Total cost for:	Option A (Diesel-powered) for 3,44 million m^3:		R16,2 million
	Option A (Electric-powered) for 3,44 million m^3:		R12,9 million
	Option B (Diesel-powered) for 1,28 million m^3:		R6,4 million
	Option B (Electric-powered) for 1,28 million m^3:		-

* Longer period proposed in boundary conditions to limit water losses indicated in brackets.

9.2.3 Lake Arthur (Figure 9.3)

a) Boundary conditions

The following dredging boundary conditions need to be considered at Lake Arthur:

- The total initial volume to be dredged is 7,5 million m^3, near the dam and main basin, in the deepest part of the original basin.
- The sediment has a high clay and silt content and is well consolidated.
- In order to minimize water losses, disposal has to be around the reservoir, contained by dikes, with a maximum pumping distance of 1,5 km.

b) Proposed dredging solution for Lake Arthur

A cutter-suction dredger was proposed, with an initial bulk dredging period of 2 years.

- Dredger: Cutter-suction:	
- Mobilization:	R260 000
- Dredging cost/m^3, including pipeline, auxiliary equipment and disposal (Diesel-powered)	R4,63
- Demobilization cost	R120 000
Total cost (diesel-powered) for dredging 7,5 million m^3:	± R34,7 million

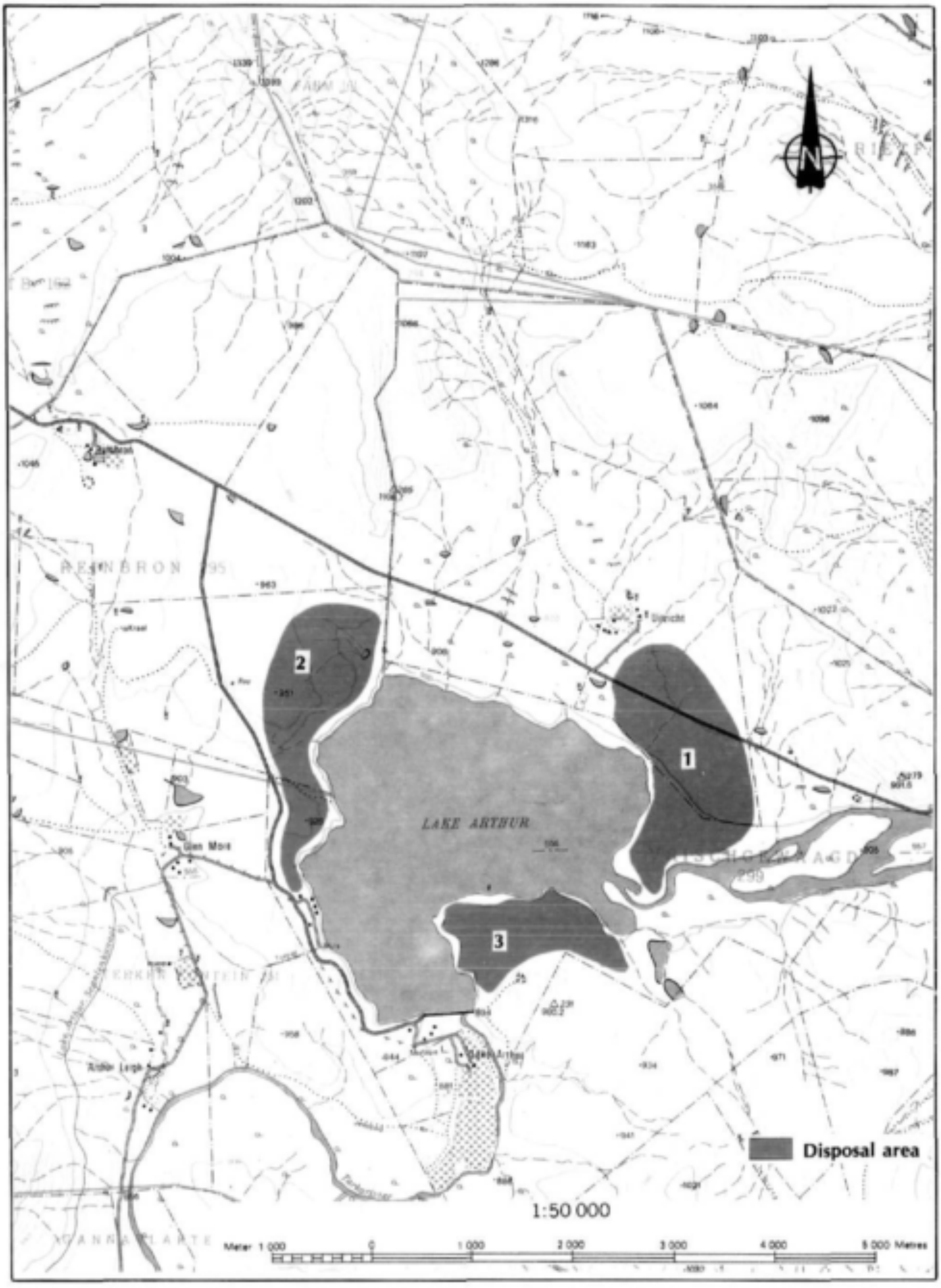


Figure 9.3: Lake Arthur: Dredging and disposal proposal

9.3 Discussion of Dredging Cost Analysis

The dredging cost estimates of the three selected reservoirs are in all cases except Prinsrivier Dam, higher than alternative schemes of water supply. The total volume of sediment to be dredged is one major factor in the determination of a low unit cost estimate. Although it is very difficult to give a generalized unit rate, it is estimated that with volumes of sediment to be dredged exceeding 25 million m^3, a unit dredging rate (including disposal) of as low as R1,50/m^3 (1994) could be achieved.

The provision of electric power instead of diesel power could more than half the dredging cost and is definitely something to consider on any reservoir dredging project. The cost of providing electric power to the reservoir bank was not considered in the cost analyses. It should be noted that the dredging rates given above are preliminary estimates.

10. BENEFICIAL USES OF DREDGED SEDIMENT

10.1 General

The use of dredged material is a well-researched subject. Ten broad categories of beneficial uses have been identified, based on the functional use of dredged material at disposal sites: The main uses (USACE, 1986) with possible reservoir dredging implementation are:

a) Habitat development refers to the establishment and management of relatively permanent and biologically productive plant and animal habitats. Four general habitats are suitable for establishment on dredged material:

- Wetland
- Upland
- Aquatic
- Island

b) Parks and recreation.

c) Agriculture, forestry. Dredged sediment can be used to amend marginal soils.

d) Construction and industrial use such as roads and brick manufacturing.

By considering dredged material as a resource a dual objective can be achieved: Reservoir sediment can be disposed of with minimal environmental damage and at least some of the costs of dredging could be covered.

An extensive survey of 150 general dredging disposal sites world-wide (Hubbard and Herbich, 1977) indicated the distribution of dredged material use as shown in **Figure 10.1**.

For this study South African conditions have been evaluated and it was decided to do more research on the possible beneficial uses of dredged sediment for:

- agricultural use, and
- brick manufacturing.

A very important aspect to consider with reservoir dredging is the volume involved. With 1 million m^3 of dredged sediment for example, it is possible to construct 21 000 small-sized houses. Reservoirs are mostly in remote areas and transportation will be a major cost factor. In South Africa the availability of raw material for the building industry is generally not a problem and it would therefore be difficult to compete with the mostly longer transportation distances required to use reservoir sediment beneficially. Only the scale of the reservoir dredging operation and co-operation with the Reconstruction and Development Programme of the Government, could make the use of sediment for the building industry socio-economically viable.

10.2 Agricultural Use

An attractive alternative for disposing of dredged sediments is to use these nutrient-rich materials to amend marginal soils. The transportation of dredged material will be a restricting factor, as mentioned previously.

The physical characteristics of dredged reservoir sediment, especially clay and silt, will have to be adjusted by mixing with coarser material to obtain a loam soil.

The possible agricultural use of sediment from 5 reservoirs in South Africa has been investigated as part of this research by the Faculty of Agricultural Sciences, University of Stellenbosch, in collaboration with the Institute of Soil, Climate and Water, Pretoria. This study is included in **Appendix A**. The key finding is that the physical character of the sediment (too fine or too coarse) is the main negative aspect of using the sediment as agricultural soil.

10.3 Brick Manufacturing

a) Clay bricks

The production of ceramic products from dredged material has been investigated internationally, mostly to dispose of toxic sediment. In South Africa the need for housing and increased water demands could be the market environment required to economically manufacture bricks, with the only limitation being high transportation cost.

Ceramic tests on sediment from South African reservoirs have been carried out and the tests look highly promising. Briquettes of sediment obtained from Darlington Dam, fired at three different temperatures are shown in the photograph in **Figure 10.2**.

Discussions with the South African Clay Brick Association confirmed that transportation costs and not the availability of raw material is the limiting cost factor in clay brick manufacturing. A distance of 50 km is more or less seen as the maximum economically transport radius of most manufacturers. One of the main manufacturers in the country, transports bricks over much longer distances by road, for example from Gauteng to KwaZulu-Natal.

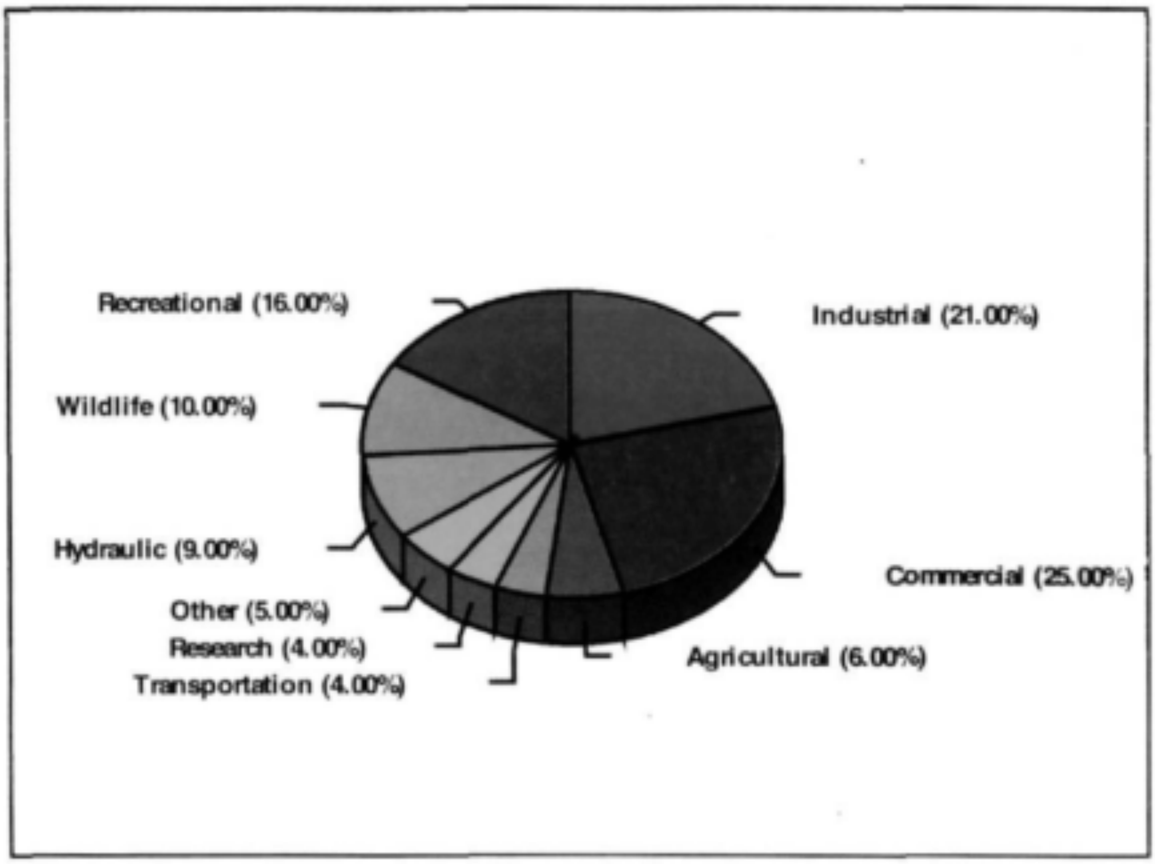


Figure 10.1: Classification of 150 dredging disposal sites according to their beneficial use

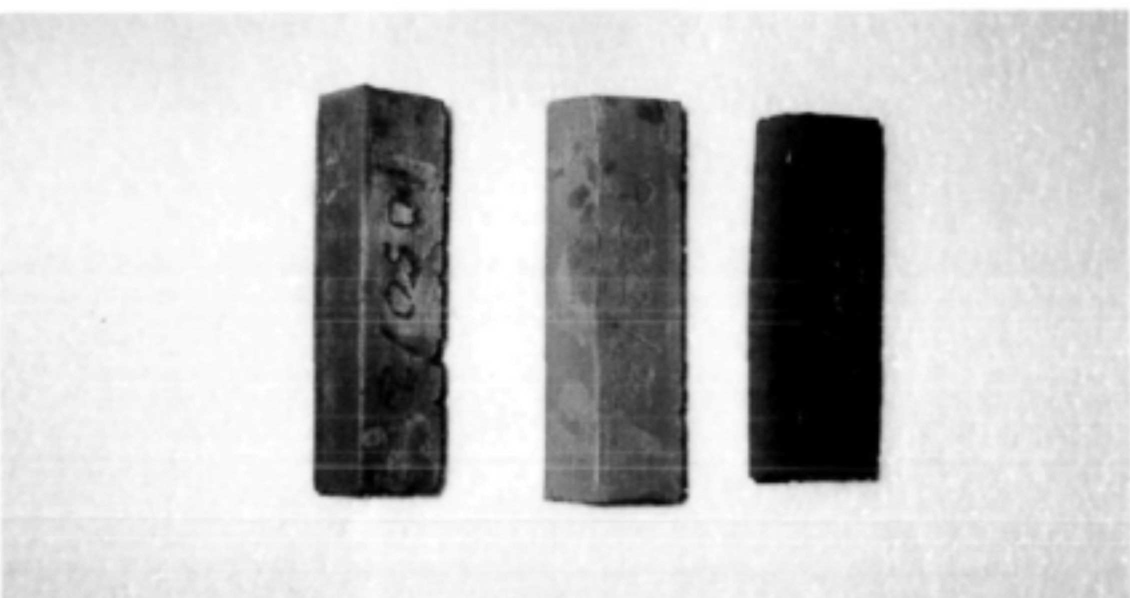


Figure 10.2: Briquettes made of Darlington reservoir sediment

b) **Cement bricks**

Initial tests with a block pressing machine have been carried out on sediment from the Krugersdrift reservoir. The fineness of most reservoir sediment will require a higher cement-sediment ratio than normally required. Discussions with the SABS indicated that shrinkage and breaking of bricks during transport will also be factors to consider.

11. CONCLUSIONS AND RECOMMENDATIONS

Reservoir dredging is being carried out world-wide, but mostly on a small scale localized at intakes, or storage dredging in small reservoirs. The cost of dredging is generally higher than the creation of additional/new storage, but technical developments in the dredging industry have narrowed this gap to a point where dredging has to be considered as a major technique to control sedimentation. This is especially true in semi-arid to arid regions where catchment or hydraulic sediment control methods cannot be implemented successfully. Limited suitable new dam sites, socio-economic considerations when raising a dam, and environmental concerns related to the construction of especially medium-scale to large-scale dams, are all factors favouring reservoir dredging.

Case histories have indicated that the selection of the correct dredging equipment for especially reservoir dredging is essential. Boundary conditions such as consolidated clay make the use of a cutter a necessity. The dredging industry is highly specialised and it is difficult to recommend a specific dredger for general reservoir dredging application. The cutter-suction and bucket-wheel dredgers with floating pipeline do, however, meet most of the requirements for reservoir dredging and should be considered in dredging depths of less than 30 m. For deeper applications, specialised grab or fluidization-pump systems are available.

Siphon dredging systems with a cutterhead could result in a considerable cost saving by eliminating the use of pumps. These systems are, however, limited by the available head, required transport distance, limitations on water loss and environmental concern with downstream disposal. With proper management of sediment-water releases, the system could be used to the benefit of the environment by restoring the sediment regime, and also of downstream users. Siphon dredging should be considered in more detail, especially with the current First World tendency of constructing smaller reservoirs.

An economical dredging analysis of some of the reservoirs in South Africa affected most by sedimentation has been carried out by evaluating the water demand and current yield, comparing dredging with an alternative method to achieve the required demand in terms of cost, and calculating a Net Present Value of dredging and the alternative (such as raising the dam). At one reservoir, Prinsrivier Dam, the arid climate and reservoir basin characteristics mean that another dam raising cannot meet the water demand. By dredging, however, a large capacity is created with a relatively small evaporative area during critical hydrological periods, and the dredged reservoir is able to meet the demand at the required assurance of supply.

General conclusions from the dredging-yield results are:

- To obtain the same yield benefit, a much smaller volume can be dredged compared to a raised dam with additional storage created.

- Dredging of all the sediment is not necessary and the required volume is determined by the water demand, run-off reservoir basin characteristics, volume of sediment, etc.

- At some reservoirs a dead storage zone for sedimentation has been provided with the lowest water release valves located above this zone. Dredging of the dead storage zone can therefore not be considered because the water cannot be utilized. It is recommended that the lowest valves are installed close to the original river bed level.

- The general assumption in water resources planning that sedimentation fills the dead storage zone with a horizontal surface level, should be analysed in more detail for existing reservoirs and final designs of new dams to evaluate the impact of loss of live storage due to sedimentation. Allowance in future for sedimentation of reservoirs can still be made, but the design of a dead storage specifically for sedimentation should be discarded.

Historical dredging costs in South Africa and a dredging cost analysis of 3 reservoirs have been evaluated and the conclusions are:

- Although difficult to generalize, the required dredging unit costs need to be in the order of less than R1,50/m^3 of sediment excavated.

- Local expertise and ties with international dredging firms in the dredging industry have grown in recent years, and unit dredging costs are lower than previously.

- The use of electric power instead of diesel power should seriously be considered in any dredging project, because it can more than halve the unit dredging costs.

- To buy a dredger and to carry out dredging often seems a viable option to government bodies. Dredging is, however, a highly specialised industry and items such as special training and maintenance are often underestimated, resulting in higher dredging costs than could be carried out by the contractor. Experience seems to indicate that government-owned equipment are also used until they are technically obsolete and highly expensive to run.

- The cost of disposal should not be underestimated and it could easily make up 20 % of the total cost of a dredging project.

Typical dredging unit costs (1994 base year) for Southern African reservoirs are indicated in **Figure 11.1**. These costs should only be used as a rough indication because each project has its own specific boundary conditions.

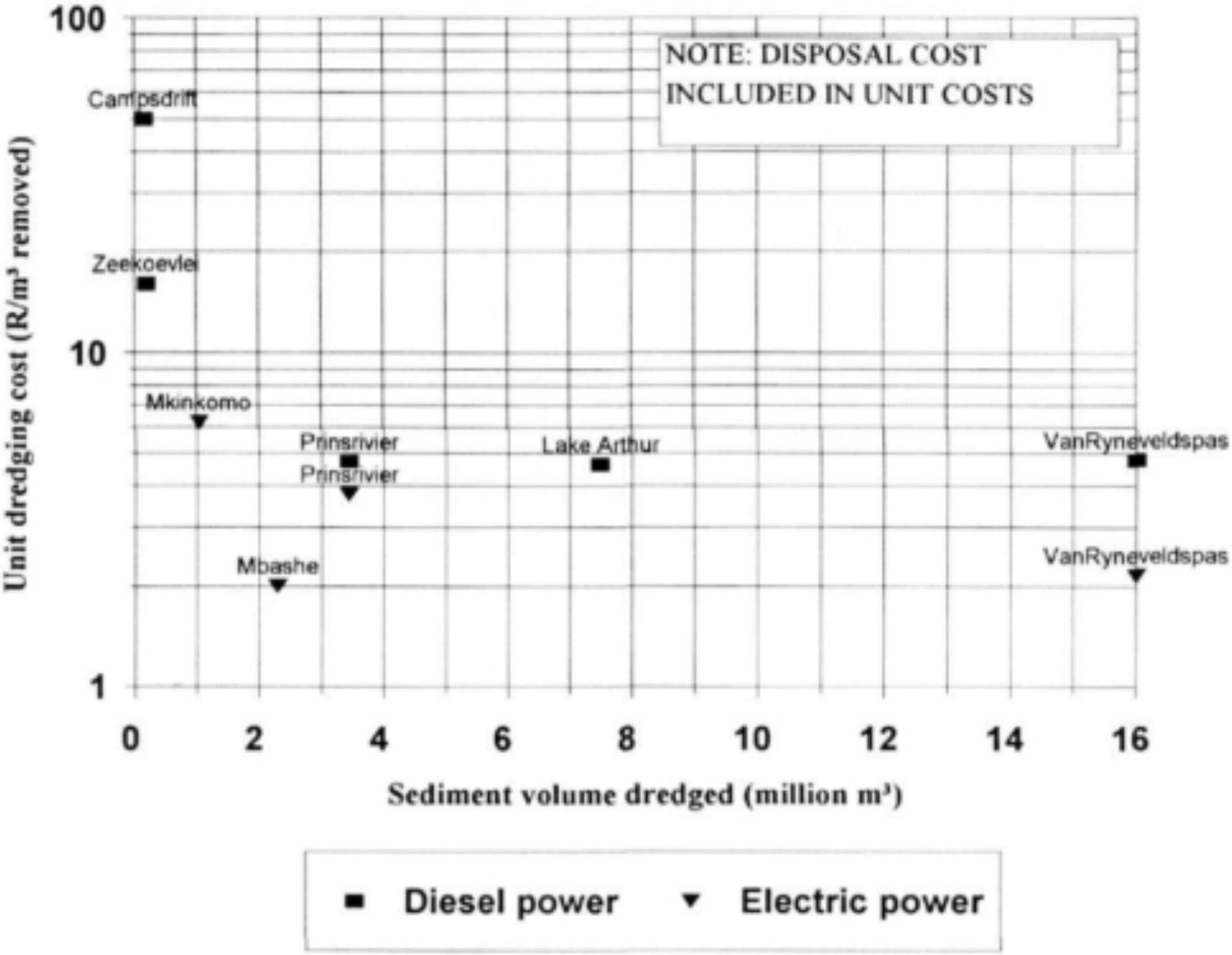


Figure 11.1: Dredging unit costs: Historical and estimated

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APPENDIX A

INVESTIGATION OF THE POSSIBLE AGRICULTURAL USE OF DREDGED SEDIMENT

AGRICULTURAL POTENTIAL OF DAM SEDIMENT SAMPLES

REPORT SUBMITTED TO
BKS (INC.), PRETORIA, 1995

BY

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1 Introduction

The Department of Soil and Agricultural Water Science was approached by BKS (Inc.) to analyse a series of sediment samples dredged from various dams in South Africa and to report on the agricultural potential of these samples. Six samples from the following dams were received (in alphabetical order):

Darlington (Jansenville, Kirkwood)
Gariepdam (Colesberg)
Krugersdriftdam (Kimberley, Bloemfontein)
Lake Arthur (Cradock)
Prinsrivierdam (Ladismith, Cape)
Van Rhyneveldspas (Graaff Reinet)

The chemical and physical analyses were restricted to those that will contribute to an assessment of the agricultural potential of the sediment. Cost of analysis also played a role in the selection process. The analyses that were performed and the motive for each analysis are listed in Table 1. All analyses were performed according to the methods prescribed by the *Non-Affiliated Soil Analysis Working Committee* (Anon. 1990). The erodability of the sediment from Lake Arthur, Darlington dam, Prinsriver dam and Van Rhyneveldspas dam were assessed with a rainfall simulation test conducted by the Institute for Soil, Climate and Water (Agricultural Research Council). No reason was given by BKS why the rainfall simulation test was restricted to four of the six samples only.

The term "agricultural potential" was interpreted to be any possible use the sediment might have in improving the general edaphic condition of soil, e.g. improving the nutrient status, or the hydrological properties of soil. This report gives a general overview of the results in terms of this interpretation of agricultural potential and, where applicable, reference to "typical" norms are included.

2 Physical properties

The texture and particle size composition of the samples were determined using an abbreviated method of the standard pipette and sieve technique. Iron and aluminium oxides/hydroxides were not removed. The results and soil textural classes are shown in Table 2. The cumulative totals of the five size classes range between 96% and 102% (i.e. do not sum to 100%) and is attributed to experimental error and the fact that no size class was determined by difference. All particles were smaller than 0.25 mm equivalent spherical diameter (e.s.d.), i.e. no medium and coarse sand were present in any of the samples. The texture of four of the six samples is classified as *clay*. The Gariep and Krugersdrift samples, are classified as *silt loam* and *sandy loam* respectively. The cause(s) for the high fine sand fraction of the Krugersdrift dam sample is unknown, but is probably related to the soils and geology of the catchment and the hydraulic and hydrological characteristics of the river feeding the dam. It might also be related to spatial variability of sediment composition within the impoundment itself.

Table 1 Chemical and physical analyses used to asses the agricultural potential of samples of dredged dam sediment

Analysis	General description and purpose of analysis	Method*
pH	1M KCl soil paste: indication of acidity	2/1
Electrical resistance	Soil cup: indication of salinity	5/1
Total carbon content	Walkley Black method: indication of organic matter and nitrogen mineralization potential	34/1
Extractable cation content	0.2M NH_4-acetate, buffered at pH 7: indication of base cation status and balance, and first assessment of soil fertility	8/1
Soluble cation content	Water saturated paste extract: required to calculate exchangeable cation content	12/1
Cation exchange capacity	0.2 M NH_4-acetate, buffered at pH 7: indication of clay mineralogy and buffering capacity of soil	12/1
Particle size composition	Pipette method: indication of particle size distribution and first estimate of a range of edaphic and hydrological properties	35/1

* Method number in "Handbook of standard soil testing methods for advisory purposes", Anon. (1990)

Although it is rather idealistic to try and define the ideal texture for agricultural lands, a loam with 18-25% clay, 40% silt and 40% medium and coarse sand can arguably be used as the norm of the textural composition of a "good" agricultural soil. In contrast with this norm and with the possible exception of the Gariep sample, the poor grading of the sediment samples, imparts the following unfavourable physical characteristics to them:

- internal drainage: very low, because of high clay content
- aeration status: impaired, because of high clay content and poor drainage
- consistency when wet: plastic and difficult to work, because of high clay content
- consistency when dry: hard and difficult to work
- surface characteristics: potential for soil crusting, will also be influenced by clay mineralogy and exchangeable cation composition

Table 2 Particle size composition of dam sediment samples (%)

Sample	Coarse & Medium Sand	Fine sand	Coarse silt	Fine silt	Clay	Textural class
Darlington dam	0.0	2.0	0.0	12.4	84.2	clay
Gariepdam	0.0	4.7	33.1	32.9	25.5	silty loam
Krugerdriftdam	0.0	77.6	4.5	3.7	13.0	sandy loam
Lake Arthur	0.0	0.2	2.2	21.2	77.5	clay
Prinsrivierdam	0.0	0.5	3.8	35.3	57.6	clay
Van Rhyneveldspas dam	0.0	0.4	0.0	20.3	81.2	clay

(Equivalent spherical diameters of size classes: coarse sand=2.00-0.50 mm; medium sand=0.50-0.25 mm; fine sand 0.25-0.05 mm; coarse silt=0.05-0.02 mm; fine silt=0.02-0.002 mm; clay <0.002 mm)

3 Chemical properties

The general chemical characteristics of the sediment samples are listed in Table 3. The pH of all samples can be described as mildly acidic to neutral and for most agricultural crops no pH adjustment will be necessary. Although free lime and traces of gypsum are present in samples with pH>7, the sediment is not suitable to be used as a source of lime or as an ameliorant for acid soils.

The electrical resistance is used as an indication of salt hazard of the soil and is inversely proportional to the salt concentration. Danger limits for soluble salts in various textures in terms of resistance (ohms) are listed in Table 4. The soluble salt content (salinity) of all samples are typical of the arid and semi-arid regions of South Africa. The Van Rhyneveldspas-, Lake Arthur and Darlington samples are fairly saline and use of this sediment on agricultural land might lead to soil salinization.

Table 3 General chemical characteristics of dam sediment samples

Sample	pH(KCl)	Resistance (ohm)	Carbon (%)	CEC (cmol(+)/kg soil)	CEC (cmol(+)/kg clay)
Darlington dam	7.3	305	0.89	21.83	25.91
Gariepdam	6.6	740	2.09	21.68	85.12
Krugerdriftdam	5.8	930	0.31	8.10	62.31
Lake Arthur	7.4	209	1.11	24.05	31.04
Prinsrivierdam	7.3	360	1.20	15.48	26.88
Van Rhyneveldspas	7.3	183	1.11	22.73	27.99

Table 4 Danger limits for salt hazard in terms of electrical resistance of a water saturated soil paste (Lambrechts, 1980)

Texture	Limiting	Non-limiting
Sand	<700 ohm	> 700 ohm
Loam	<500 ohm	>500 ohm
Clay	<300 ohm	>300 ohm

The carbon content of the samples are low to medium. According to the norms of the Soil Classification Working Group (1991) only the sediment of the Gariepdam will qualify as a humic horizon, the minimum carbon content for a humic horizon being >1.8%. The carbon content of soil can also be used as an index of the nitrogen content, more specifically the mineralizable N-content of a soil. Assuming a C:N ratio of 10:1 and a mineralization rate of 2% per year, the following amounts of nitrogen will be released per year if 150 mm of the sediment at a bulk density of 1.5 Mg/m^3 is added to agricultural lands:

Darlington	40 kg/ha
Gariep	94 kg/ha
Krugersdrift	14 kg/ha
Lake Arthur	50 kg/ha
Prinsrivier	54 kg/ha
Van Rhyneveldspas	50 kg/ha

These values are too low and the amount of sediment that must be transported too high, to make it economically feasible. Clearly, the sediment samples cannot be used as an economical ("cheap") source of either organic matter or nitrogen.

The cation exchange capacity data shown in Table 3 reflect conditions at pH 7 and are expressed both as cmol(+)/kg soil and cmol(+)/kg clay. The latter unit can serve as an indication of clay mineralogy. According to the CEC data, the sediment from Gariep and Krugersdrift contain appreciable amounts of swelling type clay minerals, probably of smectitic and/or vermiculitic origin. Too little information is available to make any conclusions concerning the clay mineralogy of the other samples.

The extractable and soluble cation composition are shown in Table 5. The reason for doing this analysis was to asses the potassium and sodium contents of the samples. Potassium is an essential macro-nutrient for most agricultural crops and in South Africa is commonly found in fairly high concentrations in the topsoil. This analysis was done to evaluate the possibility that the sediment, the most of which probably originates from topsoil of agricultural lands, might be used as a source of potassium, e.g. as a "fertilizer". The potassium content of all samples is fairly high and when expressed in units of mg/kg [*(extractable (cmol/kg) - soluble content (cmol/kg))* x *molecular weight = mg/kg*], range between 140 mg/kg (Krugersdrift) and 750 mg/kg (Lake Arthur). The potassium content is too low for the sediment to be used as a fertilizer or "top dressing". However, although too low to be used as a source of K, the potassium content of the sediment will be sufficient for most agricultural crops. For example, for wheat and maize production in the summer rainfall regions of South Africa no potassium fertilizer is recommended if the soil potassium value is >80 mg/kg (Buys, 1993).

Table 5 Chemical composition of sediment samples: A) Extractable cation concentration, B) Soluble cation concentration

	A:) Extractable cations (cmol(+)/kg)				
Sample	Ca	Mg	Na	K	ESP (%)
Darlington	23.75	10.78	1.64	1.74	5.13
Gariepdam	24.69	8.99	0.44	0.62	1.75
Krugerdriftdam	5.00	3.33	0.30	0.37	2.84
Lake Arthur	24.63	14.17	2.67	1.92	7.90
Prinsrivierdam	16.69	6.67	0.98	0.98	3.75
Van Rhyneveldspas	22.06	12.50	1.76	1.76	4.58

	B:) Soluble cations (cmol(+)/kg)				
	Ca	Mg	Na	K	Total anions
Darlington	0.30	0.26	0.52	0.04	1.12
Gariepdam	0.17	0.11	0.06	0.01	0.35
Krugerdriftdam	0.06	0.06	0.07	0.01	0.20
Lake Arthur	0.26	0.28	0.77	0.03	1.34
Prinsrivierdam	0.45	0.35	0.40	0.03	1.23
Van Rhyneveldspas	0.79	0.62	0.72	0.05	2.18

Extractable sodium in combination with soluble sodium and CEC is used to calculate the exchangeable sodium percentage, (ESP=100 x Na_{ex}/CEC). The ESP again is used as an index of sodicity hazard and dispersivity. None of the ESP values exceed the critical level of 15% (U.S. Salinity Laboratory, 1954). However, local and international experience show that in soils with an ESP >5, the potential for clay dispersion, structural breakdown and seal or crust formation increases (Shainberg, 1990) especially in the presence of low electrolyte water (such as rainfall). The ESP levels of four of the six samples and the poor particle size grading, increase the potential for surface crusting, which will result in low infiltration rates for rainfall (and irrigation), enhanced runoff and eventually, soil erosion.

The sum of exchangeable cations, i.e. extractable cations minus soluble cations, should theoretically equal the cation exchange capacity (CEC). For all six samples this is not the case with the sum of cations>CEC and is attributed to the presence of free lime and gypsum in the sediment. Proof of this is the high extractable Ca content (>15.00 cmol(+)/kg) shown in Table 5. The presence of gypsum and lime is linked to the arid and semi-arid conditions prevailing in the catchment areas of the six dams. The only sample where the sum of exchangeable cations accord well with the CEC, is the Krugersdrift sample. However, neither the absolute CEC values nor the discrepancy between exchangeable cation content and CEC impact on the agricultural potential of the sediment samples.

4 Erodability of sediment

Four samples were subjected to a rainfall simulation test to evaluate the erodability of the sediment. The test was conducted by the Institute for Soil, Climate and Water and the results were submitted to the Department of Soil and Agricultural Water Science of the University of Stellenbosch. The details of the exact methodology are not available, other than that the test were performed in containers with a surface area of 0.1323 m^2 at a slope of 5%. The results were expressed in units of kg ha^{-1} mm^{-1} as a function of cumulative rain and are shown in Table 6. It is difficult to relate these values to typical long term average sediment loads of rivers in South Africa which range between a minimum of 10 t km^{-2} a^{-1} and a maximum of 3000 t km^{-2} a^{-1} (A. Rooseboom[1], 1995, personal communication). For most of South Africa, the sediment load varies between 100 and 600 t km^{-2} a^{-1}. It would be very difficult (and rather meaningless) to try and convert the erodability values listed in Table 6 to sediment loads of rivers, differences in scale being but one obstacle in the conversion (Lal, 1994).

The erodability of two of the samples decreases with cumulative rain while the other two increases (Fig.1). Attempts were made to relate this difference in response to other soil properties (e.g. ESP, CEC, clay%, carbon content, etc.), but no explanation could be found - possibly because of a limited database.

Table 6 Erodability of dam sediment, according to a rainfall simulation test, as a function of cumulative rain

Erodability (kg ha^{-1} mm^{-1})				
Cumulative rain (mm)	V.Rhynevelds-pas	Lake Arthur	Darlington	Prinsrivier
2.84	202	406	55	380
5.69	131	348	107	329
11.38	118	338	119	305
17.08	145	317	173	298
22.77	172	295	196	275
28.46	195	280	228	276
34.15	170	291	206	267
Final Infiltration rate (mm h^{-1})	2	3.7	2	2

[1]A. Rooseboom, Professor in Civil Engineering, University of Stellenbosch.

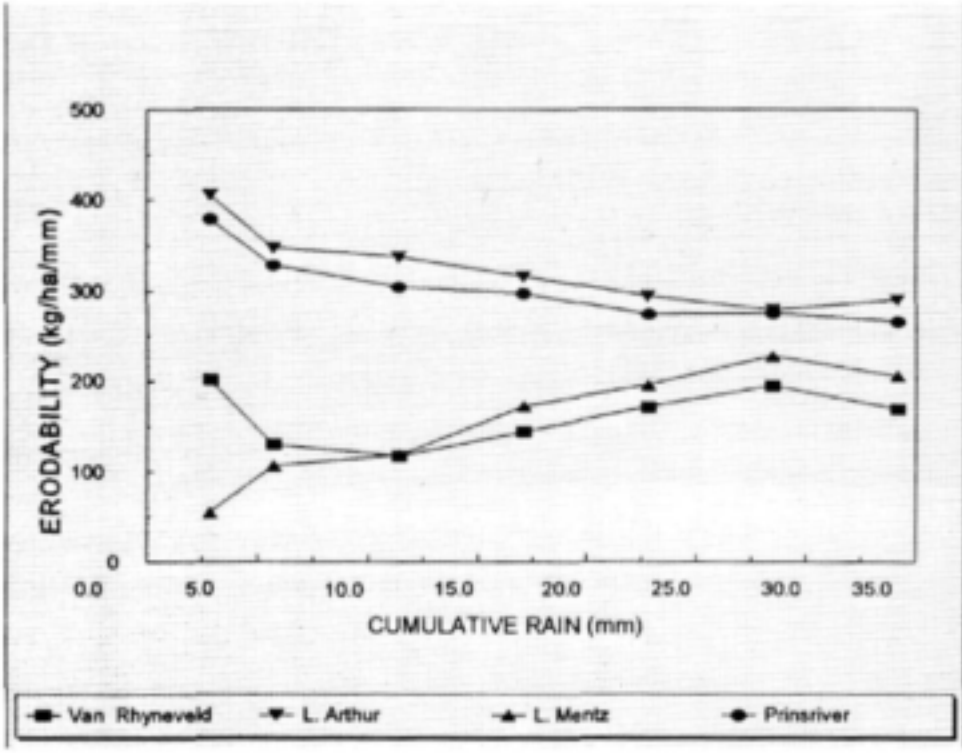

Figure 1: Erodability of dam sediment samples, based rainfall simulation tests, as a function of cumulative rain

4 Conclusions

a) The agricultural potential of the sediment from the six dams that were analysed is very limited. Although the chemical properties and nutrient status in general are above normal, the potassium and carbon content, for example is not sufficiently high to make it economically feasible to use the sediment as a topdressing on agricultural lands. It is reasonable to assume that the same conclusion will apply to the phosphorus (which was not determined).

b) The biggest shortcoming of the sediment is the poor grading. Most particles are within the silt and clay size class, which except for extreme coarse sandy soils, might do more harm than good when applied as a topdressing without mixing to normal agricultural lands. Even in the case of coarse sandy soils, such large quantities of sediment will have to be used to make any meaningful change to the texture, that the procedure and the ultimate result will not be economically viable.

c) In view of the poor grading, high clay content and possible dispersivity of the sediment, the sediment will have to be thoroughly mixed with the soil to which it is applied. If the sediment is left on the soil surface, surface crusting and sealing and the concomitant increased runoff and erosion will result.

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