A Comparison of Ten Different below-ground RWH Tanks

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Abstract

The author compares ten different designs of underground RWH tanks, including the tank that was eventually chosen as the 'Standard RWH Dam' by the Department of Water Affairs and Forestry. All the tanks have a capacity of 30000 litres.

Each tank is briefly explained, along with its advantages and disadvantages. A cost estimate of each tank is given, including a breakdown of materials and labour (with all costs converted to US dollars at the prevailing exchange rate).

The tanks include the following shapes: Cylindrical, Hemispherical, Trapezoidal and Rectangular. The materials used to build the walls include cement blocks, reinforced concrete/mortar, insitu-cast sand/soil cement, ferrocement, PVC lined earth, polyethylene.

The main purpose of the paper is to inform prospective RWH tank builders on the advantages and disadvantages of the various tanks, list the materials that are required for each, and compare the relative costs.

About the Author

In 2005 through 2007, as part of the Experimental Phase of the DWAF (Department of Water Affairs and Forestry) RWH program in South Africa, the author served on a support team as technical advisor, and later contributed to the DWAF RWH Guidelines that were published in 2008 for the Expansion Phase. In 2006, as part of the Experimental Phase the author was appointed by DWAF to design and build a number of underground storage tanks. The author has drawn from these experiences in writing this document.

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1.0 Background and Introduction

South Africa is a co-signatory to the Millenium Development Goals, the first of which is to reduce by half the level of extreme poverty and hunger in the world by 2015. As part of their contribution towards this initiative the Department of Water Affairs and Forestry (DWAF) in South Africa has embarked on a Rain Water Harvesting Programme to uplift the very poor. The program targets the issue of extreme hunger by providing a 30000 litre underground rainwater storage tank in the homesteads of the very poor who are able to show their commitment to intensive food production gardens. Studies have shown that with this quantity of water a household will be able to sustain a garden of between 100m^2 to 200m^2, even through the dry months, and thus provide the essential micro-nutrients to sustain particularly children in the first crucial five years of their lives, so preventing permanent mental and physical stunting(1). If such measures are sustained the poverty cycle will eventually be broken.

In October 2005 the author was invited to join a core team that had been tasked by DWAF to develop the RWH Program. The author's particular brief was to consider different designs and ways of building RWH reservoirs with a capacity of 30000 litres.

Particular emphasis was place on safety, which has had the effect of significantly increasing the cost of the structures, but which will prevent drownings. Safety features include (1) raising of the walls of the structures at least 500mm out of the ground, (2) roofing the structures with steel sheeting, (3) providing a lockable trapdoor, (4) providing rungs leading down into the interior of the tank, (5) providing a safety grill over the inlet structure.

In this paper the author compares ten different designs of underground RWH reservoirs (hereafter referred to as 'dams') with a view to assisting implementing agents in selecting the correct design for particular applications. The 'standard' RWH dam that was eventually selected as the preferred design and is discussed in somewhat greater detail.

The various construction materials are listed for each design, along with direct building costs. All costs have been shown in USD, where the prevailing conversion rate of ZAR10 rands per USD has been applied. However, indirect costs such as logistic and management support have been excluded, as these costs will vary from one implementer to the next, and are furthermore dependent on the number of dams being constructed.

The main advantages and limitations of the various designs are also discussed.

2.0 Brief Description of Ten RWH Dams

Most of the designs that are considered here were investigated during the Pilot Phase including the 'Box', 'Triple box', 'Standard', 'Finnbuilder', 'Ferro-cement', 'Hemisphere', 'Prism', as well as a variation of the 'conical' dam. Only the 'shotcrete' and 'plastic tank x 3' were not built, but the author is well acquainted with the former, while the latter is under consideration in the

Expansion phase. It may be seen that the dams are named either after their shape, material, or construction method.

The shapes of the various dams are illustrated in figure 1. The specific dimensions corresponding to a capacity of 30000 litres are given in appendix 1 for each dam, along with the key formulae used to calculate their capacities, surface areas, and material volumes. In appendix 2 the various materials used for the construction of each of the dams are listed complete with the required quantities. Appendix 3 gives the corresponding costs for the materials listed in appendix 2, and also indicates the amount paid to the builders. Appendix 4 is an example of how the builders are remunerated – in this case for the standard dam. The lowest wage has been set at R60 per day, or $6 per day. The total amount paid to the builder for each dam is shown in appendix 3. The figures are shown in rands and should be divided by ten to convert to USD.

The total cost of materials and payments to the builder has been abstracted from appendix 3, and is reproduced in Table 1 below. It represents the 'direct' cost of the dam.

TABLE 1 - SUMMARY OF DIRECT COSTS TO BUILD 10 RWDs

TYPE OF RWH DAM	MATERIALS	BUILDERS	TOTAL DIRECT COST	COST RATIO RELATIVE TO STANDARD DAM
	USD	USD	USD	%
Std (maxi bricks)	1600	468	2068	0.0
Finnbuider	1639	552	2191	5.9
Shotcrete	1366	497	1863	-9.9
Ferrocement	1609	600	2209	6.8
Cone	1450	445	1895	-8.4
Hemisphere	1300	488	1788	-13.5
Prism	1331	465	1796	-13.1
Plastic tank x 3	2826	755	3581	73.2
Box	1720	503	2224	7.5
Tripple-box	2057	640	2698	30.5

Table 1 does not factor in 'indirect' costs, such as management costs, logistical support, capital and running costs of vehicles and equipment, head office overheads etc, as these costs will vary from one organization to another, and are also inversely related to the number of dams to be built in an area.

The various dam types are now briefly described along with their strengths and weaknesses. The standard dam is discussed first, in some detail – and from the understanding gained by this the others can be discussed more briefly.

2.1 Standard RWH Dam

The 'Standard RWH Dam' is illustrated in figures 2 through 5. It is cylindrical in shape (see figure 1.1) with 2m high walls made from 'maxi-bricks' (290mm long x 140mm wide x 90mm high – see figure 3) standing on a 100mm thick mesh reinforced concrete floor-slab. A circumferential ring made up of 10mm high-yield reinforcing bars are inserted selectively in six of the 19 mortar beds. The walls are plastered to a thickness of 15mm, and later coated with an epoxy waterproof coating (see figure 4) which is both elastic and exceptionally tough and durable. A bandage of geofabric material is applied at the corner where the wall meets the floor, to which the epoxy is also applied.

The roof consists of 0.5mm thick galvanized IBR sheeting, supported by two 100/125 mm treated gum poles. Both the gum poles and the sheeting are tied down to the walls by 4mm galvanized wire. A hinged trap door is created in one of the sheets for access into the tank.

The independent inlet (see foreground of figure 5) and overflow structures butt up directly against the dam, and consist of blocks or bricks built on top of a mesh reinforced slab. Once again a bandage of geofabric material applied with the waterproofing epoxy ensures water tightness at the interface where these structures butt up against the dam’s wall. Water from the inlet structure flows into the dam via three 110mm PVC pipes built into the dam’s wall, and likewise, three 110 mm pipes allow water to exit into the overflow structure on the opposite side once the dam is full. The inside diameter of the dam is 5200mm, while the height of the water from the floor to the invert level for both the inlet and overflow pipes is 1425mm. At full supply level the capacity of the dam is 30000 litres.

The advantages and disadvantages of the standard dam are now considered:

2.1.1 Advantages:

(1) *Materials :* This method of construction has application where maxi bricks are locally manufactured and reasonably priced. Generally this is the case for most parts of South Africa. Even in remote rural areas maxi bricks can be obtained at relatively low cost owing to cheap labour and the availability of 'free' river sand from rivers.

(2) *Shape* : The cylindrical walls go into compression when backfilling is correctly done, thus canceling tensile stresses that would otherwise develop and possibly lead to cracks. (Note that concrete and cemetitious products are strong in compression, so whatever compression is introduced into the wall by backfilling and compacting is not harmful). This characteristic of a cylindrical dam makes it substantially more cost effective than say a box shaped dam, where earth pressures cause bending in the walls, leading to cracks, unless a significant amount of carefully placed reinforcing is provided. In spite of the cylindrical dam’s favourable shape, a nominal amount of 'insurance' reinforcing is still provided in the standard design, in the event of sub-standard backfilling allowing tensile forces to develop.

(3) *Skills* : The level of skill for the construction of the standard RWH Dam is readily within the experience of local builders. Tasks include: mixing and placing of concrete, laying blocks, plastering, waterproofing with block-brushes, securing roof-sheeting over treated poles, etc.

(4) *Pole-Arm* : Various construction processes can be substantially simplified and accelerated by installing a 'central pole & radial arm'. This simplifies the excavation, the floor-slab, the walls, and the plastering[(2).]

(5) *Cost* : Assuming materials are locally available, the Standard RWH Dam has a relatively low cost structure, where only those dams with a ratio in excess of 1 may be said to outperform the Std dam. It may be seen from table 1 that the direct cost of the standard dam is $2068.

(6) *Speed* : A 'Standard RWH Dam' can be built in 5 days on a well organized site (excluding excavation time, which takes the digging team approximately 6 days providing the ground is easily pickable).

2.1.2 Disadvantages:

(1) *Porosity*: The maxi-bricks used to build the walls are not all well compacted, and some of them are substantially porous. This necessitates the application of a waterproof coat. But the bricks are too rough to apply this coat directly to them – if this was attempted there would be substantial number of blow-holes, requiring many applications to fully close them all up – and as the waterproof epoxy is very expensive, this would be a costly exercise. The solution is to plaster the wall to achieve a smooth surface with limits the amount of epoxy waterproof required.

(2) *Movement*: It is convenient to cast the concrete slab first as this provides a hard and level platform for other activities, and especially for the construction of the walls, which are build directly onto the slab. The possibility of developing a crack at the wall slab interface exists from various movements (a) differential thermal expansion and contraction, (b) differential drying shrinkage and expansion on rewetting, (c) stress related movements from either the backfill compression the wall, or from the hydraulic pressures expanding the wall, (d) differential settlements. To overcome these movements a flexible waterproof ‘bandage’ has been place in the corner to create a seal. The bandage consists of a geofabric material impregnated with the waterproof epoxy – but as with (1) above, this adds to the cost of the dam.

2.2 Finnbuilder

This dam is also cylindrical in shape (see figure 1,1), and is virtually identical to the standard dam. The only difference is that the wall is built insitu using a traveling mould (see figure 6), which goes by the name ‘Finnbuilder’. To begin with, the mould is placed on top of the previous course, closed by means of a lever, progressively filled with a moist sand-cement mixture and compacted by hand with a special tool. The mould is then opened and gently moved forwards a distance which roughly corresponds with the length of the mould, and the whole process is repeated until the mould has traveled the fully 360 degree circuit – whereupon it is lifted out and placed on top of the newly completed layer, and the whole process repeated.

2.2.1 Advantages

(1) Materials : Where the material from the excavation is sandy it can be used to build a very satisfactory wall. Alternatively a cheap source of sand may be available nearby. In such cases significant savings in the cost of the wall will be realized.

(2) Shape : Being of the same size and shape as the 'Standard RWH Dam' it has all the advantages of economy and structural robustness that a cylindrical shape provides.

(3) Pole-Arm : By using this device [(2)] the new position for the traveling mould is quickly and accurately obtained every time the mould is moved forward. The pole/arm may be seen in figure 6.

(4) No Plaster : It is possible to proceed with the wood and steel floating operation (see figure 6) and hour or two behind the mould – all that is required is to smooth off the still-workable mix.

2.2.2 Disadvantages

(1) Unknown : The method of construction is not generally known and builders will require training.

(2) *Special Equipment* : A travelling mould such as a Finnbuilder is a specialized peace of equipment, not readily available and not cheap. But since the mould is robust and can be reused many times over, it adds minimally to the cost of the RWH Dam where many dams are to be constructed.
(3) *Sensitive* : This method of building is relatively sensitive to the water dosage. Too much water results in the walls slumping, while too dry a mix lacks plasticity resulting in 'brittleness', causing cracking and collapsing at the slightest bump when for example the mould is moved to the next position.
(4) *Slow* : The construction process is at least 50% slower than that of a conventional block wall. This is because the 'block' has to be 'manufactured' in position, and while this does away with a separate laying operation (as in a 'mortar and block' wall), this saving in time is completely overrun by the slower 'manufacturing' process of filling and stamping in situ. Where labour is expensive, this additional time is clearly a difficulty.
(5) *Shrinkage* : The wall is more prone to shrinkage cracks developing, since the wall is not 'pre-shrunk' as is the case with a wall made from conventional precast blocks that have been cured for 7 days and then left to 'dry-and-shrink' till they are 28 days old. This makes the application with a flexible waterproof coating imperative.
(6) *Cost* : It may be seen from table 1 that the ‘direct’ cost is estimated at $2191 and that the ‘Finnbuilder’ dam is 5.9% more costly than the Standard dam. If on the other hand the excavated material is suitable for manufacturing the wall, the cost of the structure would be slightly cheaper than the standard dam.

2.3 Shotcrete (Gunite)

Here too the dam has a cylindrical shape, and once again the difference relative to the two preceding dams lies only with the materials from which it is constructed – a reinforced concrete that is pneumatically applied in this case (see figure 7). The thickness of both the walls and floor may be limited to 100mm for a dam of this size since the shell is adequately reinforced and integrally cast, the concrete has a relatively high cement content, and it is well compacted owing to the high velocity of the impacting particles.

Construction sequence: Initially steel panels are set out to form a cylindrical mould. This is lined with a relatively light structural steel mesh, typically ref 100 mesh, to which is attached a number of horizontal hoops made of Y10 high tensile steel at the specified spacing (see figure 7). Next a mixture of sand-gravel-cement-water is pneumatically sprayed, starting with the floor, and then progressively moving around and upwards against the mould. Typically the spraying operation can be done in a day for a dam of this size, but with the other operations involved, such as fixing the reinforcing and setting up and stripping the shutters, a cycle time of 4 days would be usual.

2.3.1 Advantages

(1) *Application* : This method of construction has application where the implementing agent is already equipped to do shot-basting ('guniting'), whereby a sand-gravel-cement mixture is pneumatically applied to the shell (floor and wall). The method further lends itself to places where course aggregate is very expensive, while a source of fine aggregate (e.g. river sand) is available at low cost.
(2) *Fast* : The shotblasting operation, complete with the finishing process, can be completed in a single day. Using other crews to do the setting up and striping of moulds, and the placement of the reinforcing, it would be possible to spray a dam a day in this case.

Clearly this allows substantially more dams to be constructed in a given time frame, reducing the fixed indirect costs (supervision, management, overheads etc.) proportionally by spreading them over the correspondingly larger number of dams.

(3) Shape : Being of the same size and shape as the 'Standard RWH Dam' it has all the advantages of that design – see 2.1.2.

(4) No Plaster : Unlike a 'block and mortar' wall, the wood and steel floating operation is done on the same day as the pneumatic process, with no subsequent plastering process required.

(5) No Waterproofing : Shotcrete that is correctly proportioned, placed and finished, is substantially impermeable and does not require a waterproof coat. Furthermore, since the shell is cast integrally with no construction joint at the wall/floor interface, no 'bandage' is required in this zone.

(6) Strength and Durability : This type of structure is virtually unrivalled in terms of strength and durability (only surpassed by the spherical tank). Its strength is derived from the layer of structural steel mesh and hoop steel, and its durability from the relatively rich-in-cement 100mm thick 30MPa dense concrete that provides adequate protection to the reinforcing.

(7) Cost : The rapid rate of construction, coupled with a relatively thin but impervious shell translates into significant cost savings. It may be seen from table 1 that the dam costs $1863 (direct cost) which is 9.9% less than the standard dam.

2.3.2 Disadvantages

(1) Unknown : The method of construction is foreign to most implementing agents and local builders. On the other hand most of the production tasks can be quickly learned by local labour, other than that of the 'nozzleman', where specialist skill and experience is required.

(2) Special Equipment : Some items of equipment are very costly - e.g. large compressor, mixer/blender, steel moulds, large transportation truck, etc. Thus the ‘cost of money’ (interest and depreciation) can be quite significant unless a good production rate is achieved to spread them over a large number of units.

(3) Sensitive : This method of building is relatively sensitive to the water dosage (hence a skilled 'nozzleman' is required) and a suitable source of aggregate must be available.

2.4 Ferro-cement Dam

This too is a cylindrical dam (see figure 1.1), and as with the shotcrete dam this dam also starts off by erecting a cylindrical steel shutter in the excavation. Next the floor and wall are lined with one or more layers of chicken mesh. For small diameter tanks of up to 3m (see figure 8) such reinforcing may be adequate, but for larger diameters, the chicken mesh should be supplemented with structural mesh (e.g. ref 100mesh) and by a number of horizontal hoops made of Y10 high tensile steel at the appropriate spacing.

The ferro-cement dam differs from the shotcrete dam in terms of construction method. Whereas the former requires a substantial investment in machines, the shell of the ferrocement dam is built up with a simple steel trowel, in successive thin layers, and taking care to exert pressure on the trailing edge of the blade to achieve a suitable measure of compaction and hence imperviousness. The day after the first application of mortar, the steel mould is taken away so that the shell can be built up from both sides. Generally it takes a few days to build up the shell to the required thickness to prevent buckling from backfilling pressures (ideally 100mm for the RWH dam under discussion – see appendix 1 for dimensions), and also to ensure that there is adequate mortar covering the reinforcing to prevent corrosion – 30mm cover on both sides at the very least, preferably 40mm.

2.4.1 Advantages

(1) *Labour* : The method is labour intensive, creating employment.
(2) *Materials* : Suitable plaster sand is generally locally obtainable.
(3) *Shape :* Being a reinforced cylindrical structure it performs well in both compression and tension – see 2.1.2.
(4) *Plaster* : No subsequent plastering operation is required.
(5) *Waterproof* : Providing the various layers of plaster were correctly applied, and that a relatively rich mix (high cement content) was use to make the mortar, the shell should be watertight and not require a waterproof coating. Furthermore, since the shell is cast integrally with no construction joint at the wall/floor interface, no 'bandage' is required in this zone.

2.4.2 Disadvantages

(1) *Durability*: If inadequate cover of the correct compaction is provided the chicken mesh and other reinforcing corrode.
(2) *Cost:* At $2209 for materials and labour (see table 1) the ferro cement dam is 6.8% more costly than the standard dam – unless a suitable aggregate can be obtained at virtually no cost, or labour can be sourced at a low cost.

2.5 Conical Dam

This dam has the shape of a truncated cone – see figures 1.2 and 9. In this dam the excavation is in effect the external shutter for both the floor and the walls. Generally structural mesh is used to line the shell up to ground level, appropriately supplemented at regular intervals with Y10 high tensile bars – although if the ground is relatively hard or stiff, these bars may be dispensed with.

Thereafter a sand-cement-water mixture is applied to both floor and walls – once again up to ground level. The walls are built by shoveling blobs of the mix in successive upward spiraling circles, which are shaped smooth using wooded trowels. The natural angle of the cone greatly assists in preventing the mix in the wall from collapsing. Also the ground ‘shutter’ is generally absorbent to a degree, and excess water in the mix is thus absorbed, which stiffens the mixture, allowing is to support subsequent layers.

The following day the final 500mm of the wall that protrudes above ground level may be built on top of the concrete shell, using either maxi-bricks or even hollow blocks, or alternatively an external shutter may be used and the packing process continued to roof height. Later the roof is constructed as described in 2.1.

2.5.1 Advantages

(1) *Application* : This method of construction has application where there are large rocks in the wall or floor areas, since the mesh can be shaped around such.
(2) *Shape* : The inclined walls of this dam allow the walls to be hand packed - using a combination of shovels and wood floats to place and finish the sand-cement mixture.
(3) *Skills* : The level of skill required for this type of construction are readily transferable to local builders.
(4) *Pole-Arm :* The excavation, floor, and wall building processes can be done with a 'central pole& radial arm' system, achieving accurate final dimensions as a result.
(5) *No Plaster* : Unlike a 'block and mortar' wall of the standard dam, the floating operation is done on the same day, with no separate plastering process required.
(6) *No Waterproofing* : A sand-cement mixture that is correctly proportioned, placed and finished is substantially impermeable and does not require a waterproof coat. Furthermore, since the shell is cast integrally with no construction joint at the wall/floor interface, no 'bandage' is required in this zone.
(7) *Durability* : Like the shotcrete dam, this type of structure has a very strong shell with excellent durability.
(8) *Cost:* At $1895 for materials and builders (see table 1) the conical dam is 8.4% more cost effective than the standard dam.

2.5.2 Disadvantages

(1) *Depth* : The inclined walls reduce the capacity of the dam, and thus for a given footprint the depth needs to be increased to achieve parity in storage capacity. However, at an angle of 75 degrees these effects will be slight.
(2) *Pole-Arm* : The pole-arm assembly requires an increased level of sophistication to cater for the inclined walls.
(3) *Sensitive* : This method of building is relatively sensitive to the water dosage and type of sand. The excavation must be stable, so that the method cannot be used in collapsing ground.

2.6 Hemispherical Dam

A hemispherical shape (see figure 1.3 and 10) does away with the wall floor joint (as do the shotcrete and conical dams). Providing the supporting ground is relatively uniform the whole shell should be in a state of compression, which of course is ideal for a structure made from sand-cement. In this event the only real function of the reinforcing is to (a) give some tensile resistance in the event of isolated hard spots in the supporting ground (which can cause localised bending effects = tension=cracking), and (b) to limit the size of potential drying shrinkage cracks. It is however advisably to have one or more horizontal hoops of 10mm reinforcing near to ground level as generally the ground near the top is softer and less supportive. In this case this reinforcing will prevent cracking in the upper zones – since hoop stresses will be present if the lateral stresses in the water exceed the lateral restraint from the ground.

The profile of the tank lends itself to packed sand-cement. As the fresh concrete is largely supported by the ground increased speed of packing can be achieved. Only near the top does the orientation tend towards the vertical, and here a slower rate of packing will be required. The sand-cement should be floated smooth on the same day of casting, doing away with the need for subsequent plastering.

The hemispherical aspect of the dam ends at ground level, requiring a cylindrical ring to be built above this so that the dam will protrude at least 500mm above ground level. This operation may be done the day after casting the hemisphere.

2.6.1 Advantages

(1) Application : This method of construction has application where the ground is relative pickable and uniform to a substantial depth.
(2) Shape : The hemispherical shape is the most efficient in terms of volume storage, so that more storage is achieved for a given surface area.
(3) Skills : The level of skill required for this type of construction is readily transferable to local builders.
(4) Overhead beam : The hemispherical excavation may be facilitated by placing an overhead gum pole across the excavation area. A universal ball-and-socket swivel may then be fastened on the underside of the pole in the center of the pole, to which a hollow tube of the correct radius is attached. Using this as a guide, a perfect hemisphere may be achieved.
(5) Plaster : As with the conical and gunite dam, no subsequent plaster or waterproofing operations are required.
(6) Strength and Durability : This type of structure is unrivalled in terms of strength and durability. Its strength is derived from its hemispherical shape, which tends to go into a state of pure compression when filled with water – minimizing the need for steel reinforcing.
(7) Cost: At $1788 (direct cost - see table 1) the hemispherical dam is 13.5% more cost effective than the standard dam, and the most cost efficient of the ten dams.

2.6.2 Disadvantages

(1) *Deep :* The hemispherical dam is the deepest of the dams; the water is 2430mm at the center. For the cylindrical dams the equivalent volume is achieved with a depth of just 1425mm. This has implications in terms of excavating the ground – if the ground gets substantially harder with increased depth this may rule out the possibility of this type of structure.
(2) *Ground :* On the other hand this dam will also not work in ground that has a tendency to break away, given that the ground is in effect the external shutter.
(3) *High groundwater:* Caution should also be exercised where there is a high water table. A water table at 1.5m will not affect the standard dam, but may result in flotation in the case of the hemispherical dam. Furthermore, while the standard dam has a floor-slab that protrudes beyond the walls, and this acts as an anchor against uplift forces. The hemispherical dam has no such anchorage, and clearly this increases the risk of flotation.

2.7 Prism Dam

The shape of this dam may be seen in figure 1.4. It has an upper rectangle of dimensions 8400mm x 4400mm, a lower rectangle of 5550mm x 1550mm, with the lower rectangle 1425mm below the upper, and the slope 45 degrees. It has a capacity of 30.1m^3 (see appendix 1).

On top of the upper rectangle a 500mm high 'safety wall' or berm is constructed (not shown in figure 1.4) to support the elevated roof.

The bottom and inclined floor may either be lined with a PVC liner, or with a geofabric impregnated with bitumen (see figure 11). The materials for this dam are given in appendix 2, while the corresponding cost is calculated in figure 3, and summarised in table 1. In appendix 2 the option of a PVC liner is given, and on this basis the dam is substantially more cost effective than the standard dam.

2.7.1 Advantages

(1) *Accessibility :* This design has application in inaccessible areas where materials have to be carried by donkey (assuming a PVC liner or bitumen/geofabric liner are used to waterproof the dam).
(2) *Flexibility* : The liner is flexible and will accommodate settlement and differential settlement.
(3) *Tough* : The PVC liner is 750 micron thick and has substantial tensile strength to resist tearing. It also has UV filters, although in a dam with a roof this should not be an issue.
(4) *Impermeability* : No seepage will occur in PVC and bitumised geofabric lined dams - but special skills and materials are required to lay and seal the material.
(5) *Roof* : The rectangular shape means all the poles and sheets can be the same length
(6) *Maintenance* : A PVC liner can be repaired by gluing on a patch. Geofabric/bitumen liner may be repaired by the home owner by applying a patch of geofabric painted over with bitumen.
(7) *Speed* : The PVC liner can be installed in a matter of a few hours in a properly prepared excavation.
(8) *Cost* : At $1796 (direct cost - see table 1) the hemispherical dam is 13.1% more cost effective than the standard dam.

2.7.2 Difficulties

(1) *Complexity* : Specialist contractors are required to weld the PVC liner together. Achieving the correct excavated shape is relatively complex. On the other hand a geofabric/bitumen liner may be installed by local builders - after some training.
(2) *Footprint* : The dam has a relatively large footprint owing to the inclined sides of the trapezoid. In loose ground, inclinations less than 45 degrees are required for stability against shear failure (slides) and this substantially increases the footprint.
(3) *Abrasion :* Care should be taken when cleaning the dam not to puncture or abrade the liner.
(4) *Durability* : The liners are not as durable as concrete floors or block walls. The geofabric/bitumen option will require resurfacing within five to ten years, while the PVC guarantee only extends for 10 years.
(5) *Scooping :* The inclined angle makes it more difficult to scoop water with buckets, and increases the likelihood of damage to the liner during scooping actions, although this problem may be overcome by installing a pump.

2.8 Plastic Tanks x 3

In this option 3 x 10000 litre polyethylene tanks are placed inside a 3m deep excavation, and interconnected with pipes near their bases so that the tanks behave as a single 30000 litre storage facility (see figure 12). Three 110mm pipes connect the first tank with the inlet, and likewise three 110mm PVC pipes connect the last tank to the overflow structure. A 150mm thick ‘wall’ made up of a moist sand-cement mixture is placed and compacted around each tank concurrently with the backfilling operation. These ‘walls’ will prevent the backfill from collapsing in upon the tanks at a later date. It is necessary to fill the tanks with either water or sand prior to the compaction exercise so that they do not cave in from the compactive effort.

2.8.1 Advantages

(1) *Waterproofing* : The tanks have excellent waterproofing capabilities.
(2) *Durability* : The tanks should last indefinitely since they are protected from the sun.
(3) *Speed* : Once the excavation is prepared the tanks can be placed and connected together in a matter of hours. Although the subsequent compaction and backfilling process will take several days, this can be done by done by other ‘follow-up’ teams, and there can be as many of these as required.

2.8.2 Disadvantages

(1) *Depth of hole* : These tanks are 3040mm deep and 2200mm wide. To dig such a deep excavation is problematic. When an excavation is deeper than 1.5m, then the department of labour (in South Africa) stipulates that the hole either has to be shored up to prevent any injury from collapse, or the sides of the excavation must be inclined at an angle of not more than 60 degrees. This clearly has significant cost implications when it comes to excavation and significantly adds to the amount of backfilling required.
(2) *Excavation :* A normal TLB does not cope well below depths of 2.5m, after which an excavator is required. An excavator is very expensive to establish on site, and if the excavations are not in very close proximity, frequent removals from one site to the next will be required by a lowbed (very expensive), since to 'walk' an excavator over large distances causes excessive wear to the undercarriage.
(3) *Transportation* : Delivery costs can be substantial if the site where the tanks are being installed are a long distance from the tank manufacturer.
(4) *High water table* : The use of plastic tanks should not even be considered where high external water pressures are possible from a high water table, which typically occur in clayey soils with poor drainage. The alternative would be to install heavy duty ribbed tanks (see figure 13), but a 30000 litre tank of this design costs in the region of $7000 – just for the tank!
(5) *Cost* : At $3581 for materials and builders (see table 1) the plastic tank x 3 option is the most costly option of all the ten designs, and 73.2 percent more than the standard dam.

2.9 Box Dam

Generally these dams are constructed by casting a 100mm thick concrete floor, upon which four walls are constructed. An example of a box dam is shown in figures 14 and 15. The 30000 litre dam referred to in table 1 has an internal length and width of 4610mm and a useful depth of 1425mm, with the total height of the walls being 2000mm (see appendix 1). Maxi-bricks (290mm x 140mm x 90mm) were used to construct the dam, and a considerable number of Y10 steel reinforcing bars were provided to resist bending effects from backfill pressures (refer to appendix 2 for the materials and appendix 3 for the corresponding costs).

2.9.1 Advantages

(1) *Simplicity :* Virtually any builder can build this dam, as it is very similar to a normal structure.
(2) *Economy in roof sheeting* : Unlike circular roofs, no trimming is required and there is no wastage.

2.9.2 Disadvantages

(1) *Walling:* For a given capacity more walling is required compared to a circular dam.
(2) *Reinforcing:* Bending stresses occur in the walls, firstly from water pressing from the inside, although this is generally countered by the pressure exerted by the backfill – but not always, if for example the backfill was inadequately compacted. More serious is the pressure exerted by the backfill when the dam is empty. With time, as the backfill consolidates, these pressures will increase and gradually push the walls over if inadequate reinforcing was provided.
(3) *Cost:* The increased reinforcing and walling of the box dam translates into higher costs. It may be seen from table 1 that the cost of materials and builders to build this structure is $2224, which is 7.5% higher than the standard dam. Were is not for the lower roofing costs, this figure would have even been higher.

2.10 Tripple Box Dam

This dam is in effect an elongated box dam that has two internal walls that prop up the long walls. (These internal walls have pipes at their bases to so that the level in each compartment is always the same). The net effect is that the dam takes on the appearance of three smaller dams.

2.10.1 Advantages

(1) *Reinforcing:* By compartmentalizing this dam the internal length and width of the walls is reduced from 4610mm to 2660mm and since bending moments from uniformly distributed loads are proportional to the square of the span, the actual reduction in bending effects will be considerably more than the proportional change in the length would suggest – instead of a reduction of 2610/4610 = 0.58, the actual reduction is more likely to be 2610/4610 x 2610/4610 = 0.33!

2.10.2 Difficulties

(1) Even though the bending moments forces applied to the wall are substantially less, the wall should still have steel reinforcing – only it will be less. Figure 16 is an example of how such reinforcing should be laid out. It is evident from this diagram that substantially more reinforcing is required relative to a cylindrical dam which simply has a single hoop of reinforcing bar in the center of the wall. So not only is the reinforcing more, it is also more complex, and hence training and supervision will need to be at a higher level.
(2) Walls: By reducing the compartment size to one third of the area of the large box dam, there is a substantial increase in surface area. The internal area of the walls goes from

36.9m^2 for the large box, to 63.8m^2 for the three small boxes. This impacts on the cement, blocks, plaster, and most significantly of the expensive waterproofing epoxy.

(3) Cost : The result of the substantial increases in the above named building materials, notwithstanding the savings achieved in 2.10.1, is a substantially more expensive dam costing $2698 for materials and builders, which is 30.5% more than the cost of the standard dam.

3.0 Conclusion

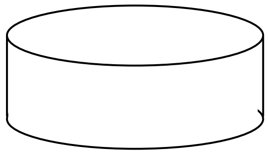
There are many ways of constructing a functional and durable RWH dam. However, the direct costs (materials and labour) vary quite significantly from one type to the other. Cost is of course not the only consideration. Durability coupled with a low maintenance costs are more of a concern to the recipient, but also to the funder who would like to see the end user making use of the dam for many years – particularly governments interested in eradicating extreme poverty. In this respect some of the cylindrical dams, which are strong and durable and require virtually no maintenance other than the occasional removal of silt in the dam, or the oiling of the lock and hinges of the trap door should be seriously considered even though they may cost more than dams which are less durable such as the prism dam with its PVC liner or bitumen/geofabric. But what table 1 does make very clear is that there are some designs that are much more costly without offering anything more in return – such as the triple box dam or the plastic tanks. The table also highlights that there are solutions, such as the hemispherical dam, that are both strong and durable, and yet most cost effective. Where ground conditions and other practicalities allow, these somewhat unconventional structures should be seriously considered.

Finally the appendices give valuable information, such as the dimensions required to achieve a given capacity for each type, or the corresponding areas and volumes which are used to calculate the volumes of materials in appendix 2 leading to the costs in appendix 3. The comprehensive list of materials (see appendix 2) assists potential implementers with logistical planning and execution.

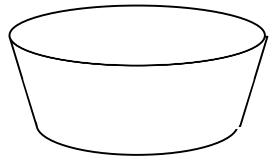
4.0 References

(1) Department of Water Affairs and Forestry ; Programme Guidelines for Intensive Family Food Production and Rainwater Harvesting; June 2007.

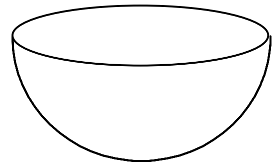
(2) Papenfus, N, J ; A Simple Mechanical Device for Building Cylindrical RWH Dams faster and better; 12th Searnet Internation Conference, Livingstone, Zambia, Dec 2008.



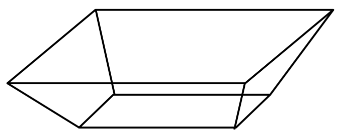
CYLINDER
Figure 1.1



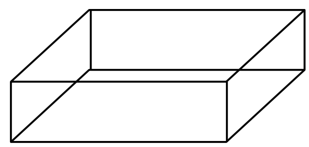
CONE
Figure 1.2



HEMISPHERE
Figure 1.3



PRISM
Figure 1.4



BOX
Figure 1.5

Figure 1 – Shapes of dams investigated in the Pilot phase.

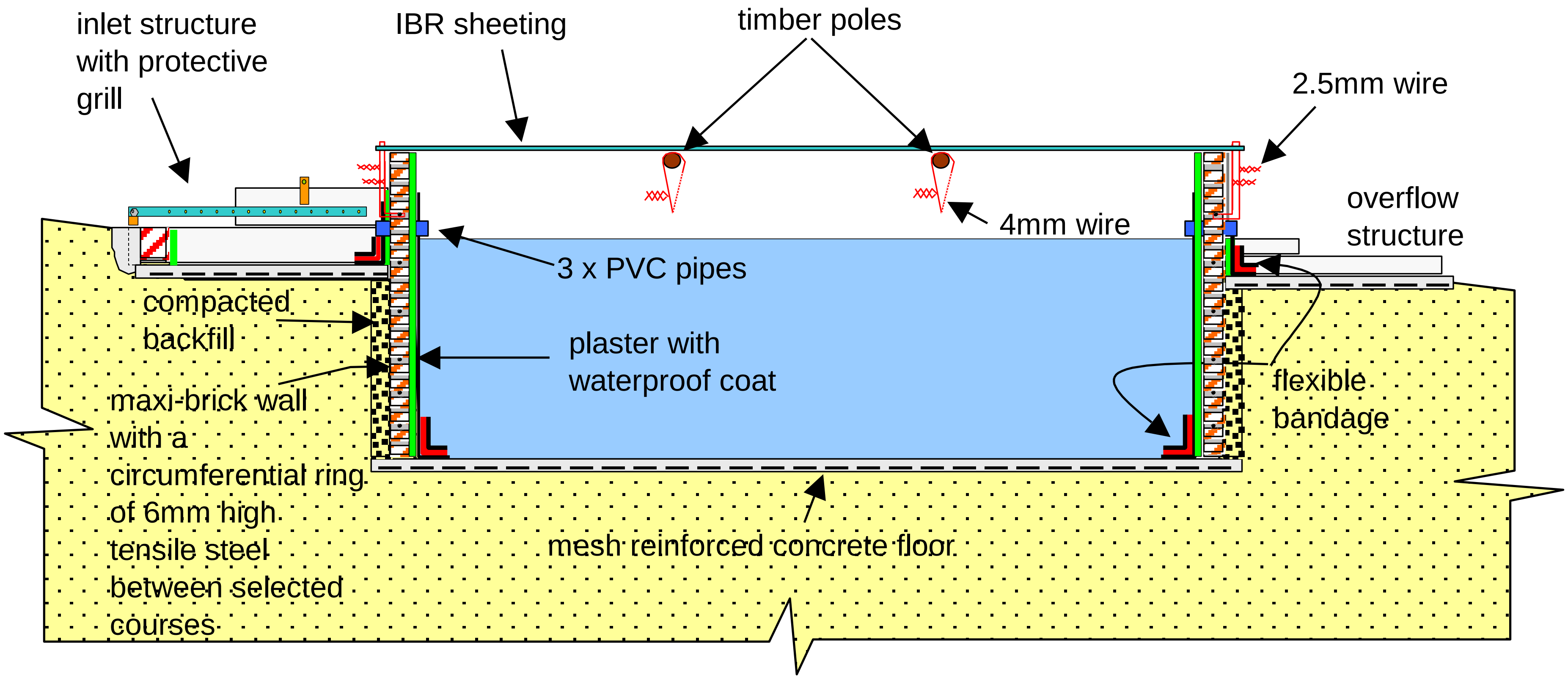


Figure 2 – Section through a ‘Standard RWH dam showing the essential elements

Figure 3 – A standard dam under construction

Figure 4 – A view inside with the waterproofing operation underway

Figure 5 – A completed Standard dam – on the day of handover to house owner Muthavhini

Figure 6 – A 'Finnbuider' traveling mould in operation. Notice the pole/arm nearby which is used to keep the Finbuilder in the correct 'orbit'. Notice too the floating process underway which does away with the need for subsequent plastering operation.

Figure 7 – Shotcrete being applied to the shell of a gunite dam. Note the Y10 hoop steel, held in position by the ref 100 structural mesh.

Figure 8 – Example of above ground ferro-cement tanks – the tanks are less than 3m diameter.

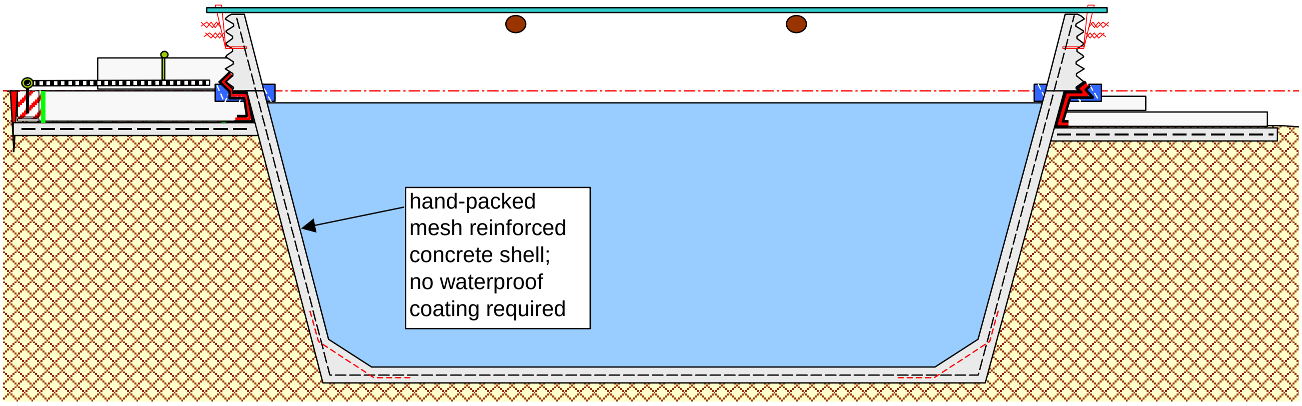


Figure 9 – Section through a conical dam.

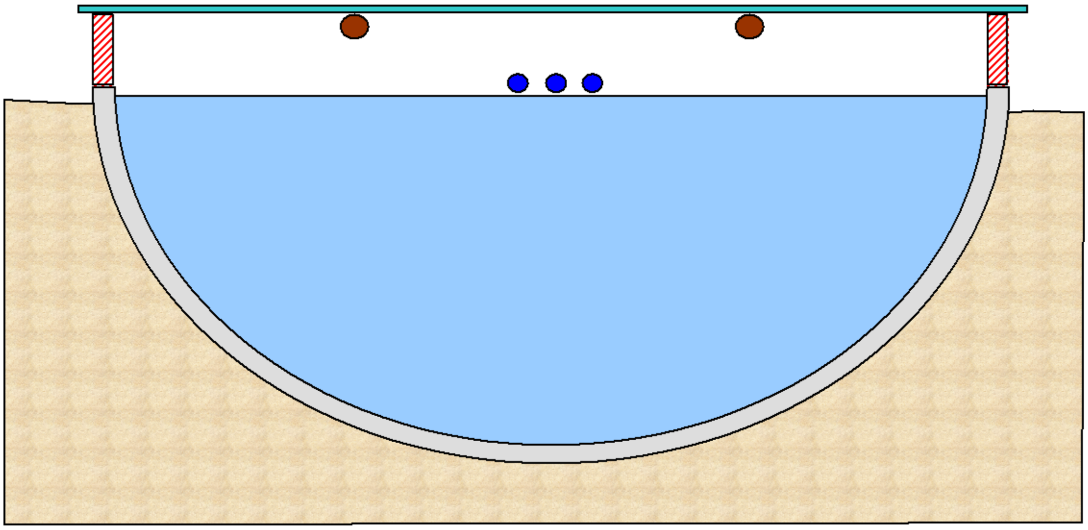


Figure 10 – Section through a Hemispherical Dam. A 500mm wall from bricks/blocks should be built of top of the hemisphere to raise the roof to a safe height.

Figure 11 – Example of a prism dam lined with geofabric.

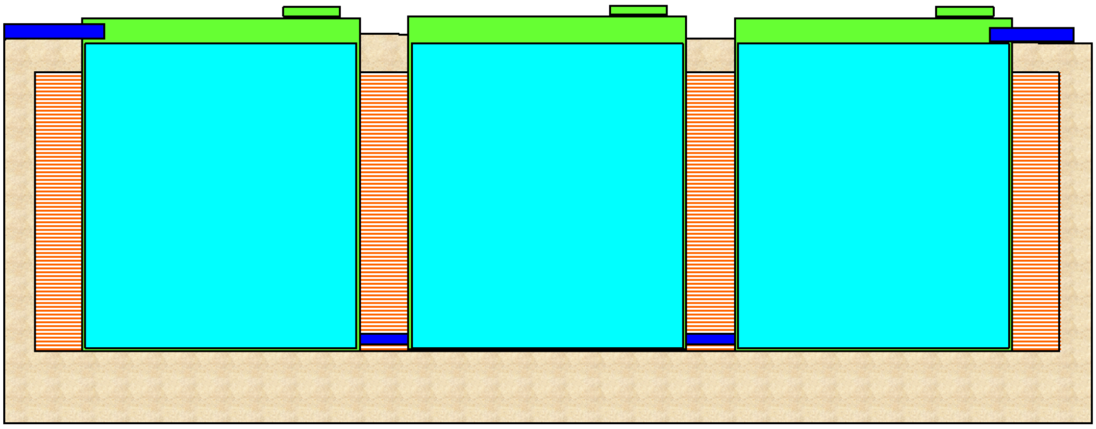


Figure 12 – Section through 3 x 10000 litre dams

Figure 13 – View of a 30000 heavy duty ribbed polyethelene tank

Figure 14 – Example of a box chamber

Figure 15 - Inlet structure for the box chamber

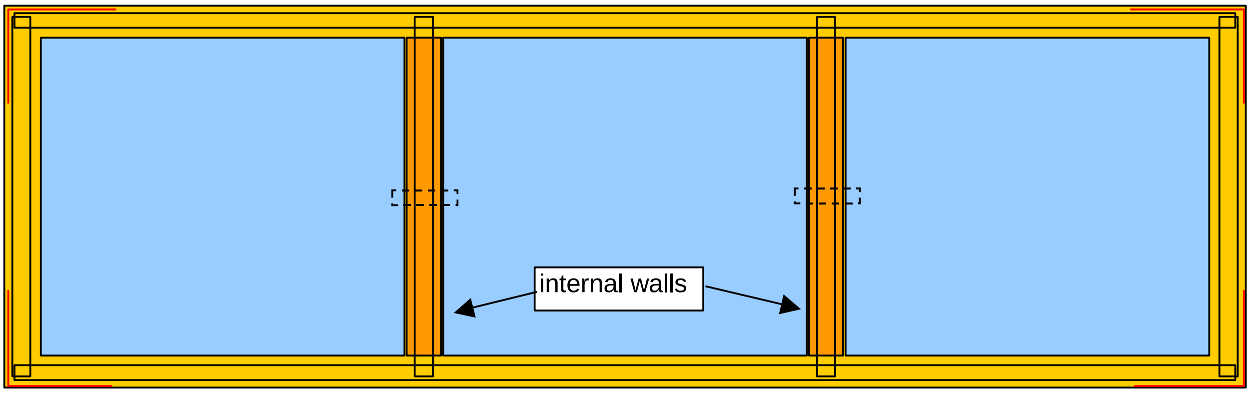


Figure 16 – Arrangement of reinforcing for a triple box chamber

APPENDIX 1 - DIMENSIONS AND RELATED FLOOR, WALL & ROOF AREAS/VOLUMES FOR TEN TYPES OF A 30000 LITRE RWH DAM

DAM	NAME		DIMENSIONS													No.	STORAGE	AREA			VOLUME			VOLUME
			H total	h water	t floor	t wall	D wall inside	D wall outside	D floor outside	L wall	B wall	wall angle	l inside	b inside		TANKS	VOLUME	FLOOR ext	WALL internal	ROOF ext	FLOOR	WALL	TOTAL	RATIO
			mm	mm	mm	mm	mm	mm	mm	mm	mm	deg	mm	mm			m3	m2	m2	m2	m3	m3	m3	
1	Std (maxi bricks)	Cylinder	2095	1425	100	140	5200	5480	5800			90				1	30.3	26.4	32.6	23.6	2.64	4.69	7.33	4.1
2	Finnbuider	Cylinder	2100	1425	100	140	5200	5480	5800			90				1	30.3	26.4	32.7	23.6	2.64	4.70	7.34	4.1
3	Shotcrete	Cylinder	2050	1425	100	100	5200	5400	5400			90				1	30.3	22.9	31.9	22.9	2.29	3.25	5.54	5.5
4	Ferrocement	Cylinder	2050	1425	100	100	5200	5400	5400			90				1	30.3	22.9	31.9	22.9	2.29	3.25	5.54	5.5
5	Cone	Trunc Cone	2325	1700	100	100	5200	5400	4489			75				1	30.1	15.8	36.4	22.9	1.58	3.64	5.23	5.8
6	Hemisphere	Hemisphere	3055	2430	100	100	4860	5060				90				1	30.1	37.1	9.5	20.1	3.71	0.95	4.66	6.4
7	Prism	Prism	2100	1425	100	1				8400	4400	45	5550	1550		1	30.1	48.7	17.3	37.0	4.87	1.73	6.60	4.6
8	Plastic tank x 3	Cylinder	3040	2900	0	150	2100	2400	2400			90				3	30.1	13.6	60.2	13.6	0.00	9.67	9.67	3.1
9	Box	Cuboid	2100	1425	100	140				4750	4750	90	4610	4610		1	30.3	24.5	36.9	22.6	2.45	5.16	7.61	4.0
10	Tripple-box	Cuboid	2100	1425	100	140				2800	2800	90	2660	2660		3	30.2	27.0	63.8	23.5	2.70	8.94	11.6	2.6

APPENDIX 2 - MATERIALS FOR TEN TYPES OF 30000 LITRE RWH DAM

Discription of Material	used in	Units	STD (maxi-bricks)	FINN-BUILDER	SHOT-CRETE	FERRO-CEMENT	CONICAL	HEMI-SPHERE	PRISM	PLASTIC TANK x 3	BOX	TRIPPLE BOX
			QTY	QTY	QTY	QTY	QTY	QTY	QTY	QTY	QTY	QTY
ref 193 mesh for floor slab	floor, I&O	m2	32.5	32.5	32.5		15.8	40.8			24.5	27.0
ref 193 mesh for wall	wall	m2			40.0		26.2					
chicken mesh (2 layers)	floor, wall	roll				144.9						
1.6mm binding wire	floor	kg	0.5	0.5	0.5	0.5	0.5	0.5			0.5	0.5
river sand	floor	m3	1.7	7.5	7.1	7.1	6.7	4.7	8.4		1.6	1.7
stone	floor	m3	1.7	1.7							1.6	1.7
cement - total	floor,walls,I&O	bags	31	50	44	44	43.7	31.5	2.2	34	32.2	49.2
water - total	floor,walls,I&O	litres	932	1763	1500	1500	1416	1300	67	1032	968	1480
PVC liner	floor,walls	liner							1			
mortar sand	wall	m3	1.17				0.35978	0.35978	0.43		1.29	2.29
maxi-bricks	wall	blocks	1026				315	315	378		1131	2010
6m x 10mm Ybars	wall	bars	18	18	18	18	18	18		0	48	29
rungs - galv	wall	rungs	5	5	5	5	5	5	5	10	5	5
110 mm PVC Pipe - class 4	wall	m	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
plaster sand	wall	m3	0.51								0.58	1.00
waterproofing epoxy	wall	kits	3.0	3							3.4	5.9
membrane material	wall/floor	m	16.2	16.2							18.3	31.7
gum poles	roof	poles	2	2	2	2	2	2	4		2	3
4mm galv tie-wire for poles	roof	kg	0.6	0.6	0.6	0.6	0.6	0.6	1.2		0.6	0.9
galvanised IBR roof sheeting	roof	m	43	43	43	43	43	43	54		33.3	34
6mm x 75mm top speed screw	roof	screws	32	32	32	32	32	32	57		28	26
roof washers	roof	washers	32	32	32	32	32	32	57		28	26
2.5mm tie-wires for sheeting	roof	kg	1.9	1.9	1.9	1.9	1.9	1.9	2.8		1.2	7.4
100mm brass hinges	roof	hinges	2	2	2	2	2	2	2.0		2	2
20mm x M5 gutter bolts	roof	bolts	16	16	16	16	16	16	16		16	16
padlock	roof	lock	1	1	1	1	1	1	1	3	1	1
Inlet and Outlet structure	I&O	set	1	1	1	1	1	1	1	1	1	1
safety grill	inlet	grill	1	1	1	1	1	1	1	1	1	1
10000 plastic tanks	tank	tank								3		
intertank connections	tank	set								2		

APPENDIX 3 - COST OF MATERIALS AND LABOUR FOR TEN TYPES OF 30000 LITRE RWH DAM

ALL COSTS ARE REPORTED IN RANDS - DIVIDE BY 10 TO OBTAIN EQUIVALENT DOLLAR COSTS

Discription of Material	**used in**		CYLINDER STD (maxi-bricks)	CYLINDER FINN-BUILDER	SHOTCRETE	FERRO-CEMENT	CONICAL	HEMI-SPHERE	PRISM	PLASTIC TANK x 3	BOX	TRIPPLE BOX
									Total			
ref 193 mesh for floor slab	floor, I&O	m2	1138	1138	1138		553	1429			858	945
ref 193 mesh for wall	wall	m2					917					
chicken mesh (2 layers)	floor, wall	roll				3345						
1.6mm binding wire	floor	kg	17	17	17	17	17	17			17	17
river sand	floor	m3	258	1138	1071	1071	1011	718	1276		239	264
stone	floor	m3	430	430							399	264
cement - total	floor,walls,I&O	bags	2068	3335	2955	2955	2912	2100	148	2289	2149	3284
water - total	floor,walls,I&O	litres	0	0	0	0	0	0	0	0	0	0
PVC liner	floor,walls	liner							2727			
mortar sand	wall	m3	176				54	54	65		194	345
maxi-bricks	wall	blocks	1539				473	473	568		1696	3015
6m x 6mm hoop Ybars	wall	bars	1051	1051	1051	1051	1051	1051		1051	2803	1686
rungs - galv	wall	rungs	500	500	500	500	500	500	500	1000	500	500
110 mm PVC Pipe - class 4	wall	m	74	74	74	74	74	74	74	74	74	74
plaster sand	wall	m3	76								86	149
waterproofing epoxy	wall	kits	1500	1500							1697	2938
membrane material	wall/floor	m	100	100							113	196
gum poles	roof	poles	287	287	287	287	287	287	510		287	239
4mm galv tie-wire for poles	roof	kg	14	14	14	14	14	14	28		14	21
galvanised IBR roof sheeting	roof	m	3361	3361	3361	3361	3361	3149	4192		2587	2667
6mm x 75mm top speed screw	roof	screws	32	32	32	32	32	32	57		28	26
roof washers	roof	washers	13	13	13	13	13	13	23		11	11
2.5mm tie-wires for sheeting	roof	kg	53	53	53	53	53	53	79		32	207
100mm brass hinges	roof	hinges	100	100	100	100	100	100	100		100	100
20mm x M5 gutter bolts	roof	bolts	16	16	16	16	16	16	16		16	16
padlock	roof	lock	40	40	40	40	40	40	40	120	40	40
Inlet and Outlet structure	I&O	set	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200
safety grill	inlet	grill	500	500	500	500	500	500	500	500	500	500
10000 plastic tanks	tank	tank								21000		
intertank connections	tank	set								400		
Waste & shrinkage		%	1454	1490	1242	1463	1318	1182	1210	623	1564	1870
Total for materials excl VAT			15997	16390	13664	16092	14497	13002	13312	28257	17204	20574
local building team (excl management and logistical support)			4680	5517	4967	6000	4450	4877	4647	7551	5032	6402
Total - materials and builders			**20677**	**21907**	**18631**	**22092**	**18947**	**17879**	**17959**	**35808**	**22236**	**26976**
% of dam's cost relative to the 'Standard' RWH dam			0.0	5.9	-9.9	6.8	-8.4	-13.5	-13.1	73.2	7.5	30.5

APPENDIX 4 - LABOUR COSTS FOR STANDARD CYLINDRICAL RWH DAM - BLOCK WALL ON RC SLAB							
Description	unit	ALE	homeowner	logistical labour	diggers	builders	roofers
setting out	days	0.25	0.25	0.25			
excavation of trial pit	days		2				
installation of central pole/arm	days	0.25		0.25			
store materials	days		as reqd				
supply water to digger/builder	days		as reqd				
supply electricity to builder/roofer	days		as reqd				
excavation of hole	days				5		
create 1m working space	days				0.5		
placement of floor reinforcing and concrete	days			0.25		1	
building of block walls	days			0.5		2	
plastering walls	days			0.5		1	
backfilling at omc	days				2		
waterproofing walls	days			0.25		0.7	
landscaping (berms and leveling)	days			0.25	1		
inlet and outlet	days				0.5	1.5	
clean up	days			0.5		0.3	
install roof	days			0.25			1
total estimated theoretical time	days	0.5	2.25	3	9	6.5	1
efficiency of labour	%			75%	75%	75%	75%
budgeted time	days			4	12.0	8.7	1.333
number of men in team	men			1	2	4	2
average rate of pay	R/day			50	60	80	100
Payment	R			**200**	**1440**	**2773**	**267**
Total payment	R						**4680**