Tailings pond design for alluvial mining effluents in Guyana

Construction and reference manual for operators

Document adapted by GGMC and CANMET
Under the
CIDA funded GENCAPD project

Draft – February 2005

TABLE OF CONTENTS

List of Pictures

List of Figures

List of Tables

1. Introduction

1.1. Background

Before the 1980's, alluvial gold was extracted mainly in the rivers of Guyana. The extractive industry would use river dredges and pump the gravel river beds on sluice box. The effluent of the river dredges contained only a small fraction of clays in their tailings. Turbidity plumes would not extend far downstream from the dredges.

Due to a lack of exploration on land, land dredging was marginal in the country. In the 1980's Golden Star did extensive exploration in the Proto-Mahdia deposits and found that the grades were not sufficient for profitable gold extraction. With time, those claims were handed back to GGMC and, with the increase in gold prices, it became profitable for small and medium operations to start land dredging by licensing those claims. Without any mechanization, except for high pressure pumps, miners would make a living out of mining if they kept their capital investment as low as possible. This meant stripping the overburden and pay gravel by jetting.

On land the overburden may contain as much as 85% content of clay that is being flushed in the creeks and rivers. Since these hard to settle particles travel in the water column for long periods, they create extended turbidity plumes that affect downstream communities for domestic water supplies.

Livan and Couture (2002) and Couture and Lambert (2002) found that these small fraction particles with the presence of decaying organic matter trapped mercury that traveled within the plumes and eventually settled on the riverbeds. Abundant mud (clay, silt and organic matter) surficial sediment layers were concentrated essentially downstream from mining operations. This is where the whole process of methyl-mercury incorporation in the aquatic food chain was most important. Mercury concentration in non-mining areas mud fractions were not significantly different than in mining areas. The abundance of mud due to jetting from land dredge operations and discharged in creeks and rivers was responsible for the unusual abundance of mercury. Since Amerindian communities have a high fish diet compared to other Hinterland communities, they are the ones prone to mercury intoxication (Lafleur *et al*, 2002).

1.2. Objectives

As mentioned in the previous section, land dredge tailings are the cause of many human impacts. It deteriorates water quality usage for downstream communities living in the vicinity of the turbidity plumes and displaces land based naturally occurring mercury in the aquatic ecosystem and, eventually, in fish eating communities.

By applying only one mitigation measure, that being tailings management practice, booth water quality for domestic purposes and methyl-mercury concentrations in fish flesh consumed could recover to better levels.

The present manual provides a theoretical and practical approach to building tailings confinement and overspill management. It is intended as a training manual for mines engineers. A more concise and check list version should be extracted and provided to mines inspectors and miners.

This document is based on information gathered during filed trips and documents produced during the GENCAPD project. In particular, the work performed by Chris Curnow, Lyod Stephen, Karen Livan and Richard Couture. Significant contributions also come from the staff of the Mines and Environmental Divisions of GGMC. Theoretical designs were extracted from the design manuals of Simons, Li & Associates (1982) and Sigma Resources (1986).

2. Available pond designs

2.1. Excavated sediment ponds

Excavated sedimentation ponds are constructed by excavating a pit or "hole" in the ground with the use of a bulldozer, a backhoe or by jetting. Generally, these types of sedimentation ponds are limited to certain surface runoff from disturbed areas at surface mines located in rolling to flat terrain and from small drainage areas. Sedimentation ponds which are constructed strictly by excavation are not used in steep sloped terrain due to the large amount of excavation that would be required to achieve the applicable storage and volume requirements. Excavated ponds are generally located off a natural drainage way.

The excavated sedimentation pond can often come from a first mine pit which serves as a preliminary settling basin. The tailings from the sluice box within the mine site are directed into the mine pit where settling of the larger size particles occurs. From the pit, the mine drainage is pumped into the excavated sedimentation pond or above ground pit where final settling occurs. Using pumps to control the inflow into the excavated sedimentation pond allows control of the retention time with the sedimentation pond. Additionally, the storage volume within the pit can be utilized, thereby reducing sedimentation pond storage requirements as long as the storage volume within the mine pit does not interfere with mining operations.

There are many advantages with the excavated sedimentation pond in Guyana (Picture 2.1). It is ideal for applications in relatively flat terrain and controlling surface runoff from small drainage areas. Installation of dewatering devices in these types of ponds is generally very expensive and

Picture 2.1 : Excavated ponds in NWD

therefore, not recommended for Guyanese operations. This leads to the pond storing water for a long period of time thus reducing the available storage volume when a storm event occurs and providing breeding grounds for mosquitoes after mine decommissioning.

2.2. Aboveground sediment ponds

An embankment sedimentation pond can be used in any type of terrain. Generally, these types of ponds are located on a drainageway. An embankment is constructed across the drainageway to form the sedimentation bond. When the drainageway bed is excavated upstream of the embankment, a combination embankment/excavated sedimentation pond is formed. Excavation upstream of the embankment provides additional storage volume capacity to an embankment sedimentation pond.

A variety of outlets may be used with the embankment and the combination embankment/excavated sedimentation pond. The most common method is to use a pipe outlet for the principal spillway and a channel cut into the top of the embankment as the emergency spillway (Picture 2.2).

Picture 2.2: Excavated pond with pipe outlet

But embankment sedimentation has some disadvantages. There is a possibility of embankment failure due to poor construction or the use of poor construction materials. Bank sloughing may occur that can decrease the sediment removal efficiency of the pond by adding sediment to the pond. Bank sloughing reduces the storage volume capacity and therefore increases the maintenance requirements. The shape of the embankment sedimentation pond is generally controlled by topography.

Callender (2004) studied aboveground tailings pond for use in conjunction with flocculants. According to the author, the above ground settling pond should ideally be suited for application during the boring down (initial pit) process in land dredging. The material used can vary from zinc sheets, wire mesh to silt fence. After this initial pit has been worked out then it can be used as a settling pond and facilitate the recycling of water.

The combination embankment/excavation sedimentation pond has the advantage of providing additional storage volume without increasing the height or size of the embankment. However, exposure of the side slopes due to upstream excavation may require that the slopes be stabilized.

2.3. Multiple sediment ponds systems

A multiple pond system is considered to be the use of two or more sedimentation ponds in a series (one downstream of the other). The concept of multiple ponds is also accomplished through compartmentalization of a single pond. The concept of multiple ponds is the occurrence of staged settling. Solids with higher settling velocities will settle in the first pond or compartment and the finer sediments will be settled in the final pond or compartment. One particular advantage to this type of system is that most of the maintenance (i.e., sediment removal) is limited to the first settling pond or compartment. Also, field applications have shown that multiple sediment ponds in a series are more efficient in removing finer particles than a single pond of equal surface area. One disadvantage in the use of multiple ponds is that more area is disturbed due to the construction of additional ponds.

2.3.1. Multiple Ponds in Series

For design of multiple ponds in series, each pond is considered as single pond and is designed as such. All the considerations of ponds location, configuration, and inlet and outlet design apply to multiple ponds. However, certain considerations for sediment storage and the design inflow rate for sizing inlet and outlet structures are required.

The design inflow rate for the multiple ponds is identical unless there is incremental increase in drainage area between ponds. It is based on the flow of the tailings slurry. This concept is illustrated in Figure 2.1. For the situation presented in Figure 2.1, Pond 1 would be designed for the runoff from drainage area A_1 and Pond 2 would be designed for the runoff from drainage area A_2 plus runoff from area A_1 routed through Pond 1.

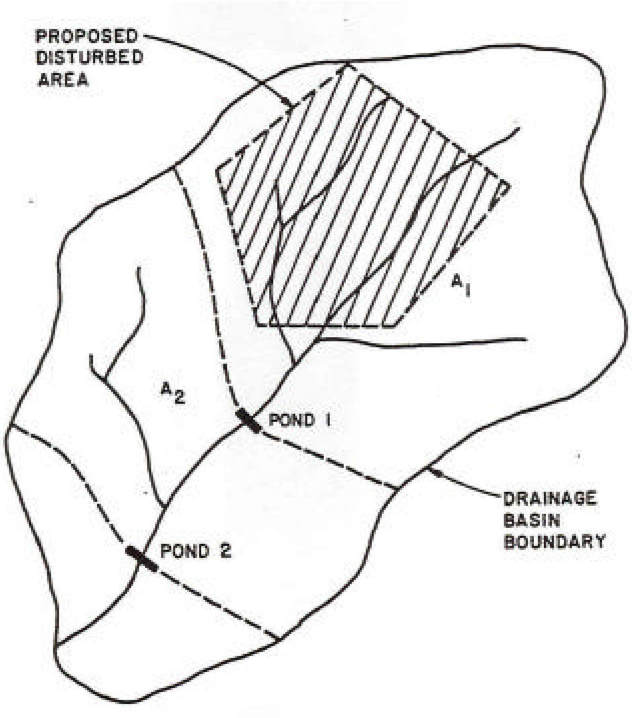

Figure 2:1 Schematic design for ponds in series

Another consideration for design and maintenance of multiple ponds in series is sediment storage volume. The first pond in a series will remove most of the larger sediment particles depending on the pond design. The second pond and the subsequent ponds in a series will receive finer and finer sediment particles. Thus, the sediment volume accumulation in the first pond will occur faster than downstream ponds due to the larger size particles being removed. From the illustration in Figure 2.1, the sediment storage volume for Pond 1 would be based on the yield from area A_1. The sediment storage for Pond 2 should be based on the yield from area A_2 and a certain percentage of the yield from area A_1 based on the trap efficiency of Pond 1.

2.3.2 Compartmentalization

A single pond compartmentalized by baffle walls constructed of wood or other suitable material provides the same staged settling as multiple ponds in series. It is similar to the design of Callender (2004) except that it is an excavated pond. However, the design flow to each compartment is different from that for multiple ponds in a series. The removal and storage of sediment in a compartmentalized pond is similar to multiple ponds in series.

For design of compartmentalized ponds, the flow rate to the first compartment is based on the upstream drainage basin. The flow rate to the second compartment and subsequent compartments is based specifically on the discharge from the upstream compartment. The flow from one compartment will be based on the outlet device which is typically some type of weir overflow.

Most of the sediment storage for compartmentalized ponds should be provided in the first compartment. The sediment storage provided in the first compartment can be based on the trap efficiency, however, a conservative storage volume should be provided to reduce the frequency of maintenance.

In Guyana, multiple ponds in series react like compartmentalization ponds. Due to generally flat topography, there is no change in the hydrograph between ponds. Multiple ponds in series are more adapted to the mining features in Guyana.

2.4. Recycling water sediment ponds

Recycling water sedimentation ponds is a semi-closed water system. It is comparable to the multiple ponds in series design with the exception that the ponds are separated by a man made sand filter. The ponds are constructed at slightly different altitude to assure gravity flow through the sand filter. Due to evaporation and minor spills, between 10 and 20% creek water is required to replenish the system. This type of construction is limited to mechanised operations since filter barriers must be constructed with a bulldozer/excavator.

In the Proto-Mahdia area, Chandan (2004) monitored a recycling pond system built by Deodat Singh's on Block 26-27 (Picture 2.3). The sluice box tailings (= 2 000 mg/L of suspended solids) are dumped on a primary aboveground pond and by gravity, reaches a second and third pond where water containing less than 20 mg/L of suspended solids is reintroduced in the mining operation. This operation has been extracting for more than 2 years and has proven successful.

Picture 2.3: Semi-closed water recycling pond. Deodat Singh's operation on Block 26-27 in the Proto Mahdia.

2.5. Present experience from the North West District

All backdams so far visited in the NWD have a central and limiting factor: the fact that the creek has never been isolated from the work grounds from the outset. With minimal mine site planning and old pits receiving the constant flow of the creek, the practice of backfilling without water recycling in a closed circuit system, brings little change in water quality (Picture 2.4). As a direct consequence of this poor planning the creek continues to flow through all old pits, whether backfilled or not. As such any further backfilling of old pits will fail to address river system water quality downstream. Until each and every operation from the top of the catchments downstream has constructed adequate diversion channels for the creek so as to ensure 100% isolation from the work grounds, then any attempts at backfilling, linking old pits and recycling water from these pits in a closed-circuit system approach, will be condemned to failure. Picture 2.5 shows an example of proper backfilling with water recycling.

Picture 2.4: Backfilling without water recycling

Picture 2.5 Example of proper old pit backfilling

The creek that passes through old pits acts to both dilute the slurry and keep it in constant motion and circulation. The "dilution effect" noted in all instances (Arakaka, Eyelash, Tiger Creek, Big Creek and Five Star) increases the distance between colloidal particles in suspension (pers. comm. Peter Hudson, September 2002) and therefore decreases their ability to attract each other as per cation exchange capacity and clay domain (plate-like charged structures) attraction. Without this attraction, large enough particles capable of settling out of suspension are prevented from forming together. In this way the slurry takes longer to fall from suspension i.e., suspended material settlement time is prolonged.

The closed-circuit system relies on isolation from the creek/river. With adequate settlement space and time, water can be recycled once two or three pits have been backfilled (and not overfilled) and subsequently connected via shallow-linking channels, designed to "skim" the supernatant from each successive pit (refer to diagram of Brasil closed-circuit system distributed within GGMC).

Another limiting factor in the successful attainment of the closed-circuit system, is the size of each work pit, with special attention being paid to the first one.

Without prior planning and additional preliminary work in the construction of an initial tailings impoundment structure, the initial bore down pit will always discharge raw/unsettled tailings directly or indirectly to the creek/river. Even if an adequate tailings management structure is built, many small land-dredge operators tend to remain for extended periods in the first pit (and for that matter in all pits) and thereby outlive the capacity of the previous pit volume. The same applies when they are in the process of backfilling old pits: failure to judge the filling rate and being aware of when to jump out results in pits being filled beyond capacity. Once overfilled a pit no longer functions as a "tailings" settlement pond, and unsettled tailings will flow out via the discharge point. If this discharge point flows into another old pit with adequate retention volume and sufficient water column height, the contamination is contained, and settlement may take place. In this way improved water quality is a function of increasing settlement time i.e., reducing water body flux and allowing only the clear supernatant to move from one pit to the next or back to the creek as necessary.

The main reason for the failure to reduce pit size, through the practice of jumping out and boring down regularly, is the unwillingness of land-dredge operators to waste the time spent in reaching the relatively thin gold-bearing gravel strata (placer gold). If the overburden is deep (e.g. 2-4 meters) it represents extra time and lost production to jump out, assuming that the gravel that is being worked is producing well. The closed circuit system also represents lost production to the operator insofar as the land between successive pits is seen as being lost from production.

Also noted in all backdams visited is the fact that the entire creek flat from ridge to ridge has been mined. Remedial work now to facilitate a dedicated channel for the creek from catchment top to bottom is therefore made more difficult as all operations have already worked the whole area. Tailings are intentionally thrown without containment on low-lying swamps, with the intention of working the swamp in the future. The dumped tailings speeds up the drying-out process and allows the land dredge to later move into an area, previously inaccessible due to inundation.

In addition, any quick-fix approach, as has been advocated by some in the form of large dams downstream to handle all tailings, is ill-advised as seasonal hydrological fluctuations are extreme and their parameters unknown. Any structure built without these important inputs will inherently be risky and open to design failure from extreme rainfall and flood events. The consequences of such failure will only exacerbate the water quality problem downstream at some undefined future time. It should also be noted that such a structure would not in fact be a tailings dam, but rather a structure to dam a creek/river that incidentally contains tailings in its flow.

2.6. Suggested sediment ponds concept for Guyana

At this point and time, it is not in the culture of the alluvial mining industry in Guyana to routinely build tailings ponds. In the past years, mining operations would receive complaints from local communities of the deterioration of the water quality due to mining. But since some of the community members were employed as labours in mining camps, the economic advantage for the local communities sort of dampened the effectiveness of the complainants.

In the last two years, the Ministry of Mines of Guyana and the Guyana Geology and Mines Commission (GGMC) have closed down a certain number of bad practice operations in the North West, Middle Mazaruni and Mahdia. The industry then asked for technical support to GGMC for building economic tailings ponds. For GGMC, this was a new experience. Neighbouring Amazonian countries have not yet done the exercise of tailings management and, therefore, could not provide the required knowledge to Guyana.

For the different designs presented here there is no absolute model that can fit the need. It will be by trial and essay that a design model will satisfy the requirements. With time, the best fit model will emerge. For now, we can only recommend the most appropriate design as a function of the mining operation scale.

For small scale mining with very limited capital investment, it is recommended to adapt the proposal of Callender (2004) as a starting point. Miners should no more be jetting one large pit. A first pit should be excavated and tailings should be dumped in an aboveground pit constructed with silt fence. Although we will address storage capacity of ponds and pits in a subsequent section, as a rule of thumb, the first pit should not exceed the retaining capacity of the aboveground pond (e.g. being similar in volume) pond. The second excavated pit can be twice the volume of the first pit since we now have two retaining ponds. Care should be taken to monitor the carrying capacity of the aboveground pond for silt and clay retention. A natural dyke should be left between each excavated pits. In such a scenario, we can easily imagine that a successful operation might have multiple excavated pits in series providing higher quality water in the process.

For medium scale operations ($\geq$ 3 sluices on the same drainage), a recycling water system is strongly recommended. More and more mining operations are mechanised. Being not as mobile as small scale mining operations and requiring sluicing all year round for a profitable venture, they have to become independent of erratic water supply. Consequently, they would find economic benefit in operating a recycling water system. To obtain adequate water quality from the recycling process they would use multiple ponds in series. This would provide quality water for a reliable operation of there pumps and in the same time, capture all suspended solids that would otherwise affect the water quality of downstream communities. The operation of Deodat Singh's in the Proto Mahdia Block 26-27 as reported by Chandan (2004) is a perfect example of this design.

3. Sedimentation ponds criteria

3.1. Site selection

3.1.1. General considerations

Selecting a sedimentation pond location requires consideration of several factors. In all cases, sedimentation ponds must be constructed in locations where it will be possible to direct or divert all tailings into sedimentation ponds throughout the life of mining operations. Other factors which are of primary importance and should be considered in selecting a sedimentation pond location include the topography of the mine site, locating major source of sediment, accessibility of the sedimentation pond, availability of construction materials, and the direction of mining. In rare instances in Guyana, these factors will limit the number of viable locations that are available for sedimentation pond construction. In particular, availability of suitable sites for a sedimentation pond location will be controlled, to a large extent, by the topography of the mine site. In addition, ponds must be constructed prior to any disturbance of the mine area. Through careful planning practices and field investigation, the sedimentation pond locations which will meet this objective can be identified.

3.1.2. Topographic considerations

In Guyana mining districts, there are very few, if any, mining operations on steep slope terrain. Most are located on mild sloped terrain. There is much more flexibility in selecting a sedimentation pond location in mild sloped terrain. The phys ical constraints imposed by the topography are less than for steep sloped terrain and therefore, more attention may be directed toward the other primary factors considered in the selection of a sedimentation pond site.

Sedimentation ponds may be located on or off drainage ways. Small drainage ways are often selected for a sedimentation pond location if a natural embankment is used with or without excavation to provide the storage volume required. Due to the milder drainage way profile the milder slopes of the valley, the sedimentation pond located in the mild sloped terrain will normally have a greater length and width for any height of dam specified, thereby providing more storage capacity.

Off drainage locations are generally preferred when there is a suitable location available for sedimentation pond construction. Natural depression areas are good locations for sedimentation ponds. An embankment can be constructed across the downstream end of the depression area and the storage volume may be increased by excavation or jetting in an aboveground pond.

3.1.3. Hydrographical considerations

The effect of dry and wet seasons is to be considered booth for the storage capacity of the sedimentation ponds and for the dilution factor of the suspended solids escaping the ponds to downstream creeks and rivers.

During the wet seasons, the introduction of drainage water in the ponds will decrease the retention time of the suspended solids before reaching the effluent and increase the size spectra of particles escaping the pond system. In a similar manner, the increase flow rate of the creeks and rivers will increase the dilution of the suspended solids back to the suspended solids limit imposed. In this case, suspended solids concentration may not change from the set limit but the sediment load escaping the pond system will increase.

During the dry season, proper operation of the ponds is required since creeks and rivers will provide minimum dilution of the effluent. This is the period where turbidity plumes must be monitored and ponds retention time adjusted to respect the suspended solids limit.

3.1.4. Mining considerations

Throughout the life of the surface mining operations, the locations of the major sources of sediment will constantly change due to the progression of mining. Sedimentation pond locations should be selected considering the direction of mining so it will be possible to direct or divert all tailings into the pond throughout the life of the mining operations. In all cases, time of exposure of cleared land should be kept to a minimum to avoid filling of the sedimentation pond prematurely.

For small scale mining operations, the lack of exploration data makes the progression of mining difficult. If an operation migrates to a location outside the existing ponds, the construction of a new aboveground pit is required. In such a case, the economic benefit of the mining operation could be handicapped.

For medium scale operations, mechanised equipment can be used to channel the new pit effluent to the existing sedimentation ponds.

3.2. Data requirements

3.2.1. Tailings flow rate

A flow analysis of the sluice box discharge must be computed. The flow rate and percentage of solids discharge should be determined to compute the volume requirement in the construction of the sedimentation ponds design.

To calculate the flow rate, Ramdas (2004) surveyed an operation using a 6 inch pump near Arakaka. Recording the surface area of the sluice and the average depth of flow on the sluice, he obtained roughly 100 litres. The travel time of the slurry through the sluice (2 sec.) permitted to compute a flow rate of $150 m^3/h$. For an 8hr operation the discharge exceeded 1 metric ton/day ($1150\ m^3$).

3.2.2. Tailings suspended solids concentration

Tailings from sluice boxes can exceed 10 g/L. Two methods are available for calculating solids concentration in the slurry: 1- Evaporation of a 5 litre sample at 65°C and weighting on a precision scale or 2- Dilution of the sample with filtered water or creek water (<30 NTU) to bring the suspended solids concentration suitable for filtration on a Gelman or Whatman fibreglass filter of a nominal pore size of 1 µm. The filters must be pre and post weighted to compute the solids weight.

Boot methods can be done in the field with the appropriate equipment, the evaporation method being more trouble free.

3.2.3. Tailings sediment size spectra distribution

The most important sediment data required to design a sedimentation pond to meet effluent limitations is the particle size distribution of the sediment influent. The particle size distribution should represent the worse condition during the life of the mine.

The first condition to be considered is before the topsoil has been replaced. The soil which is eroded, and hence the influent particle size distribution, will be represented by the graded overburden. The solid which is eroded, and hence the influent particle size distribution, will be represented by the graded overburden. The second condition to be considered is after the topsoil has been replaced. For this condition, the particle size distribution of the eroded soil will be represented by the topsoil. Whichever condition results in a particle size distribution with the highest percentage of particle sizes in the silt range (1to 74 µm) will be selected for the design influent particle size distribution. The best way to estimate the particle size distribution is to obtain size distribution information from previous and nearby mining operations. When mining operations within the same area or areas with the same soil texture exist, determination of particle size distributions of sediment runoff from existing analysis can be used. Before a particle size distribution from a nearby site is used, several considerations and comparisons must be made so the information does represent the site under consideration.

1. Soil characteristics at both sites should be very similar including soil types below the surface which are disturbed during mining.
2. Slopes, drainage, and sediment transport characteristics of both sites should be

evaluated and compared.

3. The type of mining and amount of area disturbed at both sites should be evaluated.

When these data do not exist, but nearby sites do exist, sampling and laboratory analysis should be conducted whenever possible.

Another method for developing particle size distribution information is based on the site specific soil textural class and physical properties.

Generally, soil physical properties occurring at a specific site can be identified using information given by the Geosciences Division of GGMC.

A procedure for determining particle size distribution based on soil textural class is presented for use with this manual. A textural class is simply as name given to each soil which designates the ranges of sand, silt and clay sizes it contains. This class can be obtained from soil series descriptions, other soil survey data in the vicinity, soil data from the mine plan, filed estimation by a soil scientist, or laboratory analysis. After determining the textural classification, the corresponding particle size groups are then determined from Table 3.1.

TABLE 3.1

Table 3.1 Suggested Particle Size Distribution for Soil Textural Class

Textural Class	Clay (<2µm) %	P_1 Silt (2-50µm) (%)	P_2 Very Fine Sand (50-100µm) (1%)	P_3 Fine, Medium Coarse Sand (0.1-1.0mm) (1%)	P_4 Very Coarse Sand (1.0-2.0mm) (1%)
Sand	2	10	15	35	38
Loamy Sand	5	15	20	40	20
Sandy Loam	5	25	20	20	30
Loam	10	30	10	25	25
Silty Loam	20	60	5	15	-
Silt	5	90	5	-	-
Sandy Clay Loam	25	25	10	30	10
Clay Loam	30	40	10	10	10
Silty Clay Loam	35	55	5	-	5
Sandy Clay	55	5	5	10	25
Silty Clay	45	45	5	5	-
Clay	65	20	10	5	-

Where the mining area has several soil textural classifications within the drainage boundary, a composite size distribution can be developed. For each particular soil textural classification, the sediment size distribution given in Table 3.1 will be multiplied times the fraction of the disturbed area that each soil textural class covers. The values for each soil textural class are then added together to form a representative composite size distribution. This can be performed on a nearby mining bank.

The sediment size distribution based on textural class is not recommended for use if more detailed soil data are available at the mine site. Also, it is important that the soil data describing the material below the surface (exposed during mining) be considered during development of the particle size distribution. The mines engineer should realize that the design can be no better than the information on which it is based. To help eliminate significant changes and modifications to the pond after construction, the particle size distribution utilized should be a conservative estimate.

The size distribution for steady state conditions can be significantly different from the size distribution based upon the surface and overburden soils. Generally, the size distribution for steady state conditions will be composed of smaller particle sizes. Sampling of the steady state size distribution is recommended to accurately design for base flow effluent limitations. An initial estimate of the size distribution can be developed from the overburden soil. Once the pond is operational, the effluent will have to be tested and pond modifications may be required.

3.2.4. Ponds effluent suspended solids limit

Based on the recommendation of the GENCAPD Stakeholders meeting held on October 22, 2003, a committee was formed under the direction of William Wilford of GGMC to recommend suspended solids effluent limits for gold and diamond alluvial mining. Based on the research done by Livan and Couture (2002), the limits were set as followed:

SEASON	MONTHLY AVERAGE (mg/L)	COMPOSITE (mg/L)	GRAB (mg/L)
DRY	30	40	60
WET	50	75	100

An individual sample taken during mining operation and at steady state can not exceed 60 and 100 mg/L respectively during dry and wet seasons.

Determination of solids weight can only be done by filtration of fibreglass filters of a 1µm nominal pore size and in the laboratory. The use of a vacuum pump is necessary and dilution of the sample should be conducted to filter 0,5L with 5 mg of solids retained.

3.2.5. Ponds effluent settleable solids limit

The volume of settleable solids in the effluent from a sedimentation pond is determined by a simple procedure known as the Imhoff cone test. The Imhoff cones are filled to the one-litre mark with a thoroughly mixed sample. Settling is allowed to occur for 45 minutes, the sides of the cone are gently stirred with a rod to free any particles which may be clinging to the sides of the cone, and settling is allowed to occur for an additional 15 minutes. The volume of settleable solids in the cone is then recorded as milliliters per liter (from "Standard Methods for Examination of Water and Wastewater," 15^{th} edition). It should be pointed out that some difficulty exists in reading the Imhoff cones. When dealing with fine particles such as silt, it requires practice in defining the volume of settleable solids, which is the usual case in Guyana.

Particle sizes smaller than 1 µm are assumed non-settleable under gravitational forces alone. Therefore, particles sizes smaller than one micron are not considered settleable solids in this manual. A well designed sedimentation pond will remove practically all of the sand-sized particles. Therefore, the settled volume in the bottom of the Imhoff cone will be composed primarily of silt. If particles =1µm in diameter are abundant and exceed the effluent suspended solids limit, then flocculants can be used (see Section 5).

The smallest particle which will settle through the entire height of the Imhoff cone during the test can be computed. Based upon Stroke's Law, test conditions, and assuming a specific gravity of the particle to be 2.65, this particle size is computed as 11 µm (d_o). Stokes's Law is based upon ideal settling and there are several references available which discuss Stoke's Law (Barfield *et al.*, 1981; Shames, 1962). All particles larger than 11 µm would settle during the test. Only a percentage of the particles smaller than 11 µm would be expected to settle in a sedimentation pond depending upon concentration of each particle size within the area. The objective of this design manual is to select a particle class of a particular size distribution that must be removed so that the settleable solids concentration meets effluent limitations when the sample is placed in the Imhoff cone.

4. Ponds numerical design

4.1. Sediment trapping efficiency

To meet effluent limitations, sedimentation pond design must be based on sediment size distribution and TSS concentration of the base flow entering the pond. Based on present state of the art, the most common method for developing the pond design criteria to meet a specified effluent limitation is by determining the percent of sediment removal required. The percent of sediment removal is called the trapping efficiency (E) and is equal to the weight of sediment flowing into the pond minus the weight of sediment leaving the pond divided by the weight of sediment flowing into the pond and then multiplied by 100 to obtain efficiency in percent. Thus, the trapping efficiency is given by:

$$E = \frac{W_I - W_0}{W_I} \times 100 \qquad \textbf{(4.1)}$$

Where, W_I = weight of sediment flowing into the pond

W_0 = weight of sediment flowing out of the pond

During base flow of the mining operation, the sedimentation pond will be in a steady-state condition where the water inflow volume equals the water outflow volume. The water volume can be changed to a weight of water. Dividing the weight of sediment by the weight of water will yield a concentration of TSS. Therefore, the trapping efficiency becomes

$$E = \frac{C_I - C_0}{C_I} \times 100 \qquad \textbf{(4.2)}$$

where, C_I = average sediment concentration into the pond

C_0 = average sediment concentration out of the pond

For base flow, effluent limitations are stated as a concentration of TSS. Therefore, a relationship between the influent TSS concentration and the trapping efficiency can be developed since the TSS grab concentration is known to be 60 and 100 mg/L respectively during dry and wet seasons. Once the influent TSS has been measured, the required trapping efficiency can be determined. Figure 4.1 presents this relationship for a range of effluent concentration limitations for the dry season. Knowing the influent TSS concentration, the required trapping efficiency to limit the effluent concentration to a standard can be determined from Figure 4.1.

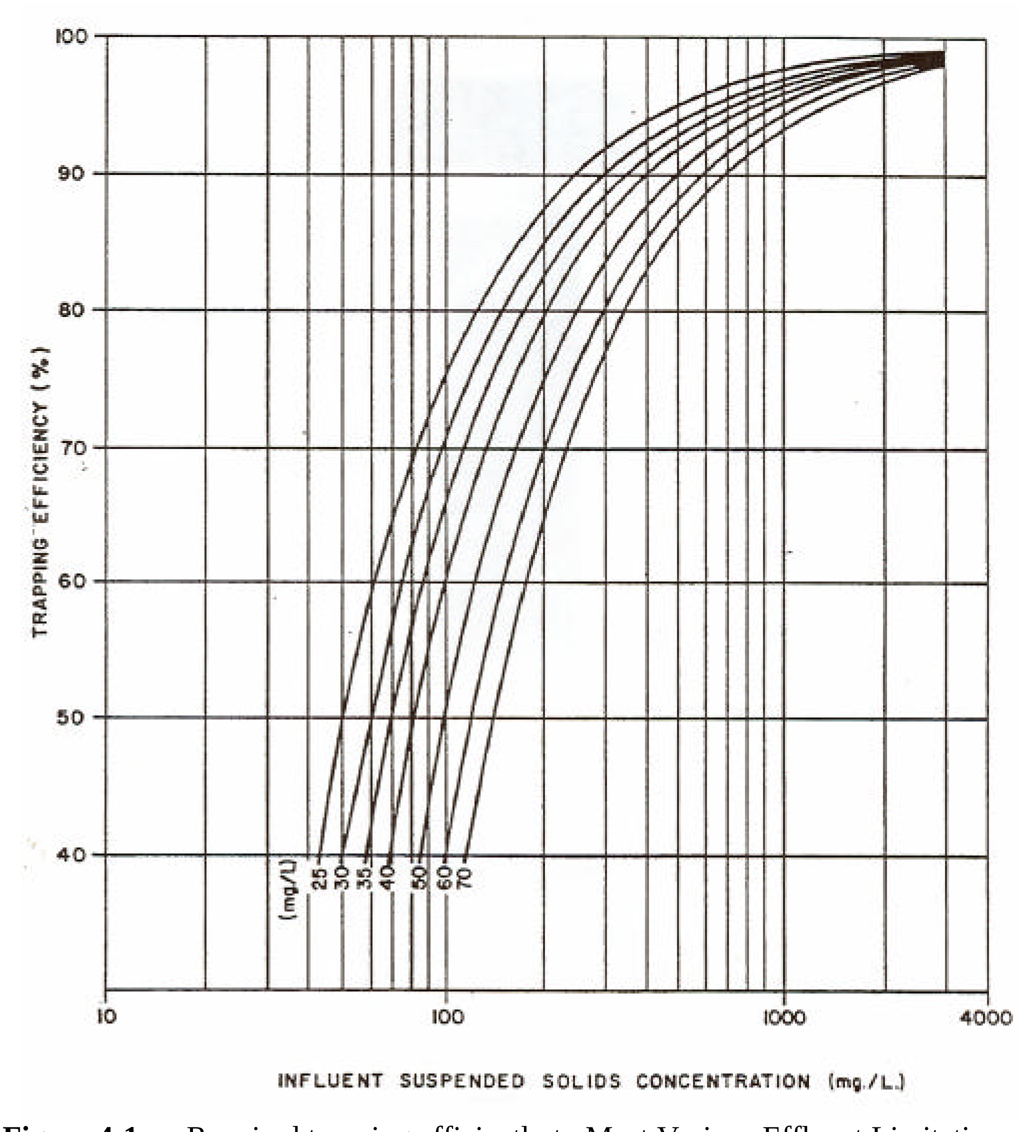

Figure 4:1 Required trapping efficiently to Meet Various Effluent Limitations

By definition, the trapping efficiency is the weight of sediment removed in the pond. The influent sediment is represented by the sediment concentration and size distribution. In additional, it is assumed that the influent sediment is evenly distributed in the water inflow. Therefore, when a sedimentation pond is designed to remove a certain particle size (d_i), the percent of sediment removal or trapping efficiency is equal to the presence of the size distribution that is larger than d_i. Figure 4.2 present the definition of the trapping efficiency for various particle sizes. This estimate of trapping efficiency is conservative since it assumes none of the particles smaller than the selected particle size (d_i) will settle in the pond. Actually, a percentage of the particles smaller than (d_i) will settle. Therefore, for each particle size, a trapping efficiency can be determined from the influent size distribution, and the suspended solids concentration can be calculated by rearranging Equation 4.2.

$$C_0 = \left(1 - \frac{E}{100} \right) C_I \qquad \textbf{(4.3)}$$

To determine whether the effluent requirements are satisfied, a relationship between the suspended solids concentration and the settleable solids concentration is required. This relationship is presented in the following section.

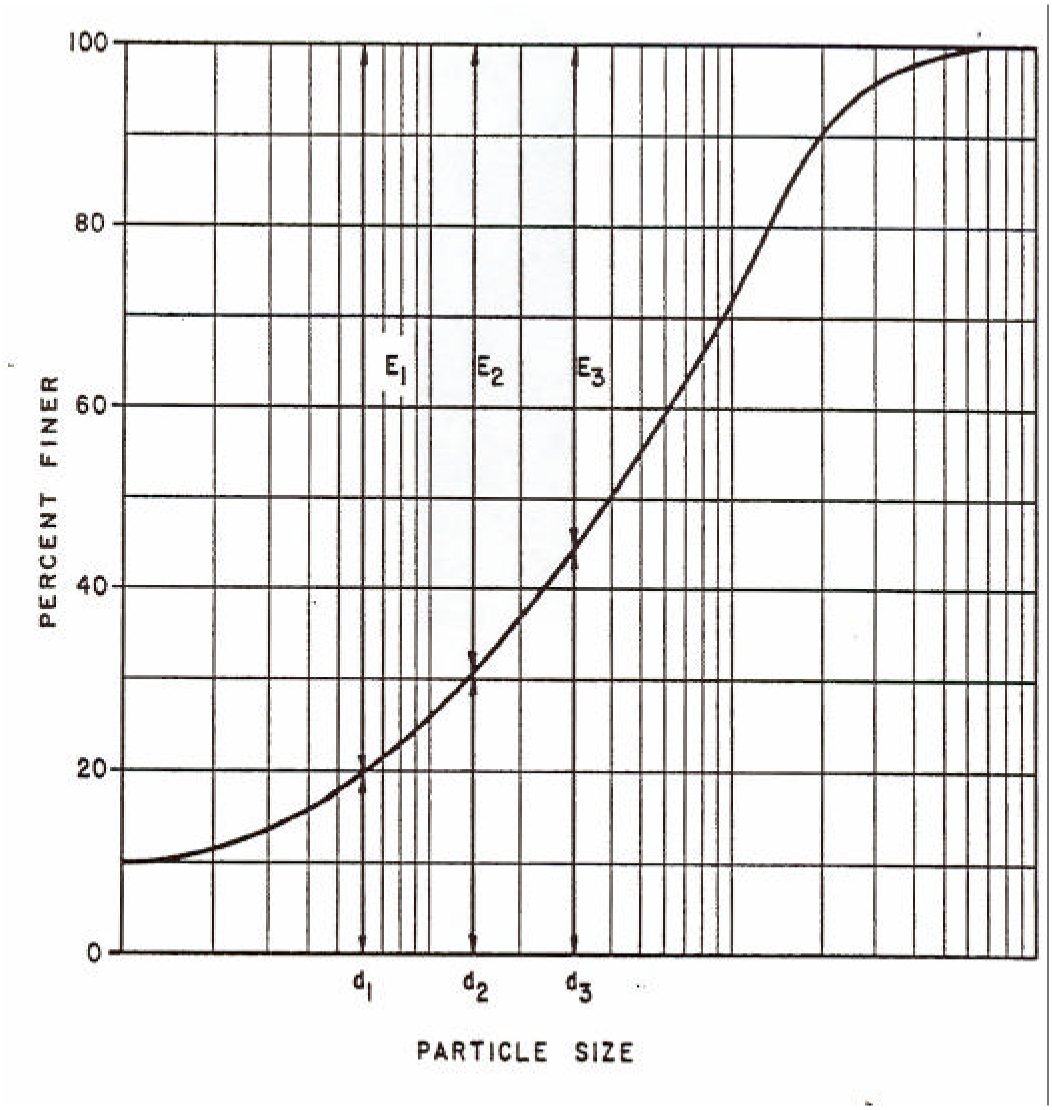

Figure 4:2 Definition of trapping Efficiency for Various Particle Sizes

4.2. Settleable solids concentration

Effluent limitations are stated in terms of a volume of settleable solids per one litre of sample. To relate the settleable solids limitation to the design of sedimentation ponds, a relationship between settleable solids and total suspended solids must be considered. Settleable solids are defined as the volume of particles that settle in the bottom of an Imhoff cone in one hour of quiescent settling.

Knowing the influent sediment size distribution, a particle size to be settled in the pond is selected and the settleable solids concentration is determined. If the settleable solids concentration is larger than effluent limitations, a smaller particle size is selected and a new settleable solids concentration is computed. Likewise, if the settleable solids concentration is smaller than the effluent limitations, a larger particle size is selected and the new settleable solids concentration is computed. Therefore, an interactive process is required to determine the particle size that the sedimentation pond must remove so the pond effluent satisfies the settleable solids limitation.

The first step in computing the settleable solids concentration is to adjust the influent sediment size distribution by subtracting out the non-settleable size (= 1 µm). Given the size distribution in Figure 4.3, it can be seen that ten percent of the sediment is smaller than1 µm . Therefore, the 90 percent of the size distribution which is settleable must be

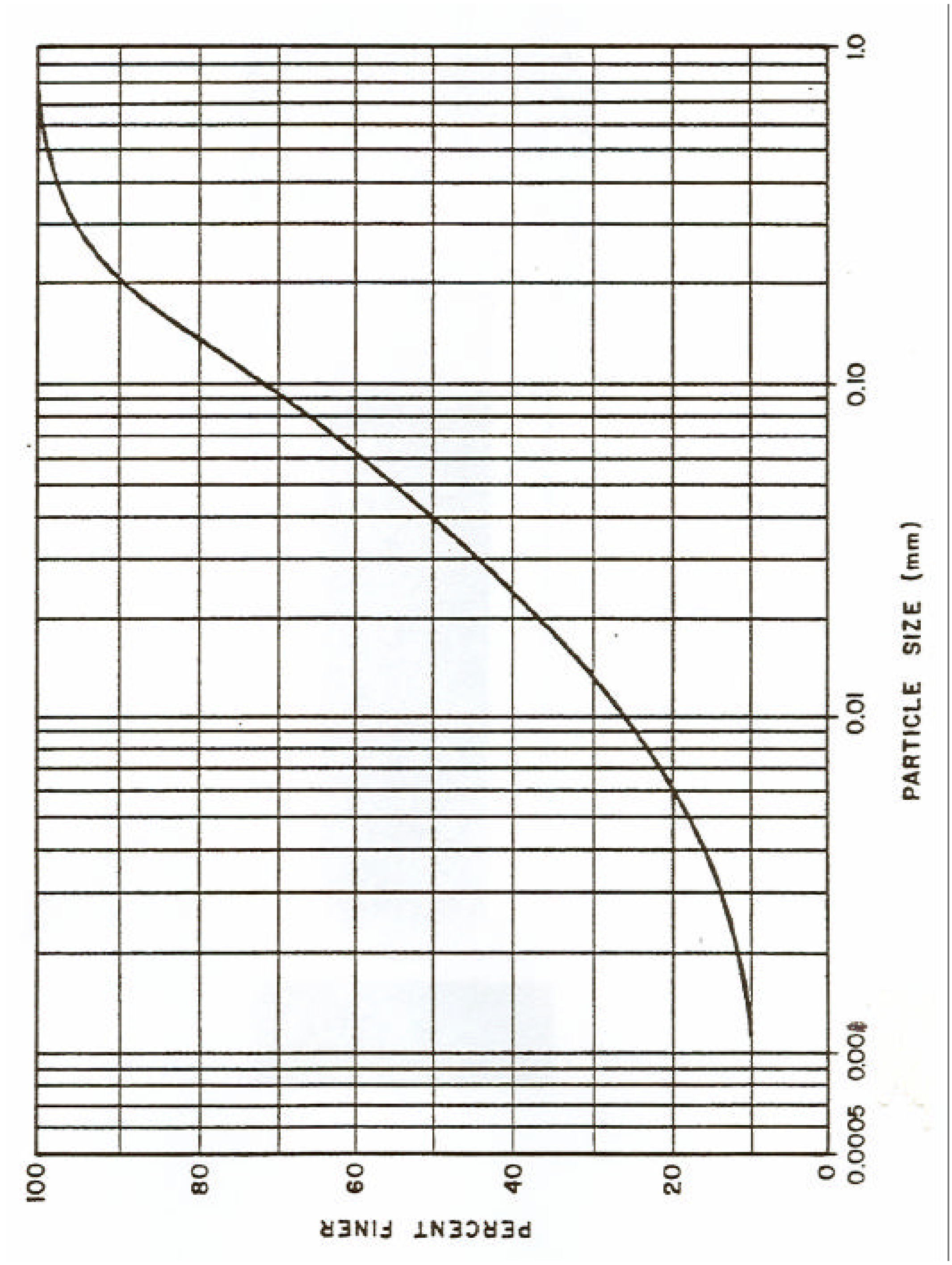

Figure 4:3 Influent Sediment Size Distribution

redistributed so that it makes up 100 percent of the size distribution. Table 4.1 show how to develop a size distribution in which all particle sizes are settleable. The settleable size distribution is presented in Figure 4.4.

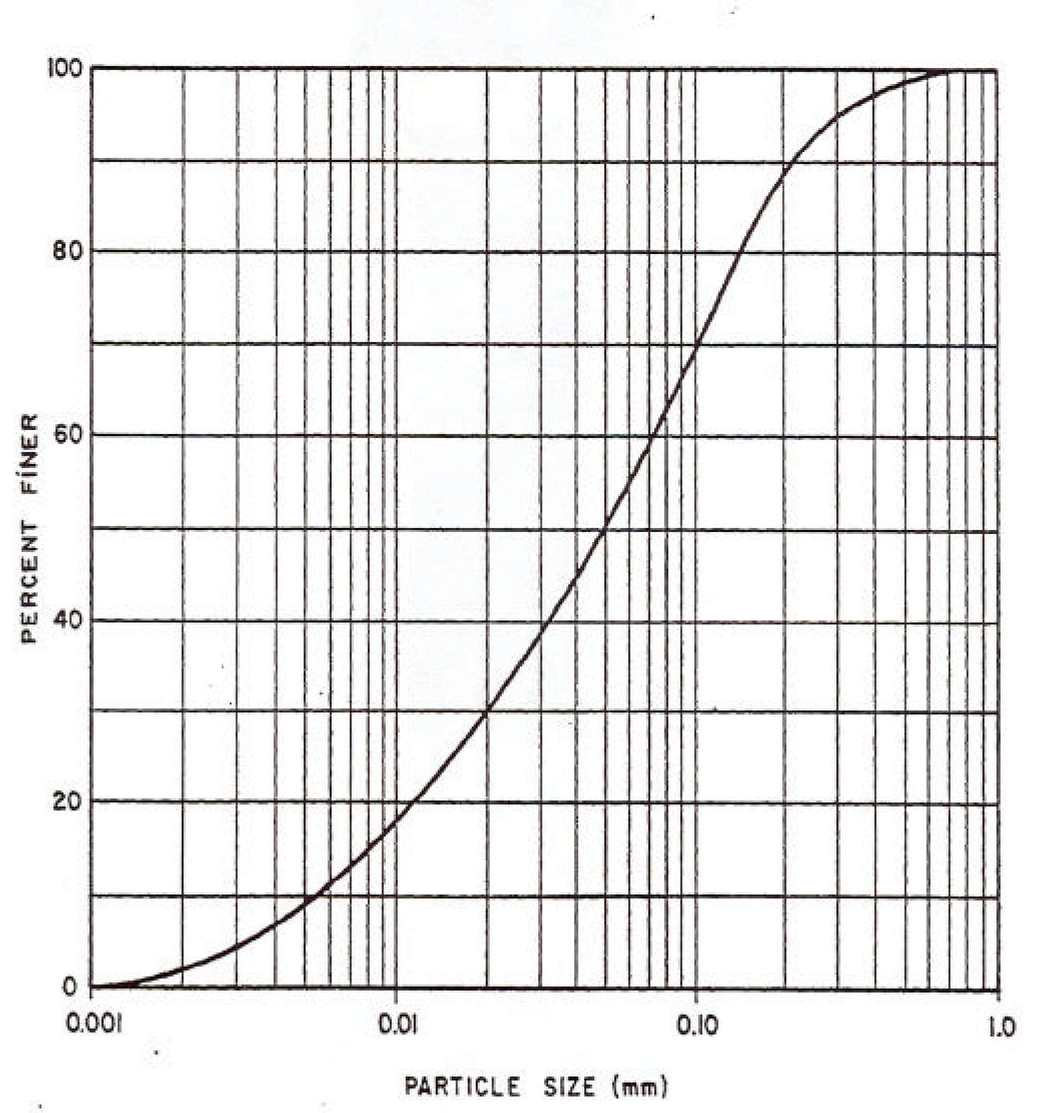

Figure 4:4 Settleable Solids Size Distribution

Table 4:1 Development of Settable Solids Size Distribution

(1) Particle Size (µm)	(2) Influent Distribution (% finer)	(3) Column 2-10	(4) Settleable Solids Size Distribution Column 3 x (100/90) (% finer)
1	10	0	0.0
42	16	6	6.7
10	26	16	17.8
40	50	40	44.4
100	72	62	68.9
200	90	80	88.9
660	100	90	100.0

A relationship between the effluent suspended solids concentration, the settleable particle size distribution, and the settled solid concentration is required. Barfield *et al.* (1981) developed an equation for the conversion of suspended solids concentration to settleable solids based on discrete particle settling and the geometry of the Imhoff cone. The volume of settleable solids is given by:

$$ss = \frac{C^*}{W}\left[\left(1 - \right) + \overset{X_0}{\underset{i=}{?}}\left(\frac{d_i}{d_0}\right)^6 ?\, X_1\right] \qquad \textbf{(4.4)}$$

where,	ss	=	settleable solids concentration (mg/1),
	c*	=	average effluent suspended solids concentration for the settleable sizes (mg/1),
	w	=	dry bulk density of the settled solids (mg/m1),
	x_0	=	fraction of particles in the effluent distribution smaller than d_o = 0.011 mm
	d_0 of	=	smallest particle which will settle through the entire height an Imhoff cone (0.011 mm),
	d_i	=	mean particle size of the interval ? x_i (mm)
	? x_i	=	fraction of effluent sediment size distribution which has a mean particle size of d_i

The average effluent suspended solids concentration for the settleable sizes is given as:

$$C^*_0 = (1 - E) \quad C_1 = (1 - E) \frac{ky}{?v} \text{ x } 10 \qquad \textbf{(4.5)}$$

where, E, ?, v, y are defined previously, and

k = fraction of the particles in the influent size distribution which are settable.

In the previous example, k would equal 0.90 since 90 percent of the influent size distribution is settleable.

The dry bulk density of the settled solids (w) would be representative of settled silt since this is the size range that will settle during the Imhoff cone test.

The fraction of the particles in the effluent size distribution which are smaller than d_o (11 µm) is donated as X_o. When a particle size is to be removed in a pond and is equal to or smaller than 11 µm , X_o will always be 1.0 and all of the particle sizes in the effluent are equal to or smaller than 11µm. All the particle sizes which have a diameter of 11 µm or larger will settle in an Imhoff cone test. The second term is Equation 4.4 determines what percentage of the particle sizes smaller than 11 µm will settle during the test.

When a particle size to be removed in the pond is larger than 11 µm, X_o is equal to the percent of the effluent size distribution which is smaller than 11 µm. For this condition, the effluent will contain particle sizes greater than 11 µm. All particle sizes greater than 11 µm will settle in the Imhoff cone during the test. The first term in Equation 4.4 describes the percent of the effluent size distribution which is larger than 11 µm and therefore, will settle during the Imhoff cone test. For this condition, X_o can be completed as:

$$X_0 = \frac{\text{\% of settleable size distribution smaller than 11 µm}}{\text{\% of settleable size distribution smaller than size to be removed in sedimentation pond}}$$

The design of a sedimentation pond to meet effluent limitations requires that a particle size to be removed be selected. A good starting point is to select a particle size of 11 µm. This makes X_o in Equation 4.4 equal to 0.1. Therefore, the effluent size distribution is made up of particles smaller than 11 µm. To evaluate the second term in Equation 4.4, the particle sizes smaller than 11 µm must be redistributed into a size distribution in which particle sizes smaller than 11 µm comprise the entire size distribution. Using the settleable size distribution presented in Figure 4.4, it can be seen that 19.5 percent of the settleable size distribution is smaller than 11 µm. This percentage of the settleable size distribution is then redistributed to be 100 percent.

This procedure starts by breaking up the settleable size distribution smaller than 11 µm into several percentage intervals. The size range for each increment is then tabulated and the mean size (d_i) is determined. This procedure is shown in Table 4.2.

Table 4:2 Size Distribution for Particles Smaller than 0.011 µm

(1) Particle Size Range (µm)	(2) Mean Size (d_i)	(3) Percent in Size Range of Settleable Size Distribution (x_i)	(4) ? x_i = (x_i / ? x_i)
1 – 2.3	0.0015	0.04	0.205
2.3 – 4.6	0.0035	0.04	0.205
4.6 – 6.4	0.0054	0.04	0.205
6.4 – 8.8	0.0075	0.04	0.205
8.8 – 11	0.0100	0.035	0.180
?		**0195**	**10**

In this example, percentage increments of 004 were chosen. There is no set value for the percent increments. However, smaller sized increments will yield a better result. The particle size range for each increment is then tabulated (column 1, Table 4.2). The particle size (d_1) in the middle of each increment is then tabulated in column 2 of Table 4.2 as mean size. The final step is to redistribute the size distribution smaller than 11 µm. This is accomplished by dividing each percent increment (column 3) by the sum of column 3. For this example, the first four entries in column 4 are found by dividing 0004 by 0195. Column 4 is the ? x_i value used in Equation 3.5 corresponding to the d_i value (column 2). Knowing this information, the settleable solids concentration in the effluent can be determined from Equation 3.5.

If the settleable solids effluent limitations are not satisfied, a particular size smaller than 11 µm is chosen to be removed. This value of X_o in Equation 4.4 will still be equal to 01. However, the particle size range in column 1, Table 4.2 will change. The particle size range will now have the upper limit of the selected particle size instead of 11 µm. Therefore, the trapping efficiency, effluent concentration, particle size range, increment size, and ? x_i will have new value and the new settleable solids concentration can be computed.

When the computed settleable solids concentration is less than the effluent limitations, larger size particles will be allowed in the effluent. Therefore, a particle size larger than 11 µm is selected to be removed in the pond. In Equation 4.4, the second term will remain the same as that which was computed for a particle size of 11 µm but will be reduced by a factor of X_o. This is one of the main reasons for selecting 11 µm as a starting point. The value of X_o will no longer be equal to 1.0. For this condition, X_o can be computed as defined previously. With the new trapping efficiency, effluent concentration, and value of X_o, the settleable solids concentration can be computed using Equation 4.4. The settleable solid concentration will increase rapidly as the particle size to be removed in the pond is increased since all particles larger than 11 µm will settle in an Imhoff cone. Therefore, when a new particle size is selected, a particle size in the range of 15 to 2 µm should be tried so the mines engineer can understand how fast the settleable solids concentration increases.

When the designer has calculated the particle size which must be removed in the sedimentation pond to meet effluent limitations, criteria for the sedimentation pond design can be determined. The determination of the design particle size to meet effluent limitations may seem confusing.

Although this approach might seem cumbersome for use in the interior, the abundance of clay and silt material in Guyana mining districts suggest such a route. After designing several settling ponds, an easier approach could be used.

4.3. Pond storage volume requirement

Knowing the particle size to be removed (Section 4.2), a depth is assumed and the corresponding required detention time is determined (Section 4.4). The available storage volume for the selected depth is determined. The required storage volume is then determined. If the available storage volume is less than the required storage volume, the depth is increased. When the available storage volume is greater than the required storage volume, the depth, retention time, storage volume, and outflow rate are established. The pond surface area, length, and width are then checked to ensure that the selected particle size is settled in the pond.

Flow routing though a sedimentation pond is determined by the rate of inflow, storage capacity of the pond, and outflow capacity for given reservoir levels. Numerous methods of reservoir routing have been developed which include the Modified Puls Method, Rippl Mass Curve, and several others. Descriptions of these methods can be found in hydrology texts and manuals.

A simplified method is used in this manual. The simplified routing method is used to determine the required storage volume and size the principal spillway to produce the required retention time so that effluent requirements are met. The simplified routing procedure requires that the peak inflow rate and runoff volume are known. The peak inflow and runoff volume can be determined from the inflow rate. This method implies two assumptions, the shape of the inflow and outflow are triangular and the initial water surface elevation is at the elevation of the principal spillway. Water routing through sedimentation ponds can be solved using Figure 4.5 and 4.6.

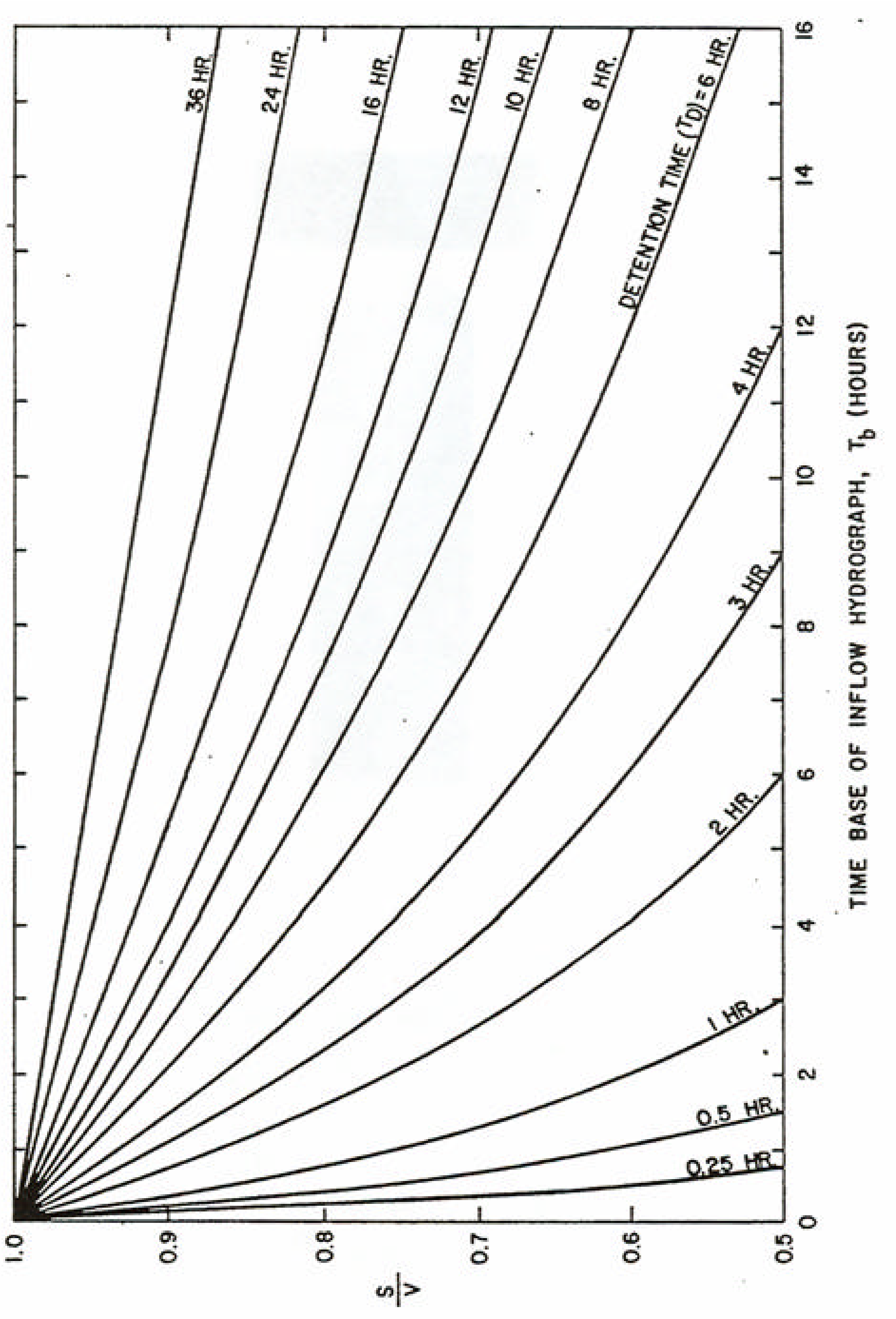

Figure 4.5 Water Routing Curve, S/V Versus T_b (WARD, HAAN, TAPP, 1979)

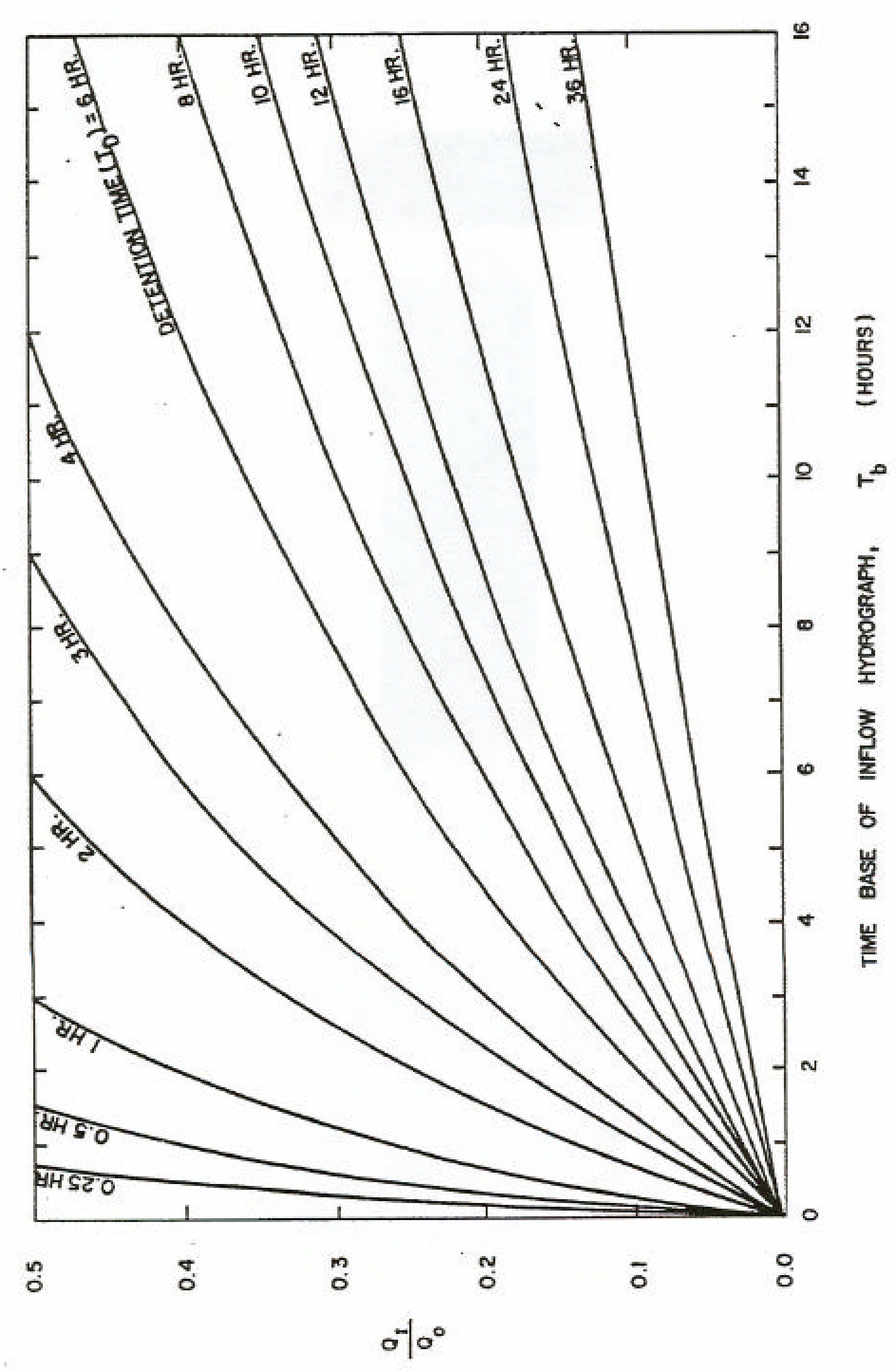

Figure 4:6 Water Routing Curve, Q_i / Q_0 Versus T_b (WARD, HAAN, TAPP, 1979)

Figure 4.5 is a graph showing the relationship between the time base of the inflow tailings (T_b) and the ratio of the required storage volume (S) to the runoff volume (v) for a range of retention time. Figure 4.6 presents the relationship between T_b and the ratio of the peak outflow rate (Q_O) to the peak inflow rate (Q_i) for a range of detention time. The time base of the inflow hydrograph is determined as:

$$T_b = \frac{v}{1800\ Q_i} \qquad \textbf{(4.6)}$$

where, T_b = time base of inflow hydrograph (hours)

v = water runoff rate (ft^3)

Q_I = peak inflow rate (cfs)

The time base can be computed based on the information from the inflow hydrograph. Knowing the time base of the inflow hydrograph and the required detention time for a selection particle size to be settled, the required storage volume and peak outflow rate can be determined using Figures 4.5 and 4.6.

4.4. Sedimentation pond configuration

The design of the sedimentation pond configuration is based upon ideal settling conditions. In actual field situations, ideal settling conditions are often difficult to reproduce. This necessitates the need to incorporate factors into the design which account for non-ideal settling conditions.

According to Sigma (1986), the pond configuration has influence on the percentage of the pond volume that is essentially stagnant (e.g. net contributing to solids removal) which they call dead space fraction. Griffin and Barfield (1983) found that the dead space fraction was related to pond length to width ratio but only weakly related to the pond inflow velocity. There results are presented in table 4.3.

Table 4.3: Relationship between dead space and length to width ratio

Length to width ratio	Dead space (%)
1:1	**30**
2:1	**25**
3:1	**20**
4:1	**15**
5:1	**10**

These results suggest that for an equal % dead space, smaller surface area ponds can have equivalent solids retention efficiency if the length to width ratio is adjusted. For small scale mining operations this translates in more benefits.

Based upon ideal settling conditions, there is a direct relationship between the retention storage depth of the pond and the retention time. This relationship can be expressed as

$$V_S = \frac{D}{3600\ T_D} \qquad \textbf{(4.7)}$$

Where, V_S = particle settling velocity (fps),

D = detention storage depth (ft), and

T_D = Detention time (hours).

The particle settling velocity is defined by Stoke's Law and is dependent upon temperatures of the water, particle size, and specific gravity of the particle. To determine the design particle size, the temperature of the water was assumed 25^o C, since this is part of the Imhoff cone test and sets the criteria which must be satisfied. In the field, the temperature of the water runoff will be closer to 10^o C. For the same particle size, settling will take longer in the water which is 10^o C than in the water which is 25^o C or 30^o C. Therefore, design of the sedimentation pond is based upon the water O.K. Assuming a water temperature of 10^o C and the specific gravity of the particle to be 2.65, Stoke's Law may be written as

$V_S = 2.254\ d^2$ **(4.8)**

where, V_S = particle settling velocity (fps) and

d = particle diameter (mm).

The result of combining Equation 4.7 and 4.8 is

$$2.254\ d^2 = \frac{D}{3600\ T_D} \qquad \textbf{(4.9)}$$

Figure 4.7 presents the relationship between the particle diameter and Retention time for various depths using Equation 4.9. To settle any size particle, the required Retention time for various depths can be found from Figure 4.7 or computed by Equation 4.9

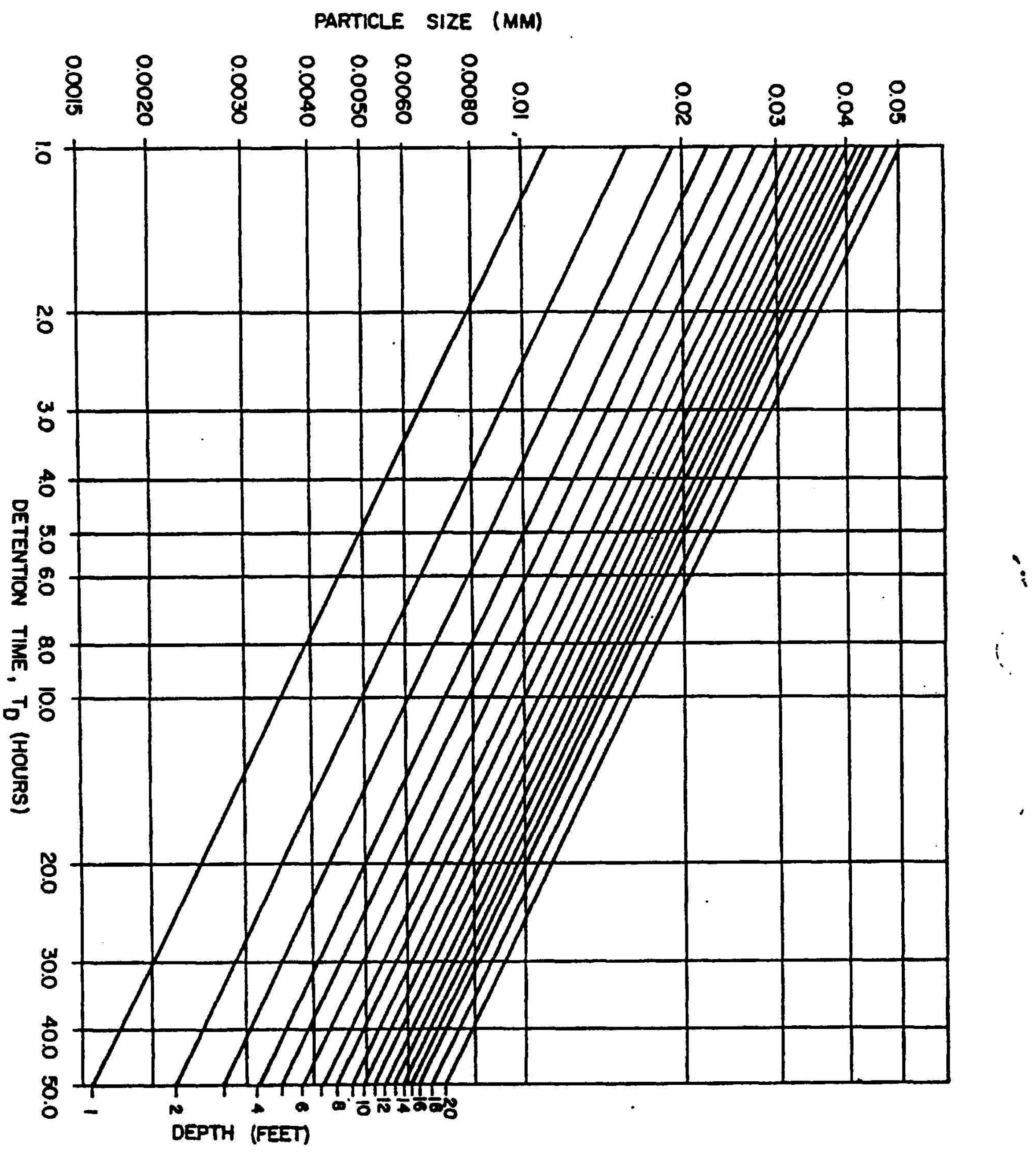

Figure 4.7
PARTICLE SIZE VERSUS DETENTION TIME FOR VARIOUS DEPTHS

There is also a direct relationship between the flow length of the pond and the Retention time. This relationship is represented as

$$V_H = \frac{L}{3600\ T_D} \qquad \textbf{(4.10)}$$

where, V_H = horizontal flow velocity through the pond (fps),

L = flow length of the pond (ft), and

T_D = detention time (hours).

The horizontal flow velocity through the pond can be computed as

$$V_H = \frac{Q_Q}{WD_1} \qquad \textbf{(4.11)}$$

where, Q_Q = peak outflow rate (cfs),

W = average width of the pond (ft), and

D_1 = total depth of the pond (ft).

Combining Equations 4.10 and 4.11 results in

$$L = \frac{3600 T_{D1}\ Q_Q}{WD_1} \qquad \textbf{(4.12)}$$

Where, $T_{D,}$ $Q_{Q,}$ W are as defined in Equation 4.11 and

D_1 = sediment storage depth plus detention storage depth, and

T_{D1} = detention time for depth D_1 from Equation 4.10

Equation 4.12 gives the required flow length of the pond to settle the design particle size. This equation is used as a check after the pond storage volume and outflow have been established. The total depth is used in Equation 4.12 since the particle will be required to settle this depth just after the pond construction is completed. If the required flow length cannot be achieved, measures described in Section 4.2 can be taken to increase the flow length of the pond.

5. Sedimentation through chemical treatment

As sediment particles become very small the time required under gravitational settling conditions becomes very large. Sediment sizes greater than 11 µm are considered to be settleable in a sedimentation pond while sizes between 1 µm and 11 µm are settleable but usually not in the time available in a typical sedimentation pond. Sediment sizes between 10^{-3} µm and 1 µm are described as colloidal dispersions and are held in suspension by electrical forces. Colloidal particles yielded from disturbed lands are primarily clays. The time required to settle one foot for each class particle is illustrated in Table 5.1.

Table 5.1: Effect of Decreasing Particle Size on Settling

Diameter of Particle (microns)	Class of Particle	Time Required to Settle One Foot
100	Very Fine sand	38 seconds
10	Fine silt	33 minutes
1	Medium clay	55 hours
= 1	Very fine clay and colloidal particles	= 230 days

5.1. Coagulants and flocculants

The use of coagulants and flocculants to increase the settling of colloidal sediments can be effective provided reasonable influent conditions can be obtained. Coagulants and flocculants are effective over a relatively narrow range of concentration in water (Figure 5.1). A change in the coagulant concentration of five times in either direction from the optimal concentration will completely eliminate any effect on colloidal settling. Even a change of twice the optimal concentration of the coagulant will reduce colloidal settling by 50 percent.

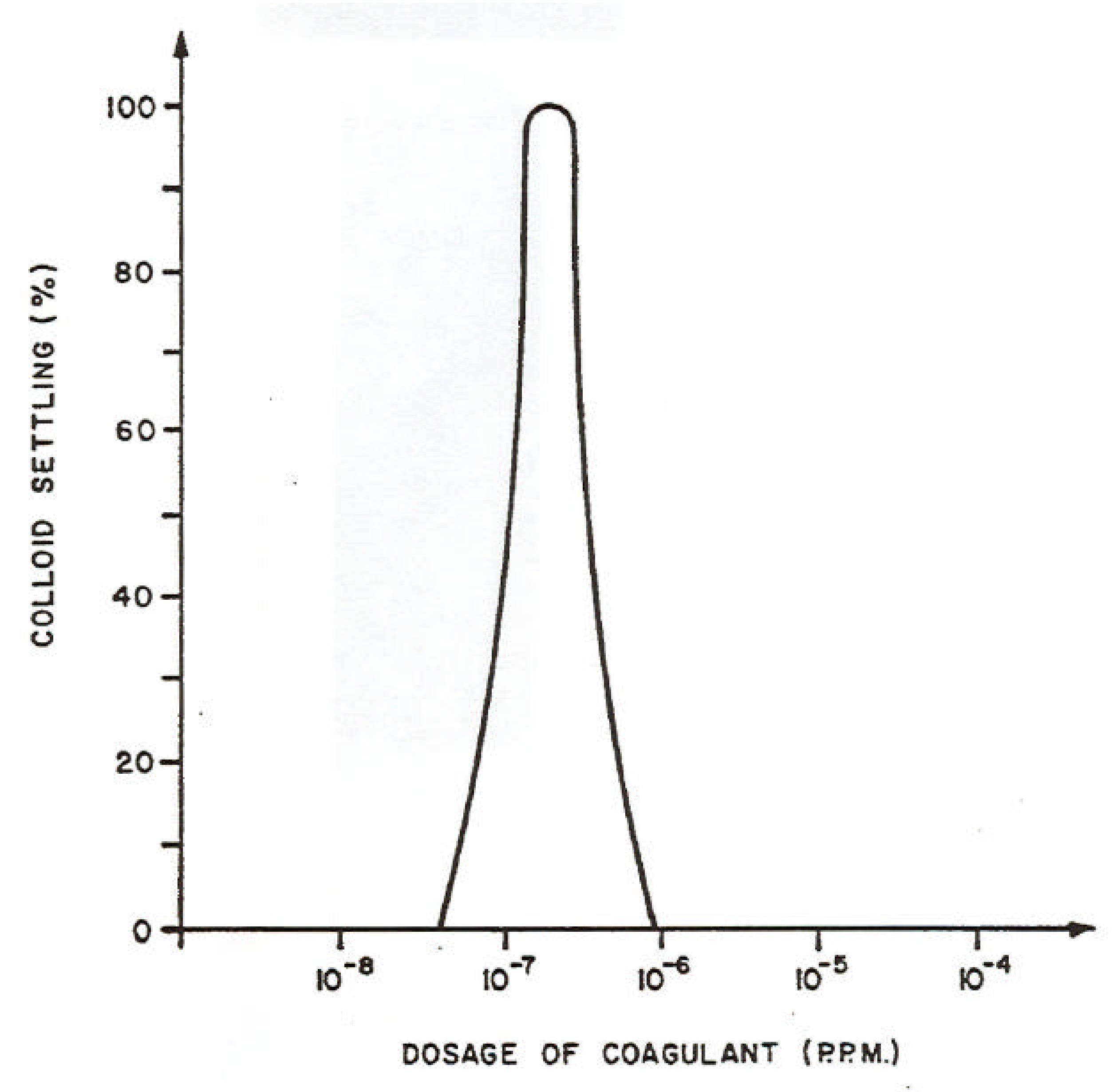

Figure 5:1 Effective Concentration Range of Coagulants and Flocculants

The inflow to a sedimentation pond will vary by an order of magnitude for a single storm and will vary by several orders of magnitude for different storm events. An application of a coagulant at a constant rate to this type of inflow condition would be unacceptable since the coagulant concentration would vary greatly.

Two approaches can be taken to controlling the coagulant concentration to maintain effective colloid settlement. One method is to control the inflow rate of water to be treated so that a constant application rate of coagulant can be used. This requires that two sedimentation ponds be used. The first pond is designed to settle coarse sediments. Coagulants are then added to the outflow of the first pond where the outflow structure has been designed to control the outflow rate within an acceptable range. In this way, coagulant would be used only for fine and colloidal sediments in the most effective and economical manner. The second pond is designed to settle fine and colloidal sediments.

An alternative method is to allow an uncontrolled outflow from the first pond and to vary the amount of coagulant based on the rate of discharge to the second pond. In this type of system, a monitoring device is required to indicate the liquid level which controls a pump delivering coagulant to the outflow. This type of system is beneficial when large discharges are being treated to meet stringent water quality requirements.

5.2. Field application in the use of chemical treatment

The use of chemical coagulants and flocculants in sedimentation ponds varies from sophisticated rate controlled application to simplified constant point applications. Most field hardware is fairly simple and consists of a storage or mixing tank for dilution of the chemical, chemical feed pump, and plastic hose to the point of application.

Most mine sites are remote, and power sources and the ability to install and maintain a sophisticated system are quite difficult. Thus, many of the existing application have been simplified to enable easier application. Very simple applications are represented by spreading of solid coagulants in roadside channels carrying disturbed area runoff where the flow in the channels scour up the coagulants; or by diverting the disturbed area runoff through barrels with solid or briquette forms of coagulants in the barrel where the flow turbulence through the barrel dissolves and mixes the coagulant. Sophistication of simple systems increases with addition of a tank for chemical storage, a feed pump, and a plastic feed line to the application point. These systems are constant rate feed that can be adjusted manually to change the dosage.

Another innovative application is being tested in the field at a mine site in Alabama. Here, the application is a solid “gel log” of synthetic, high molecular weight polyacrylamide copolymers. Initial bench tests are still required to select the most suitable flocculant. The logs are placed directly in the flow that maximum contact between the flow and the log occurs. The logs should be placed so that sufficient mixing occurs. This is done by placing the logs in or upstream of the highly turbulent flow area. The log requires a secure position in the flow so it is not washed downstream. The exact dosage requirement requires trial and error adjustments in the field by varying number of logs and observing the results. They work well under low-flow conditions, but dissolve during high runoff events. Maintenance is required to keep leaves, twigs, and sediment from covering the log and reducing contact surface and thus the dosage.

The application loses a significant amount of control during dynamic conditions where both flow rate and sediment concentration vary during a storm runoff event. The simplified methods can provide effective treatment under certain conditions, but as the conditions change and no adjustment is made, the effectiveness of the method is reduced and often nullified.

5.3. Types of coagulants

Commonly used coagulants include:

1. **Metal salts**
    - Aluminum sulfate
    - Ferrous sulfate
    - Ferric chloride

2. **Metal hydroxides**
    - Aluminum hydroxides
    - Calcium hydroxides

3. **Synthetic polymers or polyelectrolytes**
    - Anionic

- Cationic
- Nonionic

Metal salts and hydroxides are available in a dry granular form and are dissolved in clean water before mixing. Synthetic polymers or polyelectrolytes are usually available in liquid form which need not be diluted prior to use if good mixing is available. Metal salts and hydroxides are cationic and are useful in removing colloidal solids. Synthetic polymers and polyelectrolytes are cationic, anionic, or nonionic. Settleable solids which require a coagulant will use one which is normally anionic.

Advantages and disadvantages of liquid and solid coagulant will depend on a number of factors. The volume of solid coagulant needed is much greater than for liquid coagulants. Dilution of solid coagulants can be difficult under field conditions when a clean water source is unavailable or because mixing is slow. Both liquid and solid coagulants are extremely caustic and may cause severe corrosion of the containers in which they are stored. Gelled polymers are presently available which combine several of the advantages of solid and liquid polymers. They are easy to handle and transport and do not require dilution. Disadvantages of gelled polymers are the inability to control the dosage level of the coagulant where it will not work well during high flow events.

5.4. Water quality resulting from chemical treatment

The effect of coagulants on settling of colloidal particles has been demonstrated to be effective in municipal and industrial applications. Well monitored and controlled sedimentation ponds have also shown significant improvement in water quality from treatment with coagulants. The treatment of colloidal suspensions in water with coagulants is still more of an art than a science and any application will require a significant amount of testing and experimentation to produce good results. Overdosing and underdosing are significant problems to be overcome in any system, as well as the problem of adequate mixing and floc formations. Settling efficiency must be determined from test data and actual pond performance will vary from one mine site to another.

Tests on pilot scale sedimentation ponds showed that the effluent suspended solids concentration for flocculation tests were at least one order of magnitude lower than those from identical tests without flocculants (Barfield *et al.*, 1981). It was concluded from these tests that the use of chemical coagulants and/or flocculants will improve the performance of sedimentation ponds. However, the procedures to predict effluent concentrations using flocculants are not highly accurate (Barfield *et al.*, 1981).

The sediment removed from a sedimentation pond treated with coagulant will contain flocculated sediment and coagulant. Metallic salts and hydroxides are stable and will remain so after they have been disposed of, sediment containing polymers will undergo more complex interactions, possibly with micro-organisms both in the pond and in the disposed area. No definite information is known on the rate of biodegradation of various polymers by micro-organisms. Information on the toxicity of potential degradation products is also unknown. Caution should be exercised in the use of polymers because of the limited knowledge concerning the biodegradation products and their potential effects on plants, animals, and man.

5.5. Flocculants testing in Guyana

BHP Billiton (2002) conducted a series of test in Guyana for GENCAPD. A series of water treatment tests were undertaken at the mine site on the Lower Takuba River with solids contaminated jig water and with mine discharge effluent on the Upper Takuba River.

- **Lower Takuba River**

The jig tailings water (though not high in clay) was found to flocculate and settle easily with a cationic flocculant followed by the addition of an anionic flocculant, a clear supernatant was produced with the addition of approximately;

1ml 0.5% solution Percol 368

1ml 0.5% solution Percol 156

- **Upper Takuba River**

Mine discharge water entering the river was tested. The river water prior to flocculant addition is cloudy and very slow (if at all) settling suspension of clay-sized solids.

1ml 0.5% solution Percol 368 was added to 500ml river water, the cylinder was inverted five times at which time small 'pin' flocs could be seen to be forming. 1ml 0.5% solution Percol 156 was then added and the cylinder inverted again five times.

Immediately large flocs formed and the solids settled to the bottom of the cylinder after a few seconds.

The same tests were performed with 0.5% solutions of Percol 7117 and Percol 10, this combination of cationic and anionic flocculants produced similar results to the 368/156 combination. The resulting flocs were 'stringy' and the supernatant slightly cloudy.

Another test was performed with the solid polymers Percol CA1 and Percol AN1, solid forms of 368 and 156. Good flocs, a high settling rate and good supernatant clarity were achieved.

No problems were encountered in settling any of the mine effluent suspended solids with the synthetic polymers. Rapid settling rates and high clarity supernatant water is easily achieved with suitable polymers, a low solids percent and adequate reagent dosage rates.

Powdered flocculants are relatively high cost and require specialised mixing, storage and dosing equipment if they are to be used effectively and efficiently. Cationic flocculants dissolve in water readily whilst anionic flocculants can be difficult to dissolve.

In order to overcome some of these issues a range of flocculants are available in solid block form. The solid form allows the user to place a polymer block at the outfall of a discharge line containing fine suspended solids. Note, the polymer blocks are not intended for use in flows containing coarse particles, as these will quickly erode the block. The flow of water across the block dissolves sufficient polymer to flocculate and settle the solids in a settling pond (or series of ponds) before the water discharges into the receiving environment, i.e. a river or stream. The manufacturer's recommendations should be followed when the blocks are used.

GGMC did laboratory testing using alum and Magnafloc 351 (Callender, 2004). The use of flocculants reduced turbidity of effluent waters by more than an order of magnitude. But in his conclusion, Callender (2004) stresses the cost of flocculants for small scale miners and the impact on the environment where oxygen depletion can occur.

6. Ponds construction and design

6.1. Mechanised mining operation

More and more mining operations in Guyana make use of mechanised equipment. Those fortunate miners have the means of reducing the idle time before reaching the payload. They also have the opportunity of easily obeying to the mining regulations without hardship.

6.1.1. Dry stripping

Although dry stripping of the overburden is not performed on a routinely basis even with mechanised operations, it is being considered more for financial purposes then for environmental concerns. Whatever the reason, the effect on communities is positive. When dry stripping the overburden, the operation can salvage the topsoil for future agricultural purposes and put aside the clay material (Picture 6.1). This material corresponds to the hard to settle size fraction in sedimentation ponds. Put aside before hydraulicking, it significantly reduces the excursion of turbidity plumes in creeks and rivers. Curnow (2002) described the structure of typical topsoil from the North West District (Figure 6.1).

Picture 6.1: Reclaiming overburden

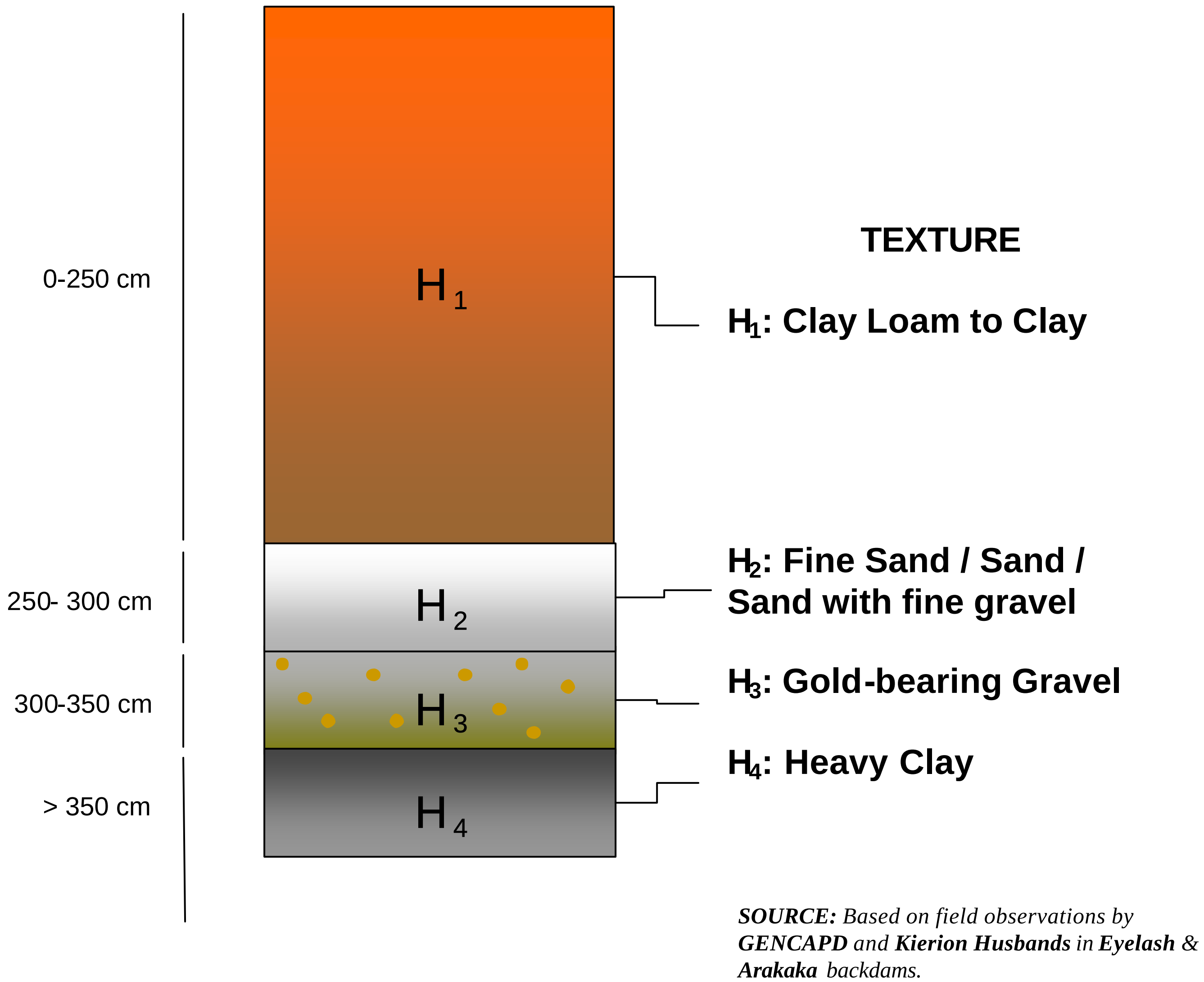

Figure 6.1: Typical topsoil structure in the NWD.

In this typical case, the mechanical removal of layer H1 before hydraulicking, skews the particle size spectra to denser particles requiring the design of a smaller dimension of sedimentation ponds and a fewer number of ponds in series. The depth of the pond will still be dependant on the storage requirement.

In the Proto Mahdia area, Couture and Lambert (2002) found that if the operation involves mining of old tailings, layer H1 is covered by a mixture of layer H1 and H2 of approximately 1 m. This requires direct feeding of the sluice with an excavator.

Depending if this operation will also mine layer H3 at the site, only a preliminary size analysis of particles will provide adequate design of the sedimentation ponds.

6.1.2. Hydraulic stripping

Hydraulic stripping involves the washing of the topsoil clay material (Picture 6.2). With the use of an excavator, embankments can be built to contain the slurry from reaching nearby creeks. In this case, the operation must previously excavate a series of ponds; the number and individual size will be a function of adequate water quality for a recycling system. In hydraulic stripping operations, building sedimentation ponds is time consuming.

Picture 6.2: Topsoil hydraulicking

6.2. Labour intensive mining operations

By definition, this mining practice requires the least capital investment and rarely finds significant return from the grades. At times it fits in the category of subsistence mining. The operations are widespread in Guyana and very mobile (Picture 6.3). They rarely work a site for more then a few months.

Picture 6.3 : Manpower operation

The most affordable sediment pond design for ma aboveground pond. It should be configured to hold the effluent of a first extraction pit. Multiple ponds in series must be constructed and water recycling must start as soon as the suspended solids concentration in the last downstream pit permits closed circuiting.

7. Pond maintenance and outlet monitoring

7.1. Pond maintenance

7.1.1. Maintaining sediment storage volume

Most sedimentation ponds should be designed with sufficient sediment storage volume for the average duration of an operation. For small scale mining operations migrating frequently, the maintenance might not be necessary. As a rule of thumb, it is recommended to clean out when the accumulated sediment reaches 60 percent of the design sediment storage volume. If the operation uses multiple ponds in series, then the upstream pond (coarser material) will require more maintenance. In order to ensure adequate storage volume, the available sediment storage volume in a pond must be monitored. Pre-defining the clean-out level is helpful for monitoring. One of the simplest means of pre-defining the clean-out level is to install a staff gauge in the pond and to determine the sediment accumulation level that requires clean out.

Cleanout of sediment is usually handled by a small dragline. For large ponds which cannot be cleaned by draglines operating from the banks, cleaning is more difficult. In such cases an excavator may be necessary.

Sediment removed from a pond is usually incorporated into the spoil material. If the removed sediment is found to contain silt material, the sediment will have to be disposed of in a more controlled manner.

7.1.2. Maintaining inlet and outlet structures

Maintenance of inlet and outlet structures is an extremely important requirement in achieving effective sediment control. All water-handling structures should be inspected after every major rain fall. Erosion damages require prompt repair to prevent further damage and to help prevent similar damage in the future.

Sediment build-up in the inlet section and filter barriers should be checked. Sediment and other debris removed from these areas should be disposed of in a manner that will prevent sediment from being carried back into the waterways at the mine.

8. Stepwise procedure for sedimentation pond design

8.1. General procedure to be used in mining districts of Guyana

Step 1 Site selection (Section 3.1)

The sedimentation pond location is selected considering the factors presented in Section 3.1.

Step 2 Hydrology (Section 3.1.3)

The peak inflow rate from the sluice(s) is determined.

Step 3 Influent sediment size distribution (Section 3.2.1)

The size distribution of the inflowing sediment is required. Where existing information from the mine site or nearby sites is available, it should be used. When there is no existing data, a size distribution can be developed using information from soil surveys.

Step 4 Sediment load

Estimate the sediment load expected from the operation. This will help determining the depth of the pond for storage capacity.

Step 5 Inflow suspended solids concentration (Section 3.2.2)

Determine the average influent suspended solids concentration.

Step 6 Settleable solids concentration (Section 4.2)

Develop the settleable sediment size distribution (particles > 1µm) from the influent sediment size distribution. Select a particle size to be removed in the pond. Determine the average effluent suspended solids concentration using the trapping efficiency, sediment yield, and runoff volume (Equation 4.5). Calculate the settleable solids concentration (SS) from Equation 4.4. If SS > 0.5 ml/l, select a smaller size particle and repeat procedure. If SS = 0.5 ml/l, go to step 7 and design pond to remove selected particle size. If SS < 0.5 ml/l, select a larger size particle and repeat procedure.

Step 7 Required storage volume (Section 3.6)

Assume a detention storage depth and determine the required detention time for the design particle size from Figure 4.7. Calculate the time base of the tailings inflow during steady state of the mining operation. Determine the required storage volume from Figure 4.5. Determine the required outflow rate from Figure 4.6. Compare the required storage volume to the available storage volume. If the available storage volume is less than the required storage volume, either:

a. Increase the embankment height and determine the new available storage volume. Repeat Step 8.
b. Excavate the pond side slopes and develop new stage storage curve. Repeat Step 8.
c. Construct a pond downstream and return to Step 1.

If available storage volume is larger than the required storage volume, check the required surface area. If the measured surface area is less than the required surface area, (1) excavate pond side slopes or (2) raise principal spillway crest. If the measured surface area is greater than the required surface area, check length-width ratio and calculate required length to settle design particle size. If the length is not large enough, increase the flow length. If the length criterion is met, check scouring. If the scouring velocity is smaller than the horizontal velocity, increase the depth and return to Step 7. If the scouring velocity is greater than the horizontal velocity, go to Step 9.

Step 8 Principal outlet

Select principal outlet type and design for the peak outflow rate and the corresponding head.

9. Bibliography

Barfield, B.J., R.C. Warner and C.T. Haan. 1981. *Applied hydrology and sedimentology for disturbed areas*. Oklahoma Technical Press, Stillwater, USA.

BHP Billiton Inc. 2002. *Diamond recovery technologyin Guyana*. Technical report produced under the GENCAPD project. 21p.

Callender, P. 2004. *Report on laboratory testing of Alum and Magnafloc as settling agents for dredge effluent*. Guyana Geology and Mines Commission. Mines Technical Section. 14p.

Chandan, D. 2004. *Mahdia tailings project: Progress report #2*. Guyana Geology and Mines Commission. Mines Technical Section. 43p.

Couture, R. and J.D. Lambert. 2002. *Mercury and land dredge alluvial mining in Guyana*. GGMC Mining week Conferences. Presentation on June 5th 2002.

Curnow, C. 2002. Tailings management in Guyana. Power Point Presentation made at GGMC under the GENCAPD project on November 2002.

Griffin, M.L. and B.J. Barfield. 1983. *Model studies for dead storage within sediment ponds*. Symposium on surface mining, hydrology, sedimentology and reclamation. University of Kentucky, Lexington, USA.

Lafleur, C., R. Couture, S. Gordon, J. Osborne and C. Mc Almont. 2002. *Hair mercury levelsof residents in interior communities of Guyana*. GGMC Mining week Conferences. Presentation on June 5th 2002.

Livan, K. and R. Couture. 2002. *Turbidity interim limits for the Potaro River*. Report presented under the GENCAPD project. 14p.

Ramdas, K. 2004. *A guideline on the construction of an aboveground tailings pond*. Guyana Geology and Mines Commission. Mines Technical Section. 19p.

Shames, I.H. 1962. *Mechanics of fluid*. McGraw-Hill Company.

Sigma Resources Consultants. 1986. *Placer mining settling ponds. Design Manual.* Department of Indian Affairs and Northern Development of Canada. SRCL S3487. 98p.

Simons, Li & Associates. 1982. *Design Manual for sedimentation control through sedimentation ponds and other physical/chemical treatment.* U.S. Department of the Interior Office of Surface Mining. 178p.