DEPARTMENT OF INDIAN AFFAIRS
AND
NORTHERN DEVELOPMENT

PLACER MINING SETTLING PONDS

VOLUME ONE
DESIGN PRINCIPLES

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CONTENTS

1. INTRODUCTION

This report reviews methods and criteria for placer mining settling pond design. The study was funded by the Canada/Yukon Economic Development Agreement as part of a program of research and development to assist the placer mining industry in meeting environmental protection standards and to improve the economic efficiency of placer mining. Volume Two of the study outlines a methodology for a placer mining settling pond research and demonstration project.

The mining and processing of placer gold generates wastewaters containing high concentrations of fine sand, silt and clay. Reduction of sediment discharges is required primarily to minimize impacts of sediment and turbidity on the aquatic environment and fish. Sediment discharge control to avoid sedimentation of water supply intakes of downstream mining operations and to allow recycling of process water in water short areas are secondary factors.

Regulation

Placer mining wastewater discharges became regulated in the Yukon Territory with the passage of the Northern Inland Waters Act in 1970 by the Parliament of Canada. Draft guidelines, proposed by Indian and Northern Affairs Canada, Fisheries and Oceans Canada and Environment Canada were discussed and debated in a formal public review in 1983. These guidelines, which have not been adopted, proposed effluent standards ranging from no discharge to 1000 mg/l suspended solids, depending upon the significance of the fisheries resources involved.

Water use and waste discharge objectives are presently contained in water licences issued to each mining operation by the Yukon Territory Water Board. Water licences issued by the Water Board generally require:

1) treatment of wastewater in settling ponds with an effluent objective of a maximum of 0.2 ml/L settleable solids; and

2) design of instream works or stream diversions for either the two year return period or five year return period flood (Ken Weagle, Yukon Territory Water Board, pers. comm.).

Compliance

The compliance of the industry in meeting water licence effluent objectives has been monitored by inspectors of the Water Resources Division of Indian and Northern Affairs Canada. Data from inspection reports for 1984 indicate that about 40% of samples of settling pond effluents were less than or equal to the 0.2 ml/L settleable solids objective. Only 21% of the samples of final effluents had a suspended solids concentration of less than 100 mg/L (Table 1.1). The data indicate that settling pond systems, as presently designed and operated, have variable effectiveness in meeting effluent quality objectives.

Limitations

The technology for suspended solids removal by sedimentation, chemical coagulation and flocculation is well developed for industrial and municipal water and wastewater treatment. However, in comparison to most industrial or municipal water users, placer mines generate wastewater volumes that are extremely large in relation to the size of the operation. Compared to major hardrock mines, placer mines can have equal or greater suspended solids and volume discharges, but a small fraction of resources such as manpower, capital and land area to apply to wastewater treatment and fine tailings storage. Topography and other minesite constraints can also make adaptation of conventional wastewater treatment technology difficult and expensive.

TABLE 1.1

YUKON PLACER MINE EFFLUENT QUALITY IN 1984

	Effluent Quality	Percentage of Samples[1]
1.	Less than or equal to 0.2 ml/L settleable solids	40
2.	Less than 1000 mg/L suspended solids	52
3.	Less than 500 mg/L suspended solids	39
4.	Less than 100 mg/L suspended solids	21

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[1] Based on 156 samples from 81 operating mines, 1984 inspection report data, Water Resources Division, Northern Affairs Program, Indian and Northern Affairs Canada, Whitehorse. The total number of operating mines in 1984 was approximately two hundred.

Several previous studies have concluded that the most practicable method of placer mine wastewater treatment is some form of settling pond system. If space is available, settling ponds that work reasonably well can be constructed with available mining equipment. However, at some mines, due to the settling characteristics of the soil or due to topographical constraints limiting the size of ponds, effluent standards of 100 or even 1000 mg/L suspended solids may not be achievable by sedimentation in ponds without the use of coagulants and relatively sophisticated wastewater and solids handling equipment.

Rationale

Establishment and enforcement of effluent standards in the future will require definition of settling pond design criteria plus delineation of the capabilities and limitations of settling pond systems designed and operated according to established criteria.

Study Objectives

The objectives of this study are as follows:

1) to provide appropriate design criteria for placer mining settling pond systems;

2) to develop a method for sizing ponds and for roughly estimating pond effluent suspended sediment concentrations;

3) to examine methods of improving pond performance; and

4) to prepare a methodology for a settling pond demonstration project (presented in Volume Two).

Definition

In this study, the term "settling pond system" is defined by the following general principles:

1) the pond effluent should consistently meet a settleable solids level of less than or equal to 0.2 ml/L;

2) creek flows not required for process water should be diverted or bypassed around the settling pond; and

3) the pond location and construction should provide for storage of sediment in a stable location not subject to erosion from "average" floods (ie. the design of stream diversions should be based on two year return period flood or greater).

Settling pond systems designed in accordance with these principles should reduce the intermittent release of high sediment loadings and provide for relatively efficient settling conditions in the ponds.

Report Outline

Proposed design criteria need to be practical and realistic. Section 2 of the report reviews the major factors that influence placer mining effluent quality and describes minesite constraints for different types of operations.

Section 3 reviews the applications and limitations of sedimentation theory and alternative pond design methods derived by previous studies. A recommended approach is presented.

Section 4 describes detailed design criteria for settling pond systems. This report is not a "design manual", but is intended to provide the rationale for certain design concepts that could be incorporated into a manual after completion of the Demonstration Project scheduled for summer 1986.

Constraints at some mining operations may limit the capability of meeting effluent suspended solids standards using conventional settling ponds. Reduction of water use through feed classification or recycling, and the addition of flocculants are possible methods of reducing solids discharges. The applications and limitations of alternative wastewater treatment methods are described briefly in Section 5.

A settling pond demonstration project will be useful to resolve some of the outstanding questions on pond design and performance and also to provide an example of "proper design" at an operating mine. Settling pond research requirements are identified in Section 6. The methodology for the demonstration project is presented in Volume Two under separate cover.

The report findings and recommendations are summarized in the final section.

2. WASTEWATER CHARACTERIZATION AND MINESITE CONSTRAINTS

2.1 SEDIMENT SOURCES AND MEASUREMENT PARAMETERS

The reduction of sediment discharges (ie. sand, silt and clay) to receiving waters is the primary focus of placer mining wastewater treatment. Effluent standards for oil and grease, mercury and arsenic have also been proposed (1983 Draft Guidelines) however, there is less potential for major problems from these pollutants. Oil and grease and mercury can be controlled by "good housekeeping" practices. Arsenic levels can be increased over natural levels by sluicing pay gravels containing arsenic minerals. However, for Alaskan placer mines, arsenic toxicity problems would appear to be very unlikely due to the relatively low concentrations that have been observed and the effective removal of arsenic by settling pond systems (Shannon and Wilson Inc, 1985).

Sediment Sources

Sediment discharges can result from the following placer mining activities:

1. **Sluicing** - washing and processing pay gravels for gravity separation of the placer gold (usually in a sluice box)
2. **Hydraulic Stripping** - hydraulic stripping of overburden using high pressure water jets (monitors)
3. **Stream Diversions** - erosion of settling pond sediments, overburden, gravel or other materials by streamflow during high flow periods as a direct result of construction of unstable stream diversion channels
4. **Groundsluicing** - erosion and thawing of overburden by directing streamflow over or against the overburden or by pushing material into the stream
5. **Surface Runoff Erosion** - erosion of disturbed areas by surface runoff (ie. thawing "black muck" is particularly susceptible).

The major emphasis of this report is the design of settling ponds for treatment of pay gravel processing effluents. Settling pond design principles would be similar for treatment of hydraulic stripping effluents, although fine grained "black muck" soils would require relatively larger ponds to provide sufficient sediment storage space and settling time.

Erosion Control

Stream diversions to bypass the settling ponds are frequently necessary to reduce the hydraulic loading and optimize settling conditions. However, stream diversions require careful planning, design and construction to be stable. Erosion of settling pond dykes and deposited fine grained sediments by streamflow may negate benefits to the environment derived from initially constructing and operating the pond.

The control of erosion of disturbed areas by surface runoff should also be incorporated into an overall sediment control plan. For example, drainage and local surface runoff from areas of stripped and thawing overburden could be directed by ditches to the main settling pond or small detention areas. Erosion control techniques for disturbed areas have been described elsewhere (EPA, 1976, Curran and Etter, 1976).

Settling pond treatment of total creek flows used for groundsluicing would not usually be practicable due to high flowrates. Groundsluicing would typically only be permitted on certain creeks within specified time periods when sediment discharges are acceptable to regulatory authorities.

Measurement Parameters

The quantity of sediment in effluents can be measured and monitored by the following parameters:

1) Settleable Solids ml/L (milliliters per liter)

The settleable solids parameter is defined as the volume of sediment that settles in one hour in a one litre Imhoff cone (approx 0.4 m high). A settling pond effluent measurement of less than 0.2 ml/L (the practical detection limit) would indicate that the settling pond is effective in removing all sand and coarse silt material (larger than about 0.01 mm) from the water.

Imhoff cones are relatively inexpensive and the mine operator can use them in the field to monitor pond performance. Monitoring results can be useful for:

- prediction of possible sedimentation problems at downstream water supply intakes;
- protection of pumps from excessive wear due to inadequate settling of abrasive coarse silt and fine sand;
- rough estimation of the possible rate of accumulation of sediments in a settling pond.

2) Suspended Solids mg/L (milligrams per liter)

The suspended solids parameter is defined as the weight of sediment in a given volume of water as determined by filtration, drying and accurate laboratory weight determination.

This parameter does not provide direct information on the settling characteristics of the sediment since the sediment can be of any grain size and type of material. Nevertheless, it is a primary parameter used for effluent quality regulation. Suspended solids measurements can be used in conjunction with effluent flowrates to calculate sediment loadings (see below).

3) **Turbidity (turbidity units)**

Turbidity is a measure of the interference of the passage of light through water caused by suspended material. Turbidity is also directly related to certain environmental impacts such as disruption of sight feeding by fish.

Turbidity measurements using a field instrument are easily obtained and can quickly indicate relative suspended solids concentrations. Less expensive tools for monitoring water clarity, such as the "clarity wedge" (Stanley, 1985) can also provide an estimate of suspended solids concentrations.

4) **Sediment Loading (ie. tonnes/day)**

The overall effectiveness of a waste treatment system for sediment removal can be monitored by determining reductions in total sediment quantity. Daily sediment loading can be calculated by multiplying the average suspended solids concentration by the daily effluent volume.

Parameters for Effluent Standards

Effluent standards can be specified using one or a combination of the measured parameters listed above. The selection of the parameters for effluent standards can have a major effect on the design of waste treatment systems. For example, effluent standards that specify only a maximum suspended solids concentration (ie. 1000 mg/L) without restrictions on water flow rates may tend to encourage high water use to "dilute" the finer grained "unsettleable" material in the pay gravels. Wastewater systems that actually reduce total sediment loadings, using recycle to reduce water flow rates, may not comply with this type of standard even though impact on the receiving environment has been reduced. Ideally, the effectiveness of a waste treatment system for a given mine should be evaluated based on the environmental impact on the receiving waters. However, in practice, specification of effluent settleable solids and suspended solids concentration standards greatly simplifies regulation, and this type of standard will likely be the major component of future regulations. Therefore, for the purposes of this report, the effluent settleable and suspended solids parameters will be considered the main standards for design and regulation of wastewater settling pond systems.

2.2 FACTORS AFFECTING POND DESIGN AND EFFLUENT QUALITY

The major settling pond design variables are surface area and volume. These variables are commonly lumped together and referred to as pond "size". Each operation requires a specific pond design volume in order to store settled material, plus a specific pond surface area to achieve effluent suspended solids criteria.

A number of complex factors affect both the rate of sediment accumulation in ponds and effluent quality. The major factors are as follows:

1) pay gravel grain size distribution and the related settling characteristics of the finer fractions;

2) pay material feed rate; and

3) pond influent flow rate.

Grain Size Distribution

The percentage of fine silt and clay in the pay gravels and the settling behaviour of this material has a direct influence on settling pond effluent suspended solids concentrations. For example, assuming 1% of the feed material is "unsettleable" in a pond, and if the sluice feed rate is 75 yd^3/hr (@ 110 lbs/ft^3) and the pond flow rate is 2500 Igpm, then the effluent concentration would be 1480 mg/L suspended solids. For this example, only 0.07% of unsettleable material in the feed would result in a concentration of 100 mg/L suspended solids.

The percentage of settleable fine sand, and silt in the pay gravels carried to the pond by the sluice effluent will determine the sediment storage volume required in the pond. For example, assuming 10% of the pay material is settled in the pond, the sluice feed dry unit weight is 110 lbs/ft^3 and the settled sludge dry unit weight is 65 lbs/ft^3, then the required sediment storage volume will be 17% of the total volume of material processed.

The above examples illustrate that a representative grain size distribution of the pay material and an understanding of the settling characteristics of the finer grained fraction (the finest one percent or less) is fundamental to pond design.

Pay Material Feed Rate

Pond effluent suspended solids concentrations and sludge storage volumes are directly proportional to pay material feed rates. Thus accurate estimation of material processing rates is necessary if a pond is to be properly sized.

Pond Influent Flow Rate

The efficiency of removal of suspended sediment by a settling pond is closely related to the pond influent flow rate. Accurate estimation of flow rates is therefore necessary for settling pond design.

Additional Factors Affecting Pond Design and Effluent Quality

Several additional factors can affect pond design and effluent quality. These factors have less impact than the three major factors listed above. Detailed discussions on these are provided in Sections 3 and 4.

The additional factors are:

- percent removal of finer sediments associated with coarse tailings disposal;
- settling and removal of sediments by the drain or a pre-settling pond upstream of the settling pond;

- settling conditions in the pond
    - surface area and volume
    - pond geometry and short circuiting
    - inlet and outlet design
    - turbulence and currents
    - natural flocculation and water chemistry
    - sludge density

In summary, sizing of settling pond systems can be completed with basic data as follows:

1) representative grain size distributions and knowledge of settling characteristics of the pay materials;

2) realistic estimates of pay material feed rates; and

3) realistic estimates of process water flow rates.

Placer mining pay gravel particle size distribution characteristics, material processing rates and water flow rates are described in the next section. As the availability of space for fine grained sediment storage and settling ponds is frequently the major constraint to settling pond construction, the review also includes an examination of the land areas available for settling ponds for different types of mining operations.

2.3 CHARACTERISTICS OF THE YUKON PLACER MINING INDUSTRY

Pay Gravel Grain Size and Settling Characteristics

For wastewater treatment, the fine sand, silt and clay fraction of the pay material (less than 0.5 mm diameter) is of primary interest in determining sediment storage volumes and effluent quality. Previous surveys of materials at Yukon placer mines have demonstrated a large variability in soil characteristics between mining operations. For example, the silt fraction (.002 mm to 0.08 mm) was observed to vary from 3% to 43% in samples taken from 15 mines (Table 2.1).

The quantity of sand, silt and clay in pay material can also vary within a single mine site. The fines content of alluvial gravel deposits are frequently non-homogeneous as a result of changing depositional environments. Near the base of the mined section, weathered bedrock can commonly contain a high proportion of silt and clay, especially if the parent material consists of schists or other rocks susceptible to clay mineral decomposition. "White channel gravels", which have been subject to low temperature hydrothermal alteration, can also have relatively high clay content.

There is very little quantitative data on the settling characteristics of the silt and clay found in placer gold deposits. The fine particle size determinations completed for most previous studies were conducted with the ASTM D422 hydrometer method. This procedure is essentially a settling test in which particle size diameters are calculated from their rate of settling. However, the test procedures include preparation of the sample with a high speed mechanical mixer to break up particle agglomerations and addition of a deflocculant (sodium hexametaphosphate) to prevent any natural flocculating tendencies. These procedures and other limitations modify the particle size distribution and settling behaviour such that the settling and particle size distribution determined by the test may be quite dissimilar to "natural" settling conditions and the "effective" particle size distribution of effluent in a settling pond.

TABLE 2.1

COMPOSITION OF PAY MATERIALS BEING MINED AT YUKON PLACER MINES[1]

MATERIALS	PROPORTION OF MATERIALS PRESENT IN SOIL SAMPLES			
	AVERAGE (Mean)	STANDARD DEVIATION	MAXIMUM	MINIMUM
Cobbles d G 76mm	36.3%	6.44	45%	25%
Sand and Gravel d L 76mm d G 0.5mm	42.4%	10.43	61%	13%
Fine Sand d L 0.5mm d G 0.08mm	8.3%	2.80	15%	5%
Silt d L 0.08mm d G 0.002mm	11.3%	7.65	43%	3%
Clay d L 0.002mm	0.9%	1.48	6%	0%

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1. From Reid Crowther and Bethell Management (1984), based on 26 samples taken at 15 mining operations.

2. d = diameter; L = less than; G = greater than

The ASTM D422 hydrometer method typically results in smaller particle sizes (higher clay content) than what would be expected to be observed in the field. Elimination of the deflocculant and use of the native creek water in the test can result in a markedly reduced clay content and dissimilar particle size distributions (Figure 1).

Column settling tests have been completed for soils from a few Yukon placer mining operations (SIGMA, 1981). These tests consisted of adding pay gravel and creek water in similar proportions to the sluicing operation, mixing to wash the gravels, pre-settling for a short period to remove the sand size particles, then decanting the simulated effluent into a 2 m high by 150 mm diameter settling column. Samples for suspended solids analysis were then periodically withdrawn from ports at varying depths in the column. The settling test results reported were highly variable between the minesites tested.

The existing database on pay gravel particle size with respect to the settling characteristics of the finer grained fractions is very limited. This is largely due to the lack of a standardized test that relates to sedimentation in settling ponds. However, the available data does indicate that there are large variations in silt and clay content between placer deposits and also within a particular deposit. Given that less than about 0.1% of unsettleable material in the pay gravel (about 50 ounces per cubic yard) can result in 100mg/L suspended solids for typical operation, it is apparent that key components of settling pond system design are obtaining representative samples and realistically assessing the quantity and settling characteristics of the silt and clay fraction.

Mining Operation Classification and Wastewater Treatment Constraints

In a study of placer mining materials handling, Wright Engineers (1986) developed a terrain based system of classifying placer mining deposits and, for each of these deposit classes, outlined typical placer mining operation characteristics. Although their classification system is partially subjective, it is useful for describing wastewater treatment constraints. The four classes of deposits proposed by Wright Engineers are:

1. Gulch
2. Narrow valley and low bench
3. Broad valley
4. High bench

The characteristics of mining operations for the above deposit classes and typical constraints to settling pond construction and operation are summarized in Table 2.2. The distribution of these deposits is given by Table 2.3. With the exception of broad valley deposits, the lack of sufficient space for settling ponds is the primary wastewater treatment constraint. However, broad valley deposits make up only about 11% of the total number of deposits classified (Table 2.3). Gulch deposit mines, where space for settling ponds is seriously constrained, make up almost one quarter of the total number of mining operations.

TABLE 2.2

CHARACTERISTICS OF MINING OPERATIONS AND CONSTRAINTS TO SETTLING POND CONSTRUCTION AND OPERATION

Deposit Class	No. Pieces of Equipment[3]	Mining Rate m^3/hr (yd^3/hr)	Process Water Rate m^3/hr (Igpm)	Valley Bottom Width m (ft)	Stream Gradient (%)	Constraints to Settling Pond Construction and Operation
Gulch	1-3	23 - 92 (30 - 120)	140 - 820 (500 - 3,000)	3 - 20 (10-65)	6-15	- insufficient space for ponds, ponds usually have to be located in main valley near mouth of gulch - construction of stable stream diversions around settling ponds in the gulch is usually infeasible due to narrow width and steep gradients - downstream settling ponds require an emergency bypass spillway to divert flood flows away from ponds, alternatively, the drain could be separated from the gulch creek channel - frequent moving of sluicebox and relatively small cuts.
Narrow Valley and Low Bench	2-4	38 - 115 (50-150)	270 - 1100 (1,000 - 4,000)	Less than 45 (150)	1-3	- stable stream diversions are usually required to bypass ponds - available space for sediment storage and settling is limited and may be insufficient within immediate areas downstream.
Broad Valley	5-6	77 - 153 (100-200)	540 - 1400 (2,000 - 5,000)	Greater than 45 (150)	0.1-1	- low gradients may require long drains to ponds and ponds may have to be entirely excavated rather than constructed at grade by berms; alternatively, effluents could be pumped to bermed ponds, or the process unit could be elevated adjacent to a bermed pond; if required, stream diversion channels would have to be designed for large flow rates.
High Bench (Small)	0-1	8 - 57 (10 - 75)	54 - 540 (200 - 2,000)	n.a.	n.a	- space for settling ponds on the bench may be limited, therefore land for settling ponds is usually required in the valley at the foot of the bench. - the valley may be narrow or broad and some of the above constraints could apply.
(Large)	3-4	57 - 77 (75 - 100)	410 - 1100 (1,500 - 4,000)			

NOTES:
1. Classification system and typical values, except process water rates, have been adapted from Wright Engineers (1986).
2. Process water rates have been roughly estimated from review of several previous studies and available data.
3. Earth-moving equipment; most commonly bulldozers, loaders and hydraulic excavators.

TABLE 2.3

DISTRIBUTION OF TYPES OF DEPOSITS IN THE YUKON

Class	Klondike	Stewart River	60 Mile River	Mayo	Burwash	Livingstone Creek	Carmacks	Other Areas	Total
Total Number	120	19	20	19	15	5	22	13	233
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
Gulch	18	21	5	32	33	100	32	23	23
Narrow Valley & Low Bench	53	68	80	52	60	0	41	62	55
Broad Valley	8	11	10	16	0	0	27	15	11
High Bench	21	0	5	0	7	0	0	0	11

Source: Wright Engineers Ltd, 1986

3. REVIEW OF SEDIMENTATION THEORY AND POND DESIGN METHODS

3.1 SEDIMENTATION THEORY

Types of Settling

Sedimentation is the separation from water, by gravitational force, of suspended particles that have higher specific gravities than water. The sedimentation process can be classified into four main types on the basis of concentration and particle interactions.

1. **Discrete** settling refers to sedimentation of individual particles in low concentration suspensions. Discrete settling particles tend to obey Stoke's Law in that the terminal settling velocity is related to particle diameter, specific gravity difference and fluid viscosity.

2. **Flocculant** settling refers to the sedimentation of dilute suspensions of particles that tend to coalesce or flocculate thereby increasing their mass and hence their settling rates. Flocculation is a characteristic of the material or combinations of materials involved.

3. **Zone** settling refers to sedimentation of intermediate concentration suspensions whereby the particles settle as a unit due to interparticle hindrance, generally developing a distinct interface between the sludge and the supernatant.

4. **Compression** settling refers to the compaction of high concentration suspensions due to the weight of particles being added to the sludge from the supernatant.

For most placer mining effluents, discrete settling would predominate. However, the influence of flocculant and zone settling on suspended solids removal is also important in determining minimum detention requirements for settling ponds. Some types of silt and clay suspensions have natural flocculation characteristics that tend to improve settling while others remain dispersed due to strongly opposed electrostatic charges. In addition, the degree of compression settling can markedly influence sludge storage volume requirements.

Analysis of Quiescent Settling

Discrete settling in quiescent systems can be described by the classic laws of sedimentation formed by Newton and Stokes. Equating the gravitational force to the frictional drag force for a falling spherical particle yields Stokes' law:

$$v_s = \frac{g}{18} \frac{(SG - 1)}{k} d^2 \qquad (1)$$

where:

v_s = particle settling velocity

g = gravitational constant

SG = specific gravity of solids (the specific gravity of the water is assumed to be 1.0)

k = kinematic viscosity

d = particle diameter

Applying conversion factors and assuming the specific gravity of the solids is 2.65, settling velocity can be expressed for various temperatures as follows:

$$v_s\ (0^oC) = 30.1\ d^2 \qquad (2)$$

$$v_s\ (5^oC) = 35.5\ d^2 \qquad (3)$$

$$v_s\ (10^oC) = 41.2\ d^2 \qquad (4)$$

$$v_s\ (15^oC) = 47.1\ d^2 \qquad (5)$$

where v_s is in units of m/min and d in mm. The settling velocities and times to settle 0.3 m for various particle sizes are given in Table 3.1.

The above equations are strictly applicable for quiescent settling of discrete spherical particles in the size range from about 0.02 mm (coarse silt) to 0.0002 mm (fine clay sizes).

TABLE 3.1

TIME FOR PARTICLES TO SETTLE IN CALM WATER AT 5°C

(specific gravity = 2.65)

Particle Size	Equivalent Diameter (mm)	Settling Velocity (m/min)	Time to Settle 0.3 m(1 foot)	
Coarse Sand	1.0	35.5	0.5	seconds
Fine Sand	0.1	0.355	51	seconds
Silt	0.06	0.128	2.33	minutes
	0.02	0.0142	21	minutes
	0.01	3.55×10^{-3}	1.4	hours
	0.006	1.28×10^{-3}	4.0	hours
Clay	0.001	3.55×10^{-5}	5.9	days

The main factors affecting quiescent settling velocities of actual silt and clay suspensions are temperature, particle shape, aggregation/flocculation, and interference with other particles.

Due to changes in water viscosity, settling velocity increases with increasing temperature. For example, theoretical settling velocities are 33% higher at 15°C than at 5°C.

Particle shape (ie. plate-shaped clay particles) affects the drag force and settling velocity. This is usually accounted for by classifying particles according to an equivalent fall diameter.

Aggregates of small silt and clay particles can form larger but less dense particles. Although aggregation and flocculation decreases the particle specific gravity, the diameter is so much greater than its component primary particles that aggregated particles typically have settling velocities higher than dispersed particles. The tendency for sediment particles to flocculate and form aggregated particles is highly site specific and can have a major effect on settling velocities.

The settling velocity of particles in suspensions with high concentrations of solids can be reduced by interparticle interference. However, these effects should not be significant for most placer effluents, except possibly near the bottom of settling ponds. For example, a relationship presented by Fair, Geyer and Okun (1968) indicates that at a silt concentration of 50,000 mg/L the settling velocity of discrete particles would be reduced to about 93% of the unhindered velocity.

The Ideal Settling Basin

An analysis of the sediment removal performance of an ideal settling basin can be made using the influent particle grain size distribution and settling velocities predicted by Stokes' law. An ideal settling basin is defined by the following conditions:

- steady state horizontal plug flow
- uniform distribution of the particles over the entire depth of the basin at the inlet
- negligible turbulence or bottom scour
- rectangular shape and constant fall depth

Based on the trajectory of particles through a settling basin, a critical velocity, v_c, can be selected which will just allow a particle to settle to the bottom (Figure 2). The critical velocity can be given by

$$v_c = \frac{H}{t} \tag{6}$$

where: H = depth of the basin
and t = detention time

For plug flow, the detention time equals the basin volume, V, divided by the flow rate, Q, or

$$t = \frac{V}{Q} \tag{7}$$

therefore, by substitution

$$v_c = \frac{QH}{V} \tag{8}$$

Because the ideal basin is rectangular with a surface area, A, the critical settling velocity can also be expressed in terms of an overflow rate

$$v_c = \frac{Q}{A} \tag{9}$$

All particles with settling velocity v_s greater than v_c will be removed by the basin. From the geometry of particle trajectories (Figure 2), it can also be shown that the fraction X of particles removed with a settling velocity v_s less than v_c will be

$$X = \frac{v_s}{v_c} \tag{10}$$

In a typical suspension, a large gradation of particle sizes occurs. To determine the removal efficiency of the basin for a given settling time it is necessary to determine the particle sizes and settling velocities for the entire range of particles present. The removal efficiency, R, (total fraction removed) can then be calculated by

$$R = (1 - X_c) + \sum_{0}^{X_c} \frac{v_s}{v_c} \, dx \qquad (11)$$

where: $(1 - X_c)$ is the fraction of particles with v_s greater than v_c;

X_c is the fraction of particles with v_s less than v_c; and

dx is the fraction of particles within a specified size range with an average settling velocity v_s.

Basic Model for Settling Pond Analysis

Because of its simplicity, the ideal settling basin analysis is commonly used for the design of sedimentation basins for discrete settling. However, this method of analysis has several limitations; the chief ones being the lack of consideration of turbulence and currents, shortcircuiting, irregular basin geometry and scour of bottom deposits. Complex mathematical and computer models have been proposed to attempt to take into account some or all of these factors (Wilson et al, 1984). Unfortunately, none of these methods appear to be practicable or useful for application to placer mining settling pond design. As a replacement for the complex models, it has been proposed that the ideal basin analysis be modified by empirical factors that account for non-ideal conditions (Tapp et al, 1981). Equation (8) for critical settling velocity can be modified as follows:

$$v_c = \frac{K_1 QH}{V - K_2 V} \qquad (12)$$

where:

K_1 = non-ideal settling factor (to account for turbulence and currents)

K_2 = dead space fraction (to account for pond shape and short circuiting)

Q = flow rate through pond

H = average pond depth

V = pond volume

The values for the empirical factors K_1, and K_2 are not well defined. To account for non-ideal settling, EPA (1976) proposed using a $K_1 = 1.2$. This value may be suitable for initial trials of the method.

K_2 represents the fraction of the pond volume that is essentially stagnant (dead space) and does not contribute to sediment removal. The effective amount of dead space within sediment ponds can be determined by comparing theoretical hydraulic detention time to actual hydraulic detention time as measured by dye studies. In dye studies with a physical laboratory model, Griffin and Barfield (1983) found that the deadspace fraction was related to pond length to width ratio but only weakly related to the pond inflow velocity (inlet conditions). From Griffin's results, the deadspace fraction can be estimated roughly as follows:

Length to Width Ratio	**Dead Space Fraction (K_2)**
1:1	0.30
2:1	0.25
3:1	0.20
4:1	0.15
5:1	0.10

The general procedure for using the theoretical model to predict the removal efficiency of a settling pond can be briefly summarized as follows:

1. determine the effective particle size distribution for the pond influent suspended material;

2. determine pond flow rate, average depth, volume, length to width ratio, K_1 and K_2 and then calculate the critical settling velocity using equation (12);

3. determine the total fraction of sediment removed by equation (11).

Verification of the accuracy of theoretical settling pond models is difficult even by closely controlled laboratory experiments. For example, a constant sediment grain size distribution in the experimental pond influent would need to be maintained. Problems have been experienced in accurately measuring influent grain size distributions, maintaining constant material characteristics and accounting for the effects of particle aggregation (Wilson et al 1984). Also, there is no completely acceptable method for predicting the effects of turbulence and currents (Barfield et al. 1981).

In summary, there is uncertainty as to the accuracy of the basic theoretical method. However, in conjunction with settling tests, the method may be useful for initial pond sizing. The practical aspects of using this procedure and a review of methods proposed by previous studies are discussed in the following sections.

3.2 REVIEW OF PREVIOUS STUDIES AND LITERATURE

A number of Yukon and Alaskan studies have previously addressed the treatment of placer mining effluents using settling pond systems. These studies were reviewed to examine previously used methods of settling pond analysis and design, to determine the most common practical problems in developing settling pond systems and to obtain basic data on water use, material feed rates, soil characteristics and minesite constraints.

Literature on settling pond technology other industries was found to be of limited relevance as sedimentation is rarely used without chemical coagulation. In general, industries required to meet rigid effluent standards use flocculants and/or coagulants to provide positive control over the sedimentation process.

An exception to the above is the open pit coal mining industry which has undertaken research for the design of settling basins to treat surface runoff. However, settling basin design for runoff is different from placer mining settling pond design because runoff flows are highly variable depending on the rainfall intensity pattern during a storm event, and also, the total quantity of sediment entering the pond is much lower than in the case of a placer mine. Nevertheless, the results of some of these studies provide insights as to the difficulty of theoretically modelling the settling performance of real ponds (see Section 3.1).

A list of the reports reviewed for this study is given in the reference section. Only certain references, arranged in chronological order, were selected for specific comment below. The scope of the review comments is limited to examining aspects relevant to settling pond system sizing and design.

1. **"Evaluation of Wastewater Treatment Practices Employed at Alaskan Gold Placer Mining Operations".** Prepared for the US E.P.A., Washington DC, by Calspan Advanced Technology Center, July, 1979.

    - 11 mines were described and sampled for effluent quality;

    - settling ponds were generally too small and shallow to be effective and they filled quickly with sediment;

    - feed classification significantly reduced water use and improved settling conditions in ponds;

    - settleable solids was recommended as the primary control parameter as it relates directly to pond effectiveness;

    - removal of settleable solids to 0.15 ml/L or less resulted in consistent removal of suspended solids to less than 262 mg/L (nine mines);

The findings of this study supported the premise that an effective settling pond for settleable solids removal will result in a major improvement in suspended solids levels.

2. **"Placer Mining and Water Quality"**, Alaska Department of Environmental Conservation, Juneau, Alaska, November, 1979.

This reference described three methods of settling pond sizing as follows:

1) The theoretical method based on pay gravel particle size analysis and ideal settling basin theory (similar to Section 3.1).

2) The jar sample or settling test method to determine the settling time to obtain a given supernatant quality. The pond is then sized to have an equivalent detention time.

3) The arbitrary detention time method, whereby ponds are sized only on the basis of flowrate

$$\text{(i.e. detention time} = \frac{\text{pond volume}}{\text{pond flowrate}} = \text{24 hours)}$$

The methods were evaluated by ADEC and resulted in the following comments:

"The accuracy of the theoretical method, wherein the overburden material is sampled and analyzed, depends on the sample being truly representative of the material encountered.

Similarly, with the jar sample method, changes in material size can greatly affect settling time, although new samples can readily be taken to determine settling times for different materials.

The arbitrary detention time method offers a starting point or basis for the pond size. However, it must be used in conjunction with depth criteria to determine pond area.

Each of these three methods can be used, and a pond size determined. The pond should be allowed to operate to determine if the sediments are settling out to meet the requirements. A lower rate of feeding the pond with resulting longer retention time can be used and the resultant effluent checked.

The experience and use of the particular pond and the water handling system is the best means to determine pond size. Soils and topography are all important in determining pond efficiency, so a trial and error method of sizing at a particular mine site is suggested."

The pond design approach advocated by this study is to attempt to initially size the pond system but to expect to have to modify and develop the system through experience.

3. **"Water Use Technology for Placer Mining Effluent Control"**, prepared for the Department of Indian Affairs and Northern Development by Sigma Resource Consultants Ltd, 1981.

   Major recommendations of this study were as follows:

   1) Placer mine wastewater treatment systems should be developed on a site specific basis. For the system to be cost effective, the miner should consider modifying water use, mining methods and mine layout.

   2) In addition to effluent quality considerations, settling pond design should provide for:

      - adequate sludge storage volumes;

      - well designed creek diversions that are stable during flood conditions.

Column setting tests with simulated effluents were used to predict settling pond performance. Insufficient data on actual ponds was collected to evaluate this method as an accurate means of sizing ponds. However, for two sites with operating ponds of a reasonable size, suspended solids levels in the columm (after a period of time equal to the theoretical detention time of the pond) were fairly close to the suspended solids levels observed in grab samples of the pond effluent (see below):

	Minesite	**Detention Time (hrs)**	**Column Test Suspended Solids (mg/L)**	**Pond Effluent Suspended Solids (mg/L)**
(1)	Kostem Resources, Little Gold Creek	11	30	50 - 60
(2)	Frank Taylor, Duncan Creek	3 (approx)	400	500

4. **"Settling Pond Design"**, S. Sexton, Alaska Department of Environmental Conservation, March, 1982.

This report presented examples of settling pond design using theoretical methods. Particle settling velocity data were obtained from column tests or hydrometer grain size analyses (ASTM D422). A pond overflow rate was selected that would remove a certain percent of suspended solids. "Scale-up" factors were then applied to compensate for non-ideal settling.

The design approach utilized in the Sexton report is essentially the same as the basic theoretical model described earlier. However, the proposed scale-up factors of about 4.6 to 5.7 appear to be unreasonably large. They were based on column test data developed by R and M Consultants (1982) which for several reasons were misleading (see comments below).

The Sexton report placed emphasis on sizing the ponds for sediment storage. The calculations of sediment storage volumes were based on the observed settleable solids levels in the pond influent multiplied by the estimated flow volume. Providing that settleable solids measurements are representative of average pond influent characteristics, this method should provide an adequate estimate of sediment storage volume.

5. **"Placer Mining Wastewater Settling Pond Demonstration Project Report"**, prepared for Alaska Department of Environmental Conservation by R and M Consultants, Inc. Fairbanks, Alaska, June, 1982.

The objectives of the R and M study were very similar to the present study and its subsequent demonstration project phases. The experience gained by the Alaska study is therefore of direct interest. Unfortunately, there were circumstantial problems and a few key errors made in project planning and analysis that reduced the value of the project. These are briefly outlined below:

Demonstration Project Planning

The demonstration pond was too shallow and too small to effectively remove settleable solids consistently (ie. the initial retention time was only 4 to 5 hours with an average depth of only about 2.5 feet). Pond performance deteriorated as sediment accumulated in the pond.

During pond construction, a flood in the creek wiped out a part of the pond dyke. The stream diversion channel was apparently not adequately constructed prior to pond construction.

Sampling and Analysis

Wastewater grab samples for column settling tests were collected immediately downstream of the sluicebox. This procedure is an inappropriate method of obtaining representative pond influent settling data for reasons as follows:

1) Suspended solids concentrations (and particle size distributions) can fluctuate by orders of magnitude in less than a few minutes depending on the characteristics of the material being loaded into the dump box and the point in the loading cycle.

2) The wastewater samples would have had relatively high concentrations of entrained sand because of the turbulent conditions just below the sluice. The column tests therefore indicated very high percent removals of suspended solids as calculated from initial column concentrations. In contrast, the settling pond influent would have contained very little sand as this material would settle out in the drain channel. The percent removals achieved by the pond would therefore be much lower than that predicted by the column test since the actual material entering the pond would be finer and slower settling than the material used in the column test. R and M and Sexton (1982) (see above) based their analyses on the assumption that the column test particle size distributions and the pond influent particle size distributions were equivalent. This assumption resulted in misleading study conclusions.

Placer mining wastewater solids concentrations and particle size distributions are highly variable, depending on materials handled and loading rates at the time of sampling. In the R and M study only two samples of the pond influent and effluent were collected per day. The range and true average of wastewater solids concentrations would have been much better defined by more intense sampling over a one or two day period.

R and M developed a semi-empirical relationship between the estimated "smallest particle size settling in the pond" and settling velocity (overflow rate). This relationship was based on an assumed pond influent particle size distribution calculated from a pay dirt grain size analysis (ASTM

D422 hydrometer method) and on the assumption that all particles greater than 0.3 mm would be removed in the drain. Because the actual pond influent particle size distribution was not determined directly by measurement, the derived relationship is of dubious value.

R and M correlated the observed percent removal of suspended solids at eight minesites with the percent finer than 0.02 mm (medium silt) in the pay gravels. Their conclusion was as follows:

"The relative fraction of clay and silt sized particles in the material being mined is the most critical parameter affecting the efficiency of sedimentation in settling ponds. A good correlation between sedimentation efficiency (percent removal of influent suspended solids) and the amount of fine grained soil in the pay dirt can be obtained without consideration of pond size, discharge flows and other variables."

6. **"Placer Mining Settling Pond Design Handbook"**, prepared for Alaska Department of Environmental Conservation by R and M Consultants, Inc., January, 1983.

In this handbook, sizing of sedimentation ponds to meet 0.2 ml/L settleable solids is based primarily on achieving an overflow rate of less than 3700 USgpm/acre as derived from the field studies (ie. the 1982 R & M study). No method for estimating sediment storage or required settling pond volumes is proposed. However, it is recommended that a pre-settling pond sized to remove 1/6 (16.7%) of the volume of pay material processed, be constructed and cleaned out regularly upstream of the main settling pond.

The design method proposed in the handbook ignores the effects of variation in soils between different minesite. Sizing of ponds is based on "typical" data without site specific testing.

7. **"The Attainment and Cost of Placer Mining Effluent Guidelines"**, prepared for the Interdepartmental Committee on Placer Mining (ICPM) by the Department of Fisheries and Oceans and Environment Canada, Whitehorse, March, 1983.

An example of sizing a two pond settling pond system to meet an effluent standard of 1000 mg/L was presented. The major design assumptions were:

Primary Pond

- minimum 20 minute retention time
- sediment storage for 45 days of production, then clean out or build new pond
- base storage volume on grain size curve, production rate and deposited sediment density.

Secondary Pond

- 18 hour retention time was assumed for the example but site specific settling tests were recommended to help size ponds more accurately;
- the effect of natural flocculation would probably help to improve secondary pond effluent quality over the quality predicted by the theoretical calculation from grain size data.

The pond retention time design criteria were recognized by the authors of the report to be somewhat arbitrary, but were believed to be appropriate for a "typical" operation. For the example presented, the mine and wastetreatment characteristics were as follows:

Feed Rate:	70 yds^3/hr for 7.5 hours/day	
Water Use:	4000 Igpm	(1090 m^3/hr)
Percent Sand and Silt to Primary Pond:	18% of feed	
Percent Clay:	7% of feed	
Primary Pond:	Area	= 2340 m^2 (½ acre)
	Initial Volume	= 4690 m^3
Secondary Pond:	Area	= 39250 m^2 (10 acres)
	Initial Volume	= 19620 m^3 (0.5 m deep)

Given that the above example is "typical", a 10 acre secondary pond (approx 330 feet wide by 1300 feet long) would be physically impossible for gulch, narrow valley, and some broad valley sites, with total valley bottom widths, allowing for roads and stream diversions, of less than about 400 feet. Even with reduced flowrates, the proposed 18 hour retention time criteria would appear to be infeasible for a large proportion of mining operations.

With respect to sizing the secondary pond for 18 hours retention time at 4000 Igpm, the example is actually assuming 24 hours per day operation, not the 7.5 hours stated. A pond capable of handling 7.5 hours of sluicing without a deterioration in effluent quality would be adequate since an additional 16.5 hours between sluicing periods would be available to enhance settling. The pond volume to provide a true 18 hour retention time, without consideration of sludge storage, would be in the order of 10,000 m^3.

8. **"An Assessment of the Proposed Yukon Placer Mining Guidelines"**, prepared for the Klondike Placer Miners Association by IEC Beak Consultants Ltd, August, 1983.

This report critized several aspects of Reference 7, "The Attainment and Cost of Placer Mining Effluent Guidelines". A major comment, as outlined above, was that the lack of space at most mines would contrain the construction of large ponds. Citing data from the 1982 R and M study, the report suggested that at least 35 hours retention intead of 18 hours would be more typical of ponds that could achieve 1000 mg/L. The IEC Beak report also criticized the lack of provision of additional sludge storage volume in the secondary pond for low density settled clay.

9. **"Commentary on Placer Mining Effluent Treatment"**, by D W Averill, Environmental Protection Service, Burlington, Ontario, April 1984.

In a discussion of the application of settling pond technology, Averill commented that "....the 1000 mg/L objective would be unattainable in any size of unaided sedimentation system, except at those sites where the pay gravel contains very few fine particles or the suspension is unstable because of the particular characteristics of the water." This conclusion is based on the apparent proportion of clay found in placer mine deposits, and the theoretical settling velocities of clay size particles, and the large ponds required to remove clay. Furthermore, he stated, "Chemical coagulation will evidently be required at the majority of placer mining sites if the proposed effluent guidelines are to be met."

These conclusions may only be partially correct. First, sampling data collected by DIAND (Table 1.1) indicates that 52% of mine effluent samples met the 1000 mg/L standard (at least for the period of sampling) with existing pond technology. Second, there is limited data on the actual settling characteristics of the "clay" fraction of Yukon placer mine pay gravels. As explained in Section 2.3, the widely used ASTM D422 hydrometer method, which includes mechanical mixing and deflocculant addition, tends to significantly increase the apparent "clay" content. Thus, Averill's dismissal of unaided sedimentation in ponds may be overly pessimistic.

10. **"A Study of Polyacrylamide Flocculants in the Yukon Placer Mining Industry"**, prepared for the Department of Indian Affairs and Northern Development by Reid Crowther and Partners Limited and Bethell Management, May, 1984.

    The data presented in this report is helpful in characterizing certain aspects of the Yukon placer industry. Unfortunately, the wastewater treatment settling tests performed did not include measurement of supernatant water quality for unaided settling. Also, the soil grain size analyses were all performed by the ASTM D422 method which does not relate well to the actual settling characteristics (see earlier discussion in Section 2.3).

11. **"Treatment of Placer Mining Effluents Using Settling Ponds"** prepared for Government of Yukon by Ken Weagle Environmental Consultant Ltd, December, 1984.

    This study documented the performance of settling pond systems at 22 Yukon placer mines. The data is useful for characterizing the ranges of water use, feed rates and pond performance. Weagle attempted to derive relationships between pond overflow rate and particle settling velocity, and to quantify the effects of pond length to width ratios. He also documented some of the effects of settling in a drain channel and developed a method of estimating suspended solids concentration in pond effluents.

    To support the type of analysis attempted, further data would have been helpful as follows:

    - measurement of average pond depth and estimation of pond retention time (bottom scour and excessive pond flow velocities were evident in some cases where the ponds were nearly full of sediment);

    - pay material grain size analysis by the "modified" hydrometer method as discussed in Section 2.3 (ie. no deflocculant, reduced mixing and use of local creek water);

- completion of settling tests to assess the relative importance of flocculant settling;
- direct measurement of pond influent grain size distribution.

As outlined in the comments on Reference 5, R and M (1982), the major difficulty in relating settling pond performance to particle size distribution is having a realistic estimate of the **pond influent** particle size distribution. In the Weagle study, the pond influent particle size distribution was only indirectly approximated. The subsequent relationships derived between overflow rate and particle size are therefore unreliable.

By sampling every two hours over a 24 period, Weagle documented the variability in pond effluent quality that can occur as a result of intermittent sluicing. The period of continuous sluicing in relation to the settling pond detention time is important in assessing whether or not the settling process is approaching "steady state" conditions.

Samples of settling pond sludge were collected from 14 of the ponds near the pond outlets. The particle size distributions of the sludge included some "clay" sizes, possibly indicating that natural flocculation was occurring.

At 18 of the sites, sediment samples were collected from the bottom of the drain near the pond inlet. The maximum particle size in this material typically ranged from about 0.1 mm to 1 mm. The effectiveness of the drain in removing sediment increased with length and reduced gradient.

Thirteen of the 22 mines sampled had less than or equal to 0.2 ml/L settleable solids in the settling pond effluent. For these mines with effective ponds, the average suspended solids concentration was 1120 mg/L and the maximum was 5056 mg/L. For eight mines with effluents containing settleable solids levels of between 0.1 and 0.2 ml/L the average suspended solids concentration was 1840 mg/L.

12. **"1984 Placer Mine Inspection Data"**, Water Resources Division, Indian and Northern Affairs Canada, Whitehorse.

    A summary of results of the 1984 data is given in Table 1.1. In comparison with the Weagle data for the same mining season, 13 mines with effluents containing 0.1 to 0.2 ml/L settleable solids had an average effluent suspended solids concentration of 774 mg/L with a maximum of 3730 mg/L. However, this data may not be representative of steady state conditions following extended periods of sluicing.

    The Water Resources Division data, plus the Weagle (1984) data indicate that out of a total of 21 samples containing 0.1 to 0.2 ml/L settleable solids, 9 samples exceeded 1000 mg/L suspended solids.

13. **"Development and Demonstration of Treatment Technology for the Placer Mining Industry"**, prepared for Environment Canada by Stanley Associates Engineering Ltd and Canviro Consultants Ltd, March, 1985.

    The main objective of this study was to develop and demonstrate the application of polymer flocculants to placer mining wastewater treatment. Major study findings related to settling pond design and operation included:

    - the importance of site specific minesite constraints and material characteristics in developing a wastetreatment system;

    - the importance of designing the system for sludge storage, pond cleaning and space to store dredged solids.

    Unaided settling tests were performed in a 23 litre pail on primary pond effluent for the Airgold site. The effluent from the secondary pond (with an initial theoretical detention time of 34 hours) contained from 150 - 500 mg/L suspended solids for unaided settling conditions. For comparison, the settling test supernatants contained about 60 - 120 mg/L at the end of the 24 hour test period.

Based on pay gravel particle size analyses, material feed rates and effluent flow rates, the clays in the pay dirt were expected to yield approximately 2000 mg/L in the final effluent from the secondary pond. The actual average secondary pond effluent concentraton was 346 mg/L.

This difference could have been attributable to the tendency of the ASTM D422 methodology to give an unrealistically high clay content as compared to natural settling particle size distributions. Also, the typical daily sluicing period of about 13 hours was less than the theoretical pond retention time of 34 hours. The maximum suspended solids levels associated with "steady state" conditions may not have been reached.

14. **"Placer Mining Wastewater Treatment Technology Project"**, prepared for the Alaska Department of Environmental Conservation by Shannon and Wilson Inc., March, 1985.

The Shannon and Wilson study concentrated on evaluating the costs and benefits of sluice water recycling. With respect to settling pond design criteria, they recommended that miners should generally follow the ADEC settling pond design handbook (see reference 6 above). However, Shannon and Wilson also recommend providing extra pond volume for sludge storage. For each bank cubic yard of pay dirt processed, they recommend providing about 0.5 cubic yard of sludge storage volume in addition to a minimum of 2 feet of water over the settled solids.

The above sludge storage volume of about 50% of the volume of material processed is high in comparison to the example of 17% given in Section 2.2. The 50% figure would probably be an extreme case for Yukon mines. A method to estimate sludge storage requirements is recommended in Section 4.

3.3 RECOMMENDED DESIGN APPROACH

Two basic methods for sizing ponds have emerged from previous work as follows:

Alternative 1: Ponds can be sized on an arbitrary hydraulic retention time or overflow rate basis. For example, DFO and Environment Canada (1983) suggested providing 18 hours retention for a suspended solids standard of 1000 mg/L. The approach is to apply this 'rule of thumb' for all mines, regardless of pay gravel fines content or settling characteristics.

Alternative 2: Ponds could be sized in accordance with pay gravel grain size and/or settling test data and the basic theoretical settling pond model.

Alternative 1 is easy to use. However, strict application of an arbitrary 'rule of thumb' would result in oversized ponds for some mines and undersized ponds for others, depending on the site specific soil characteristics. Given the large variations in soils, it would be difficult to choose an appropriate rule for sizing ponds that is based only on flowrate.

Alternative 2, which involves collection and analysis of site specific soils data, is preferable but more difficult to apply than Alternative 1. There are many practical limitations in obtaining representative samples, determining sediment settling characteristics, and modeling the placer mining process and settling pond system. Application of Alternative 2 can therefore be more complicated and may not necessarily yield consistently accurate results.

A standardized pond sizing procedure based on settling pond theory and site specific data is required to advance the development of placer mining wastewater treatment. Experience will be necessary to demonstrate its usefulness. Data accumulated using this procedure could provide a basis for developing realistic design standards in the future.

Outline of Proposed Settling Pond Sizing Method

The recommended approach for sizing the settling pond system is given below. Detailed application of the procedure is described in Section 4.

1. Determine basic mine operation data including:

    a) representative pay gravel grain size distribution and fine grained fraction settling characteristics
    b) material feed rate
    c) pond flow rate

2. Determine the minimum pond volume to consistently remove settleable solids by providing a minimum hydraulic retention time.

3. Determine the additional pond volume required to store the accumulated sludge. Base the sludge volume estimate on material feed rates, grain size distribution, estimated pond removal efficiency (see step 5) and estimated sludge density.

4. Layout the system within the available space at the minesite to provide the required total pond volume.

    - Sludge storage requirements in the main settling pond can be greatly reduced by constructing a small upstream pre-settling pond to remove fine sand and coarse silt. The primary criteria for pre-settling pond design is the provision of regular sediment removal and out-of-pond storage space for the sediments.

    - The geometry of the main settling pond will be determined to a large extent by the site topography, however the design should consider minimum depth, length to width ratios, baffles and inlet and outlet conditions.

5. Estimate Pond Removal Efficiency and Effluent Suspended Solids.

   - Rough estimates of pond removal efficiency and effluent suspended solids can be obtained using the basic theoretical pond model and site specific settling test data.

   - If the estimates of effluent suspended solids exceed the required standards by a large margin, then it may be necessary to anticipate the development of an alternative waste treatment plan involving larger ponds, recycle, flocculants etc. (see Section 5).

6. Construct and operate the settling pond system.

   - Operating experience with a pond system sized for settleable solids removal and sludge storage would normally be recommended prior to investing in a more expensive or elaborate system.

4. SEDIMENTATION POND DESIGN

This section reviews the methods of obtaining appropriate data, presents detailed design criteria for sizing ponds and explains the method of estimating pond removal efficiency and effluent suspended solids. The application of the design approach is demonstrated by the use of examples.

4.1 BASIC DATA DETERMINATION

4.1.1 Pay Materials

Sampling

The validity and accuracy of the pond sizing procedure depends on obtaining representative pay gravel samples. For operating mines, the silt and clay content variations and the geology of the deposit may already be understood through previous mining experience. Presently exposed cuts should be carefully examined and the zones of silty or clean gravels identified. Samples should then be obtained by combining shovelsfull of the various materials in proportion to the quantity of each material mined. Sampling of a representative vertical undisturbed section of the deposit is recommended. If the fines content is variable from one area of the cut to another, samples from more than one section of the cut should be taken, combined and thoroughly mixed. For later reference, it would also be useful to describe the various types of materials sampled. A minimum sample volume of about one cubic foot (about 100 pounds) is recommended.

The grain size sieve test is limited to handling 75 mm (3 inch) minus material and therefore it is necessary to estimate and record the proportion of oversize. The estimate can be based on visual examination, or by roughly measuring the proportion of oversize material under a tape measure or grid. For example, a tape measure can be extended 5 m or more over the deposit. The ratio of the combined length of all 75 mm or larger stones directly under the tape divided by the length of the tape will give an estimate of the oversize fraction.

At new mines, where the deposit is inaccessible, obtaining a representative pay gravel sample may be impractical. However, development of the project may involve trenching or digging of pits for test sluicing. In this case, the exposed pay gravels and bedrock could be examined and sampled.

A large variability in the fines content of the deposit increases the difficulty of obtaining a representative sample. For example, if weathered bedrock at the base of the deposit contains discontinuous pockets of clay, the sample may contain a much higher or lower clay content than is representative of the deposit as a whole. Conversely, a relatively uniform fines content in the deposit should reduce the difficulty of obtaining a representative sample and would increase confidence in the sludge storage and effluent quality estimates.

Grain Size Analysis

The combined sieve and hydrometer particle size analysis method described by ASTM D422 should be used, but with the following modifications (see Section 2.3):

a) minesite creek water should be used for making up the soil suspension instead of distilled water (collect at least one liter for each hydrometer analysis);

b) deflocculant should not be added;

c) dispersion and mixing of the soil and water should be accomplished by placing the palm of the hand over the open end of the 1000 ml graduate and inverting it several times to ensure that no soil is stuck to the base, followed by shaking for 30 seconds. Mechanical or air-jet mixing should not be used;

d) any difficulty in dispersing the soil and any observation of flocculation during the test should be recorded and submitted with the report;

e) the results of the grain size analysis should be presented in tabular as well as graphical format (to minimize possible errors in reading the graphs).

Additional Settling Tests

The hydrometer particle size analysis, as modified above, is a standardized method of conducting settling tests, which provides both particle size distribution and settling characteristics. However, additional settling tests involving pond influent may also be desirable for the following reasons:

1) The hydrometer test initial concentration of 50,000 mg/L may not simulate the settling characteristics associated with the actual 5,000 to 25,000 mg/L encountered in pond influent.

2) Direct measurement of supernatant suspended solids may provide a higher level of confidence than concentration estimates based on particle size analysis, feed rates, flow rates and settling theory.

The general procedure for conducting direct settling tests consists of obtaining a representative sample of pond influent, transferring the wastewater into a suitable settling vessel, and measuring and plotting the decrease in suspended solids concentration of the supernatant versus time. To allow for non-ideal settling and shortcircuiting, an adjusted pond retention time can be estimated as follows:

$$t = \frac{V - K_2 V}{K_1 Q} \qquad (13)$$

where: t = estimated retention time

V = pond volume

Q = pond influent flow rate

K_1 and K_2 = empirical factors to account for non-ideal settling and dead space fraction (see Section 3.1)

The estimated pond effluent concentration would be equal to the test concentration at the estimated pond retention time.

Settling tests can be performed with actual wastewater samples, or with simulated wastewater, created by mixing pay gravel and creek water in the same proportion as used in sluicing. Each method has advantages and disadvantages.

Testing of Actual Wastewater

Advantages

- avoids uncertainties in flowrate and feed rate estimation and in modeling the settling conditions below the sluice and in the drain.

Disadvantages

- several tests may be required over an extended period to obtain representative results, a single sample is unlikely to be representative;
- needs operating mine.

Testing of Simulated Wastewater

Advantages

- the simulated wastewater is likely to be representative if care has been taken in obtaining a representative pay gravel sample;
- the mine does not have to be in operation.

Disadvantages

- depends on the accuracy of flow rate and feed rate estimation;
- doesn't take into account the settling conditions below the sluice and in the drain.

TABLE 4.3 (Cont'd..)

```
7. MAIN POND NO. 1
        GEOMETRY
   Length=                    170.00 m
   Width=                      50.00 m
   Average initial depth=      2.00 m
   Initial Volume=                              17000.00 m3
   Final required volume=                        3408.75 m3        Based on five hours retention
   L/W ratio=                                       3.40
   SEDIMENTATION CALCULATIONS
   K1(non-ideal settling)=    1.20
   K2(dead space factor)=                           0.18
   Critical velocity=                          1.96E-03 m/min
   Critical particle size=                       0.0074 mm
   Ideal retention time=                          24.94 hr        For initial volume
   Est. retention time=                           17.04 hr        Considering effect of K1 and K2
   Overflow rate=                                0.0802 m3/hr/m2        1190 Igpm/acre
      SEDIMENT STORAGE
   (1-Xc)=                    0.106                               Fraction with vs > vc. see calculation below
   Sum of vs/vc*dx=           0.010
   Fraction removed=                              0.116
   Material removal rate=                         12.29 tonnes/hr
   Sediment volume rate=                          10.97 m3/hr     @ 1.12 tonnes/kg  (70 lbs/ ft3)
   Pond life=                                   1239.02 hr
      EFFLUENT QUALITY
   Fraction passing=                              0.015
   Material passing=                               1.62 tonnes/hr
   Effluent concentration=                         2381 mg/L
```

TABLE 4.3 (Cont'd..)

***********PARTICLE SIZE DISTRIBUTION CALCULATIONS************

SIEVE SIZE (inches)	d(mm)	SETTLING VELOCITY vs (m/min)	FRACTION FINER THAN	FRACTION IN SIZE RANGE dx	*****PRE-SETTLING POND*****			******MAIN POND NO. 1******		
					FRACTION REMOVED vs/vc*dx	CRITICAL PARTICLE SIZE	FRACTION REMAINING	FRACTION REMOVED vs/vc*dx	CRITICAL PARTICLE SIZE	FRACTION REMAINING
3	76.20		1.00							
1.5	38.10		0.91							
0.75	19.10		0.82							
0.5	12.70		0.78							
0.375	9.52		0.73							
#4	4.76		0.63							
#10	2.00		0.50							
#20	0.8400		0.39							
		1.41E+01								
#40	0.4200		0.31							
		3.98E+00								
#60	0.2500		0.26							
		1.41E+00								
#100	0.1490		0.23							
		4.41E-01								
#200	0.0740		0.180			0.074mm				
		1.59E-01		0.03000	0.02445		0.00555	0.45205		
	0.0600		0.150							
		8.87E-02		0.03000	0.01362		0.01638	0.74308		
	0.0400		0.120							
		3.19E-02		0.06000	0.00980		0.05020	0.31959		
	0.0200		0.060							
		7.99E-03		0.02000	0.00082		0.01918	0.07830		
	0.0100		0.040							
		3.20E-03		0.00500	0.00008		0.00492	0.00805		
	0.0090		0.035							
		2.56E-03		0.00500	0.00007		0.00493	0.00647		
	0.0080		0.030							
		2.00E-03		0.00500	0.00005		0.00495	0.00505		
	0.0070		0.025						0.0074mm	
		1.50E-03		0.00300	0.00002		0.00298	0.00228		0.00070
	0.0060		0.022							
		1.07E-03		0.00400	0.00002		0.00398	0.00218		0.00179
	0.0050		0.018							
		7.19E-04		0.00800	0.00003		0.00797	0.00293		0.00504
	0.0040		0.010							
		4.35E-04		0.01000	0.00002		0.00998	0.00222		0.00776
	0.0030		0.000							
		2.22E-04		0.00000	0.00000		0.00000	0.00000		0.00000
	0.0020		0.000							
		7.99E-05		0.00000	0.00000		0.00000	0.00000		0.00000
	0.0010									
		2.87E-05		0.00000	0.00000		0.00000	0.00000		0.00000
	0.0008									
		1.74E-05		0.00000	0.00000		0.00000	0.00000		0.00000
	0.0006									
				SUM =	0.04898		SUM =	0.00961		
							(1-Xc)=	0.10612		

A suitable settling test column consists of a 150 mm diameter clear plastic tube 2.0 m high fitted with sampling ports at depths of 0.6 and 1.2 m. Samples for suspended solids analysis are then withdrawn at timed intervals.

Previous column tests with placer mining wastewaters have shown that the suspended solids concentration is relatively independent of depth for a given settling time (SIGMA, 1981; R and M, 1982). Averaging the results from the two depths would therefore normally be appropriate. However, if large differences in concentration with depth are noted, a 3 m high column with additional ports should be utilized. Analyses of flocculant settling as described by Metcalf and Eddy Inc (1979) could be attempted.

Less precise settling tests can also be conducted in large pails, barrels, graduated cylinders, jars etc. The accuracy and repeatability of the tests is improved by using a relatively large vessel, minimizing disturbance in withdrawing samples, and shading the test vessel from the sun. Visual observations of the settling process can be useful and therefore a clear walled container is recommended.

The greatest source of error in effluent concentration estimates based on settling tests is probably the representivity of the test sample. The best sampling and testing approach for a mining operation would therefore vary depending on site specific factors.

4.1.2 Material Feed Rates

The average volume of pay gravel processed on an hourly, daily and seasonal basis should be carefully estimated. The preferred measurement method would be to survey cross-sections of the ground before and after excavation of a cut, calculate the bank (in-place) volumes of pay gravel and relate this volume to the recorded hours of sluicing. An alternative method would be to count loader or backhoe bucket-loads per hour, determine the loose volume of material per load and apply a conversion factor to estimate bank volume (ie. as explained in the Caterpillar Performance Handbook).

4.1.3 Pond Influent Flow Rates

The pond influent flow rate would normally be equal to the process water flow rate, plus any additional inflows including diversion of creek water to the pond as make-up water for recycle, and drainage and seepage inflows.

The flow rate should preferably be measured in the drain channel upstream of the pond by current metering and the velocity-area method.

This method is based upon the continuity equation:

$$Q = Av \qquad (14)$$

where:

Q = the volume rate of discharge
A = the cross sectional area normal to the mean velocity
v = the mean velocity in the cross section

The required equipment includes a measuring tape, a wading rod (survey rod) and a current meter instrument.

A channel section exhibiting uniform flow, a regular streambed, a measureable velocity, and an adequate depth for the current meter is selected and then divided into approximately 20 subsections. Sufficient subsections are chosen to ensure that no more than 10 percent of the total discharge occurs in any subsection.

The depth of each subsection (a "vertical") is then sounded with a wading rod. For depths less than 450 mm the mean velocity is measured with the current meter at 0.6 depth from the water surface. The mean velocity for depths greater than 450 mm is determined by averaging the velocity readings at 0.8 depth and 0.2 depth from the water surface.

The discharge for each subsection is calculated by multiplying the subsection cross-sectional area by the mean subsection velocity. The total discharge is then calculated by adding the subsection discharges.

Several alternative methods of flow measurement are available. Flows can be estimated by measuring the water level at hydraulic structures that have a known relationship between water level and flow (ie. culverts, weirs and flumes) or by the use of one of several types of flowmeters for measuring flow in pipes. A rough approximation of flow rate can also be obtained by measuring the depth of water in the sluice and use of the Manning equation (R and M, 1982) or by use of pump discharge and estimated system curves. If a current meter is not available, a rough estimate of the velocity in the drain can be obtained by timing of floats. As a general recommendation, the most accurate estimates of flowrate would normally be obtained by the velocity-area method using a current meter to measure velocities.

4.2 POND VOLUMES AND AREAS

The major criteria for pond sizing are as follows:

1. Size and design the pre-settling pond for removal of fine sand

2. Size the main settling ponds for a minimum hydraulic retention time plus storage of sediment for one seasons production.

The proposed method for sizing settling ponds is illustrated below by example calculations for a hypothetical mining operation (Table 4.1).

4.2.1 Pre-Settling Ponds

A pre-settling pond is a small pond or deepened section of the drain located between the sluice and the main settling pond. The purpose of constructing and maintaining this pond is to remove fine sand from the effluent and thereby reduce the required main settling pond sediment storage volume. In general, it is less costly to use conventional loaders and dozers to clean out the deposited fine sands from a pre-settling pond than to use non-conventional equipment to dredge the same material mixed with silts and clays out of larger settling ponds. Therefore, if space for the settling pond system is limited, constructing and operating a pre-settling pond will usually be cost effective.

TABLE 4.1

DATA FOR A HYPOTHETICAL PLACER MINING OPERATION

1. Hours of Sluicing: 100 days @ 8 hours per day
2. Feed Rate: 125 yds^3/hr (95.6 m^3/hr)
3. Water Use Rate: 2500 Igpm (682 m^3/hr)
4. Grain Size Distribution:

Material	Size (mm)	Percent of Feed
Cobbles	G 76	37.1
Sand and Gravel	L 76 G 0.5	42.4
Fine Sand	L 0.5 G 0.075	9.2
Silt	L 0.075 G 0.002	11.3
Clay	L 0.002	0

NOTE: This distribution is based on the mean values given in Table 2.1 except that the proportion of clay has been reduced. G = greater than; L = less than. The corresponding grain size curve is shown in Figure 3.

Pre-Settling Pond Area

To remove all particles in the effluent coarser than 0.075 mm (200 mesh), the surface area of the pre-settling pond should be sized to have an overflow rate of 7.5 $m^3/hr/m^2$ (2.6 $Igpm/ft^2$). This value is based on Stokes' law at a temperature of 5^oC (equation 3) and equation (12) with $K_1 = 1.2$ and $K_2 = 0.25$, assuming a rectangular basin. For the example operation in Table 4.1, the pre-settling pond area would be:

$$\frac{682\ m^3/hr}{7.5\ m^3/hr/m^2} = 91\ m^2$$

Dimensioning to suit the site, the length and width could be 15 m x 6 m.

An overflow rate of 7.5 $m^3/hr/m^2$ (2.6 $Igpm/ft^2$) defines the minimum recommended pre-settling pond size. The pre-settling pond could be much larger if the miner has an effective method of excavating and disposing of the deposited sediments.

Fraction of Pay Material Trapped

To calculate sediment accumulation rate, cleanout frequency and seasonal material production, it is necessary to estimate the fraction of the pay material that would be trapped in the pre-settling pond. Sampling of coarse tailings piles indicate that the upper "cut" point on the grain size distribution is about 0.5 mm (SIGMA, 1981). However, the actual "cut" is imprecise and will vary depending on the geometry of the drain below the sluice. For example, some finer material will be entrained with the coarse tailings and some coarser sands will be washed downstream into the pre-settling pond.

The lower "cut" point can be defined by the critical particle size corresponding to the pond overflow rate, or 0.075 mm (200 mesh) in the above example. However, a significant quantity of material finer than the critical particle size will also be trapped in the pre-settling pond as described in equation (11). This effect can be taken into account by a detailed calculation as presented later in this section.

For the purposes of a rough estimate of the sediment removed by the pre-settling pond, the fraction of the pay material trapped can be assumed to the the fraction less than 0.5 mm and greater than 0.075 mm. For the example in Table 4.1, this fraction is 9.2%.

Unit Weight of Deposited Sediments

Unit weight, or dry density, is the dry weight of soil per unit volume. The unit weight of freshly deposited submerged sediments is dependent on the grain size of the material and can be estimated from the following equation (Barfield et al, 1981).

$$W = 1.55\, F_s + 1.12\, F_m + 0.42\, F_c \qquad (14)$$

where: W = unit weight of sediment in tonnes/m^3

F_s = sand fraction, greater than 0.0625 mm

F_m = silt fraction, less than 0.0625 mm and greater than 0.004 mm

F_c = clay fraction, less than 0.004 mm, as determined by ASTM D422 (American Geophysical Union grain size classification)

If the sediments contain a significant proportion of silt and clay, consolidation of the deposits with time and dewatering will significantly increase the unit weight of the deposited material. Methods to estimate soil density changes with time and with dewatering are given by Barfield et al (1981) and ASCE (1975).

Sediment Accumulation Rate

A typical unit weight, or dry density, for well graded pay gravel as measured in place (bank measure) is estimated to be 1.76 tonnes/m^3 (110 lbs/ft^3). Pay gravel unit weights would generally be expected to fall within the range from 1.60 to 2.0 tonnes/m^3 (100 to 125 lbs/ft^3). From equation (14), the deposited fine sand unit weight would be approximately 1.55 tonnes/m^3. Therefore the sediment accumulation rate for the example mine would be:

$$95.6\ m^3/hr \times 0.092 \times \frac{1.76}{1.55} = 10\ m^3/hr$$

Cleanout Frequency

The use of loaders or dozers to excavate the deposited fine sand from the pre-settling pond limits the maximum water depth to about 0.7 m. A minimum water depth of about 0.3 m is required to maintain relatively low horizontal water velocities through the pond, such that the fine sand is not scoured off the bottom and re-suspended. The cleanout frequency can be estimated roughly to be:

$$\frac{15\text{ m} \times 6\text{ m} \times 0.4\text{m}}{10\text{ m}^3/\text{hr}} = 3.6\text{ hours}$$

The cleanout frequency will vary depending on the proportion of sand removed with the coarse tailings and the trap efficiency of the pond. Experience with the system would be necessary to determine actual cleanout requirements.

Required Out of Pond Storage

The unit weight of the fine sand would not change significantly following dewatering and disposal in a relatively loose state. Therefore, the total out of pond storage volume required for the excavated sediments would be:

$$10\text{ m}^3/\text{hr} \times 800\text{ hrs/season} = 8000\text{ m}^3/\text{season}$$

The details of how this material will be handled need to be included in the mining plan.

4.2.2 Main Settling Ponds

Minimum Detention Time for Settleable Solids Removal

A settling pond's capability for effective removal of settleable solids deteriorates when it becomes nearly full of sediment. From the data presented in Table 4.2 a minimum detention time of about 5 hours would provide marginally adequate settling conditions. The minimum pond water volume at the end of the pond operating life would therefore be:

$$5\text{ hr} \times 682\text{ m}^3/\text{hr} = 3410\text{ m}^3$$

TABLE 4.2

OBSERVED EFFLUENT SETTLEABLE SOLIDS LEVELS FOR SETTLING PONDS WITH VARIOUS DETENTION TIMES

Estimated Theoretical Detention Time (hrs)	Effluent Settleable Solids (ml/L)	Reference and Comments
5	L 0.5	R and M (1982) Minesite #16
6	1.6	R and M (1982) Minesite #8
5	L 0.2	R and M (1983), based on recommended overflow rate and a pond depth of 1 m
8	L 0.2	Weagle (1984), based on a regression analysis of overflow rate vs settleable solids assuming a pond depth of 1 m
2 - 3	0.3 approx	Weagle (1984), average of eight ponds marginally meeting 0.2 ml/L criteria, assuming a pond depth of 1 m
4	L 0.2	EPA (1977), recommended criteria if pond is a minimum of 1.5 m deep
6	0.2 - 0.5	Shannon and Wilson (1985), pond depth assumed to be 1 m deep
10	-	BC Ministry of Energy Mines and Petroleum Resources, recommended minimum detention time for recycle pond (B. Gordon, pers. comm.)

L = less than

Fraction of Pay Material Trapped

The proportion of the pay material trapped depends on the effectiveness of both the pre-settling pond and the main settling pond. For the purposes of roughly sizing the pond, the pond can be assumed to trap all of the material that passed through the pre-settling pond. The fraction of pay gravel trapped in the main pond would therefore be 11.3% (Table 4.1).

Unit Weight of Deposited Sediment and Sediment Volume

For the example operation, the deposited sediment is predominantly silt sized. From equation (14) the unit weight is estimated to be 1.12 tonnes/m^3. The seasonal volume of sediments accumulating in the pond would therefore be:

$$95.6\ \mathrm{m^3/hr} \times 0.113 \times \frac{1.76}{1.12} \times 800\ \mathrm{hrs} = 13{,}600\ \mathrm{m^3}$$

Main Settling Pond Volume and Approximate Surface Area

The required main settling pond volume would be the sum of the minimum detention time volume plus the estimated seasonal volume of sediment or:

$$3410\ \mathrm{m^3} + 13{,}600\ \mathrm{m^3} = 17{,}010\ \mathrm{m^3}$$

For an actual operation, the number of ponds, the average pond depth and total surface area will be related to the geometry of the site. For the hypothetical example, it is assumed that a single pond with an average depth of 2 m is feasible. The pond surface area would then be:

$$\frac{17{,}000}{2} = 8500\ \mathrm{m^2}\ (2.1\ \text{acres})$$

4.3 POND SYSTEM LAYOUT

A method for estimating pond size and sediment handling requirements has been described. The next step in the procedure is to layout the pond system. Because of the importance of operation characteristics and site specific constraints (Table 2.2), the ponds and sediment storage and handling should be an integral part of the mining plan.

The components of the waste treatment system that are discussed in this section include:

1. Stream Diversions and Flood Protection
2. Pre-Settling Pond Design
3. Main Settling Pond Design

As stated earlier in the Introduction, this report provides the rationale for certain concepts and information that could be incorporated into a future settling pond design manual.

4.3.1 Stream Diversions and Flood Protection

Design Standards

The objective of flood protection work is to prevent sudden stream channel shifting, failure of main settling pond dykes or other major sediment losses. In cases where bank erosion and channel widening would not cause large sediment losses, a design standard based on the two year return period flood[1] may provide an adequate level of protection. However, if failure of a stream diversion could cause extensive erosion of fine sediments, a more stringent design standard would be required. Appropriate design standards should be established on a site specific basis depending on the risks and extent of possible damage and on the costs of flood protection works.

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[1] A two year return period event has a probability of occurrence of 50% in any one year.

Design Procedure

A general procedure to design a placer mine stream diversion would be as follows:

1. Select the channel routing and determine the channel profile (slope)
2. Estimate design flows
3. Size the channel cross-section and estimate design velocities
4. Design bank protection as required to protect unstable materials
5. If required, plan further stream channel stabilization and modification measures to promote fish habitat recovery.

The most important design factor to minimize sediment losses is routing. The diversion profile should be maintained at as low an elevation as possible and similar to or lower than the original stream gradient. Diversions on side hill slopes, sharp bends, and rapid changes in gradient should be avoided. The channel should also be excavated in stable materials such as gravels with a large proportion of cobbles, or bedrock, if it can be ripped. Possible future mining areas and the best alignment following mining should be considered in order to avoid frequent re-diversion of the stream.

Design flows can be roughly estimated by methods given in Janowicz (1986). However, there is limited flow measurement data for watersheds with drainage areas of less than 10 km^2 and, therefore, estimates derived by any method for these small creeks should be used with caution. Miners' previous experience with floods on a particular creek over a period of several years can provide valuable guidance as to the adequacy of flood protection works.

The channel cross-section, design velocities and required size of granular materials for bank protection can be estimated from observations of the existing channel and from open channel hydraulics manuals. Where risks of major damage are high, the design should be completed or reviewed by a Professional Engineer.

A source of suitable bank protection material can be the oversize cobbles and boulders from the grizzly. Quarrying of rock riprap or use of other erosion control materials would usually be prohibitively expensive. Thus, careful planning of the diversion channel route is essential in minimizing erosion protection requirements.

Gulch Operations

Because of limited space and steep gradients, settling ponds for gulch operations usually have to be located in the main stream valley near the mouth of the gulch. The gulch creek and the sluice effluent would normally occupy the same channel. However, during heavy rains, even small gulch creeks can be damaging, if permitted to flow uncontrolled through downstream settling ponds. Also, for long term storage of sediment in abandoned ponds, it would not be desirable to have the creek permanently routed through the ponds. Therefore, a flood bypass spillway and channel should be constructed as described below.

Assuming that the settling pond is located near the mouth of the gulch in the main stream valley, the bypass spillway could be situated just upstream of the pond. The spillway cross-section should be constructed as a low rock weir with a crest elevation set just slightly higher than the normal settling pond water elevation. In the event of a flood, the normal settling pond outlet capacity would be exceeded, the pond water level would rise and the excess flow would be diverted through the spillway and bypass channel.

When the pond becomes full of sediment and is to be abandoned, an armoured dyke should be constructed to block off the entrance to the pond. The spillway would then be reconstructed to make the bypass become the permanent creek channel.

As a general recommendation, settling pond dykes should not be constructed across the full width of a gulch or a narrow valley. The creek channel would then be permanently flowing over and through fine grained sediments and failure of the pond outlet works would result in large sediment losses. An exception could be made where the pond spillway was intended to be permanent and was adequately designed for handling rare flood events.

4.3.2 Pre-Settling Pond Design

An effective pre-settling pond requires regular removal of trapped sediment to a designated disposal area. The most common equipment types for stacking of coarse tailings are loaders and dozers. This equipment can also be used to clean pre-settling ponds if the pond has a firm base and if the maximum depth of water does not exceed machine limitations. For example, a D-8K dozer and 980B loader would be capable of operation in a pond with about 0.7 m depth of water, however, extensive operation in dirty water can increase machine maintenance requirements. Loaders equipped with "dry shoe" or caliper disc brakes would have reduced braking power when wet, and any fine granular materials becoming embedded in the brake lining would reduce brake life. The Caterpiller 980C, 988B and 992C wheel loaders have sealed oil cooled multiple disc brakes and the brakes on these machines would be unaffected by operating in wet conditions (S. Anderson, Finning Tractor Co., pers. comm.).

Wright Engineers (1986) have proposed tailings pumping and desanding with hydrocyclones as an alternative method of tailings disposal. The dewatering of fine sand by the hydrocyclone and small settling ponds created within the coarse tailings disposal area would replace the function of the pre-settling pond.

The pre-settling pond design criteria introduced in Section 4.2.1 and above can be summarized as follows:

- provide a pond surface area with a maximum overflow rate of 7.5 $m^3/hr/m^2$ (2.6 Igpm/ft^2), larger pre-settling ponds could be effective if sediment removal and disposal space can be provided
- provide a length to width ratio of between 2:1 to 5:1
- construct on firm foundation materials to allow cleaning by conventional earthmoving equipment

- locate adjacent to areas suitable for disposal of the estimated volumes of excavated sediments
- limit pond depth to a safe operating depth for the equipment, or alternatively, drain the pond prior to cleaning
- cleanout the pond whenever the pre-settling pond has lost its effectiveness. For small ponds, this may be several times per day. The rate of deterioration of pond effectiveness could be determined by monitoring influent and effluent settleable solids.

4.3.3 Main Settling Pond Design

Layout and Number of Ponds

The layout of settling ponds for a specific operation depends on many site related factors. The primary objective is to devise a mining plan that can provide the required annual pond volume over the projected life of the deposit. For example, a mining plan that uses up space for ponds faster than new areas are created by the mining operation may result in increased waste treatment costs in subsequent years of operation.

The estimated seasonal pond volume would be preferably provided by a single large pond, or, if necessary, by a series of smaller ponds. If possible, the largest of a series of ponds should be constructed at the downstream end of the system. Because the largest pond is the most effective pond for removal of fine sediments, it is desirable to prolong its life by utilizing the sediment storage capacity of the smaller upstream ponds first.

An example pond layout for a narrow valley operation is shown in Figure 4. This mine layout is similar to the Henderson Creek operation described in SIGMA (1981). Because of the narrow valley width and space requirements for coarse tailings, the width and length of each pond is limited to about 30 m x 45 m. Also, to minimize backwater seepage into the active cut, the depth of the pre-settling pond and pond No. 1 would have to be less than 1 m. The depth of downstream ponds could be increased to about 2.5 m as the active cut moves upstream. Sediment excavated from the pre-settling pond would be stacked with the coarse tailings. Downstream ponds would not be cleaned out.

For the hypothetical mining operation in Table 4.1 and the above layout, approximately five or six ponds would provide the required 17,000 m^3 of pond volume. If the average depth of the pay gravels was 2 m, the operation would mine approximately seven cuts per season. The proposed mining plan would therefore generate sufficient areas for new ponds.

Length to Width Ratio

The hydraulic efficiency of a pond, or the ratio of the actual mean detention time to theoretical detention time, has been found to be dependent, in model studies, on length to width ratios (Griffin and Barfield, 1983). Given that the estimates for the dead space factor (K_2) in Section 3.1 are reasonable, the effects of length to width ratio on the required pond surface area can be roughly estimated using equations (12) and (9). For example, a pond with a length to width ratio of 5:1 could have a surface area of about 20% less than an equally effective pond with a length to width ratio of 1:1.

As a design guideline, settling ponds should have length to width ratios of at least 2:1 with an ideal of 5:1 or greater. Exceptionally long and narrow ponds may be subject to excessive horizontal velocities and resuspension of deposited sediment unless adequate depths are provided.

Baffles

At some mines, site topography may preclude the construction of ponds with favourable length to width ratios. Construction of a baffle could be considered as one way to improve pond performance. A possible baffle construction method is to construct a berm of coarse tailings or oversize material into the pond. However, the berm can occupy a significant proportion of the pond volume and a small gain in pond performance may be offset by a loss of sediment storage volume. For operations that utilize recycle, a U-shaped pond with the baffle berm in the middle is an effective layout for increasing pond length to width ratio and reducing pumping distance.

Pond Depth

The minimum average pond depth for a new pond should be at least 1.5 m (5ft). Depending on the grain size distribution of material in the pond influent, the deposited sediment will build out in a sloping wedge thinning towards the outlet. Assuming that a relatively thinner layer of sediment accumulates near the outlet, the pond should become "full" only when the retention time is no longer sufficient to effectively remove settleable solids. If the pond was constructed with very shallow initial depths, the pond could lose its effectiveness much sooner due to excessive horizontal velocities and bottom scour near the outlet.

Pond Inlets

Model experiments (Griffin & Barfield, 1983) indicated that pond inlet velocity had relatively little impact on the hydraulic efficiency of laboratory scale ponds. However, where short circuiting could occur due to density currents of colder sediment laden influent, it would be advisable to reduce pond influent velocity. This could be achieved by constructing a permeable coarse rock berm across the entrance of the pond, to slow down and "spread out" the flow. A similar type of inlet baffle may also be effective where the pond length to width ratio is low and an in-pond baffle would take up too much pond volume.

Pond Outlets

The pond outlet should be designed with consideration of the following criteria:

1) **hydraulic efficiency** - locate to give the longest flow distance from the inlet;

2) **capacity** - size the primary spillway for maximum inflow rate; an emergency overflow spillway should also be provided;

3) **erosion control** - the energy of the effluent leaving the pond should be dissipated by either the use of a drop inlet type spillway or the use of protected outfalls.

In clarifier design, hydraulic efficiency is improved by constructing an outlet with a long weir length. However, for settling ponds, it would be difficult to maintain a long weir outlet that was exactly level and free of debris. The small expected benefit in improved performance would probably not be worth the additional cost. Hydraulic efficiency of settling ponds is generally maximized by locating the outlet(s) to maximize the flow distance from the inlet. R and M (1983) recommended providing multiple outlets, with one outlet for every 45 m (150 ft) of pond width.

Assuming that the stream diversion and upstream flood protection works have been adequately constructed to divert flood flows around the pond, the emergency overflow spillway should not have to be an expensive or elaborate structure. Typically, the emergency overflow would consist of constructing a short low elevation section of the pond dyke, about 0.3 m above normal pond level, at a point where overtopping would not cause a washout of the dyke. The spillway channel should be excavated in suitable native materials or lined with rocks as required. Design examples are given in EPA (1976) and R and M (1983).

The capacity of the primary outlet should be adequate to take the maximum pond inflow with a minimum operating freeboard of 0.6 m. For ponds handling significant quantities of surface runoff and for large ponds in windy areas, the freeboard requirement should be increased to 1 m. Capacities of riser type spillways are given by R and M (1983).

The type of spillway construction can vary depending on the preference of the operator and availability of materials. Suitable types would include riser type spillways, culverts, pump return box overflows, rock lined open channel spillways, timber crib weirs or drop structures etc. For all types, the flow capacity should be checked, possible seepage should be controlled and provisions should be made for erosion control at the outlet (ie. placement of a pad of oversize material in the outfall area).

Dyke Construction

Proper embankment construction is necessary to prevent dam failures. Attention should be given to:

- location to minimize impacts from failure
- foundation conditions
- suitable embankment materials and good compaction during construction
- adequate crest widths and side slopes

For safety reasons, settling pond dam heights should generally be limited to less than 3 to 5 m (10 - 16 feet). Further design guidelines are given by R and M (1983).

Pond Cleaning

Removal of sediment from full settling ponds can be accomplished by:

1) draining and excavating with dozers and/or loaders (limited to shallow ponds on firm soils)
2) draglines or backhoes operating from the pond dykes
3) small truck-portable floating dredges
4) slurry pumps (Wright Engineers, 1986)

Constraints to pond cleaning include provision of a suitable sediment disposal area and the high costs of handling difficult materials. If possible, the waste treatment plan should avoid the requirement for cleaning of large ponds. In a discussion of the economics of placer deposit exploitation, Debicki (1983) stated that:

> "It is thus important that as little waste material as possible is moved, that what is moved is moved as few times as possible, and that what is moved is moved as economically as possible."

4.4 ESTIMATION OF POND PERFORMANCE

4.4.1 Calculation Method

Pond effluent suspended solids can be calculated using the basic theoretical pond model described in Section 3.1 (equations 1, 11 and 12). A spreadsheet computer program has been assembled to facilitate the calculations. The use of this program is demonstrated in Table 4.3 using the example input data presented in Section 4.2. The grain size curve in Figure 3 has been converted into tabular form and is presented along with the particle size distribution calculations at the bottom of Table 4.3.

The computer spreadsheet routine follows the steps listed below. All required input data are listed under the Input heading. The program recalculates the output data whenever changes are made to the inputs. The particle size distribution calculations require some manual manipulation.

Items 1 to 5

a) Calculates the hourly mass rate of feed material.

b) Adjusts the mass rate for the percent oversize to estimate the rate of material described by the grain size curve (Figure 3).

c) Estimates the "cut" particle size and fraction passing the coarse tailings disposal operation (ie. for a "cut" size of 0.5 mm the fraction passing is 0.33).

Item 6 Pre-Settling Pond

a) Calculates the critical velocity, v_c for the pre-settling pond using equation (12) and determines the corresponding critical particle size using Stokes' law (equation 1) by solving for critical particle diameter, d_c.

TABLE 4.3

PLACER MINING SETTLING PONDS
ESTIMATION OF SEDIMENT STORAGE VOLUMES AND EFFLUENT QUALITY

COMPANY: HYPOTHETICAL OPERATION
CREEK: (SEE TABLE 4.1)

	INPUT	OUTPUT	REMARKS
1. WATER FLOW RATE=	2500 Igpm	682 m3/hr	
2. MATERIAL FEED RATE=	125 yd3/hr	95.63 m3/hr	Bank (in place) volume measure
Seasonal production=	800 hr	76500 m3	
3. MATERIAL DRY DENSITY=	110 lbs/ft3	1.76 tonnes/m3	Bank (in place) unit weight
Hourly mass rate=		168.51 tonnes/hr	
4. OVERSIZE ADJUSTMENT			
Maximum size=	3.00 in	76.20 mm	
Percent oversize=	37.00 %		Estimated in field
Fraction passing=		0.63	Adjusts for Percent Oversize
Undersize feed rate=		106.16 tonnes/hr	Rate of material described by grain size table below
5. COARSE TAILINGS			
Particle size=	0.50 mm		Estimated upper "cut" size for pre-settling pond
Fraction passing=	0.33		From grain size curve
Undersize feed rate=		35.03 tonnes/hr	
6. PRE-SETTLING POND			
GEOMETRY			
Length=	15.00 m		
Width=	6.00 m		
Initial depth=	0.70 m		
Final depth=	0.30 m		
Initial volume=		63 m3	
Final volume=		27 m3	
L/W ratio=		2.50	Length to width ratio
SEDIMENTATION CALCULATIONS			
K1(non-ideal settling)=	1.20		
K2(dead space factor)=		0.23	
Critical velocity(vc)=		1.95E-01 m/min	Equation (12)
Critical particle size=		0.0742 mm	Stokes' law @ 5 degrees C
Fraction finer than=	0.180		From grain size curve
(1-Xc)=		0.15	Fraction with vs > vc
Sum of vs/vc*dx=	0.049		See calculation below
Ideal retention time=		0.04 hr	Based on minimum volume
Est. retention time=		0.03 hr	Considering effect of K1 and K2
Overflow rate=		7.58 m3/hr/m2	112405 Igpm/acre
SEDIMENT CLEANOUT			
Fraction removed=		0.199	(1-Xc)+ sum vs/vc*dx
Material removal rate=		21.12 tonnes/hr	
Sediment volume rate=		13.63 m3/hr	@ 1.55 tonnes/kg (97 lbs/ft3)
Pond life=		2.64 hr	
Seasonal volume=		10903 m3	
EFFLUENT QUALITY			
Fraction passing=		0.131	Fraction passing coarse tailings less fraction removed by pre-settling pond
Material passing=		13.91 tonnes/hr	
Effluent concentration=		20402 mg/L	

b) Refers to the grain size table to determine that the fraction of material finer than d_c is 0.18.

c) Calculates the fraction removed by the pre-settling pond using equation (11) and the grain size distribution table:

  i) Determines the fraction of particles "$(1 - X_c)$" with settling velocities, v_s greater than the critical velocity v_c, allowing for the coarse tailings disposal operation (ie. 0.33 - 0.18 = 0.15).

  ii) Determines the fraction of particles removed with settling velocities less than the critical velocity (ie. "sum of vs/vc * dx" = 0.049)

  iii) The total fraction removed = 0.15 + 0.049 = 0.199.

d) Estimates the sediment volume accumulation rate, pond life and seasonal volume using an appropriate unit weight.

e) Determines the fraction passing the pre-settling pond (ie. 0.33 - 0.199 = 0.131) and effluent suspended solids:

$$\frac{0.131 \times 106.16 \text{ tonnes/hr}}{682 \text{ m}^3\text{/hr}} \times 10^9 \text{ mg/tonne} \times 10^{-3} \text{ m}^3\text{/L}$$

$$= 20{,}400 \text{ mg/L}$$

f) Determines the fraction remaining in each particle size class in the pre-settling pond effluent (see bottom of table) to estimate the particle size distribution of the main pond influent.

Item 7 Main Pond No. 1

a) Dimensions the pond to suit the mine site topography and to provide the required initial volume of 17,000 m^3 as estimated in Section 4.2.

b) Calculates critical velocity, critical particle size and fraction removed by the same methods as used for the pre-settling pond. The estimated main pond influent particle size distribution is used in the calculation.

c) Estimates the pond life using an appropriate sediment unit weight.

d) Estimates the fraction passing (ie. 0.131 - 0.116 = 0.015) and effluent suspended solids, assuming that "steady state" conditions in the pond are reached following an extended period of sluicing.

$$\frac{0.015 \times 106.16 \text{ tonnes/hr}}{682 \text{ m}^3\text{/hr}} \times 10^6 = 2400 \text{ mg/L}$$

e) Determines the fraction remaining in each particle size class in the pond effluent to estimate the particle size distribution in the influent to Main Pond No. 2.

Main Pond No. 2

The calculation could be continued for any number of ponds using the estimated effluent particle size distribution for the upstream pond as the influent particle size distribution for the downstream pond.

The initial pond sizing calculation described in Section 4.2 does not consider the fraction of particles removed by the pre-settling pond with settling velocities less than the critical velocity. The detailed computer calculation estimated that this fraction, as described by the term, "sum of vs/vc * dx", would increase the fraction removed by about 33%. Therefore, the computer method (Table 4.3) indicates that the pre-settling pond would have to be cleaned out more frequently and require more storage space for the excavated sediments than as estimated by the initial sizing method.

The computer method estimated the life of the main settling pond to be about 50% greater than the 800 hours estimated by the initial sizing method. Greater sediment removal by the pre-settling pond, as explained above, plus the loss of sediment in the main pond effluent resulted in a smaller estimate of sediment volume in the main pond.

4.4.2 Sensitivity Analysis

The sensitivity of the computer calculation to changes in the data and basic assumptions was investigated. The parameters examined included:

- the coarse tailings "cut" size
- flow rate
- length to width ratio
- pre-settling pond size
- main pond size

The general application of the calculation results discussed below would differ between mining operations depending on the paydirt grain size curves.

Coarse Tailings "Cut" Size

The example calculations assume that only the material larger than 0.5 mm would be disposed of with the coarse tailings. The removal of material finer than this "cut" size with the coarse tailings would significantly reduce the pre-settling pond cleanout frequency and seasonal volume of fine sand. For the example, if the "cut" size was 0.25 mm, the seasonal volume of fine sand removed from the pre-settling pond would be reduced by about 35%. Effluent quality from the pond system would be essentially unchanged.

Flow Rate

The possible effects of changes in process water flowrate were investigated with the computer model (Table 4.4). A reduction in flowrate, possibly by increased classification of feed material, results in increased trap efficiency in the pre-settling pond and therefore extended life of the main pond. The pond volume required to provide the minimum 5 hours retention is also reduced. The

TABLE 4.4

THE EFFECTS OF FLOWRATE CHANGES ON POND PERFORMANCE AND EFFLUENT QUALITY FOR THE HYPOTHETICAL MINING OPERATION

Process Water Flow Rate (m^3/hr)	Process Water Flow Rate (Igpm)	Main Settling Pond Life (hours)	Effluent Suspended Solids (mg/L)	Effluent Sediment Loading (tonnes/hr)
682	2500	1240	2380	1.6
545	2000	1420	2620	1.4
341	1250	1730	2380	0.8
1090	4000	1110	2100	2.3

Note: The pre-settling pond and main pond dimensions were not changed except for the case of the 1090 m^3/hr flow where the pre-settling pond was increased in size to achieve effective removal of fine sand with an overflow rate of 7.5 $m^3/hr/m^2$.

main pond trap efficiency also improves and the total sediment loading in the effluent can be significantly reduced. However, the effluent suspended solids levels are unimproved and may even deteriorate.

An increase in process water flow rate would require that the pre-settling pond would have to be enlarged to maintain effective removal of fine sand. Even if this were done, the life of the main pond would be reduced because of the increased pond volume required to provide the minimum 5 hours retention. Trap efficiency of the main pond would decrease and effluent sediment loadings would increase. However, the effluent suspended solids levels may be improved due to dilution.

Length to Width Ratio

Increasing the length to width ratio of the main pond from 2:1 to 5:1, but maintaining a constant pond surface area of 8500 m^2, would result in a 13% reduction in effluent suspended solids. Assuming that the K_2 values given in Section 3.1 are reasonable estimates, changing pond geometry would not have a major impact on effluent quality.

Pre-Settling Pond Size

Increasing the size of the pre-settling pond to the same size as the main pond would have the following effects:

- the large pre-settling pond would have to be cleaned, or abandoned, after 484 hours (about 60 days) of sluicing;
- the final effluent quality would be improved only slightly from 2380 mg/L to 1590 mg/L;
- the estimated main pond operating life would increase from 1240 hours to 28,000 hours, assuming that the pre-settling pond had been cleaned.

Main Settling Pond Size

Increasing the surface area of the main settling pond by a factor of four (ie. 340 m long x 100 m wide) would reduce the estimated suspended solids levels in the pond effluent from 2380 mg/L to 173 mg/L.

4.4.3 Testing of the Computer Method with Available Data

Data from six mining operations, as reported in previous studies, were used to test the suitability of the method in predicting observed effluent suspended solids (Table 4.5). Three of the selected operations were studied by SIGMA (1981) and had grain size curves determined by the hydrometer method using local creek water without deflocculant. However, mechanical mixing had been used. Data for the other three operations were obtained from Reid Crowther (1984) and Stanley (1984). Grain size curves for these operations had been obtained by the standard ASTM D422 method.

In general, the results in Table 4.5 indicate that the calculation method estimates effluent suspended solids levels that are higher than the levels actually observed in the field or in settling tests. The major reason for this is probably the "over estimation" of the fine silt and clay fraction in the hydrometer test due to mechanical mixing and deflocculant addition. A secondary reason would be over estimation of material feed rates and flowrates in comparison to the actual average feed rates and flowrates affecting the pond effluent at the time of sampling. The calculation assumes that steady state conditions are reached following continuous sluicing for a period longer than the retention time of the pond system. This assumption would be reasonably valid for mines that operate two shifts per day. For smaller mines, the calculations would be representative of pond effluent quality only when the pond is approaching the end of its operating life and the hydraulic retention time in the pond is less than the number of hours of continuous sluicing.

Further comprehensive data is required to adequately determine the validity of the effluent suspended solids estimation method. However, the computer method does appear to be a useful tool for planning sediment handling and sizing of multiple pond systems.

TABLE 4.5

EXAMPLES OF ESTIMATES OF SETTLING POND SEDIMENT STORAGE AND EFFLUENT QUALITY

No.	Mine and Creek	Flow Rate to Pond		Material Feed Rate (3 inch minus) (m³/hr)	Percent Passing 0.01 mm	Percent Passing 0.006 mm	PRE-SETTLING POND (OR DRAIN)¹								MAIN SETTLING POND									DATA SOURCE AND AND REMARKS
		(Igpm)	(m³/hr)				Length (m)	Width (m)	Initial Depth (m)	Overflow Rate (Igpm/acre)	Overflow Rate (m³/hr/m²)	Cleanout Frequency (hr)	Estimated Effluent Quality (mg/L)	Observed Effluent Quality (mg/L)	Length (m)	Width (m)	Initial Depth (m)	Overflow Rate (Igpm/acre)	Overflow Rate (m³/hr/m²)	Ideal Retention Time (hr)	Pond Life (hr)	Estimated Effluent Quality (mg/L)	Observed Effluent Quality (mg/L)	
1.	Frank Taylor Duncan Creek	1,900	518	31 (2.5 hrs per day)	1.5	0.2	15	7.5	0.5	68,000	4.58	5	5,100	3,800	82	33	1.5	2,840	0.193	7.8	760	[illegible]	400	SIGMA (1983) - Calculation is sensitive to material feed rate which was only approximate. Hydrometer test done with creek water and without deflocculant.
2.	Kostem Resources Little Gold Creek	4,000	1,090	107 (22 hrs per day)	1.2	0.2	15	7.5	0.5	144,000	9.70	1.3	12,800	13,300	120	60	1.7	2,250	0.152	11.2	400	1,120	[illegible]	SIGMA (1983) - Material was observed to have extreme natural flocculating characteristics. Hydrometer test done with creek water and without deflocculant.
3.	Fromme Holdings Seymour Creek	3,500	955	46	1.0	0	50	20	1.5	14,200	0.955	43	1,325	1,700 760 (2 samples)	no additional ponds									REID CROWTHER (1984)- Material had no clay fraction.
4.	Yukon Jack Dominion Creek	2,990	814	130 (8 hrs per day)	5.0	3.0	140	70	1.4	1,240	0.0833	140	7,400	-	150	70	2.0	2,150	0.0778	26	34,000	5,700	20-160	STANLEY (1984)- Hydrometer test ASTM D422 apparently results in over-estimation of suspended solids in this case. Ponds are large relative to sluicing time.
5.	Airgold Dominion Creek	[illegible],090	570	60 (13 hrs per day)	4.0 (paydirt sample No. 1) 2.0 (paydirt sample No. 2)	2.4 1.2	91	15.	1.4	6,200	0.418	56 70	6,800 3,300	4,000 4,000	90	50	4.3	1,800	0.127	34	16,000 26,000	4,790 2,000	350 350	STANLEY (1984)- Results are for two paydirt samples taken 1 week apart - note the sensitivity of the results to percent passing 0.006 mm. ASTM D422 over-estimates unsettleable fraction, and ponds are large relative to sluicing time.
6.	Territorial Gold Henderson Creek	2,500	682	120 (6 hrs per day)	2.0	1.0	30	15	0.7	22,500	1.52	3.9	11,100	10,000 (column test)	100	50	2.0	2,020	0.136	14.7	1,410	3,400	1,000 (column test @ 15 hrs)	SIGMA (1983) - Comparison of results using typical mining rates to settling test results. Material feed rate may be over estimated.
		8,300	2,265	120			30	15	0.7	75,000	5.03	4.2	5,600	2,000 (observed in field)	100	50	2.0	6,700	0.453	4.4	0	1,610	-	Creek flowing into cleanout pond, main pond has less than 5 hours retention when new, but note that dilution improves effluent quality.

NOTES:

1. The 15 m x 7.5 m pre-settling pond for the Taylor and Kostem operations is hypothetical. The actual operations had considerable settling occurring in the drain and directly below the sluice.
2. The material feed rate for the Fromme Holdings operation was based on feeding the sluicebox at full capacity.
3. The main settling pond for the Territorial Gold operation is hypothetical.

5. ALTERNATIVE METHODS OF REDUCING EFFLUENT SUSPENDED SOLIDS

Operating experience with settling ponds designed primarily for sediment storage and effective settleable solids removal may show that a significant proportion of these ponds cannot achieve the proposed effluent suspended solids standard of 1000 mg/L. Only a few operations processing paydirts with a low fines content, or with extreme natural flocculating characteristics, may be able to achieve a standard of 100 mg/L by plain sedimentation. Site limitations may not permit increasing the size and number of ponds in an attempt to meet effluent suspended solids standards.

Major reductions in effluent suspended solids can be achieved by total recycle (zero discharge) and by treating final effuents with flocculants. Reduced water use, through increased classification, can facilitate total recycle by reducing the size of ponds and pumping system required. Similarly, reduced water use, either by increased classification or by partial recycle, can reduce chemical treatment costs. Flow reduction, by itself, can reduce sediment loadings, but would not normally improve settling pond effluent suspended solids concentrations. The improved settling efficiency of the ponds is offset by the reduction in dilution.

5.1 TOTAL RECYCLE

A total recycle system involves pumping process water from a single settling pond or series of ponds. Any water losses through seepage are compensated for by pumping additional makeup water from the stream. Surface water drainage would typically be diverted away from the pond system to prevent surface discharge during rainstorm events. Seepage of pond water to the ground would be encouraged as long as adequate filtration was achieved prior to effluent surfacing.

Possible constraints and limitations to total recycle include:

1) excessive groundwater inflows at some sites may preclude a zero discharge system (Shannon and Wilson, 1985);

2) the buildup of relatively high concentrations of unsettleable fine silt and clay in the recycle circuit may reduce washing effectiveness and fine fine gold recovery;

3) excessive pump wear can result if the settling pond system does not remove abrasive fine sand and coarse silt upstream of the pump;

4) increased costs over flow through systems.

Total recycle systems are widely used by placer mines in British Columbia. The systems typically consist of a pre-settling pond and one or more main ponds in series with a minimum of 10 hours theoretical retention time. The pre-settling pond is cleaned regularly and the main ponds, if necessary, are usually cleaned on an annual basis. Process water flowrates and pond volumes are minimized and gold recovery is enhanced by screening to generally 6 mm (1/4 inch) or finer before sluicing. Providing that the ponds are effectively removing settleable solids, excessive wear on conventional water pumps is not usually a problem (B. Gordon, BC Ministry of Mines, Prince George, BC pers. comm. and Olynyk, 1986).

Shannon and Wilson (1985) conducted pilot sluicing studies to determine the possible effects of high suspended solids concentrations on fine gold recovery. For the test conditions, water containing up to 200,000 mg/L of clay suspension did not affect the recovery of salted gold ranging in size from -30 to +60 mesh. However, the paydirt material feeding rates used (ie. pounds per minute per foot width of sluice) were a factor of 10 or more lower than rates typical of Yukon sluicing operations. Therefore, the results may not be generally applicable and further research would be necessary to resolve this issue.

The costs of total recycle would vary considerably between mines depending on site specific factors. Detailed cost estimates for three operations in Alaska indicated that recycling would increase total operating costs an average of 23 percent over the yearly operating costs of the mines with flow through settling pond systems (Shannon and Wilson, 1985).

Much lower recycle costs, including all settling pond construction and operation costs, were estimated by DFO and Environment Canada (1983). The estimated increase in total operating costs to provide a total recycle system was in the order of 2% (\$0.13/m^3 of paydirt processed; assuming a typical total operating cost of \$6/m^3)[1]. However, this estimate was reviewed by IEC Beak (1983) and they suggested that a more realistic estimate for the increase in total costs for total recycle would be in the order of 37% (\$2.24/m^3 of paydirt processed; assuming a typical total operating cost of \$6/m^3). Further detailed designs and cost estimates for several actual Yukon operations would have to be completed to obtain a better estimate for the "average" cost of total recycle.

5.2 FLOCCULANTS

Organic polymer flocculants assist the sedimentation process mainly by the mechanisms of: 1) interparticle bridging to increase particle size and 2) destabilization of colloids by electrostatic charge neutralization. Bench-scale testing has demonstrated that polymers can be effective in reducing supernatant suspended solids levels for a variety of Yukon placer mine effluents (SIGMA, 1981; DFO and Environment Canada, 1983; Reid Crowther, 1984; and Stanley, 1985). However, flocculants have not been incorporated into wastewater treatment systems used by the placer industry in British Columbia, Alaska and the Yukon. A full-scale demonstration project was undertaken in 1984 by Environment Canada (Stanley, 1985), and a further research and demonstration project is planned for 1986.

Constraints to the general application of organic polymer treatment for placer mining effluents include:

- costs for equipment, labour and chemical
- the necessity for a source of clean water for polymer solution make-up

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[1] Costs of placer mining in the Yukon were reported to range from \$4.00 to \$10.50/m^3 and were most often to be approximately \$6.00/m^3 (Debicki, 1983).

- to utilize lower cost dry chemical products, relatively complex polymer mixing and feeding equipment and a dependable electrical power source is required

- the possible requirement to handle flocculated sludge, which may have a lower density and greater volume than untreated sediment.

The costs of organic polymer treatment will vary between mines depending mainly on the quantity of flocculant, which is dependent on:

- the required final effluent suspended solids level

- effluent settling characteristics

- effluent flowrates and sediment loading at the point of flocculant addition.

Stanley (1985) estimated total annual operating costs for polymer aided settling systems including amortized capital costs for equipment, labour costs and chemical costs, but not including pond construction and sludge handling costs. Depending on labour and chemical requirements, the estimated cost to meet a standard of 1000 mg/L ranged from \$0.49 to \$0.88/m^3 of paydirt processed. The estimated cost to meet a standard of 100 mg/L ranged from \$0.53 to \$1.94/m^3. Assuming a typical total annual cost of \$6.00/m^3 of paydirt processed, a polymer aided settling system could increase total annual operating costs by 8 to 32%.

Addition of polymer flocculants may significantly reduce sludge density and thereby increase sludge storage and pond volume requirements. Further data are required to estimate the possible range of densities that can be achieved for polymer treated sludge in full scale settling ponds.

Application of flocculants in placer mine waste treatment would appear to have the greatest potential in the following situations:

- facilitation of recycle where the buildup of unsettleable fines is unacceptable;

- reduction of the required size of settling ponds where space is limited (recognizing that a sludge handling system and alternative sludge storage space would have to be provided).

6. SETTLING POND RESEARCH REQUIREMENTS

Further work is required to better understand the parameters affecting the performance of settling pond systems and to demonstrate the application of the proposed settling pond sizing and effluent quality estimation methods. Research objectives should include:

1. Refine the proposed procedures for estimating sediment handling and storage requirements:

   a) evaluate various sampling strategies to obtain representative paydirt samples;

   b) evaluate the accuracy of both the initial sizing and computer methods for estimating sediment volumes for an operating mine.

2. Evaluate pre-settling ponds at an operating mine:

   a) compare the actual sediment removal efficiency with predicted removal efficiency;

   b) determine the optimum geometry of pre-settling ponds that can be cleaned by conventional earthmoving equipment.

3. Determine the minimum hydraulic retention time for effective settleable solids removal.

4. Evaluate the application of the basic theoretical model (computer method) for estimation of pond effluent suspended solids:

   a) apply the proposed procedure at operating mines and assess the accuracy of the method;

   b) investigate the effects of pond length to width ratio and inlet berms, on pond short circuiting and check that the preliminary estimates for K_2 (deadspace fraction) are reasonable.

c) refine the basic theoretical method and by developing an appropriate correction method to account for hours per day of sluicing in relation to pond retention time and possibly by revising the preliminary estimate for the empirical factor K_1, which allows for non-ideal settling.

5. Conduct additional settling tests with simulated and actual effluents and evaluate the accuracy of effluent suspended solids predictions based on these tests;

6. Operate a total recycle (zero surface discharge) system at a Yukon placer mine as waste treatment method. Develop methods and additional criteria for designing ponds to facilitate total recycle without chemical flocculation.

7. Evaluate the actual costs of providing effective settling pond treatment at a Yukon placer mine demonstration project with and without total recycle.

The suggested detailed approach for achieving these objectives is outlined in Volume Two of this study, **Demonstration Project Methodology.**

7. WASTEWATER TREATMENT COST ASSESSMENT

Plain sedimentation in well-designed settling ponds may not meet effluent standards at a significant number of mines. Many operations would have to upgrade their waste treatment systems by utilizing larger ponds, total recycle, reduced water use and/or flocculants. The impact of the increased costs to meet proposed effluent standards is a major concern to both the Yukon placer industry and regulatory agencies. Therefore, reliable cost estimates for systems designed to meet these specifications are essential in establishing achievable standards for environmental protection.

Placer mining waste treatment cost estimates generated by previous studies are highly site specific and unreliable for general application. Similarly, the proposed 1986 settling pond demonstration project cost studies may have limited relevance in directly resolving general cost issues. The estimation of accurate costs of industry compliance with a given set of effluent standards is hindered by variability in conditions between mines, lack of practical data on applying waste treatment concepts and the complexity of the calculations and required assumptions. To make a reasonable estimate of the cost of industry compliance, detailed waste treatment system designs would have to be prepared for a large proportion of the industry.

A comprehensive government funded program to complete the detailed designs and cost estimates for a large number of mines would be expensive and may not necessarily be accepted as being accurate by the mining industry. Alternatively, development of the required feasibility and cost information could be conducted through a cooperative government-industry effort. The placer mine operators would be expected to provide the basic site data and to develop the waste treatment designs and cost estimates. The cost estimates would be based on a unit cost schedule established co-operatively by government and industry. Government personnel would provide technical assistance to facilitate wastewater management system design and cost estimation. This assistance could utilize an easy to use micro-computer based program and associated design manual. Government personnel would be expected to operate the program and be familiar with the data input requirements. Waste treatment plans and costs for individual operations would be updated and revised annually to reflect the actual operating experience and costs of the waste treatment systems. Following at least one season of operation under this system, the miners could prepare realistic cost projections for waste treatment systems to meet proposed effluent standards.

A conceptual flowsheet for the proposed computer program is shown in Figure 5. The diagram illustrates the interaction between placer mining activities and water quality plus outlines the parameters that describe these activities. The basic theoretical settling pond model as outlined in this report would be a major component of the general model. The proposed research and demonstration projects will develop additional support data for the model.

The proposed procedure would establish:

a) a set of standard input data requirements to be collected by miners (ie. sluice feed rates, water use rates, paydirt grain size analyses, settling test data, preliminary settling pond and waste treatment system layouts giving available pond areas and sediment storage volumes, and cost information);

b) a quick and efficient method for performing a series of relatively complex calculations (ie. water and material balances for placer mining systems, and sizing and cost estimation of major system components);

c) a method for performing sensitivity analyses to determine the changes in expected effluent quality and costs with different recycling or settling pond layouts, unit costs, soil characteristics, feed rates, water use rates, flocculants etc;

d) a schedule for selection of typical input data, such as soil types and settling rates for case studies where site-specific data are unavailable;

The collection of site specific technical and cost data and analysis of this data by the miners using a standardized methodology would provide government with an annual estimate of industry waste treatment costs and a realistic projection of costs to meet proposed effluent standards.

8. SUMMARY AND RECOMMENDATIONS

This study has developed design criteria and a method for sizing placer mining settling ponds and estimating effluent quality.

Settling Pond System Design Criteria

Recommended criteria are outlined as follows:

1) The total settling pond volume should be sufficient to store the estimated seasonal volume of deposited sediments.

2) A minimum pond water volume, equivalent to a retention time of 5 hours, should be maintained at all times to consistently remove settleable solids to a level of 0.2 ml/L, or less. The average water depth of a new pond should be at least 1.5 m.

3) Stream diversions and flood protection should be carefully planned to minimize sediment losses and instability.

4) A pre-settling pond should be constructed for operations where settling pond space is limited. This pond should be cleaned out regularly with conventional equipment to minimize the volume of fine sand and coarse silt entering the main settling pond. Storage space for the excavated sediments should be provided. The overflow rate of the pre-settling pond surface area should not exceed 7.5 $m^3/hr/m^2$ (2.6 $Igpm/ft^2$).

5) A single large settling pond is preferred since it will be capable of producing lower effluent suspended solids levels than several smaller ponds with an equivalent total surface area. If it is necessary to construct a series of smaller ponds due to site restrictions, the largest pond should be at the downstream end of the system.

6) Settling ponds should ideally have a length to width ratio of at least 5:1. A minimum ratio of 2:1 may be acceptable in restricted areas.

7) Main settling ponds should be provided with a primary spillway and an emergency overflow spillway. Design considerations include capacity, location to maximize the hydraulic efficency of the pond, downstream erosion control and adequate freeboard.

8) Settling pond dykes and dams should be constructed with adequate consideration of safety, foundations, embankment materials, compaction, crest widths and side slopes.

Proposed Procedure for Settling Pond Design

The recommended design procedure is outlined below. Initial sizing calculations (steps 1 to 3) can be completed by hand. Estimation of pond effluent suspended solids using settling pond theory (step 5) can be facilitated by use of a personal computer "spreadsheet" program. Effluent suspended solids can also be estimated from additional settling tests.

1. Determine basic mine operation data including:

    a) representative pay gravel grain size distribution and fine grained fraction settling characteristics
    b) material feed rate
    c) pond flow rate

2. Determine the minimum pond volume to consistently remove settleable solids by providing a minimum hydraulic retention time.

3. Determine the additional pond volume required to store the accumulated sludge. Base the sludge volume estimate on material feed rates, grain size distribution, estimated pond removal efficiency and estimated sludge density.

4. Layout the system within the available space at the minesite to provide the required total pond volume.

5. Estimate Pond Removal Efficiency and Effluent Suspended Solids.

   - Rough estimates of pond removal efficiency and effluent suspended solids can be obtained using a pond model based on discrete settling and ideal settling basin theory. Pond effluent suspended solids can also be estimated from settling test data.

   - If the estimates of effluent suspended solids exceed the required standards by a large margin, then it may be necessary to anticipate the development of an alternative waste treatment plan involving larger ponds, recycle and/or flocculants.

6. Construct and operate the settling pond system.

   - Operating experience with a pond system sized for settleable solids removal and sludge storage would normally be recommended prior to investing in a more expensive or elaborate system.

Limitations

1) Representative sampling of the silt and clay content of pay gravels and accurate estimation of processing rates is necessary for realistic estimation of effluent quality.

2) The proposed method of sizing ponds and estimating performance is based on sedimentation theory for discrete settling in an ideal settling basin. Non-ideal conditions such as turbulence, currents, and short-circuiting are taken into account by empirical factors. The effects of other factors including natural flocculation, settling in the drain, removal of fines with coarse tailings and non-steady state conditions should be evaluated by

settling tests. The use of more complex sedimentation models cannot be justified due to the uncertainties in their application and the lack of necessary input data.

3) The feasibility of constructing effective settling pond systems may be seriously constrained by site specific factors including available space, steep stream gradients and lack of suitable construction materials for embankments and erosion control.

Recommendations

1) A proposed modified procedure for the hydrometer test (ASTM D422) for pay gravel grain size analysis should be followed if the test data are to be used for estimating settling pond performance.

2) The proposed criteria and procedure for pond design, sizing and estimating effluent suspended solids should be refined and evaluated by field studies.

3) Additional criteria and design procedures should be developed for total recycle systems without chemical flocculation.

4) Cost data for providing effective settling pond treatment with and without total recycle should be developed from detailed studies at a Yukon placer mine demonstration project.

5) The costs of placer mining wastewater treatment to meet proposed effluent standards should be assessed on an industry wide basis. Government should provide technical assistance to mine operators to facilitate preparation of designs and cost estimates.

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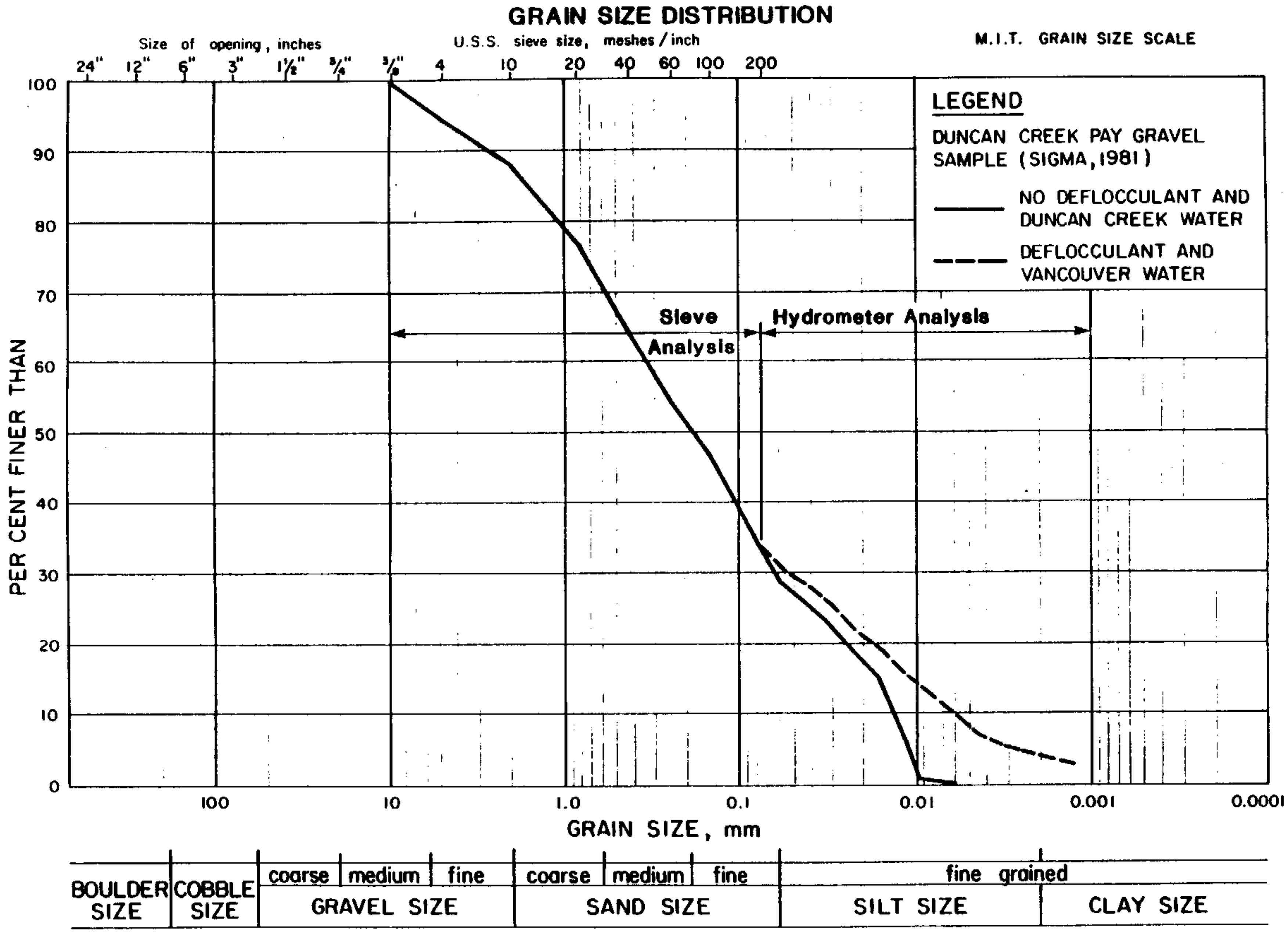

TYPICAL EFFECT OF DEFLOCCULANT ON HYDROMETER GRAIN SIZE ANALYSIS

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FIGURE 1

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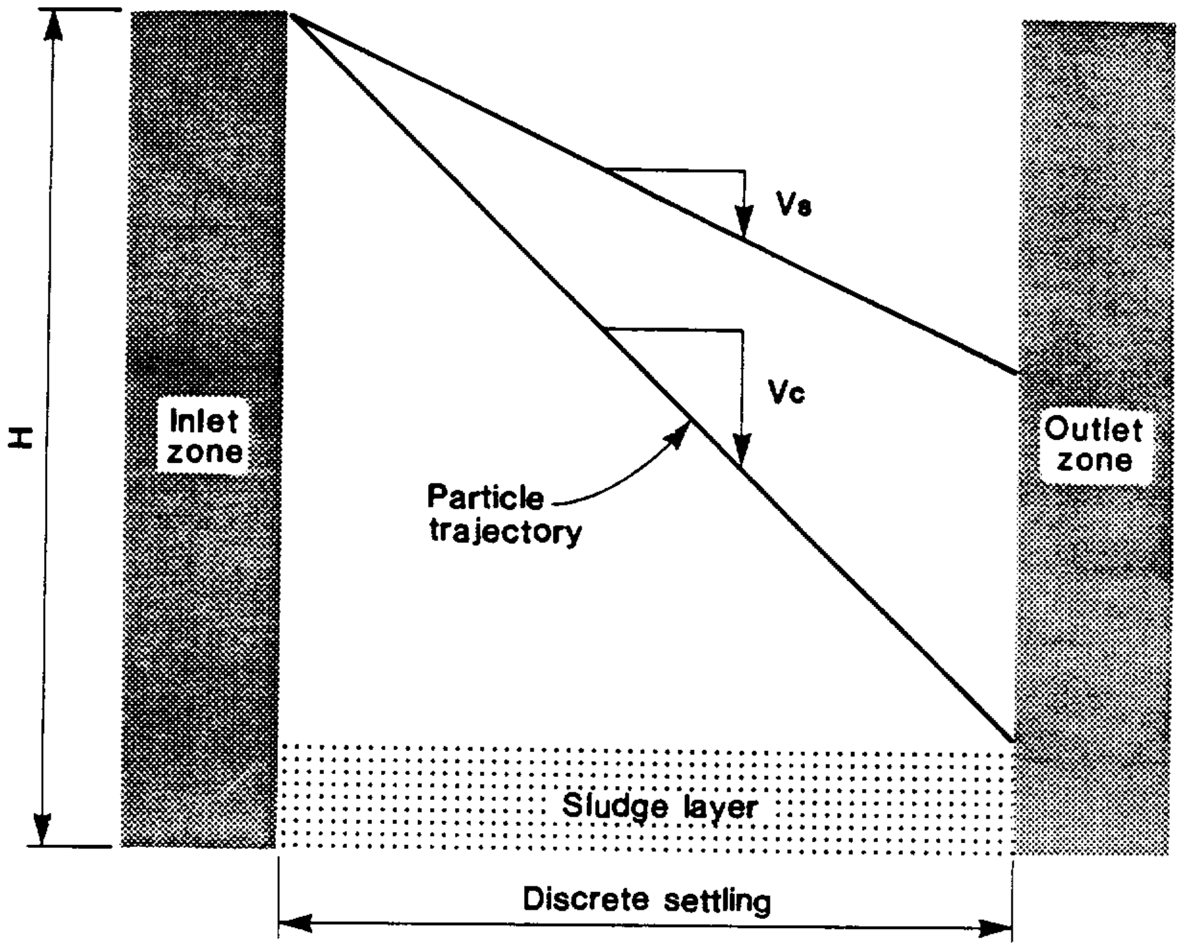
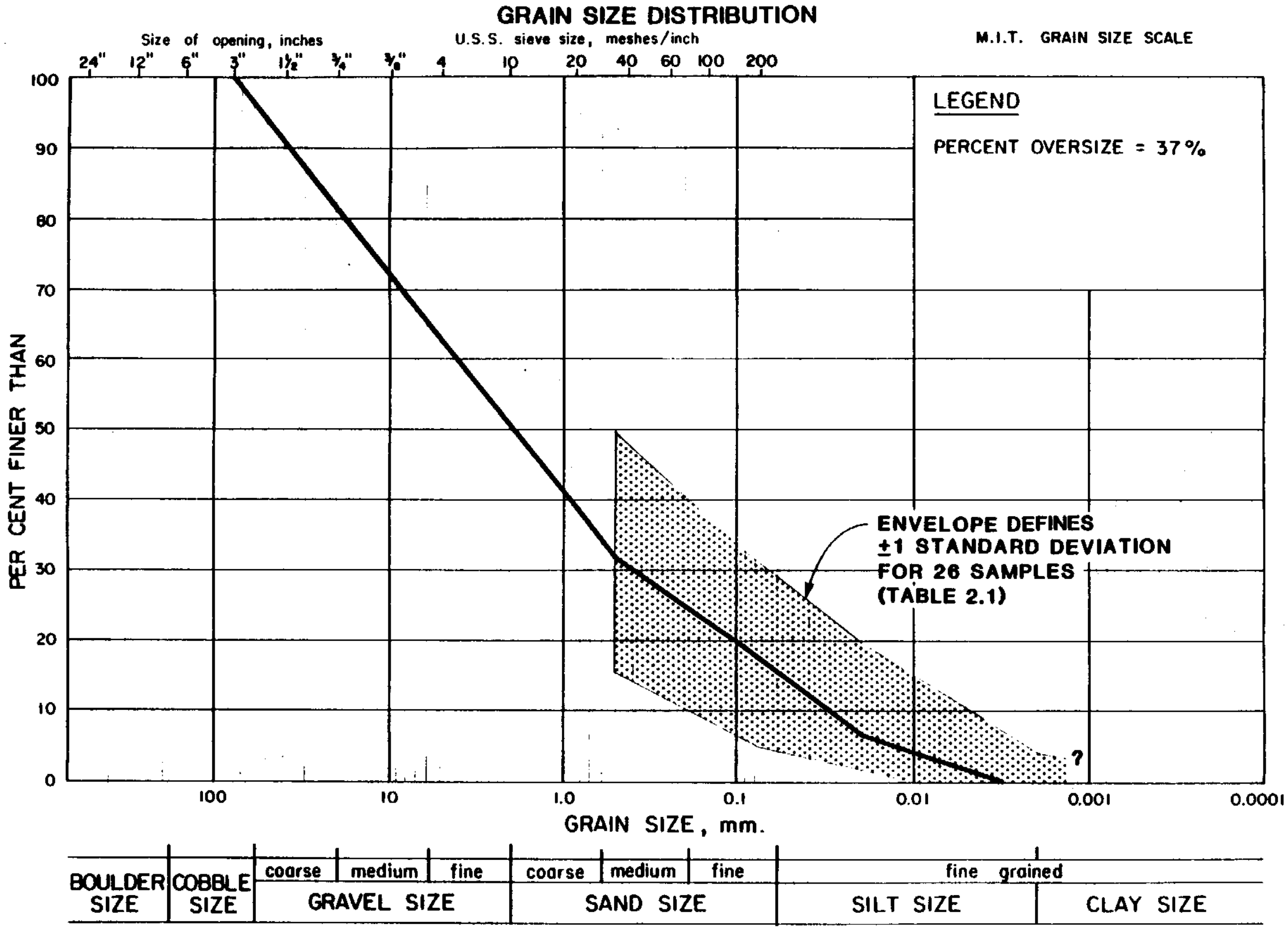


SETTLING IN AN IDEAL SETTLING BASIN

FIGURE 2



GRAIN SIZE CURVE
FOR HYPOTHETICAL MINING OPERATION

FIGURE 3

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4.4 ESTIMATION OF POND PERFORMANCE

4.4.1 Calculation Method

Pond effluent suspended solids can be calculated using the basic theoretical pond model described in Section 3.1 (equations 1, 11 and 12). A spreadsheet computer program has been assembled to facilitate the calculations. The use of this program is demonstrated in Table 4.3 using the example input data presented in Section 4.2. The grain size curve in Figure 3 has been converted into tabular form and is presented along with the particle size distribution calculations at the bottom of Table 4.3.

The computer spreadsheet routine follows the steps listed below. All required input data are listed under the Input heading. The program recalculates the output data whenever changes are made to the inputs. The particle size distribution calculations require some manual manipulation.

Items 1 to 5

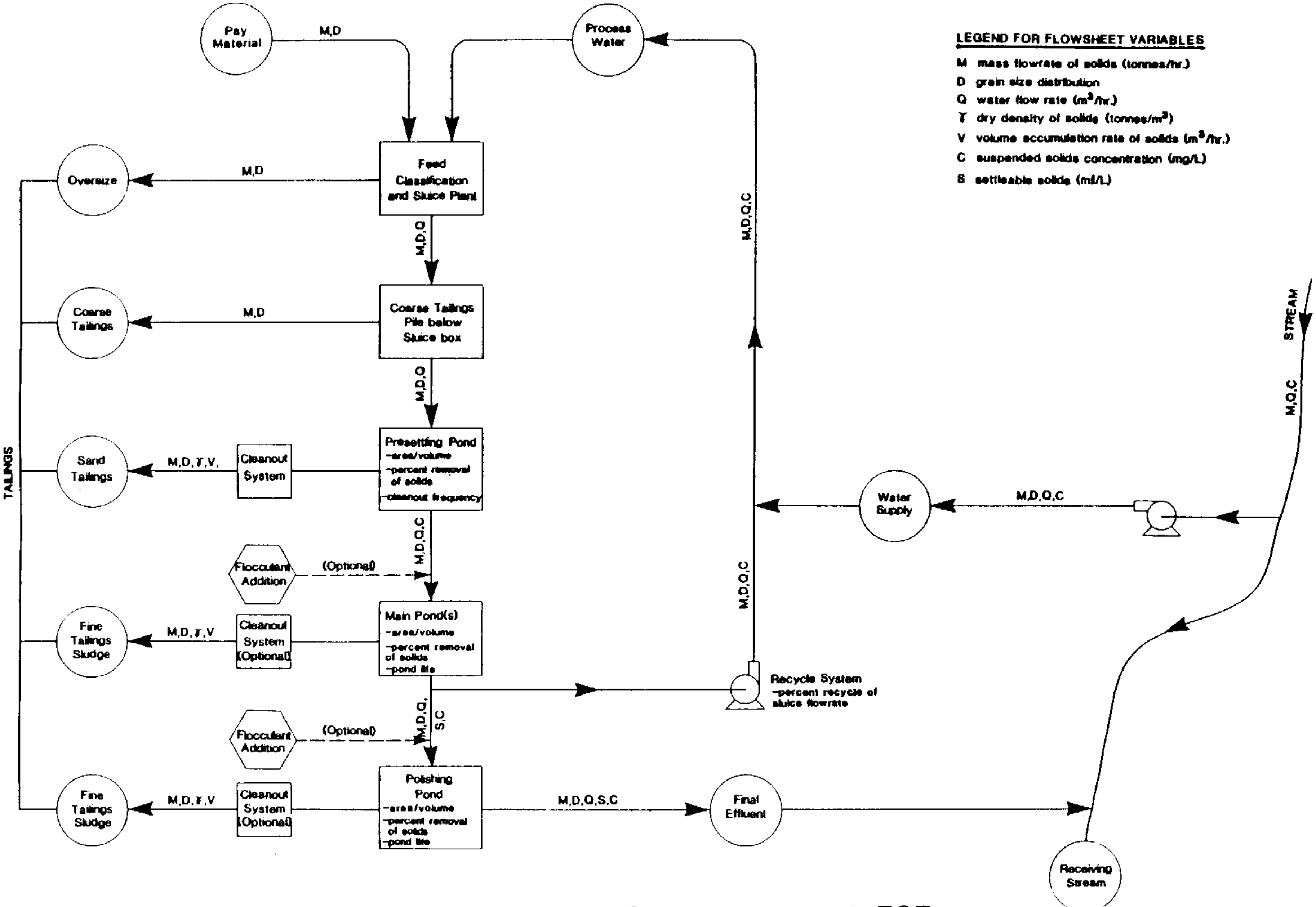
a) Calculates the hourly mass rate of feed material.

b) Adjusts the mass rate for the percent oversize to estimate the rate of material described by the grain size curve (Figure 3).

c) Estimates the "cut" particle size and fraction passing the coarse tailings disposal operation (ie. for a "cut" size of 0.5 mm the fraction passing is 0.33).

Item 6 Pre-Settling Pond

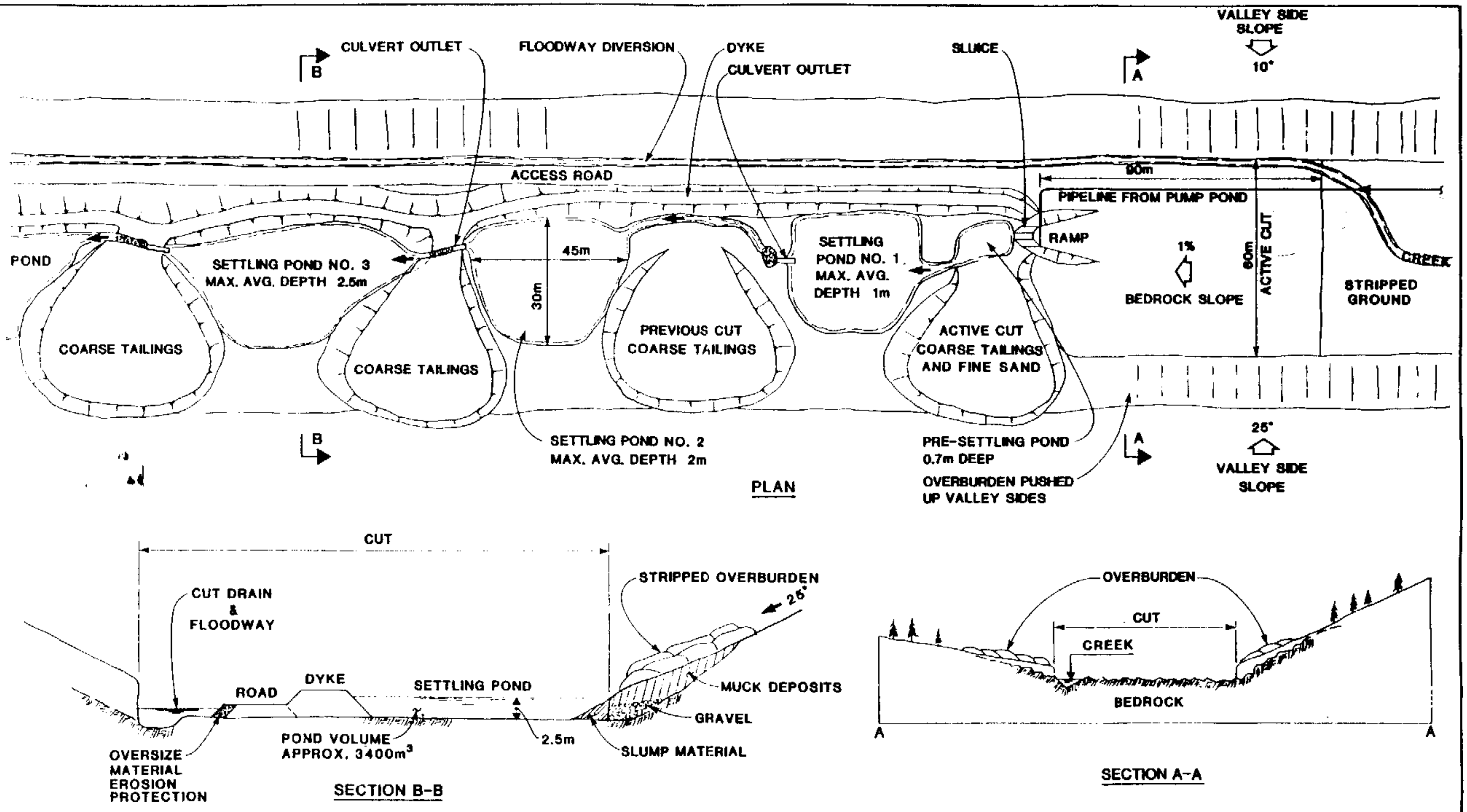
a) Calculates the critical velocity, v_C for the pre-settling pond using equation (12) and determines the corresponding critical particle size using Stokes' law (equation 1) by solving for critical particle diameter, d_C.



GENERAL MODEL FOR SETTLING POND SIZING AND PREDICTING EFFLUENT QUALITY

FIGURE 5

4-235



N.T.S.

NARROW VALLEY
SETTLING POND LAYOUT

FIGURE 4