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TREATMENT OF RUNOFF CONTAINING SUSPENDED SOLIDS RESULTING FROM MINE CONSTRUCTION ACTIVITIES USING SEDIMENTATION PONDS

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ABSTRACT

Sedimentation control during mine construction is attracting increased interest and regulation. The significance of this for the proponents of new mines and regulators suggests the need *for more detailed planning and testing prior to construction* for activities that could potentially generate sediment. The topic of designing the appropriate sedimentation pond size to remove nonfilterable residue (TSS) from contaminated runoff is discussed. Designing the appropriate pond size has been based on a "traditional" approach and methodology in BC which has assumed that the surface area of the pond should be large enough to settle out approximately 10 fi and larger particles for the maximum ten-year, 24-hour rainfall event. This approach is not related to the particle size distribution of the soils to be disturbed nor the soil erosion rates, and therefore cannot predict the pond discharge quality. If the "traditional" design methodology results in regulatory compliance, it is merely a fortuitous outcome of the design process, and a reflection of the absence of "abundant fines" in the soils. Modification to this "traditional" approach is suggested so that we predict the optimum surface area of the sedimentation pond, the need to use settling aids and whether the pond discharge will meet statutory requirements. The appropriate time to perform these predictions and testing is recommended; during the review stage (under the Environmental Assessment Act in BC). Although this approach is not novel, it will hopefully enable the more blatantly *problematic soils* to be identified and receive more focus prior to actual construction (e.g. preparations to select and obtain approval for the use of effective and non-toxic flocculants well ahead of the construction taking place, and placing more emphasis *on planning* sedimentation control strategies).

OVERVIEW OF SEDIMENTATION POND DESIGN

Erosion from Mines/Construction

Mining activities, during the construction phase may generate suspended solids in runoff entering receiving waters. Soil erosion rates may increase from 2 to 40,000 times, reaching typical levels of approximately 17,000 tonnes/year/km^2 for construction activities and operating surface mines (Goldman et al 1986 handbook and Ward et al 1979). The most important aspect which may cause excessive sediment discharges to receiving waters is the presence of abundant unsettleable fine particles in the soils being excavated, or otherwise disturbed. Whether such soils become problematic with respect to permit compliance and receiving water quality, depends on:

- ***Mass loading and concentration of TSS in the influent to the pond, and the portion of this loading which is unsettleable particles.***

- ***The size "split", or the particle separation size, which the pond is capable of achieving.***

Hence, there is a need to *relate the size distribution of the soils to be disturbed to the pond being designed, and the predicted pond discharge quality.* Many jurisdictions specify a minimum pond area, or volume (e.g. BC limits inflow rate to about *0.0001* m^3 */s /1.0 square metre* of pond area (Howie, 1981), which is a common design parameter for pond sizing and pertains to settling the plus 10 micron particles. Some US jurisdictions require pond sizing in terms of volume and geographical location (e.g. Maryland, 0.5 inches/acre, or a pond size of 1,300 yd^3/acre drained - Hill, EPA) and this method is considered to be an inefficient methodology to specify minimum sedimentation pond requirements (does not define settling pond area). Once constructed, the pond area A_{pond} m^2 is fixed and is the most important pond size design parameter (refer to Figure III). The inflow rate Q m^3/s determines the "separation" particle size of the pond, since $A_{pond} = Q/V_{d50}$ (V_{d50} m/s = the settling velocity of the d_{50} diameter particle, which is the minimum particle size settled out for a given inflow rate into the: pond). Note that pond depth and retention time, without the appropriate calculated pond area (i.e. $Q/V_{d50}m^2$) could result in an "under-designed" pond.

The Howie 1981 "guideline" indicates that the probability of exceeding the pond discharge quality (i.e. "capture" of the +10 micron particles) is 87.8% for a 20-year mine life. If this probability is acceptable for a 20-year mine life, then a 2-year flood event should be equally acceptable (to regulators) for a 1-year construction period (based on probability calculations, which indicates a 50% probability of exceeding discharge quality). In addition, discharge quality "failure" may be acceptable occasionally provided the receiving water objective for TSS concentration is still achieved downstream of the discharge (see Figure IV for details).

Sedimentation Pond Design in BC

In BC the settling pond surface area, A_{pond} m^2 is designed for the 24-hour, 10-year maximum precipitation event (rain plus snow melt) and a correction factor of 1.2 is also applied (Howie 1981, EPA handbook, 1976, pages 77 to 79, and Sigma Resources, 1986, pages 3-22 to 4-8). The components of this "correction factor" deserves more attention during pond design. The components of the "correction factor" an; a mixture of various physical features such as pond shape, depth, inflow energy dissipation, outflow facility, etc. These aspects of the pond shape and other physical features must be effectively incorporated into the design of the pond, and are adequately addressed in the literature (e.g. chapter 8, Goldman et al 1986 handbook). The BC methodology represents a "cautionary" or BACT (best available control technology) approach which requires the pond to be designed to remove "settleable" particles (i.e. approximately 5 to 10 micron ideal *spherical* particles, and 20% to 100% larger particles for "real" particles in runoff, depending on the particle shape, surface roughness, etc.). The onus is still on the proponent to meet permit discharge TSS concentration and receiving water requirements (note that TSS concentration *and* turbidity site-specific objectives must be met in receiving waters in BC). As the percentage of particles finer than minus 10 microns increases in the runoff feeding the pond, so will the TSS and turbidity increase in the pond discharge, making it more difficult to comply with receiving water objectives for turbidity (turbidity increases for a given TSS concentration as the particle size of the suspended solids decreases).

Predictive Methods Available for Sedimentation Pond Size Design

A literature search (for example, Hill, EPA paper, Ward et al 1979, Oscanyan 1975, Tiyamani 1994, Estep-Johnson et al 1988, Carroll 1988, Poe et al 1983) reveals some predictive models/methodologies. Some models utilize the Universal Soil Loss Equation (USLE) which employs broad categories of soil size distribution (e.g. gravel, sand, very fine sand, silt, clay) rather than using a more precise particle size distribution of the soil. Some of these models predict sediment load into the pond, but do not predict "worst case scenarios" in terms of discharge quality based on the soil particle size analyses. Most models appear to focus on measurement of input/output TSS for ponds which are *operating* and do not take into account the *particle size distribution* of the soils. By not *predicting* pond input TSS concentration and not taking into account the particle size distribution of the soil, this is considered to be a distinct disadvantage with respect to EC's requirements. Oscanyan, however, proposes a predictive design method based on measured particle size distributions of the soils and focuses on sediment removal efficiency, rather than discharge quality. Proponents (and their consultants) of new construction projects are encouraged to investigate the use of available models to ascertain their usefulness in predicting pond discharge quality.

BC's SEDIMENT CONTROL REQUIREMENTS AND HOW THIS MAY INFLUENCE THE POND DESIGN METHOD SELECTED

In BC, discharges must meet permitted discharge requirements for TSS concentration and under the definition of "pollution" in the *Waste Management Act,* discharges must not cause exceedences of receiving water site-specific objectives, *hi* BC, regulatory requirements for sedimentation control during mine construction now requires more emphasis on "site-specific" pond design (and therefore indirectly places more emphasis on sedimentation control measures). In light of this new development, the disadvantages of using the "traditional" methodology, which ignores the particle size distribution of the soils, may (depending on site-specific soil and rainfall conditions) result in:

- "Unexpected" violations of the *Waste Management Act* and associated consequential costs.
- A "hasty" research/implementation of a settling aid addition system and the need to construct additional ponds.
- Temporary curtailment of some construction activities, particularly during high rain fall events.
- Overlooking alternative strategies because the size distribution of the soils were not taken into account (alternative construction methods and erosion prevention methods, together with alternative strategies which may collectively be sufficient to minimize exceedences of sedimentation pond permit discharge levels and site-specific receiving water objectives).

The BC *Waste Management Act* is applicable to construction activities. Section 3 of this Act prohibits a person from introducing TSS into the environment in the course of conducting an "industry, or trade or business", unless the discharge is authorized by a permit. The *BC Water Quality Criteria* may be used for the purposes of establishing pollution as defined in the *Waste Management Act. In* addition, the *Federal Fisheries Act* prohibits the discharge of any deleterious substance into water frequented by fish or to a location where it may enter into water frequented by fish. Sediment has been found to be a deleterious substance.

If the sedimentation pond design must be capable of meeting pond discharge/receiving water regulatory requirements, without unnecessary over-design, then the design should be based on site-specific conditions and site-specific testing. For example, it could be based on:

(a) A soil sampling program.

(b) Estimated 95-percentile, 10-year 24-hour, and 2-year 24-hour precipitation events. Estimation of the TSS concentration entering the pond (using pond inflow rates and estimated soil loss) are then used to perform "simulated" settling pond clarification tests.

(c) If testing results performed in (b) indicates that "natural" settling alone is insufficient to produce acceptable sedimentation pond discharge quality and/or receiving water quality for 95-percentile/"worst case" runoff conditions into the pond, then the following is suggested: particle zeta potential measurements and flocculant-aided and/or coagulant-aided settling tests.

(d) In cases where settling aids are required, toxicity testing requirements must be defined in order to facilitate regulatory approval in a timely manner.

(e) If "problematic" soils are present, investigate maximizing erosion control strategies and construction activities and timing with respect to rainfall events to minimize sediment input to the sedimentation pond.

PARTICLE SETTLING IN PONDS - PHYSICAL LIMITATIONS

A certain amount of "luck" is involved in sedimentation control: if the mineral deposit is in a location where soils exhibit low fractions of minus 10 micron particles, then the "traditional" pond design should be all that is required. The proponent (and regulators) should nonetheless require that an absence of *problematic* soils is what the construction and operation phases will in fact be dealing with in order to better define the cost implications for the proponent and regulatory implications for government environmental departments. Without this approach, proponents (and regulators) may encounter "surprises" when construction commences and this implies unexpected higher costs to control soil loss and to produce acceptable discharge quality, while regulators are then faced with "reacting" to violations of such legislation as the Federal Fisheries Act and the Waste Management Act (in BC) and the consequential impact on government resources (legal sampling expeditions, more frequent site inspections, preparation of legal cases, court appearances, dealing with "interested parties", etc.). A knowledge of the physical limitations of sedimentation ponds is essential to proponents and legislators in order to understand the significance of sedimentation control during the review and operational phases of the project. This knowledge is particularly necessary if problematic soils are encountered.

Stokes' equation, which relates particle settling velocity and particle size, does not take into account the movement of the fluid molecules, or *Brownian motion,* on the fine particles and how this prevents settling of approximately the 0.01 mm (10 μ) and finer particles, unless *agglomeration/coagulation/flocculation* is taking place. Agglomeration occurs when particle charge is sufficiently low to allow the *van der Waals* attractive forces to cluster particles, which then settle faster. Coagulation occurs when Al, Fe, Ca, etc. compounds are added and form hydroxides which lower the particle surface charge and "enmesh" particles in the metal hydroxide precipitate. Flocculation occurs when high molecular weight organic flocculant compounds are added which then strongly *adsorb* onto particles (and *may* lower surface charge) to form fast-settling floes. The *van der Waals* attractive forces (Slater et al, 1968) may therefore cause agglomeration, and then settlement of the minus 10 micron particles if the *magnitude* of the surface charge (zeta potential) is less than +/- 5 mv. "Natural" agglomeration in a sedimentation pond, if it is occurring, will result in enhanced settling rates which are greater than those predicted by the Stoke's equation. It is noted that "elevated" particle surface charge for many of the runoff sediment particle mineral forms is high enough to "prevent" agglomeration (Strum and Morgan text and King SAIMM Monograph). Particle-particle repulsion induced by the surface charge then exceeds the *van der Waals* attractive force, preventing "natural" agglomeration of the fine particles. Without agglomeration, these fine particles are prevented from settling by the "energy" imparted by the water molecules. It is important to note that these common mineral particle surface charges are pH-dependent and commonly exhibit the high negative zeta potential at the pH typical of runoff (i.e. pH range of 6.5 to 8.0). Particle surface charge is usually defined by a pH-zeta-potential curve. The zero point of charge (ZPC) is; of particular interest in particle settling. Most of the common mineral particles encountered in sedimentation ponds will have a characteristic ZPC occurring at significantly atcidic pHs (e.g. for quartz the $Z_{pH=2.5}$ = zero mv). At the pH of runoff, the $Z_{pH=7.0}$ = -50 mv for quartz, for example. It is therefore evident that runoff particle surface charge is primarily determined by the mineral composition of the particle and the pH: at pH = 7.0 the concentrations of H^+ and OH^- are in balance, yet the runoff particle typically exhibits a large negative charge due to preferential adsorption of OH^- ions; at the ZPC, for quartz, i.e. at pH = 2.5, adsorption of OH^- ions is in equilibrium with adsorption of H^+ ions to produce the zero particle charge, yet the ratio $[OH^-]/[H+]$ is very low (i.e. is 10^{-9}). It is therefore useful to determine what minerals the eroded fine particles are composed of, although the same end result is achieved by zeta potential measurements of the fine runoff participate. To assume that runoff particles are strongly negatively charged is an over simplification, since there are also many common minerals with ZPCs close to neutral pH and even alkaline pHs. Settling tests are of the most value, since the degree of clarification (and the TSS concentration) in the supernatant reflects more closely how regulatory requirements will be achieved.

The "science" of particle suspension destabilization therefore allows us to deduce general limitations of sedimentation ponds and how to best go about testing settling aids to provide "intervention" if "natural" particle settling is too slow:

(a) There is a lower limit to the particle size which will settle out in a sedimentation pond.

(b) Fine particles remain in suspension if the particle surface charge is significant (i.e. if it is more than about +/- 5 mv for the particles finer than approximately 10 microns).

(c) While Brownian motion cannot be "removed"/adjusted, particle surface charge can.

(d) While the use of coagulants should not be ruled out altogether as a settling aid, flocculants are the settling aids of choice and their use with *nontoxic* "flocculant aids" also merit investigation, particularly if a *negatively* charged flocculant is to be applied.

(e) Positively charged flocculants are the most effective generally for runoff (compared to negatively charged flocculants) but are typically of much higher toxicity than negatively charged flocculants.

(f) As a last resort, the use of a positively charged flocculant, followed by the addition of a negatively charged flocculant (to "destroy" the residual positivity) may need to be investigated but will be difficult to obtain approval for the use of positively charged flocculants in BC.

(g) The use of flocculants presents practical challenges, cost implications and the need for toxicity testing. Erosion reduction strategies (EPA Technology Transfer 1976, Sections I, II and III, Goldman et al text, chapters 6, 7 and 10, Gray and Leiser text, sections 3, 4 5 and 6) should also be exhausted concurrently, *since this may substantially reduce eroded "fines" entering the pond such that the pond discharge TSS quality is then acceptable.*

(h) If there is no alternative other than the use of settling aids to achieve discharge compliance, then flocculant selection/toxicity testing should be initiated at least one year prior to the commencement of construction activities. Discussions with the applicable Regional Waste Manager should be initiated in BC prior to toxicity testing to ascertain the level of toxicity testing required (e.g. MELP and/or DFO approved 96 Hour testing on fish, fish eggs, sediments containing flocculant, etc.).

Further pertinent details on flocculant toxicity and application are found by reviewing references: Slater et al 1968, Zêta Meter publication, Strosher 1989, Bratby text, Spragg and Gehr, Haniza 1978, Biesinger et al 1986, Kitchener 1972, Allan et al 1985, Foundation for Water Research, 1996, Chandler 1986, Alberta Environmental Centre.

OBTAINING REGULATORY APPROVAL TO USE SETTLING AIDS IN BC

The "simplest" case for a flocculant-use proposal/approval scenario (in BC), is when the addition dosage of flocculant is 0.05 T.U. or less (1.0 T.U., i.e. Toxic Unit, is the concentration of toxicant which kills 50% of the test fish in 96 hours). The next, but more complex proposal, is when the addition dosage is 1.0 T.U., or less, and the T.U. in the watercourse is 0.05 or less. Testing of the proposed flocculant on fish eggs and benthic organisms is now a more common requirement (in BC). The more effective flocculants (positively charged) generally produce a much higher T.U. Hence the development of the cationic/einionic flocculant addition systems. The bottom line, environmentally, is the T.U. in the watercourse. The positive/negative proposals will require a more complex (and costly) flocculant addition/control system since cationic flocculant may be added in error, without the anionic flocculant. Although flocculant is assumed to be over 90% adsorbed (irreversibly) onto particles in the pond, flocculant may be added in error with insufficient particles/retention time to fully adsorb the flocculant. The negatively charged (anionic) flocculants typically yield 96 Hour LC_{50} concentrations in the 100's and 1000s ppm, whereas the cationics are in the 1.0 to 10 ppm range.

DESIGNING POND AREA USING SOIL SIZE DISTRD3UTION AND "USLE"

Particle Size of Separation and "Classifier" Efficiency

Assuming a pond is properly designed with respect to the physical requirements, a pond may then be viewed as one of the more highly efficient size classifiers. In mineral processing, particle size classification efficiency is referenced to the efficiency of recovering every size fraction by measuring the size distribution of the feed (or, size distribution of C_{in} mg/1 TSS concentration for the pond inflow), the "captured" particles and the pond discharge (C_{out} mg/1 TSS concentration). Figure III shows a theoretical depiction of this idea. Oscanyan, 1975 confirms that a properly designed pond will capture virtually all of the plus d_{50} particle size the pond is designed to "remove". Poorly designed ponds may exhibit "low efficiency" due to (a) insufficient pond area relative to the inflow rate, and (b) a ∫-type particle efficiency separation curve, which would be caused by such physical pond design features as short-circuiting, excessive inflow energy and turbulence, lack of pond depth, poorly designed outflow facility, inappropriate pond length to breadth ratio, inefficient pond shape, excessive wind action, etc. If a sedimentation pond is deemed to be *"'inefficient'",* it is crucial to determine whether this is based on (a) Inadequate pond size and/or (b) Lack of "sharpness of size separation", i.e. more of a ∫-type separation curve than a ∫-type curve (see Figure III). When the "sharpness of size separation" becomes "perfect", the ∫-type curve progresses to a ⌋-type curve in which all particles larger than the d_{50} particle size are captured in the pond at a 100% efficiency. This high pond particle size removal efficiency is in part attributed to the relatively low ratio of solids to liquids characteristic of sedimentation ponds compared to other particle size classifiers such as hydrocyclones (which operate at 10% to 70% solids).

Stake's equation does riot take into account the inability of particles finer than 5 to 10 microns to settle. This aspect may be confirmed by perfoiming settling tests on appropriate soil samples. Figure III indicates the conventional method to calculate pond efficiencies. For a size classifier which makes an efficient size "split" (the ⌋-type "perfect" size split) at the d_{50} particle size, efficiency is virtually equivalent to $(1 - S_{d50})$ or $C_{out} - (C_{in}\text{-}S_{d50})$ mg/1, where S_{d50} represents either the percent or the fractional amount passing the d_{50} particle size in the soil sample size distribution, or the minus 5 mm portion of the soil sample. If settling aids are used, then the pond particle "capture" efficiency will depend on the effectiveness of applying the settling aids, which is not governed by Stoke's equation but is a function of how well the added flocculant is allowed to adsorb onto *all* the particles entering the pond, and of course, the effectiveness of the flocculant selected.

Estimating Pond Inflow/Outflow Quality

Oscanyan, 1975 recommends assuming that eroded solids are virtually all minus 5 mm particles entering the pond. The soil loss entering the pond would therefore be estimated as:

- $C_{in} = \dfrac{R_{event}}{R_{annual}} \times \dfrac{A_e}{Q} \times 10^3$ in mg/l and $C_{out} = (C_{in}) \times (S_{d50})$ mg/l

  Where C_{in} = mg/l TSS concentration in the inflow to the pond. C_{out} = mg/l TSS concentration in the outflow from the pond. R_{event} = precipitation for the storm "event" being calculated. R_{annual} = annual precipitation. A_e = soil loss, as kg/s (calculated using the *Universal Soil Loss Equation*). Q = m^3/s inflow rate to the pond based on the precipitation "event" and applied runoff coefficient, and for 1.0 km^2 of watershed. Units are: $R_{storm}/R_{annnual}$ and S_{d50} are unitless, A_e is in kg/s (note, not the usual units). S_{d50} = the percentage/fractional amount passing the d_{50} particle size fraction in the particle size distribution of the minus 5 mm soil sample.

Annual soil loss, A_e , is calculated based on a variety of factors, and in most cases where there is a variation in particle size and erosion rate within the pond "watershed", (A_e x S_{d50}) would be calculated by summing the various $A_{e1}.S^1_{d50}$, $A_{e2}.S^2_{d50}$, $A_{e3}.S^3_{d50}$ .... values and then using the weighted average (A_e x S_{d50}) value.

Estimating the Range of "Fines" in the Eroded Soil which Adversely Effect Pond Discharge Quality

The objective of this calculation is to establish broad limits for soil particle size distribution in the soils to be eroded into the pond and link particle size with the sedimentation pond discharge quality (refer to Figure V). The key factor is to link the sedimentation pond particle size removed (i.e. the d_{50} and larger particle sizes) to the proportion of this particle size which is in the pond inflow TSS concentration. For the example in Figure V, for a pond designed to "remove" 10 micron and coarser particles:

- the soils could generally contain a range of 0.1% to 0.5% minus 10 microns and the expectation is that the pond discharge has a good likelihood of meeting regulatory requirements (see Figure IV and Figure V).

The same limits apply to the pond designed to remove a d_{50} particle size (the corresponding S_{d50} % in the soil size distribution should fall within the range 0.1% to 0.5% if the pond discharge is to achieve 100 mg/1). In this case, as the particle size the pond is designed to separate increases, the required pond area decreases.

This exercise should be performed for the 95 percentile rainfall rate to confirm that the pond discharge quality has a likelihood of meeting regulatory discharge levels for TSS concentration 95% of the time. This approach may be used to design a pond to remove particles of size d_{50} rather than arbitrarily designing the pond to remove 10 micron and coarser particles. This *economic option* is only feasible if (C_{in} x $S_{10\,\mu}$) in mg/l is less than pond discharge TSS concentration limits specified by regulators - note that $S_{10\mu}$ is the minus 10 μ fraction from the particle size analysis of the soil. Gray, 1982 and EPA, 1976 suggest adjustments to the erosion and precipitation rates (in the absence of more site-specific information): the 24-hour precipitation rate is usually more intense for a six hour period (this fortuitously coincides approximately with the retention time of the pond).

The estimation of soil loss for particular rainfall events should be performed by a professional with experience in this field (the examples used above are somewhat over-simplified for convenience). Rainfall kinetic energy increases from 0.148 ft-lb/ft^2/hour for a drizzle to 300.7 ft-lb/ft^2/hour for a cloudburst and the soil loss is proportional to the kinetic energy of the rain droplets. The objective is to generate the most representative erosion rate and pond inflow rate to increase the reliability of the predictions. The numbers used are for illustration purposes; nonetheless, it is apparent that *the amount of "fines " in the soil is a crucial parameter*[1] *in determining pond discharge quality (more important than pond area, and precipitation rate).*

Receiving Water Quality Impact

For the "worst case" rainfall event selected, if the discharge quality exceeds 100 mg/1, then the receiving water objectives downstream of the discharge should be "calculated". As indicated in Figure IV, 1 and Figure IV, 2, the receiving water "assimilative capacity" specified in the *BC Receiving Water Criteria,* when utilized in a regulatory permit, may afford significant "excursion" of the sedimentation pond discharge quality above the "typical" permit levels (assuming a reasonable amount of dilution and TSS concentration to be "naturally" present upstream of the point of discharge into the watercourse).

Settling Tests

It is recommended that pond design be augmented with settling tests using "simulated" conditions runoff into the pond. The amount of water which should be added to soil samples to represent the TSS concentration entering the pond will be known from the USLE calculations.

Performing settling tests gains the advantage of observing the sedimentation characteristics of credible portions of the soil prior to their disturbance. A complicating factor associated with performing settling tests is that the erodible portion of the soil (assume to be the minus 5 mm particle sizes) must be combined with the *appropriate* amount of water (preferably site water). Also, the settling jar/column should preferably be similar in height as the pond depth to obtain the most comparable results. Smaller testing jars may be used, but this then requires the use of Stoke's equation: calculate how long particles will take to settle 10 cm in the test jar for 100, 90, 80, ... 5 micron particles. Extract samples at a fixed depth above the 10 cm point to measure TSS concentration and turbidity at the 10 cm depth (for example, it should take about 17 minutes for 10 micron particles to settle 10 cm). Make a plot of mg/1 (and turbidity) and time. If the pond is 1 metre deep it will take 10 times as long to achieve the same supernatant quality as in the test jar. It is considered to produce more accurate results if all the supernatant above the 10 cm depth is removed as the sample to measure TSS concentration and turbidity (after thorough mixing of the extracted supernatant sample). A number of representative soil samples would have to be tested on this basis and ensure that all the soil samples are similar. Once sufficient time has elapsed to allow all settleable particles to fall below the 10 cm level in the test jar, (say 18 to 20 minutes) the "end point" TSS concentration in the supernatant should not decrease significantly (after 17 minutes, since these will be "unsettleable" particles) and this sample should be a good indication of the pond supernatant quality, for a pond designed to remove plus 10 micron particles. Supernatant quality is affected more by the portion of the soil particle analysis which is finer than 10 microns than the ratio of solids to liquids entering the pond.

The Sigma, 1986 report, section 4, recommends using a 3 m column testing method, from which samples are extracted after various settling times, and TSS concentration measured from various ports in the column. The 3 m test column appears to be more representative of the sedimentation pond settling characteristics compared to "scaled-down" columns. The settling test results derived from large columns have the potential to eliminate some of the errors associated with settling rates calculated from Stoke's equation (the non-spherical shape of "real" runoff particles requires at least a 20% larger pond area, compared to the area deduced from Stoke's equation). While settling tests gain the advantage of eliminating the particle "shape-factor" component of the "correction factor", additional components of the "correction factor" must still be applied to settling rates derived from settling tests, due to the imperfect construction/operation of sedimentation ponds compared to the settling jar. Li addition, settling; tests gain the advantage of revealing any "natural" agglomeration associated with a particular project site, which, if it is present, may result in enhanced settling rates (which are greater than settling rates of discrete particles predicted by the Stoke's equation). Also, if there are significant minus 10 micron particles in the soil samples tested, this will be detected visually when performing the settling tests. Once the settling tests are organized, it is a relatively simple procedure to perform flocculant-aided settling tests. Conversely, the settling tests may act as an initial "screening" test to determine whether "problematic" soils will be encountered during the construction phase. If the settling tests show that:

- test column supernatant quality to be well within regulatory requirements for TSS concentration (for settling rates reflecting the 95-percentile runoff rate into the pond), and
- test column supernatant quality to exceed regulatory requirements for TSS concentration (for settling rates reflecting the 24-hour, two year runoff rate into the pond), but receiving water objectives will be met,

then, the settling tests replace the need for soil particle size analyses. Soil particle size analyses are still recommended, since they will, when combined with the settling test results, provide a greater level of confidence in the prediction of the sedimentation pond discharge quality.

SUMMARY

It is recommended that proponents of new mines generating sediment from construction activities design a procedure which incorporates the following (at least one year prior to construction, or as otherwise directed by regulatory authorities):

(1) Under the direction of a soil erosion specialist, estimate TSS concentration into the pond. Use 95-percentile and 2-year, 24-hour, and 10-year 24-hour precipitation events.

(2) Perform appropriate soil sampling size analyses and estimate TSS concentration in pond discharge.

(3) If (2) reveals discharge levels for the 95-percentile precipitation to exceed 100 mg/1 TSS concentration discharging from the pond (or whatever regulatory TSS mg/1 level is applicable) then reconsider erosion prevention strategies, recalculate soil loss into the pond, and if pond discharge quality for the routine operation of the pond is still predicted to exceed 100 mg/1, then embark on settling aid testing.

(4) If(I) and (2) indicate that the; routine operation of the pond produces acceptable pond discharge quality, but the "worst case" precipitation event is unacceptable, then determine whether the receiving water objective for TSS will be met/exceeded. Discuss this aspect with the applicable regulators to determine whether excursion of permitted discharge levels during high storm events is acceptable (assuming receiving water objectives for TSS are met).

(5) If phase (1) to (4) reveals that settling aids are necessary, the arduous task of selecting settling aids which are both effective and non-toxic (and approved by regulators) should begin soon enough prior to construction to allow the necessary fish, fish egg, and other aquatic organism to:dcity testing to be completed. Also, sufficient time is necessary to select and install ilocculant equipment and design an appropriate layout at the site, upstream of the pond, to ensure adequate mixing and conditioning of the flocculant(s) to allow them to *be* effective.

FIGURE I -Testing Methods and Rationale to Investigate the Need for Settling Aids

"NC" = signifies possible noncompliance of permit. 100 mg/l is used for the sake of example only. x = the % passing, or fractional amount, of the minus 10 micron portion of the TSS entering the pond or the minus 10 micron (μ) portion of the minus 5 mm component of the soil. "x" also signifies the "PROBLEMATIC" level of minus 10 μ % passing (i.e. problematic in terms of "causing" high TSS in pond effluent). Figure V, estimates the value of "x" to be approximately 0.5% by weight passing the 10 μ particle size, but it must be estimated on a site-specific basis.

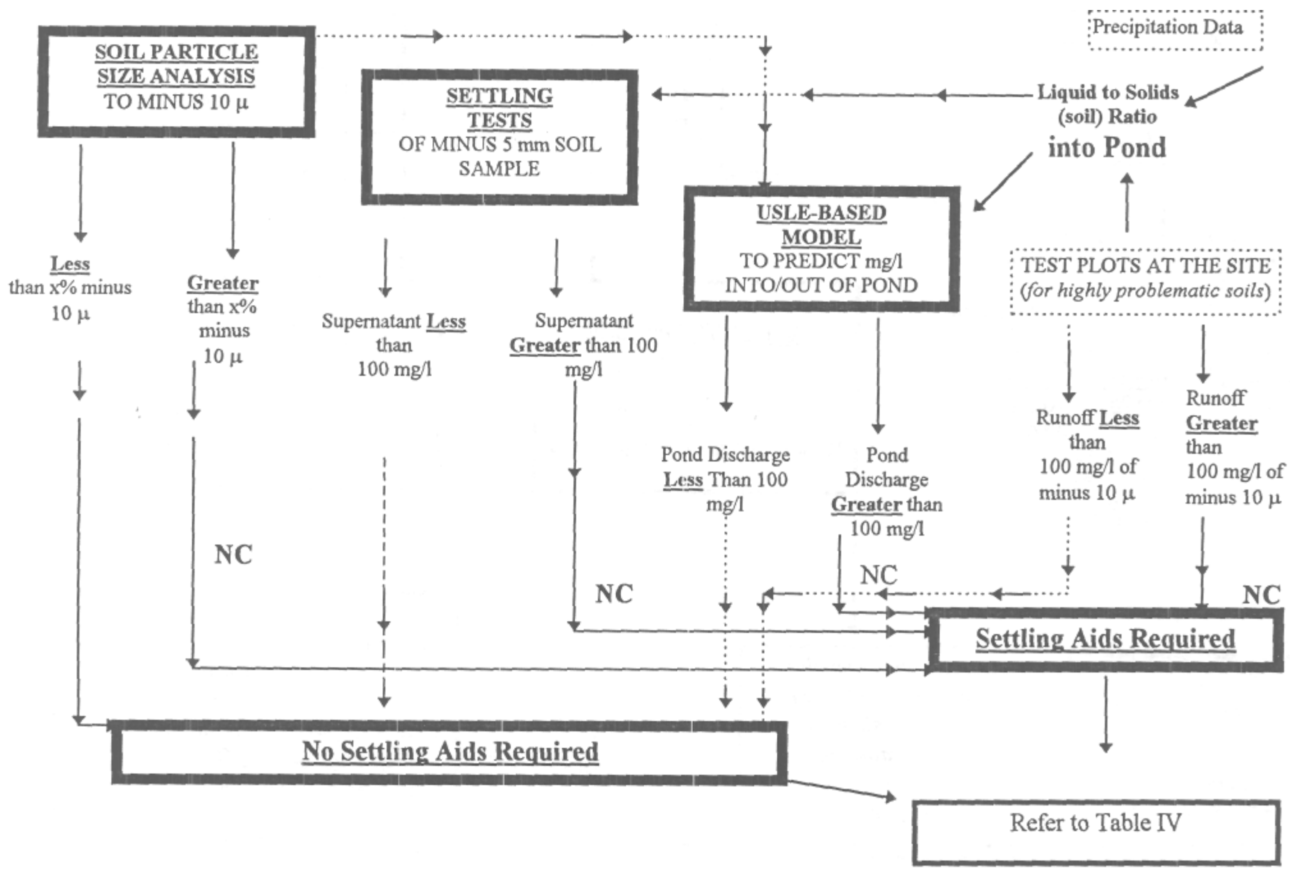


Figure II -Soil Particle Size Analysis and USLE to Predict Sedimentation Pond Discharge Quality

Note: USLE = Universal Soil Loss Equation; Q is the m^3/second flow into the pond; S% = percentage passing a given size fraction; d_{50} = the particle size which has a 50% chance of settling in the pond or discharging from the pond; S_{d50} = the percentage passing particle size d_{50} in the particle size analysis for a particular soil, *or it is approximately equivalent to the particle size analysis of the TSS entering the pond*; A_e = the soil eroded in tonnes/year/square kilometer, or, for a specific rainfall event, as tonnes/km^2 (when calculated for a particular rainfall event, units are kg/s, for convenience); $R_{average}$ = the "particular" precipitation "event" in cm; R_{annual} = precipitation in cm for the year; C_{in} = TSS in mg/l in the pond inflow; C_{out} = TSS in mg/l in the pond outflow.

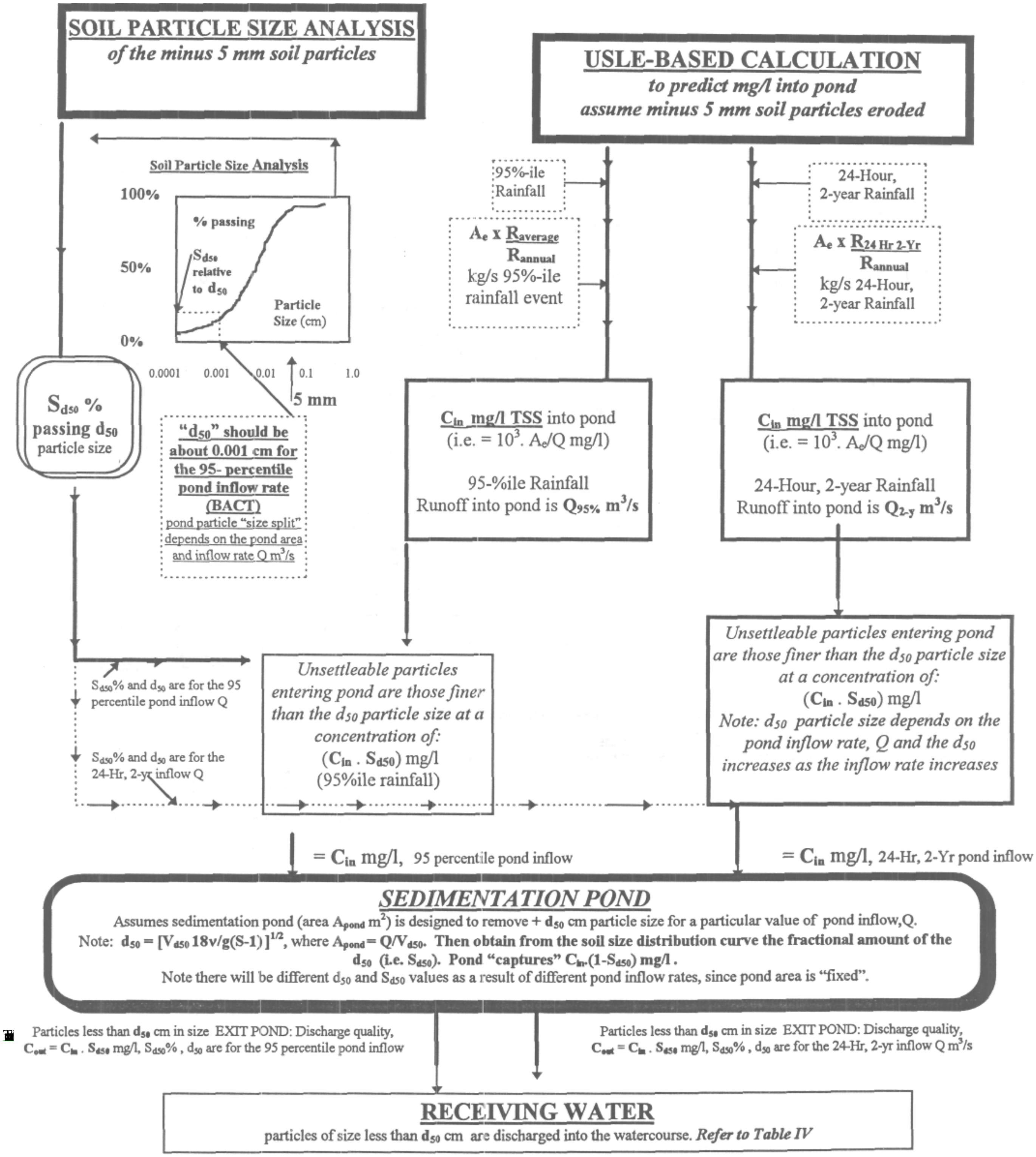
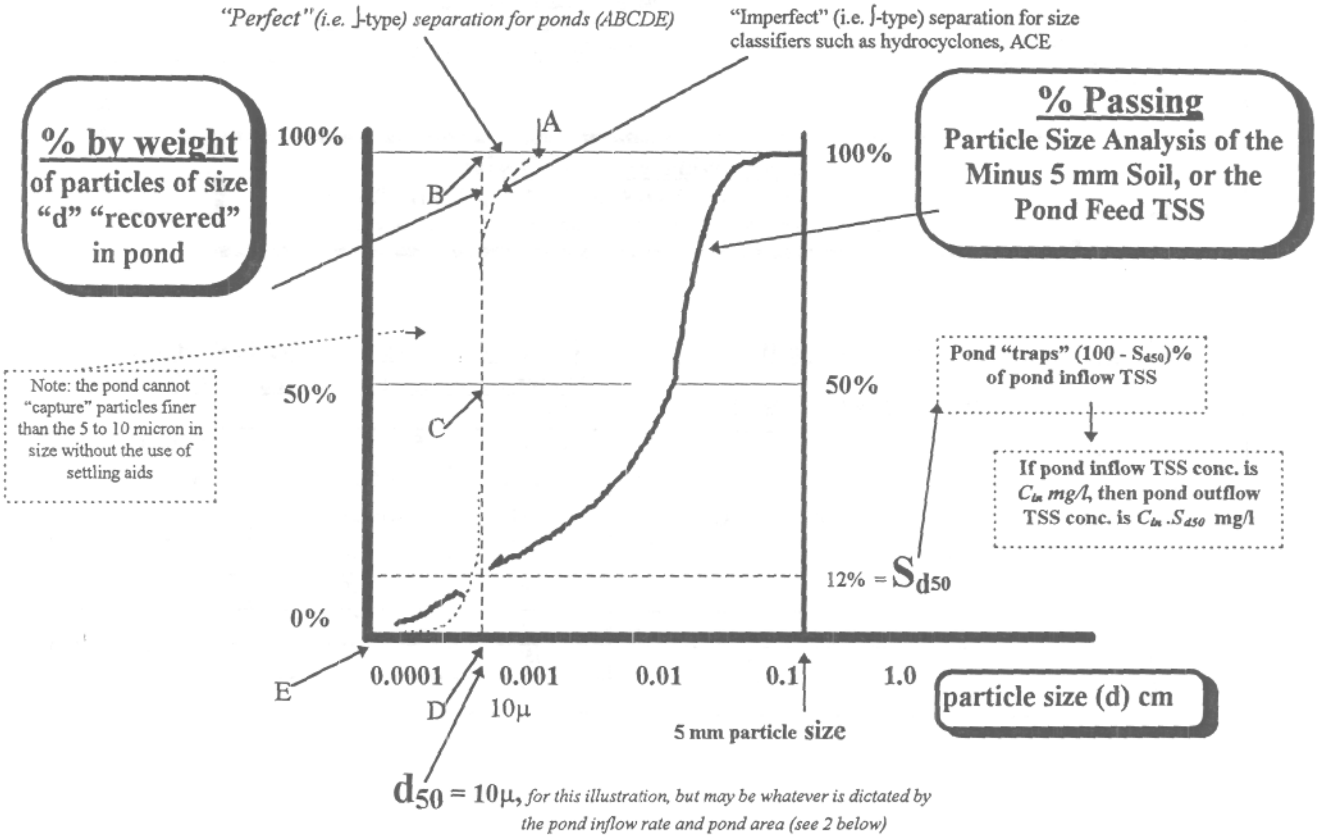


Figure III - Sedimentation Pond TSS Removal Efficiency

Note: d_{50} = the particle size which has a 50% chance of settling in the pond or discharging from the pond; d = particle size (in general) in cm; V_{d50} = settling rate (cm/s) of the particle of d_{50} cm diameter; Sd_{50} = the percentage passing particle size d_{50} in the particle size analysis for a particular soil, *or it is approximately equivalent to the particle size analysis of the TSS entering the pond*; C_{in} = TSS in mg/l in the pond inflow; C_{out} = TSS in mg/l in the pond outflow; Q = pond inflow, m^3/s; A_{pond} = pond area, m^2. For ponds with efficient physical design, the separation curve is close to "perfect" - ponds potentially have the ability to provide a high "sharpness" of separation compared to particle size classifiers in general.



1 - Settling Rate -V in cm/s

$V = [g\,(S - 1)d^2\,]\,/18\nu$ *in general* and $V_{d50} = [g\,(S - 1)d_{50}^{\,2}\,]\,/18\nu$ at a particular pond inflow rate which results in the pond "capturing" particles of size d_{50} cm and larger. In general, $V = [981\,(S - 1)d^2]\,/18\nu$ and at 20^0C ν is 1.002×10^{-2} poise (S = S.G. and for quartz is 2.65). This simplifies to $V = 9 \times 10^3 \times d^2$, and for 20^0C and a 10 micron particle, V is 0.009 cm/second. The corresponding pond design size parameter is 0.0001 $m^3/s/m^2$ (i.e. inflow rate limit per square metre of pond).

2 - Size Split - d_{50} in cm

$d_{50} = [\,(Q/A_{pond})\,(18\nu/g\{s\text{-}1\})\,]^{1/2}$ and the % passing the d_{50} particle size in the pond feed, S_{d50}, is obtained from a particle size analysis of the TSS into the pond (i.e. for existing ponds), or S_{d50} is obtained from a particle size analysis of the soils to be eroded into the pond.

3 - Pond Area - A_{pond} in m^2

$A_{pond} = Q/V_{d50}$, or $A_{pond} = Q.18\nu/[g\,(S_{d50}\text{-}\,1)d_{50}^{\,2}\,]$ - note V_{d50} is in m/s to calculate pond area.

4 - Pond TSS "Trapping" Efficiency

Pond TSS "Capture", or "Trapping" efficiency is $E = 100(1 - S_{d50})\%$. If input/output TSS concentrations are know, the "conventional" method to express efficiency is

$E = [\,100\,(C_{in} - C_{out})\,/\,C_{in}\,]\ \%$.

Figure IV - BC Receiving Water TSS Criteria (or Site-Specific Objectives)

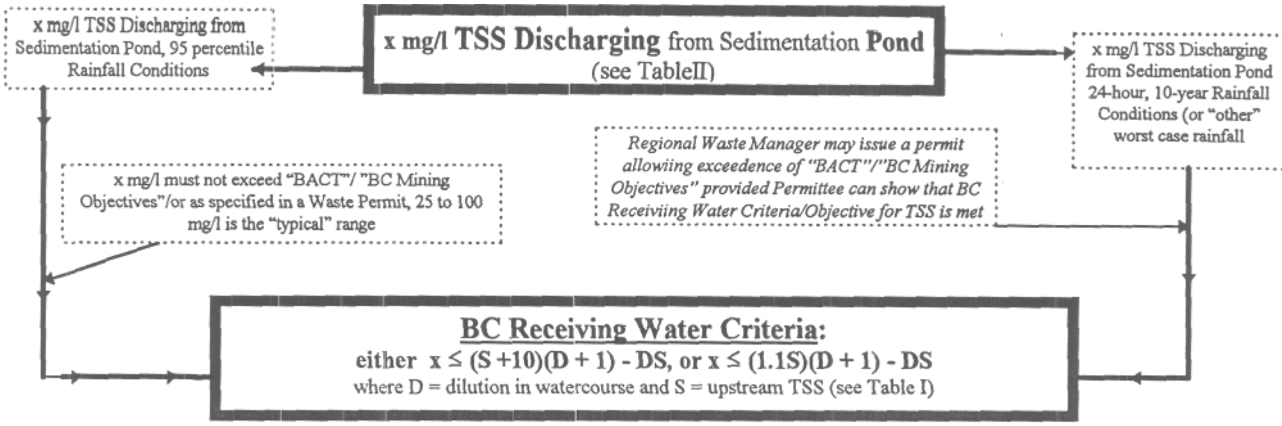


Table IV, 1 - Example; Pond Discharge 100 mg/1. Available Receiving Water Dilution 5 or Less

Pond Discharge Quality, TSS in mg/l	Background TSS, mg/l Upstream of Discharge Point S	Dilution of Pond Discharge in The Receiving Water D
100	40	1
100	23	2
100	15	3
100	10	4
100	7	5

Table IV, 2 - Example: Available Receiving Water Dilution 5 or Less and Low Upstream

Pond Discharge Quality, TSS in mg/l	Background TSS, mg/l Upstream of Discharge Point S	Dilution of Pond Discharge in The Receiving Water D
60	20	1
90	20	2
120	20	3
150	20	4
180	20	5

TSS

Figure V - Approximate Estimation of "Problematic Fines" Fraction in Soil

First apply "limits" to the calculation for soil loss for a particular rainfall event, to estimate the probable limits of fine particles in the soil which may the cause the pond (inflow and) discharge quality to be exceeded:

$$\frac{R_{storm}}{R_{annual}} \times \frac{A_e}{Q} \times 10^3$$

is equivalent to C_{in} mg/l entering the pond for a specific rainfall event and a 1.0 km^2 of "watershed" being considered, for a corresponding pond area, and $C_{out} = C_{in} . S_{d50}$ **mg/l.**

If we consider broad limits for C_{in} (for example, for $[(R_{storm}/R_{annual}).(A_e)]$, assign wide limits to R_{storm}/R_{annual} of 0.05 to 0.1, and for the annual erosion rate for mine/construction sites of 17,000 tonnes/year/km^2 assign limits of 3,400 to 20,000 tonnes/year/km^2. The wide limits for $[R_{storm}/R_{annual}).(A)]$ are then 170 to 2,000 tonnes/24-hour rainfall event/km^2, or 2.0 kg/s to 23 kg/s.

The limits for the pond effluent then become:

$$(10^3/Q)\ (2.0 \times S_{d50}) \leq C_{out} \leq (10^3/Q)\ (23 \times S_{d50})$$

and $C_{out} \leq 100$ **mg/l** is the statutory discharge limit. The limits for **Q** are 0.09 m^3/s to 0.26 m^3/s.(*Note precipitation range used is 1.5 cm to 4.5 and, 50% runoff coefficient.*), or the limits then become:

$$(2.2 \times 10^4 \times S_{d50}) \leq C_{out} \leq (8.8 \times 10^4\ S_{d50})$$

and the limits for S_{d50} become:

$$0.001 \leq S_{d50} \leq 0.005,$$

or, ***if the pond is designed to remove a particle size*** d_{50}***, (and coarser) then the soil content of this particle size entering the pond must not exceed the wide range of 0.1% to 0.5% passing the*** d_{50} ***particle size, if the pond discharge is to meet 100 mg/l or less TSS concentration.***

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