Reservoir Conservation

Volume II

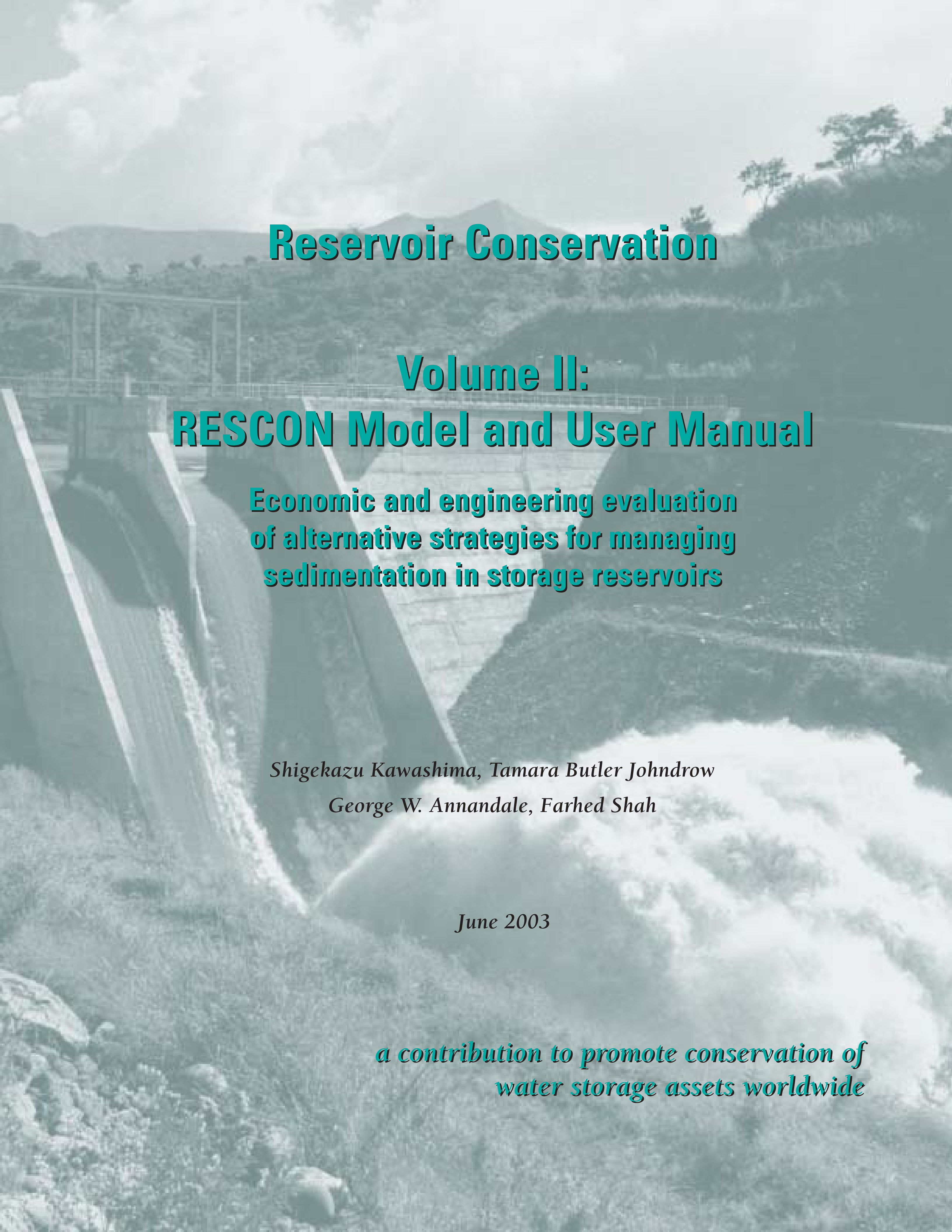
RESCON Model and User Manual

economic and engineering evaluation of alternative strategies for managing sedimentation in storage reservoirs

Shigekazu Kawashima · Tamara Butler Johndrow
George W. Annandale · Farhed Shah

June 2003

A CONTRIBUTION TO PROMOTE CONSERVATION OF WATER STORAGE ASSETS WORLDWIDE



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Cover photo by Alessandro Palmieri: *Little Beles Dam in Ethiopia's lowlands at the onset of the flood season, when erosion from the highlands in the background brings great amounts of sediments.*

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1. INTRODUCTION

Volume I of the book outlines the RESCON approach to reservoir sedimentation management. This volume details the mathematical model that has been developed as part of the RESCON research. The RESCON model should be regarded as a preliminary tool to be improved and adapted as necessary; the user is advised to use caution and engineering judgment when interpreting its results. The model has been written in good faith. However, the authors cannot accept responsibility for any errors or omissions it may contain or any liability or damage that may result from its use. The RESCON model is not a substitute for more detailed studies. It should be used for options screening and to rank those most promising. In general, the RESCON model is more suited for application to a portfolio of reservoirs rather than to individual ones.

The RESCON model is an Excel based computer program designed to assess the engineering feasibility and rank the economic performance of a selection of sediment management techniques. The following sediment removal techniques are considered:

- Flushing
- Hydrosuction (HSRS)
- Traditional Dredging
- Trucking.

In addition, net economic benefits of the scenario involving "No sediment removal" are also computed as the benchmark case. An "environmental safeguards" approach allows the user to select the best economic alternative subject to any specified environmental and social safeguard policies. The program may be used for existing dams as well as proposed dams.

Before using the program the user is encouraged to read both volumes of this book.

2. STRUCTURE OF PROGRAM

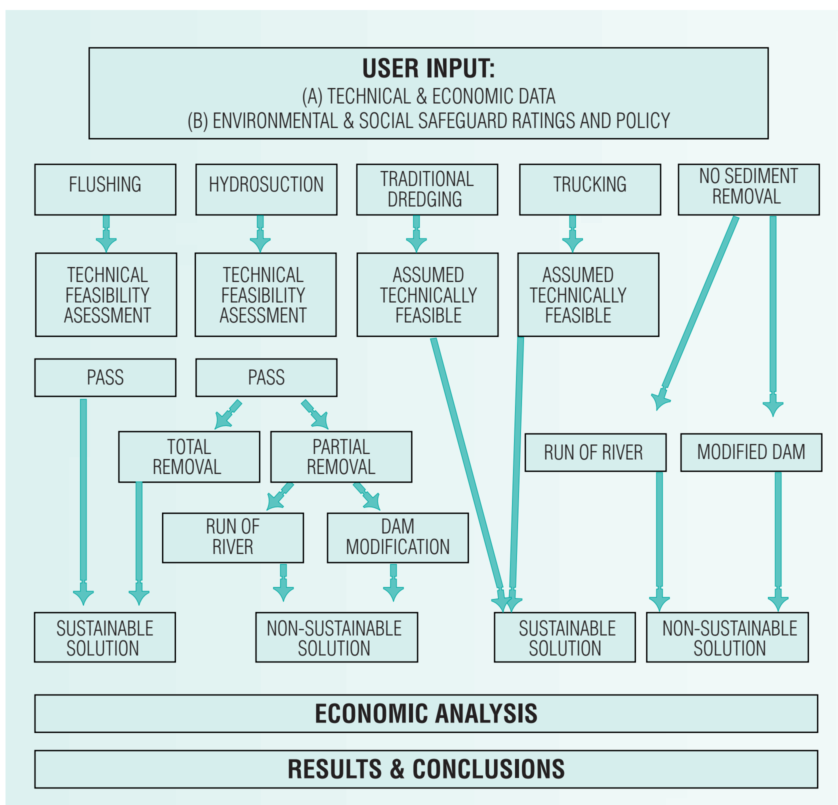
The overall goal of the RESCON approach is to select a sediment management strategy that is technically feasible and also maximizes net economic benefits. Figure 2.1 illustrates the main steps involved in this process. Site-specific technical and economic data are first obtained. Flushing and hydrosuction are then tested for technical feasibility (see Annex 1 for details). If the techniques pass this test, their economic returns are computed and compared with those of traditional dredging, trucking and the "no intervention" scenario.

Economic optimization is performed for each of the sediment management options in separate sub-programs. The objective is to maximize net returns from practicing the given option. Reservoir yield, which is based on remaining reservoir capacity (via Gould's Gamma function) and the unit value of this yield are key determinants of annual revenue. Costs include annual operations and maintenance costs and any periodic sediment removal expenses. Revenues and costs that accrue over time are discounted prior to aggregation. The program also allows initial construction costs, for proposed dams, and capital expenditure costs associated with installing a flushing system in an existing dam, to be included in the net present value (NPV) calculation.

Optimal control theory is used to maximize the aggregated net benefits. The solution may take two forms:

1. SUSTAINABLE, where reservoir capacity is maintained in perpetuity, or
2. NON-SUSTAINABLE, where the reservoir fills with sediments in finite time. This has two sub-solutions:
   2a. the dam is decommissioned at an optimally determined time allowing the salvage value (=cost of decommissioning minus any benefits due to decommissioning) to be collected at this time; or
   2b. the dam is maintained as a "run-of-river" project even after the reservoir is silted.

FIGURE 2.1
PROGRAM STRUCTURE



It is important to note that the optimal terminal time (and terminal capacity) in this case will depend on the magnitude of the salvage value.

Where option 2(a) is the optimal solution, the program calculates an annual retirement fund payment which, if invested, will earn interest and accumulate to equal the costs of decommissioning at the optimal terminal time.

The program assumes that flushing, dredging and trucking always lead to sustainable outcomes. For the case of HSRS, the outcome is dependent on whether the maximum sediment removal capability is sufficient to remove all incoming sediment every year. If this is possible, the solution is sustainable. Otherwise, the non-sustainable outcome occurs (in its two possible manifestations). NPV of the "no sediment removal" strategy is also computed for purposes of comparison. Indeed, for some reservoirs, this strategy may well dominate the others in economic terms. The results of the comparison of all strategies are reported along with a summary of other useful technical and economic information.

The sediment management strategies tested may have positive or negative environmental and social impacts. It is desirable to take account of these effects in the decision making process. The RESCON program can be used to determine the selection of a desirable sediment management strategy subject to environmental and social safeguards specified by the user. Should the NPV with safeguards imposed prove to be lower than that without these policies, the financial opportunity cost of implementing safeguards is also estimated.

3. SEDIMENT MANAGEMENT ALTERNATIVES

Introduction

Volume I provides an outline of available sediment management alternatives. This chapter presents the technical description and optimization procedure associated with each of the sediment management alternatives considered by the RESCON model. Although there are broad similarities, each management option has a few distinguishing characteristics that merit attention. Possible time paths of usable storage capacity vary by sediment management option and are presented below. Mathematical formulations are presented in Chapters 4 and 5. The reader is also referred to Chapter 5 of Volume I.

No Sediment Removal

There is no sediment removed from the dam under this management alternative. Remaining capacity is reduced as sediment accumulates and eventually one of two possible outcomes will occur:

- Decommissioning of the dam
- Maintenance of the dam as a run-of-river project.

In the case of decommissioning, the dam is removed at an optimally determined time. Annual net benefits and salvage value of the dam are the key determinants of the desirable timing of dam decommissioning. The program also calculates an annual retirement fund based on the salvage value and the optimal timing of the dam removal. In the case of run-of-river operations, it is assumed that the entire reservoir capacity is depleted by sedimentation before such operations begin. It is also assumed that run-of-river benefits are available only if the dam has a power generation facility. An annual retirement fund is not calculated as the structure of the dam is maintained forever under run-of-river operations.

Flushing

Technical feasibility
Flushing is implemented by opening low-level outlets and drawing down the water surface elevation behind the dam to temporarily re-establish river flow along an impounded reach, eroding a channel through the sediment deposits and flushing the eroded sediment through the outlet. In this manner, a large amount of previously deposited sediment can be removed in a short period of time.

The basis of the technical model for flushing is Atkinson (1996) which quantifies aspects of reservoirs that are likely to be successful in flushing at complete drawdown. The two major criteria Atkinson develops are sediment balance ratio (SBR) and long-term capacity ratio (LTCR). The RESCON model determines technical feasibility of flushing based on SBR alone. LTCR criterion should be met, but failure does not eliminate flushing from the available economic options (see Annex 2 for details).

Atkinson states that with full drawdown in a reservoir, the quantities of sediment deposited between flushing operations should balance the quantities removed by flushing. The SBR expresses this sediment balance as the ratio of sediment mass flushed annually to the sediment mass depositing annually. It is expected that a sediment balance can be achieved for SBR values greater than unity, thus satisfying this criterion.

The LTCR is a ratio of the reservoir's sustainable capacity to its original capacity. Sustainable capacity is the reservoir volume that can be achieved over the long-term by flushing. The capacities are calculated using a simplified reservoir geometry based on user input.

Atkinson develops four more criteria to assess flushing feasibility. The RESCON model uses these criteria as guidelines to provide additional confirmation of the feasibility of flushing.

- Incomplete drawdown of the reservoir can be a constraint; the extent of drawdown, expressed as a ratio, (DDR) should be greater than 0.7 for sufficient drawdown conditions.
- Because SBR is affected by incomplete drawdown, SBR is re-calculated for conditions of full drawdown, as an indicator of the potential for flushing if low-level gates would be installed (SBRd).
- Channel width formation caused by flushing must be sufficient; predicted flushing width should be similar to the assumed representative bottom width of the reservoir for successful flushing (FWR).
- Side slopes in the scoured valley formed by flushing should be such that the top width of the scour channel roughly conforms to the top width of the reservoir. Flushing would, in such a case, be ideal (TWR).

For equations and details of the criteria and guidelines, see Atkinson (1996).

Optimization Framework

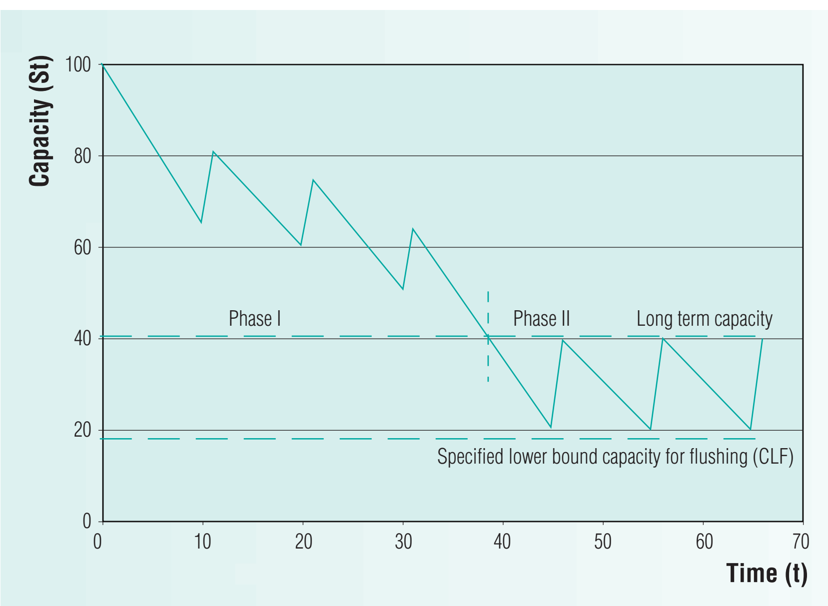
Flushing occurs at intervals determined by the program to maximize aggregate net benefits. The program assumes there are two phases to the flushing operation. The two phases are independent of each other because the transition point is pre-determined by the site-dependent LTCR. In Phase I, periodic sediment removal is practiced until the reservoir capacity reaches its long-term capacity. Once this point is reached, Phase II begins and all subsequently accumulated sediment is flushed periodically, thereby sustaining the reservoir at its long-term capacity (See Figure 3.1 below).

The solution depicted in Figure 3.1 also holds for an existing dam if the remaining reservoir capacity is larger than the dam's long-term capacity (LTC); although the duration of phase I would be shorter than if flushing began when the dam was new. If the remaining capacity is smaller than LTC, however, then there would only be Phase II.

The amount of sediment removed in Phase II is determined by the LTCR and accumulated sediment (original capacity less storage at time t), which is LTCR*(So-St). Thus, the amount of sediment removable by flushing increases as the remaining capacity decreases. Quite obviously, the remaining capacity is likely to converge to a higher level than predetermined long-term capacity if flushing frequency is sufficiently short. The RESCON program, however, eliminates such cases from consideration. In other words, the program determines the optimal flushing cycle length under the technical assumption that the pre-determined long-term capacity has to be reached. The number of years until LTC is reached is also calculated for each possible cycle length because net benefits in the sustainable phase need to be discounted to the present prior to aggregation.

In Phase II, economic optimization is rather simple because the remaining capacity always goes back to the long-term capacity after each flushing event. The RESCON program calculates NPV for all possible cycle lengths in this phase and determines the optimal cycle independently from the cycle length in Phase I. The program reports the optimal cycle length and the amount of flushed sediment for Phase II. The NPVs for Phases I and

FIGURE 3.1
POSSIBLE TIME PATH OF REMAINING CAPACITY FOR FLUSHING



II are then aggregated and the cycle length in Phase I is chosen to maximize this sum.

Finally, there is a point to note about technical lower bounds for flushing. The user may select a technical lower bound for flushing—CLF—but the remaining capacity must be allowed to go below the site-specific long-term capacity. When the reservoir capacity cannot go below the site's long-term capacity because of the specified technical lower bound, the user will be alerted to increase CLF. This technical constraint puts an upper bound on the cycle length in Phase II.

Hydrosuction Sediment Removal System (HSRS)

Technical Description

HSRS is similar to conventional hydraulic dredging except that energy for the dredging operation is supplied by the hydrostatic head at the dam instead of pumps. It therefore requires no significant external power, whereas conventional dredging does. The water and sediment mixture is usually discharged directly into the river downstream of the dam.

The hydrosuction technical model is based on Hotchkiss and Huang (1995). Details are provided in Annex 1. The method requires input of reservoir length (assumed to be the length of the pipeline as a worst case), available energy head at the dam, deposited sediment information and a hydrosuction pipe diameter. The method calculates the velocity of the sediment water mixture through the hydrosuction pipeline by determining the energy available in the pipeline to move the given sediment. The method assumes an initial friction in the pipe, then recalculates the friction based on the mixture velocity. Thus, an iteration scheme is required to obtain a solution. If a solution converges for volumetric flow rate of the mixture, it can be used to determine the volume of sediment removed over a year.

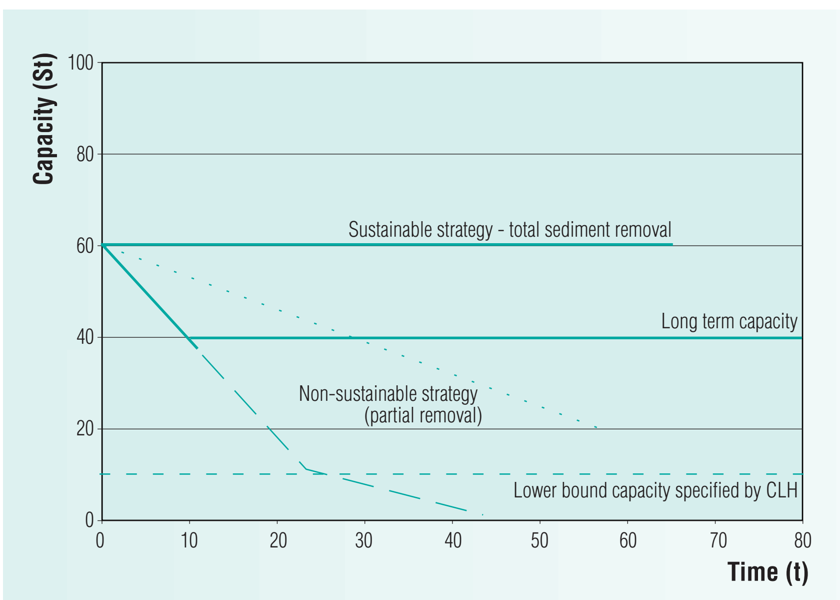
Optimization Framework

Hydrosuction is assumed to occur annually and the timing of HSRS installation is determined through economic optimization. If the entire amount of incoming sediment is removed each year, then the solution is sustainable. Therefore, the long-term capacity is determined by the remaining storage capacity at which HSRS is installed. The user may put a technical constraint on the capacity loss allowable before HSRS has to be installed. This is done with the parameter CLH (maximum percentage of capacity allowable). For example, if the user specifies CLH as 50 percent, HSRS with total removal must be initiated before 50 percent of original capacity is lost due to sedimentation.

With partial removal, sediment accumulates over time even after HSRS is installed and this results in a non-sustainable outcome. As with the non-sustainable solution discussed in the "no-removal" case, there are two possible scenarios: decommissioning or a run-of-river operation. Note, however, that the productive life of the dam will be longer than in the "no removal" case. The program reports the optimal timing of HSRS installation, the amount of sediment removed every year and the terminal time for the case of partial removal. The annual retirement fund is also calculated in case decommissioning is required and the salvage value is negative.

FIGURE3.2

POSSIBLE TIME PATH OF REMAINING CAPACITY FOR HYDROSUCTION



Possible time paths of remaining capacity by hydrosuction are presented in Figure 3.2. Existing capacity is either maintained with full removal (sustainable solution) or declines with partial removal (non-sustainable solution). For existing dams, however, note that any capacity lost prior to introduction of HSRS cannot be recovered with this method.

Traditional Dredging and Trucking

Technical Description

Traditional hydraulic dredging removes reservoir sediment by pumping water entrained sediment from a reservoir bed (Turner 1996). Many types of dredges exist and removal efficiency depends on dredge choice and complex physical parameters that are reservoir dependent. To keep the computer program generic the user is asked to provide a concentration by weight of sediment removed to water removed during dredging operations. The suggested default value is 30 percent, but if studies have shown otherwise for the reservoir in question, the user should input his or her own value.

Trucking is the removal of accumulated sediment from a drained reservoir using heavy equipment. Technical feasibility depends on whether the volume of sediment that must be removed can be physically trucked in the time available for the reservoir to be emptied. Another consideration is accessibility of the reservoir for heavy equipment.

The program assumes both trucking and dredging are technically feasible regardless of the removal rate required. Therefore, the user needs to exercise caution when interpreting the results as it may not be practicable to remove large quantities of sediments. The program provides guidance in its outputs to assist the user in overriding the recommendations of the program where applicable.

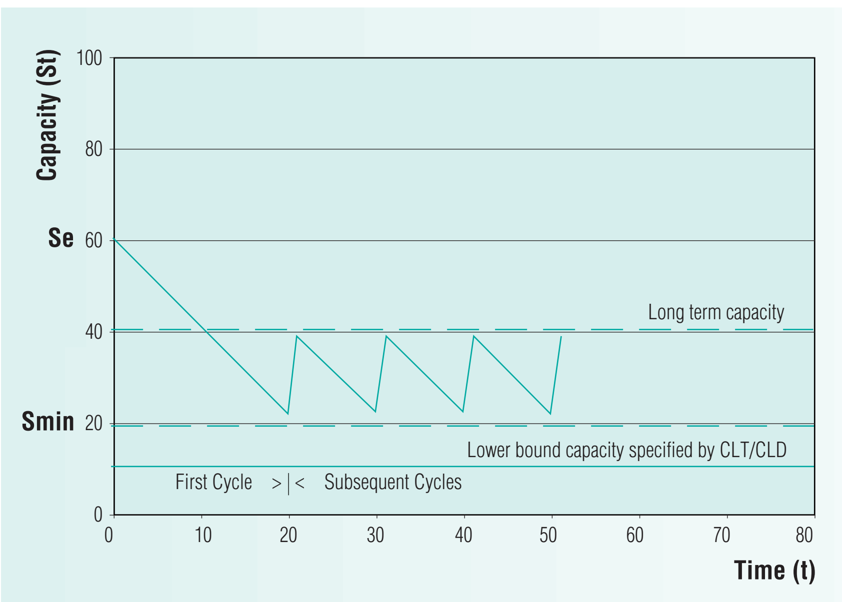
Optimization Framework

Traditional dredging and trucking are practiced at intervals that are computed optimally. There are two phases for each technique: Phase I and Phase II. In the case of a new dam, no sediment removal is practiced in Phase I, while periodic sediment removal is practiced in Phase II. The solution is sustainable because the amount removed at any time is equal to the additional accumulation since the previous event. It is assumed that the amount of sediment removed per event is constant over time, but the first phase duration is allowed to be different from the length of each cycle in Phase II. Upper and lower bounds of remaining reservoir capacity are obtained through economic optimization (see Figure 3.3 below). The optimal duration of Phase I determines the lower bound of remaining reservoir capacity (Smin) and the optimal cycle length in Phase II determines the sustained remaining reservoir capacity, LTC.

The optimally determined lower bound (Smin) is always higher than technical lower bounds that are given by users (through CLD: maximum percent of reservoir capacity loss allowable CLT: same, but for trucking). Thus, the optimal time path of remaining active capacity satisfies technical requirements imposed by users. The optimally determined amount of sediment removed is the observed difference between the LTC and the optimally determined lower bound (Smin). This optimally determined

FIGURE 3.3

POSSIBLE TIME PATH OF REMAINING CAPACITY FOR DREDGING AND TRUCKING (SE>SMIN)



amount of sediment removed per event also satisfies the technical requirement imposed by ASD and AST (Maximum percent of accumulated sediment removed per event). The user also specifies MD and MT (Maximum amount of sediment removed per event), but these parameters are not treated as technical constraints. However, the user will be alerted if the optimally determined amount of sediment removed exceeds MD and/or MT. In such cases, the user may adjust ASD/AST to make the optimally determined amount of sediment removed less then the physical maximum limits specified by MD and MT. The program indicates if the optimally determined amount of sediment removed is technically feasible.

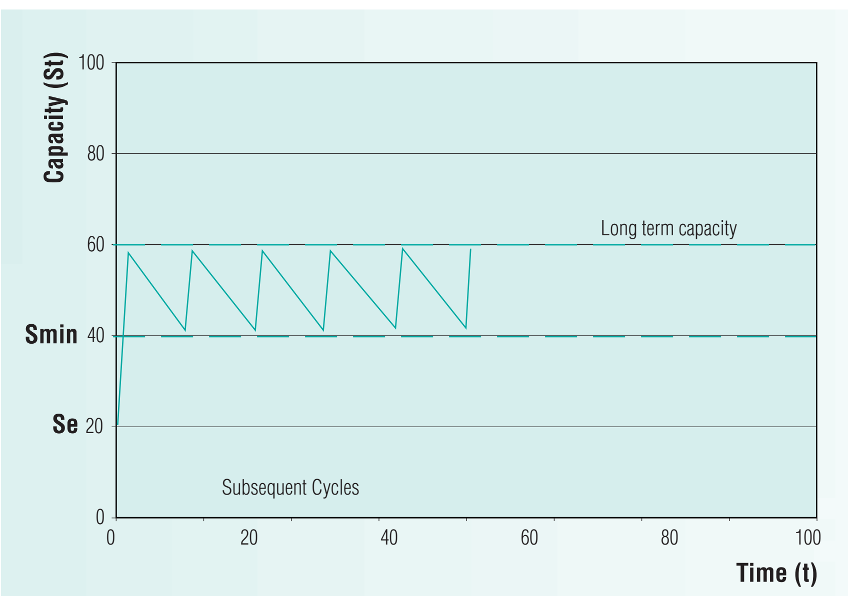
The optimal time path of sediment management obtained in the above manner also applies to an identical existing dam if the remaining capacity of this dam ranges between the optimally determined minimum capacity (Smin) and initial capacity (So). On the other hand, if the remaining capacity of the existing dam (Se) is below Smin, the optimal time path for such an existing dam has to be recalculated. In such a case, one sediment removal event occurs immediately. However, the upper and lower bounds of reservoir capacity are still optimally obtained because the amount of sediment removed by first event is allowed to be different from that by subsequent events. (see Figure 3.4 below). For the case involving Se<Smin, the amount of sediment removed by initial dredging (or trucking) determines LTC and the subsequent cycle determines lower bound (Smin).

The main difference between traditional dredging and trucking is whether the reservoir is emptied during the years in which sediment removal occurs. While trucking requires the reservoir to be emptied, traditional dredging does not. During the year in which trucking occurs, the yield and therefore the benefits are assumed to be zero. Thus, the optimal cycle between sediment removal events is likely to be longer with trucking than traditional dredging.

The program reports the optimally determined cycle length, the amount of sediment removed and the LTC. Parameter values specified by the user, such as CL, ASD and AST, are used as constraints and optimally determined values within these constraints are reported. The user also specifies unit costs of dredging and trucking. For the unit cost of dredging, the user has the option of entering a value or using the pre-programmed diminishing unit cost of dredging function (by entering "N/A").

FIGURE 3.4

POSSIBLE TIME PATH OF REMAINING CAPACITY FOR DREDGING AND TRUCKING (SE<SMIN)



4. TECHNICAL AND ECONOMIC FORMULAE

Yield Estimation

The RESCON model assumes that the reservoir is in a steady state condition. A relationship between yield (water available for use) with a given reliability (probability of providing yield) and reservoir capacity is implemented in the model to determine a quantity of water that can be given economic value. Gould's Gamma distribution (1964) is used for this purpose. The Gould equation, solved for reservoir yield is:

$$W_t = \frac{4 \cdot S_t \cdot V_{in} - Zpr^2 \cdot sd^2 + 4 \cdot Gd \cdot sd^2}{4 \cdot \left(S_t + \frac{Gd}{V_{in}} \cdot sd^2 \right)} = W(S_t), \quad (1)$$

where:

W_t = reservoir yield at time t (volume),

S_t = remaining reservoir capacity after year t (volume),

V_{in} = mean annual water inflow (volume),

Zpr = standard normal variate of p%,

Gd = adjustment factor to approximate the Gamma distribution (offset from the normal distribution),

sd = standard deviation of incoming flows calculated from the user specified coefficient of variation and V_{in}.

Equation (1) is calculated for every time step, t, in the economic model.

Equation (1) is depicted in Figure 4.1. As resevoir volumes decrease due to sedimentation, the reliable yield also decreases.

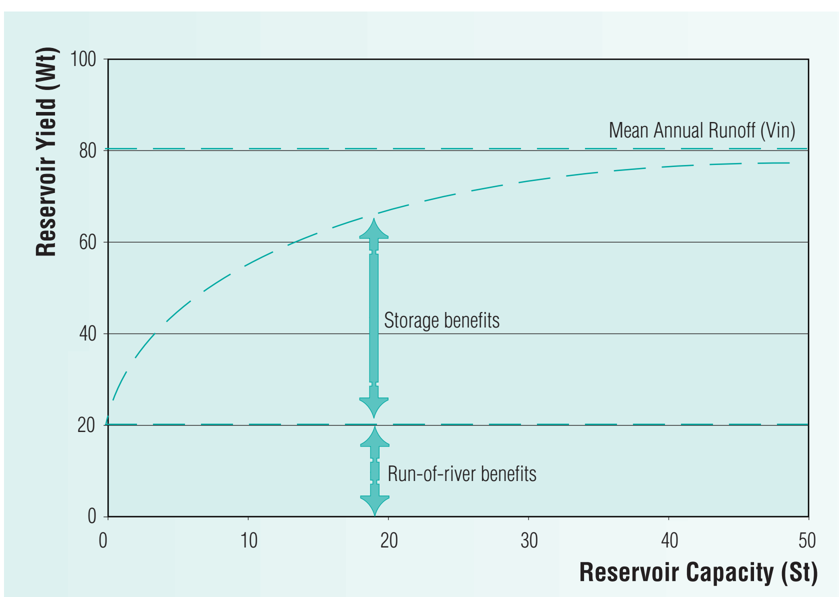
Water Required for Sediment Removal in Economic Models

Flushing

When Flushing is carried out, the reservoir is completely emptied. During the year in which Flushing occurs, the water yield (W_t) is determined as follows,

FIGURE 4.1

RESERVOIR CAPACITY/YIELD RELATIONSHIP



$$W_t = s1 \cdot W(0) + s2 \cdot \left(W(S_{t+1}) - W(0)\right) \qquad (2)$$

where:
- s1 is the fraction of Run-of-River benefits available in the year flushing occurs.
- s2 is the fraction of storage benefits available in the year flushing occurs.
- W(0) is water yield from run-of-river project.
- $W(S_{t+1})$ is water yield from storage capacity after flushing.

Hydrosuction

Hotchkiss and Huang's hydrosuction method (1995) gives sediment flow rate and mixture flow rate in the hydrosuction pipeline. Water required to remove sediment is thus assumed to be:

$$Y_t = \left(\frac{Q_m}{Q_s}\right) \cdot X_t \qquad (3)$$

where:
- Q_m = mixture flowrate (volume per time),
- Q_s = sediment flowrate (volume per time), and
- X_t sediment removed in year t (volume).

Traditional Dredging

The user specifies the parameter Cw, concentration by weight of sediment to water removed. The water volume required to remove a given sediment volume is then:

$$Y_t = \left(\frac{100^{*}2.65}{Cw}\right) \cdot X_t \qquad (4)$$

where:
- Y_t water required to remove X_t (volume).

Trucking

Although the reservoir is emptied during the years in which trucking occurs, trucking itself does not use any significant volume of water. Thus, during the year in which trucking occurs, the water yield (W_t) is assumed to be zero for simplicity.

Cost Calculation in Economic Models

Economic relationships and formulae used for calculating various types of cost are presented below. These formulae help the user to check whether default values are relevant to a specific site as well as the pertinence of numerical data entered.

Unit Cost of Hydrosuction

Unit cost of hydrosuction is determined as follow,

$$CH = \frac{HI}{DU \cdot Q_s}$$

where:
- CH is a unit cost of hydrosuction
- HI is a cost of capital investment to install HSRS
- DU is the expected life of HSRS
- Q_s is the technical maximum sediment transport rate (annual).

Unit Cost of Dredging

Wherever possible users are encouraged to enter their own values. If the user does not enter a value for the unit cost of dredging, the program can estimate a value based on other studies, as follows:

IF X<150,000 m3 CD (X) = 15.0
IF X>16,000,000 m3 CD (X) = 2.0
Else CD(X) = (6.61588727859064)*(X/(10^6))^–0.431483663524377

Where:
- X = amount of sediment dredged per cycle (m3)
- CD = unit cost of dredging (US$/m3)

The unit cost of dredging decreases as the amount of sediment removed (X) increases.

Unit Cost of Construction

Wherever possible users are encouraged to enter their own values. Should that not be possible, the program calculates default value of unit cost of construction based on original storage capacity (So).

IF So>500,000,000 m3 c=US$0.16/m3
Else c=3.5–0.53*LN(So/1000000)

Unit cost of construction (c) decreases as the original capacity (So) increases.

Annual operations and maintenance cost

The annual operations and maintenance cost, C1 is assumed to be a function of original construction cost of the dam. Thus, annual operations and maintenance cost is calculated as;

$$C1=omc*c*So$$

where:

C1 = annual operations and maintenance cost, US$

c = unit cost of dam construction, US$/m3

So = original storage capacity of reservoir

omc = operations and maintenance coefficient is entered by the user.

5. ECONOMIC OPTIMIZATION FRAMEWORK

The economic problem is to choose a sediment removal technique and the manner in which it is to be used (i.e., schedule and amount of sediment removed) so as to maximize life-time aggregate Net Present Value (NPV). This problem is solved in two steps.

First, the following optimization is performed for each technique (and for the "do nothing alternative").

$$\begin{gathered}\text{Maximize} \sum_{t=0}^{T} NB_t \cdot d^t - C2 + V \cdot d^T \\ \text{subject to}: S_{t+1} = S_t - M + X_t,\end{gathered} \tag{5}$$

given initial reservoir capacity and other physical and technical constraints.

The symbols used in the above formulation are defined as:

- NB_t = annual net benefits in year t
- d = discount factor (defined as 1/(1+r), where r is rate of discount)
- C2 = initial cost of construction for proposed dam (= 0 for existing dam)
- V = salvage value
- T = terminal year
- S_t = remaining reservoir capacity in year t
- M = trapped annual incoming sediment
- X_t = sediment removed in year t.

The second step is to select the technique that yields the highest value of the above objective function. Annual net benefits, NB_t, will depend on physical as well as economic considerations that are specific to the technique used for sediment removal. The relevant formulae are stated below, followed by explanation of notation.

Flushing

(See below) (6)

Hydrosuction (HSRS)

$$NB_t = P1 \cdot W(St) - (P1 - PH) \cdot Y_t - C1 - CH \cdot X_t \tag{7}$$

Traditional Dredging

$$NB_t = P1 \cdot W(S_t) - (P1 - PD) \cdot Y_t - C1 - CD(X) \cdot X_t \tag{8}$$

Trucking

$$\begin{gathered} NB_t = P1 \cdot W(S_t) - C1 - CT \cdot X_t \\ (\text{with } W_t = 0 \text{ if } X_t > 0) \end{gathered} \tag{9}$$

No Removal

$$NB_t = P1 \cdot W_t - C1 \tag{10}$$

W_t is a function of S_t as determined by Gould's gamma function

$$NB_t = \begin{Bmatrix} P1 \cdot W(S_t) - C1 \quad \text{if } X_t = 0 \\ P1 \cdot \left[s1 \cdot W(0) + s2 \cdot \left(W(S_{t+1}) - W(0)\right)\right] - C1 - F1 \quad \text{if } X_t > 0, \text{First} \cdot \text{Flushing} \\ P1 \cdot \left[s1 \cdot W(0) + s2 \cdot \left(W(S_{t+1}) - W(0)\right)\right] - C1 \quad \text{if } X_t > 0, \text{Subsequen} \cdot \text{Flushing} \end{Bmatrix} \tag{6}$$

Y_t is the water needed for sediment removal
X_t is sediment removed
P1 is the unit value of reservoir yield
C1 is annual operations and maintenance cost.

Water used during hydrosuction and dredging may have value downstream—the respective unit values are indicated by PH and PD. Additional costs associated with using water to remove sediment using hydrosuction and dredging are stated in unit terms as CH and CD.

CT is the unit cost of sediment removal with trucking.

FI, the capital cost of installing a flushing system, is incurred when the first flushing is practiced.

Sediment removed with each strategy is subject to control (except for hydrosuction). The schedule of removal is determined optimally for each strategy. For non-sustainable outcomes, the terminal year T is also determined by the program and is sensitive to parameter values. In case decommissioning is required and salvage value is negative, the annual retirement fund contribution is calculated as:

$$k = -mV/((1+m)T-1),$$

where m is the rate of interest earned on investment of the retirement fund and is allowed to differ from the discount rate r.

Further details of the optimization procedures are available in Volume I of this Book.

6. USER INTERFACE AND ILLUSTRATIVE EXAMPLE

Introduction

The typical user is likely to be interested mostly in the Input (Checklist) and Economic Results and Conclusions sections of the program. Instructions and explanatory comments are available on these pages in the Excel program. Much of the critical information contained therein is reproduced below for the convenience of the user. Data from the Tarbela Reservoir (in Pakistan) is used to provide an illustrative example.

User Input and Results Pages

For the successful operation of the program the user must accept the activation of macros on start up the program and enter all data in the order requested on the data entry sheets. Data entry is on the following sheets:

- "User Input (Checklist)" – for all technical and economical parameters
- "User Input (Env. Safeguard)" – for the social and environmental safeguard parameters.

Once all data have been entered. the "calculate results now" icon should be clicked to run the model. The results are shown on the subsequent sheets. A summary of the results is presented in the sheets entitled:

- "Flushing Tech Results"
- "HSRS Tech Results"
- "Econ. Results and Conclusions."

Illustrative Data

Example input/output for the model run for Tarbela dam is shown on the following pages.

Care must be exercised when interpreting the results of the modeling. This is well demonstrated by the illustrative data given on the following pages.

The model concludes that the technique yielding the highest aggregate net benefit is dredging. However, careful examination of the detailed results shows that the model is assuming 135 million m3 is being removed by dredging per year. The largest ever dredging operation in the world only achieved approximately 1 million m3 in one year. Therefore this result is clearly meaningless and a warning is provided by the model in the form of Table 6.

Trucking is also shown with a high aggregate NPV. Again for trucking to be feasible over 23million loads of a 96m3 capacity truck would be required. Clearly this is not technically feasible and a warning is provided by the model.

Flushing therefore is the only feasible sustainable solution and has an aggregate NPV in excess of all of the non-sustainable solutions.

RESCON PROGRAM **REVISION A01: 11 APRIL 2003**

Disclaimer:
This program has been produced in good faith to aid practitioners in the field to undertake initial screening of options at a pre-feasibility level. The program should be used by experienced practitioners and the results critically reviewed. The authors of this program cannot take any responsibility for decisions made based on the results it produces.

DIRECTIONS FOR USE:

1. Please make sure macros are activated.
2. User inputs should be made only in the worksheets named 'User Input'. Do not make any changes to the other worksheets.
3. The information requested in the cells highlighted yellow must be provided. Default values are suggested in many cases, but the user should review these and make appropriate changes.
4. Input cells which are not highlighted do not require an input. The values reported in these cells are explained under "Description". The user is encouraged to provide their own estimates instead of the suggested default values. However, if the default is calculated with an equation, that equation will be lost when a new value is typed in the cell. To return to the default equations and values, click [GO BACK TO DEFALUT VALUE].
5. After entering all data (including Environmental Safeguards - if desired), press the calculate button.
6. Results are displayed under "Flushing Tech Results", "HSRS Tech Results", and "Econ. Results & Conclusions."

RESERVOIR GEOMETRY

Parameter	Units	Description	Value
S_o	(m^3)	Original (pre-impoundment) capacity of the reservoir	14,300,000,000
S_e	(m^3)	Existing storage capacity of the reservoir	11,360,000,000
W_{bot}	(m)	Representative bottom width for the reservoir—use the widest section of the reservoir bottom near the dam to produce worst case for criteria	1,000.0
SS_{res}		Representative side slope for the reservoir. 1 Vertical to SS_{res} Horizontal.	1.5
EL_{max}	(m)	Elevation of top water level in reservoir—use normal pool elevation.	475.0
EL_{min}	(m)	Minimum bed elevation—this should be the riverbed elevation at the dam.	335.0
EL_f	(m)	Water elevation at dam during flushing—this is a function of gate capacity and reservoir inflow sequence. The lower the elevation the more successful any flushing operation will be.	410
L	(m)	Reservoir length at the normal pool elevation.	95000
h	(m)	Available head—reservoir normal elevation minus river bed downstream of dam	140.0

WATER CHARACTERISTICS

V_{in}	(m^3)	Mean annual reservoir inflow (mean annual runoff)	80,000,000,000
Cv	(m^3)	Coefficient of Variation of Annual Run-off volume. Determine this from statistrical analysis of the annual runoff volumes	0.1
T	(^{0}C)	Representative reservoir water temperature	10.0

SEDIMENT CHARACTERISTICS

Parameter	Units	Description	Value
P_d	(tonnes/m^3)	Density of in-situ reservoir sediment. Typical values range between 0.9 - 1.35.	1.35
M_{in}	(metric tonnes)	Mean annual sediment inflow mass.	200,000,000
¥	1600, 650, 300, 180	Select from: 1600 for fine loess sediments; 650 for other sediments with median size finer than 0.1mm; 300 for sediments with median size larger than 0.1mm; 180 for flushing with Qf < 50 m3/s with any grain size.	300
Brune Curve No	1 2 3	Is the sediment in the reservoir: (1) Highly flocculated and coarse sediment (2) Average size and consistency (3) colloidal, dispersed, fine-grained sediment	2
Ans	3 or 1	This parameter gives the model a guideline of how difficult it will be to remove sediments. Enter "3" if reservoir sediments are significantly larger than median grain size (d50) = 0.1mm or if the reservoir has been impounded for more than 10 years without sediment removal. Enter "1" if otherwise.	3
Type	1 or 2	Enter the number corresponding to the sediment type category to be removed by hydrosuction dredging: 1 for medium sand and smaller; 2 for gravel.	1

REMOVAL PARAMETERS

Parameter	Units	Description	Value
Hp	1 or 2	Is this a hydroelectric power reservoir? Enter 1 for yes; 2 for no.	1
Q_f	(m^3/s)	Representative flushing discharge. This should be calculated with reference to the actual inflows and the flushing gate capacities. (See Volume I, Annex D for guidelines)	5,000
T_f	(days)	Duration of flushing after complete drawdown.	20
N	(years)	Frequency of flushing events (whole number of years between flushing events)	1
D	(feet)	Assume a trial pipe diameter for hydrosuction. Should be between 1 - 4 feet.	4.0
NP	1, 2, or 3	Enter the number of pipes you want to try for hydrosuction sediment removal. Try 1 first; if hydrosuction cannot remove enough sediment, try 2 or 3.	3
YA	Between 0 and 1	Maximum fraction of total yield that is allowed to be used in HSRS operations. This fraction of yield will be released downstream of the dam in the river channel. It is often possible to replace required maintenance flows with this water release. Enter a decimal fraction from 0 - 1.	0.1
CLF	(%)	Maximum percent of capacity loss that is allowable at any time in reservoir for Flushing. For an existing reservoir, this number must be greater than the percentage of capacity lost already. Sustainable solutions will attempt to remove sediment before this percent of the reservoir is filled completely.	80
CLH	(%)	Maximum percent of capacity loss that is allowable at any time in reservoir for Hydrosuction. For an existing reservoir, this number must be greater than the percentage of capacity lost already. Sustainable solutions will attempt to remove sediment before this percent of the reservoir is filled completely.	60
CLD	(%)	Maximum percent of capacity loss that is allowable at any time in reservoir for Dredging. For an existing reservoir, this number must be greater than the percentage of capacity lost already. Sustainable solutions will attempt to remove sediment before this percent of the reservoir is filled completely.	60
CLT	(%)	Maximum percent of capacity loss that is allowable at any time in reservoir for Trucking. For an existing reservoir, this number must be greater than the percentage of capacity lost already. Sustainable solutions will attempt to remove sediment before this percent of the reservoir is filled completely.	60
ASD	(%)	Maximum percent of accumulated sediment removed per dredging event. Sustainable removal dredging will be subject to this technical constraint.	90
AST	(%)	Maximum percent of accumulated sediment removed per trucking event. Sustainable removal trucking will be subject to this technical constraint.	90
MD	(m^3)	Maximum amount of sediment removed per dredging event. The user is warned if this constraint is not met, but the program still calculates the NPV. Use default value unless better information is available.	1,000,000
MT	(m^3)	Maximum amount of sediment removed per trucking event. The user is warned if this constraint is not met, but the program still calculates the NPV. Use default value unless better information is available	500,000
Cw	(%)	Concentration by weight of sediment removed to water removed by traditional dredging. Maximum of 30%. Do not exceed this default unless you have studies for your reservoir showing different dredging expectations.	30

ECONOMIC PARAMETERS

Parameter	Units	Description	Value
E	0 to 1	If dam being considered is an existing dam enter 0. If the dam is a new construction project enter 1.	0
C	($/m³)	Unit Cost of Construction. The default value given here is a crude estimate based on original reservoir storage capacity. The user is encouraged to replace this value with a project specific estimate.	0.16
C2	($)	Total Cost of Dam Construction. This cost is calculated as unit cost of construction times initial reservoir storage volume (C2 = So*c*E). If you entered E = 0 above, your total construction cost will be taken as 0; if you entered E = 1, this cost will be calculated in the above manner.	0
r	decimal	Discount rate.	0.06
m	decimal	Market interest rate that is used to calculate annual retirement fund. This could be different from the discount rate "r".	0.03
P1	($/m³)	Unit Benefit of Reservoir Yield. Where possible use specific data for the poject. If no data is available refer to Volume 1 Annex F report for guidance.	0.2
V	($)	Salvage Value. This value is the cost of decommissioning minus any benefits due to dam removal. If the benefits of dam removal exceed the cost of decommissioning, enter a negative number.	4,576,000,000
omc		Operation and Maintenance Coefficient. This coefficient is defined as the ratio of annual O&M cost to initial construction cost. Total annual O&M cost is calculated by the program as C1= omc*c* So.	0.01
PH	($/m³)	Unit value of water released downstream of dam in river by hydrosuction operations This could be zero, but may have value if downstream released water is used for providing some of required yield.	0.02
PD	($/m³)	Unit value of water used in dredging operations. This could be zero, but may have value if settled dredging slurry water is used for providing some of required yield.	0.02
CD	($/m³)	Unit Cost of Dredging--The user is encouraged to input her/his own estimate. Should this be difficult at the pre-feasibility level, enter "N/A" to instruct the program to calculate a default value of the unit cost of dredging. The calculated value is reported in Econ. Results.& Conclusion Page.	N/A
CT	($/m³)	Unit Cost of Trucking--The user is encouraged to input her/his own estimate. Should this be difficult at the pre-feasibility level, the default value is recommended.	13.00

FLUSHING BENEFITS PARAMETERS (Reference Chapter 4 Equation 2)

s1	decimal	The fraction of Run-of-River benefits available in the year flushing occurs. (s1 ranges from 0 to 1)	0.9
s2	decimal	The fraction of storage benefits available in the year flushing occurs. (s2 ranges from 0 to 1)	0.9

CAPITAL INVESTMENT

FI	$	Cost of capital investment required for implementing flushing measures. The cost entered will be incurred when flushing is first practiced.	0
HI	$	Cost of capital investment to install Hydrosuction Sediment-Removal Systems (HSRS)	1,000,000
DU	years	The expected life of HSRS.	25

Environmental and Social Safeguards Page

This page is optional. Please proceed further only if you are interested in determining the impact of Environmental and Social Safeguard Policies on the selection of a desirable sediment management strategy; otherwise do not make any changes to this page.

Safeguard ratings for each sediment management strategy are explained in Table 1. The value of 1 is assigned to no impact or to possible benefits, the value of 4 is the worst condition. Safeguard policy criteria that determine the maximum allowable environmental and social damage are reported in Table 2. These range from A to D are based on the sum of safeguard ratings and the maximum value of these ratings. Further guidance is available in Volume I.

TABLE 1

Safeguard Ratings for Each Sediment Management Strategy	Safeguard Ratings
No impact and potential benefits	1
Minor impact	2
Moderate impact	3
Significant Impact	4

TABLE 2

Safeguard Policy Criteria	Interpretation	Policy Level
6	No impact and potential benefits	A
7 to 11, with no 3's	Minor Impact	B
12 to 15 or at least one 3	Moderate Impact	C
16 or higher, or at least one 4	Significant Impact	D

Directions for Use: Enter the safeguard ratings (1 to 4) in Table 3 and safeguard policy levels (A to D) in Table 4. The default values of safeguard ratings are taken as 1 and the safeguard policy level as A. These default values make all policies acceptable from social and environmental safeguard perspective.

TABLE 3

ESTIMATED ENVIRONMENTAL AND SOCIAL IMPACT LEVELS

Possible Strategies	Technique	Estimated Environmental & Social Impact Levels (Enter 1 to 4)						Total
		National Habitat	Human Uses	Resettle-ment	Cultural Assets	Indigenous Peoples	Transboundary Impacts	
Nonsustainable (Decommission) with No Removal	N/A	1	1	1	1	1	1	6
Nonsustainable (Decommission) with Partial Removal	HSRS	1	1	1	1	1	1	6
Nonsustainable (Run-of-River) with No Removal	N/A	1	1	1	1	1	1	6
Nonsustainable (Run-of-River) with Partial Removal	HSRS	1	1	1	1	1	1	6
Sustainable	Flushing	1	1	1	1	1	1	6
Sustainable	HSRS	1	1	1	1	1	1	6
Sustainable	Dredging	1	1	1	1	1	1	6
Sustainable	Trucking	1	1	1	1	1	1	6

TABLE 4

SAFEGUARD POLICY CRITERIA

	Policy Level
Maximum allowable environmental and social damage (A to D)	A

FLUSHING FEASIBILITY CRITERIA CALCULATIONS

Developed from: Atkinson, E. 1996. The Feasibility of Flushing Sediment from Reservoirs, TDR Project R5839, Rep. 0D 137. HR Wallingford

Results Summary

The following are Atkinson's empirical criteria and guidelines. The required and suggested values, and calculated values from your user inputs are included. When the SBR criterion is met, the program will calculate economic results for your reservoir. Please also note the results of the other criterion and guidelines below.

Criterion	Required	Calculated	Notes
SBR	> 1	2.11	Can be flushed if > 1, otherwise not.
LTCR	preferably > 0.35	0.36	Use caution if < 0.35.

Guidelines	Suggested	Calculated	Notes
DDR	> 0.7	0.46	Additional confirmation to assist in deciding whether flushing is feasible
FWR	> 1	0.91	
TWR	~ 1	0.71	
SBR_d	> 1	5.29	

Helpful hint: If SBR is less than one: try increasing frequency of flushing by decreasing the value assigned to the parameter "N" on the User Inputs page.

FLUSHING FEASIBILITY CRITERIA CALCULATIONS (continued)

Conclusion

It is technically feasible to have sustainable flushing solution because annual volume of sediments flushed from reservoir is greater than or equal to the annual inflow of sediments. The summary information shown in the box below is used in the economic model.

Days of Complete Drawdown Flushing	20 days
Flushing Flowrate	5,000 (m^3/s)
Max. Possible Mass Sediment Flushed per Event	3.84E+08 (metric tons)

FEASIBILITY OF HYRDOSUCTION SEDIMENT-REMOVAL SYSTEMS (HSRS)

Tolerance Check =	OK: The iteration scheme yielded the following results for your hydrosuction pipeline choices. See Results Summary below.

RESULTS SUMMARY

Sediment Transport Rate, Qs =	1.91E-04 (m^3/s) =	22 (metric tons/day) =	7468.927 (metric tons/yr)
Reservoir Volume Restored =	1.65E+01 (m^3/day)		6035.497 m^3/year
Mixture Velocity, Vm =	1.3 (m/s)		
Mixture Flowrate, Qm =	1.52 (m^3/s)		
Sediment Concentration through hydrosuction Pipe, C =	5.66E+01 (ppm)		

Conclusion

Not technically feasible to have sustainable HSRS.

FLUSHING FEASIBILITY CRITERIA CALCULATIONS

g	(m^2/s)	Acceleration due to gravity (constant)	9.8

BRUNE TRAP EFFICIENCY CALCULATION

Parameter	Units	Description	Calculated Value
SBrune_ratio		Excel Calculates this value which will be used in calculating Brune Trap Efficiency.	0.1788
TE_High	(%)	Excel Calculates Brune Curve trap efficiency using fits of high curve.	99
TE_Median	(%)	Excel Calculates Brune Curve trap efficiency using fits of median curve.	91
TE_Low	(%)	Excel Calculates Brune Curve trap efficiency using fits of low curve.	96
TE	(%)	Excel Assigns a value for Trap Efficiency from the 3 Brune Curve results using the user choice of High, Median or Low.	91.1

FLUSHING CHANNEL SIDE SLOPE AND FLUSHING WATER SURFACE ELEVATION CALCULATIONS

Parameter	Units	Description	Value
SS_s		Representative side slope for deposits exposed during flushing.	0.39
El_f	(m)	Water surface elevation at the dam during flushing (from user input sheet).	410.0

SBR CALCULATIONS—THE SEDIMENT BALANCE RATIO IS THE RATIO OF THE SEDIMENT FLUSHED ANNUALLY TO THE SEDIMENT DEPOSITED ANNUALLY:

Parameter	Units	Description	Calculated Value
W_{res}	(m)	Representative top width of the reservoir upstream from the dam at the flushing water surface based on the reservoir bathymetry	1225.0
W_f	(m)	The actual flushing width is estimated using a best-fit equation resulting from empirical data (Atkinson, 1996)	905.1

SBR CALCULATIONS—THE SEDIMENT BALANCE RATIO IS THE RATIO OF THE SEDIMENT FLUSHED ANNUALLY TO THE SEDIMENT DEPOSITED ANNUALLY:

Parameter	Units	Description	Calculated Value
W	(m)	Representative width of flow for flushing conditions—Because the width at the bottom of the reservoir before impoundment may limit the channel width that can be achieved with flushing, Wres and Wf are compared to choose the smaller as the representative	905.1
S		Estimated longitudinal water slope during flushing	0.001
Q_s	(tonnes /sec)	Sediment load during flushing—Corrected or not corrected depending on whether reservoir in question is similar or not similar to Chinese reservoirs in Atkinson's report (Ans)—note that 0.00006 < S < 0.016 according to Morris and Fan (1998) for this equation.	222.11
M_f	(tonnes)	Sediment mass flushed in a flushing event	383,801,320
M_{dep}	(tonnes)	Sediment mass depositing between flushing events	182,288,176
SBR		Sediment balance ratio is the ratio of the sediment flushed annually to the sediment deposited annually; must be greater than 1 for feasible conditions	2.1

(continued on next page)

LTCR CALCULATIONS—THE LONG TERM CAPACITY RATIO IS A RATIO OF THE SCOURED VALLEY AREA TO THE RESERVOIR AREA FOR THE ASSUMED SIMPLIFIED GEOMETRY:

See Figure 10 of Atkinson for a sketch of the simplified trapezoidal cross section used in approximating the reservoir as a prismatic shape. A section at the dam site is used to determine the ratio of cross-sectional area for the channel formed by flushing

Parameter	Units	Description	Calculated Value
W_{tf}	(m)	Scoured valley width at the top water level based on the representative flow width for flushing conditions	955.5
W_t	(m)	Reservoir width upstream from the dam at the top water level for the simplified geometry assumed:	1420.0
A_{f1}	(m^2)	When Wtf <= Wt, the reservoir geometry does not constrict the width of the scoured valley; thus the scoured valley cross-sectional area is the average of the reservoir top width and the bottom scour width, multipied by the depth of flow in the scoured area.	60467.8
h_m	(m)	When Wtf <= Wt, constricted scour valley dimension as shown in Atkinson Figure A4.2	-143.8
h_t	(m)	When Wtf <= Wt, constricted scour valley dimension as shown in Atkinson Figure A4.2	208.8
h_f	(m)	When Wtf <= Wt, constricted scour valley dimension as shown in Atkinson Figure A4.2	65.0
A_{f2}	(m^2)	When Wtf > Wt, the scoured valley is constricted as in Figure A4.2 of Atkinson; thus, a more complex geometry using h_m, h_t, and h_f must be calculated to determine the scoured valley cross-sectional area	108956.5
A_f	(m^2)	Scoured valley area applicable to this reservoir	60467.8
A_r	(m^2)	Reservoir cross-sectional area—estimated from the average of the reservoir top and bottom widths, multiplied by the total depth of water in the reservoir	169400
LTCR		Long term capacity ratio is a ratio of the scoured valley area to the reservoir area for the assumed simplified geometry.	0.36

DDR CALCULATION—THE EXTENT OF RESERVOIR DRAWDOWN IS UNITY MINUS A RATIO OF FLOW DEPTH FOR THE FLUSHING WATER LEVEL TO FLOW DEPTH FOR THE NORMAL IMPOUNDING LEVEL:

Parameter	Units	Description	Calculated Value
DDR		DDR should be greater than 0.7 for drawdown to be sufficient	0.46

FWR CALCULATION—FLUSHING WIDTH RATIO CHECKS THAT THE PREDICTED FLUSHING WIDTH, WF, IS GREATER THAN THE REPRESENTATIVE BOTTOM WIDTH OF RESERVOIR, WBOT:

Parameter	Units	Description	Calculated Value
FWR		FWR should be greater than 1; if not, see TWR calculations	0.91

TWR CALCULATIONS—TWR CHECKS THAT THE SCOURED VALLEY WIDTH AT TOP WATER LEVEL FOR COMPLETE DRAWDOWN IS GREATER THAN THE RESERVOIR TOP WIDTH:

Steep side slopes in the scoured valley will be a constraint when 1) FWR is a constraint, or 2) reservoir bottom widths are small when compared to the widths at full storage level. The reservoir top ratio, TWR, quantifies a side slope constrain

Parameter	Units	Description	Calculated Value
W_{bf}	(m)	W_{bf} is the bottom width of the scoured valley at full drawdown. It is the minimum of W_{bot} and W_f	905.1
W_{td}	(m)	W_{td} is the scoured valley width at top water level if complete drawdown is assumed	1013.6
TWR		Checks that the scoured valley width at top water level for complete drawdown is greater than the reservoir top width; If FWR is a constraint, should have TWR > 2. If FWR not a constraint, TWR approaching 1 sufficient.	0.71

SBRD CALCULATIONS—SBRD IS THE SEDIMENT BALANCE RATIO BASED ON FLUSHING FLOWS; IT IS INDEPENDENT OF DRAWDOWN

SBRd is calculated the same as SBR, except ELf = Elmin

Parameter	Units	Description	Calculated Value
W_{res}	(m)	A representative top width of the reservoir upstream from the dam at the flushing water surface based on the reservoir bathymetry	1000.0
W_f	(m)	The actual flushing width is estimated using a best-fit equation resulting from empirical data (Atkinson, 1996)	905.1
W	(m)	The representative width of flow for flushing conditions—Because the width at the bottom of the reservoir before impoundment may limit the channel width that can be achieved with flushing, Wres and Wf are compared to chose the smaller as the representative width of flow for flushing conditions	905.1
S		The estimated longitudinal water slope during flushing	0.001
Q_s	(tonnes /sec)	Sediment load during flushing—Corrected or not corrected depending on whether reservoir in question is similar or not similar to Chinese reservoirs in Atkinson's report—note that 0.00006 < S < 0.016 according to Morris and Fan (1998) for this equation.	557.73
M_f	(tonnes)	Sediment mass flushed annually	963,749,306
M_{dep}	(tonnes)	Sediment mass depositing annually which must be flushed	182,288,176
SBR_d		Sediment balance ratio is the ratio of the sediment flushed annually to the sediment deposited annually; must be greater than 1 for feasible conditions	5.29

HYDROSUCTION PIPELINE SIZING TO DETERMINE FEASIBILITY OF HYRDOSUCTION SEDIMENT-REMOVAL SYSTEMS (HSRS)

USER INPUT VALUES CONVERTED TO ENGLISH UNITS:

Parameter	Required Units	Description	Value
h	(ft)	Available head—reservoir water surface elevation at normal pool minus tailwater elevation on downstream side of dam or other determined hydrosuction pipe outlet location	459

USER INPUT VALUES CONVERTED TO ENGLISH UNITS: (continued)

Parameter	Required Units	Description	Value
L	(ft)	Pipeline length from location of hydrosuction operations to tailwater or other determined outlet location	311,600
r_d	(lb/ft^3)	Density of reservoir in situ sediment	84
r_w	(lb/ft^3)	Density of water	62.4
Q	(cfs)	Assume a trial flowrate through pipe	25

ASSUMED VALUES IN ENGLISH UNITS FOR THE FOLLOWING INPUT PARAMETERS (STEP 1 OF HOTCHKISS AND HUANG, 1995):

Parameter	Required Units	Description	Value
g	(ft^2/s)	Acceleration due to gravity (constant)	32.2
e	(ft)	Roughness height—assuming steel pipe material.	0.00015
sg		Sediment specific gravity in HSRS pipe: 2.65 for quartz (sand and gravel); 2.8 for silt&clay.	2.65
sumKi		Assumed total minor energy loss coefficient for possible minor losses in the hydro-suction piping system. Minor losses include energy losses at entrance, exit, bends, connections, and valves. Losses summed.	6.0
d_{100}	(mm)	Grain size for which 100 percent of reservoir sediment sample is finer.	9.5000
d_{90}	(mm)	Grain size for which 90 percent of reservoir sediment sample is finer.	3.6000
d_{65}	(mm)	Grain size for which 65 percent of reservoir sediment sample is finer.	1.3000
d_{50}	(mm)	Grain size for which 50 percent of reservoir sediment sample is finer.	0.7300
d_{30}	(mm)	Grain size for which 30 percent of reservoir sediment sample is finer.	0.4200

GENERAL CALCULATIONS

Parameter	Units	Description	Calculated Value
Apipe	(ft^2)	Trial pipe cross-sectional area.	12.6
V	(fps)	Trial velocity through pipe.	2.0
n	(ft^2/s)	Kinematic Viscosity for assumed temperature. Empirical equation from Yang (1996). (Assumes atmospheric pressure.)	1.407E-05

REMAINING STEP 2.
DETERMINE DRAG COEFFICIENT (CD) FOR EACH SIZE FRACTION AND THEN A WEIGHTED COMPOSITE CD USING AN ITERATIVE PROCESS.

Parameter	Units	Description	Calculated Value
Cd_{100}		Assumed Cd for d_{100} grain size.	1.0
Cd_{90}		Assumed Cd for d_{90} grain size.	1.0
Cd_{65}		Assumed Cd for d_{65} grain size.	1.0
Cd_{50}		Assumed Cd for d_{50} grain size.	2.0
Cd_{30}		Assumed Cd for d_{30} grain size.	4.0
Cd		Composite Cd for sediment sample	2.07
w_{100}	(fps)	Fall velocity for d_{100} grain size using equation determined from force balance on sediment particle.	1.49
w_{90}	(fps)	Fall velocity for d_{90} grain size using equation determined from force balance on sediment particle.	0.92
w_{65}	(fps)	Fall velocity for d_{65} grain size using equation determined from force balance on sediment particle.	0.55
w_{50}	(fps)	Fall velocity for d_{50} grain size using equation determined from force balance on sediment particle.	0.29
w_{30}	(fps)	Fall velocity for d_{30} grain size using equation determined from force balance on sediment particle.	0.16
Re_{100}		Reynold's Number for d_{100} using its fall velocity	3292
Re_{90}		Reynold's Number for d_{90} using its fall velocity	768
Re_{65}		Reynold's Number for d_{65} using its fall velocity	167
Re_{50}		Reynold's Number for d_{50} using its fall velocity	50
Re_{30}		Reynold's Number for d_{30} using its fall velocity	15
b		Assume shape factor for most natural sands applies here	0.7
Cd_{100}		Calculates updated Cd from Reynold's Number for d_{100}.	1.18
Cd_{90}		Calculates updated Cd from Reynold's Number for d_{90}.	1.11
Cd_{65}		Calculates updated Cd from Reynold's Number for d_{65}.	1.23
Cd_{50}		Calculates updated Cd from Reynold's Number for d_{50}.	1.83
Cd_{30}		Calculates updated Cd from Reynold's Number for d_{30}.	3.55
Cd		Updated composite Cd for sediment sample	2.01
w_{100}	(fps)	Updated fall velocity for d_{100} grain size using equation determined from force balance on sediment particle.	1.37
w_{90}	(fps)	Updated fall velocity for d_{90} grain size using equation determined from force balance on sediment particle.	0.87
w_{65}	(fps)	Updated fall velocity for d_{65} grain size using equation determined from force balance on sediment particle.	0.50
w_{50}	(fps)	Updated fall velocity for d_{50} grain size using equation determined from force balance on sediment particle.	0.30
w_{30}	(fps)	Updated fall velocity for d_{30} grain size using equation determined from force balance on sediment particle.	0.17
Re_{100}		Updated Reynold's Number for d_{100} using its fall velocity	3033
Re_{90}		Updated Reynold's Number for d_{90} using its fall velocity	729
Re_{65}		Updated Reynold's Number for d_{65} using its fall velocity	150
Re_{50}		Updated Reynold's Number for d_{50} using its fall velocity	52
Re_{30}		Updated Reynold's Number for d_{30} using its fall velocity	16.2
Cd_{100}		Updates Calculation of Cd from Reynold's Number for d_{100}.	1.17

(continued on next page)

REMAINING STEP 2. (continued)

Parameter	Units	Description	Calculated Value
Cd_{90}		Updates Calculation of Cd from Reynold's Number for d_{90}.	1.11
Cd_{65}		Updates Calculation of Cd from Reynold's Number for d_{65}.	1.25
Cd_{50}		Updates Calculation of Cd from Reynold's Number for d_{50}.	1.80
Cd_{30}		Updates Calculation of Cd from Reynold's Number for d_{30}.	3.42
Cd		Updated composite Cd for sediment sample	1.97
w_{100}	(fps)	Updated fall velocity for d_{100} grain size using equation determined from force balance on sediment particle.	1.37
w_{90}	(fps)	Updated fall velocity for d_{90} grain size using equation determined from force balance on sediment particle.	0.87
w_{65}	(fps)	Updated fall velocity for d_{65} grain size using equation determined from force balance on sediment particle.	0.49
w_{50}	(fps)	Updated fall velocity for d_{50} grain size using equation determined from force balance on sediment particle.	0.31
w_{30}	(fps)	Updated fall velocity for d_{30} grain size using equation determined from force balance on sediment particle.	0.17
Re_{100}		Updated Reynold's Number for d_{100} using its fall velocity	3038
Re_{90}		Updated Reynold's Number for d_{90} using its fall velocity	729
Re_{65}		Updated Reynold's Number for d_{65} using its fall velocity	149
Re_{50}		Updated Reynold's Number for d_{50} using its fall velocity	52
Re_{30}		Updated Reynold's Number for d_{30} using its fall velocity	17
Cd_{100}		Updates Calculation of Cd from Reynold's Number for d_{100}.	1.17
Cd_{90}		Updates Calculation of Cd from Reynold's Number for d_{90}.	1.11
Cd_{65}		Updates Calculation of Cd from Reynold's Number for d_{65}.	1.26
Cd_{50}		Updates Calculation of Cd from Reynold's Number for d_{50}.	1.79
Cd_{30}		Updates Calculation of Cd from Reynold's Number for d_{30}.	3.36
Cd		Updated composite Cd for sediment sample	1.95
w_{100}	(fps)	Updated fall velocity for d_{100} grain size using equation determined from force balance on sediment particle.	1.37
w_{90}	(fps)	Updated fall velocity for d_{90} grain size using equation determined from force balance on sediment particle.	0.87
w_{65}	(fps)	Updated fall velocity for d_{65} grain size using equation determined from force balance on sediment particle.	0.49
w_{50}	(fps)	Updated fall velocity for d_{50} grain size using equation determined from force balance on sediment particle.	0.31
w_{30}	(fps)	Updated fall velocity for d_{30} grain size using equation determined from force balance on sediment particle.	0.17
Re_{100}		Updated Reynold's Number for d_{100} using its fall velocity	3038
Re_{90}		Updated Reynold's Number for d_{90} using its fall velocity	729
Re_{65}		Updated Reynold's Number for d_{65} using its fall velocity	149
Re_{50}		Updated Reynold's Number for d_{50} using its fall velocity	52
Re_{30}		Updated Reynold's Number for d_{30} using its fall velocity	17
Cd_{100}		Updates Calculation of Cd from Reynold's Number for d_{100}.	1.17
Cd_{90}		Updates Calculation of Cd from Reynold's Number for d_{90}.	1.11
Cd_{65}		Updates Calculation of Cd from Reynold's Number for d_{65}.	1.26
Cd_{50}		Updates Calculation of Cd from Reynold's Number for d_{50}.	1.79
Cd_{30}		Updates Calculation of Cd from Reynold's Number for d_{30}.	3.36
Cd		Updated composite Cd for sediment sample	1.95

STEPS 3 - 8

WHERE: STEP 3. DETERMINES PARAMETERS NEEDED TO CALCULATE THE NON-FLOW PARAMETER, "a"; STEP 4. ESTIMATES HEADLOSS GRADIENT THROUGH THE HYDROSUCTION PIPE, BASED ON THE INITIAL GUESS FOR PIPE DIAMETER AND FLOWRATE AND MINOR LOSS ESTIMATION; STEP

Parameter	Units	Description	Calculated Value
Y		Calculate Y from Hotchkiss equation (2):	0.03
Y		Calculate Y from Hotchkiss equation (2):	0.03
K		Zandi and Govatos (1967), according to Hotchkiss, determined the value of K, based in Y.	280.0
m		Zandi and Govatos (1967), according to Hotchkiss, determined the value of m, based in Y.	-1.93
a		Non-flow parameter, a, is a combination of non-flow variables from Hotchkiss equation (8):	4.563E+06
Jm	(ft/ft)	Calculated headloss gradient in hydrosuction pipe	0.001
Re		Reynold's number for the mixture flow in the pipe.	5.655E+05
f		Equation developed from Moody diamgram yields trial friction factor value.	0.013
Qs	(cfs)	Maximum sediment transport rate under available headloss gradient, calculated using Hotchkiss (1996) equation (12).	0.001784
Vm	(fps)	Calculates trial optimum mixture flow velocity from Hotchkiss equation (11).	4.08
Rm		Calculates the mixture flow Reynold's number.	1.159E+06
fm		Calculates the mixture friction coefficient, fm, using the explicit formula given by Swamee and Jian (Streeter and Wylie, 1985) [Hotchkiss equation (14)].	0.012

STEP 9:

USING VM, EXCEL RECALCULATES JM AND FM, AND COMPARES WITH VALUE OF FM CALCULATED IN STEP 8. REPEATS STEPS 3 THROUGH 8 UNTIL THE DIFFERENCE BETWEEN FM VALUES CALCULATED IN SUBSEQUENT STEPS IS WITHIN ACCEPTABLE TOLERANCE (USUALLY 2-3 ITERATIONS).

FIRST ITERATION OF STEPS 3-8

Parameter	Units	Description	Calculated Value
Y		Update Y from Hotchkiss equation (2):	0.11
K		Zandi and Govatos (1967), according to Hotchkiss, determined the value of K, based in Y.	280.0
m		Zandi and Govatos (1967), according to Hotchkiss, determined the value of m, based in Y.	-1.93
a		Update non-flow parameter, a, is a combination of non-flow variables from Hotchkiss equation (8):	4.563E+06
Jm	(ft/ft)	Update headloss gradient in hydrosuction pipe	0.001
Qs	(cfs)	Update maximum sediment transport rate under available headloss gradient, calculated using Hotchkiss (1996) equation (12).	0.002
Vm	(fps)	Updates trial optimum mixture flow velocity from Hotchkiss equation (11).	4.27
Rm		Updates the mixture flow Reynold's number.	1.213E+06
fm		Updates the mixture friction coefficient, fm, using the explicit formula given by Swamee and Jian (Streeter and Wylie, 1985) [Hotchkiss equation (14)].	0.012

SECOND ITERATION OF STEPS 3-8

Parameter	Units	Description	Calculated Value
Y		Update Y from Hotchkiss equation (2):	0.12
K		Zandi and Govatos (1967), according to Hotchkiss, determined the value of K, based in Y.	280.0
m		Zandi and Govatos (1967), according to Hotchkiss, determined the value of m, based in Y.	-1.93
a		Update non-flow parameter, a, is a combination of non-flow variables from Hotchkiss equation (8):	4.563E+06
Jm	(ft/ft)	Update headloss gradient in hydrosuction pipe	0.001
Qs	(cfs)	Update maximum sediment transport rate under available headloss gradient, calculated using Hotchkiss (1996) equation (12).	0.002
Vm	(fps)	Updates trial optimum mixture flow velocity from Hotchkiss equation (11).	4.28
Rm		Updates the mixture flow Reynold's number.	1.216E+06
fm		Updates the mixture friction coefficient, fm, using the explicit formula given by Swamee and Jian (Streeter and Wylie, 1985) [Hotchkiss equation (14)].	0.012

THIRD ITERATION OF STEPS 3-8

Parameter	Units	Description	Calculated Value
Y		Update Y from Hotchkiss equation (2):	0.12
K		Zandi and Govatos (1967), according to Hotchkiss, determined the value of K, based in Y.	280.0
m		Zandi and Govatos (1967), according to Hotchkiss, determined the value of m, based in Y.	-1.93
a		Update non-flow parameter, a, is a combination of non-flow variables from Hotchkiss equation (8):	4.563E+06
Jm	(ft/ft)	Update headloss gradient in hydrosuction pipe	0.001
Qs	(cfs)	Update maximum sediment transport rate under available headloss gradient, calculated using Hotchkiss (1996) equation (12).	0.002
Vm	(fps)	Updates trial optimum mixture flow velocity from Hotchkiss equation (11).	4.28
Rm		Updates the mixture flow Reynold's number.	1.216E+06
fm		Updates the mixture friction coefficient, fm, using the explicit formula given by Swamee and Jian (Streeter and Wylie, 1985) [Hotchkiss equation (14)].	0.012

FOURTH ITERATION OF STEPS 3-8

Parameter	Units	Description	Calculated Value
Y		Update Y from Hotchkiss equation (2):	0.12
K		Zandi and Govatos (1967), according to Hotchkiss, determined the value of K, based in Y.	280.0
m		Zandi and Govatos (1967), according to Hotchkiss, determined the value of m, based in Y.	-1.93
a		Update non-flow parameter, a, is a combination of non-flow variables from Hotchkiss equation (8):	4.563E+06
Jm	(ft/ft)	Update headloss gradient in hydrosuction pipe	0.001
Qs	(cfs)	Update maximum sediment transport rate under available headloss gradient, calculated using Hotchkiss (1996) equation (12).	0.002

(continued on next page)

FOURTH ITERATION OF STEPS 3-8 (continued)

Parameter	Units	Description	Calculated Value
Vm	(fps)	Updates trial optimum mixture flow velocity from Hotchkiss equation (11).	4.28
Rm		Updates the mixture flow Reynold's number.	1.216E+06
fm		Updates the mixture friction coefficient, fm, using the explicit formula given by Swamee and Jian (Streeter and Wylie, 1985) [Hotchkiss equation (14)].	0.012

FIFTH ITERATION (FINAL) OF STEPS 3-8

Parameter	Units	Description	Calculated Value
Y		Update Y from Hotchkiss equation (2):	0.12
K		Zandi and Govatos (1967), according to Hotchkiss, determined the value of K, based in Y.	280.0
m		Zandi and Govatos (1967), according to Hotchkiss, determined the value of m, based in Y.	-1.93
a		Update non-flow parameter, a, is a combination of non-flow variables from Hotchkiss equation (8):	4.563E+06
Jm	(ft/ft)	Update headloss gradient in hydrosuction pipe	0.001
Qs	(cfs)	Update maximum sediment transport rate under available headloss gradient, calculated using Hotchkiss (1996) equation (12).	0.002
Vm	(fps)	Updates trial optimum mixture flow velocity from Hotchkiss equation (11).	4.28
Rm		Updates the mixture flow Reynold's number.	1.216E+06
fm		Updates the mixture friction coefficient, fm, using the explicit formula given by Swamee and Jian (Streeter and Wylie, 1985) [Hotchkiss equation (14)].	0.012

RESULTS SUMMARY

Tolerance Check =		**Solution Convergence, OK**	
Sed. Trans. Rate, Qs/pipe =		0.00	(cfs)
	=	7	(yd^3/day)
	=	8	(US tons/day) based on in situ sediment weight , e.g. r_s ~ 1.2.
Sed. Trans. Rate, Qs,total =		0.01	(cfs)
	=	22	(yd^3/day)
	=	25	(US tons/day) based on in situ sediment weight , e.g. r_s ~ 1.2.
Mix. Velocity, Vm =		4.3	(fps)
Mix. Flowrate, Qm/pipe =		53.8	(cfs)
	=	144917	(tons/day) based on specific weight of water (r_w = 62.5, sg = 1)
Mix. Flowrate, Qm/pipe =		53.8	(cfs)
	=	144917	(tons/day) based on specific weight of water (r_w = 62.5, sg = 1)
Conc. In Pipe, C =		5.66E+01	(ppm)

VALUES OF ABSOLUTE ROUGHNESS FOR NEW PIPES.

Pipe Material	e (feet)
Drawn tubing	0.000005
Commercial steel, welded steel, wrought iron	0.00015
Galavanized iron	0.0005
Cast iron, average	0.00085

VALUES OF MINOR ENERGY LOSSES FOR VARIOUS TRANSITIONS AND FITTINGS.

Pipe Material	K
Pipe entrance	1
Pipe exit	0.5
Globe valve, wide open	10
Angle valve, wide open	5
Gate valve, wide open	0.19
Gate valve, half open	2.06
Elbow bend (short to long)	0.9 to 0.6
45o elbow bend	0.4

TYPICAL POORLY GRADED GRAIN SIZE DISTRIBUTIONS

Lookup "Type" Value	Particle Size	% Finer				
		d_{100}	d_{90}	d_{65}	d_{50}	d_{30}
2	Gravel (mm)	75	61	36	27	15
1	Med Sand (mm)	9.5	3.6	1.3	0.73	0.42
3	Silt & Clay (mm)	9.5	0.11	0.045	0.026	0.01

ECONOMIC RESULTS & CONCLUSIONS

TABLE 1
ECONOMIC RESULTS AND CONCLUSIONS SUMMARY

Possible Strategies	Technique	Aggregate Net Present Value
Do nothing	N/A	2.34388E+11
Nonsustainable (Decommissioning) with Partial Removal	HSRS	2.34387E+11
Nonsustainable (Run-of-River) with No Removal	N/A	2.34597E+11
Nonsustainable (Run-of-River) with Partial Removal	HSRS	2.34596E+11
Sustainable	Flushing	2.36784E+11
Sustainable	HSRS	Total Removal with HSRS is technically infeasible, See Partial Removal with HSRS
Sustainable	Dredging	2.36989E+11
Sustainable	Trucking	2.32439E+11

ECONOMIC CONCLUSION:

Strategy yielding the highest aggregate net benefit:		Sustainable
Technique yielding the highest aggregate net benefit:		Dredging
The highest aggregate net benefit is:	$	2.370E+11

DETAILED RESULTS:
NONSUSTAINABLE (DECOMMISSION)

# of years until Partial Removal Option with HSRS is practiced:	1	years
# of years until retirement for Decommission-with No Removal Option:	85	years
# of years until retirement for Decommission: Partial Removal Option with HSRS:	85	years
Remaining reservoir capacity at retirement for Decommission-with No Removal Option:	17,624,580	m^3
Remaining reservoir capacity at retirement for Decommission: Partial Removal Option with HSRS:	18,089,313	m^3

Annual Retirement Fund Payment for nonsustainable options: Decommission	12,110,403	$
Annual Retirement Fund Payment for nonsustainable options:Partial Removal with HSRS	12,110,403	$

NONSUSTAINABLE (RUN-OF-RIVER)

# of years until Partial Removal Option with HSRS is practiced:	1	years
Approximate # of years until dam is silted for Run-of-River-with No Removal Option:	86	years
Approximate # of years until dam is silted for Run-of-River-with Partial Removal Option:	86	years

SUSTAINABLE

Long term reservoir capacity for Flushing	5,104,423,800	m^3
Long term reservoir capacity for HSRS	Not applicable	m^3
Long term reservoir capacity for Dredging	7,278,529,502	m^3
Long term reservoir capacity for Trucking	7,953,670,896	m^3

Approximate # of years until dam is sustained at long term capacity for Flushing	50	years
Approximate # of years until dam is sustained at long term capacity for HSRS	Not applicable	years
Approximate # of years until dam is sustained at long term capacity for Dredging	30	years
Approximate # of years until dam is sustained at long term capacity for Trucking	41	years

Approximate # of Flushing events until dam is sustained at long term capacity	0	times

TABLE 2
FREQUENCY OF REMOVAL

Strategy	Technique	Cycle/Phase	Frequency of Removal (years)
Nonsustainable-with Partial Removal	HSRS	Annual cycle	1
Run-of-River (Nonsustainable)-with Partial Removal	HSRS	Annual cycle	1
Sustainable	Flushing	Phase I	No Flushing occurs
Sustainable	Flushing	Phase II	2
Sustainable	HSRS	Annual cycle	Not applicable
Sustainable	Dredging	Phase I	30
Sustainable	Dredging	Phase II	1
Sustainable	Trucking	Phase I	41
Sustainable	Trucking	Phase II	17

TABLE 3

SEDIMENT REMOVED PER EVENT

Strategy	Technique	Cycle/Phase	Sediment Removed (m^3)
Nonsustainable-with Partial Removal*	HSRS	Annual cycle	5,533
Run-of-River (Nonsustainable)-with Partial Removal	HSRS	Annual cycle	5,533
Sustainable	Flushing	Phase I	0
Sustainable	Flushing	Phase II	270,056,558
Sustainable	HSRS	Annual cycle	Not applicable
Sustainable	Dredging	Phase I	N/A
Sustainable	Dredging	Phase II	135,028,279
Sustainable	Trucking	Phase I	N/A
Sustainable	Trucking	Phase II	2,295,480,740

TABLE 4

OPTIMAL VALUES OF ASD/AST AND CLF/CLD/CLT

Technique	ASD/AST(%)	CLF/CLD/CLT
Flushing(Phase I)	N/A	66
Flushing(Phase II)	3	
HSRS	N/A	N/A
Dredging(Phase I)	N/A	49
Dredging(Phase II)	2	
Trucking(Phase I)	N/A	59
Trucking(Phase II)	27	

TECHNICAL COMMENTS

Average expected concentration of sediment to water flushed per flushing event:	44,421	ppm
Average expected concentration of sediment to water released downstream of dam per hydrosuction event:	57	ppm
Average expected concentration of sediment to water removed from reservoir per dredging event:	300,000	ppm

Note: Because reservoir is dewatered prior to a trucking event and river is diverted during a trucking event, material removed is moist sediment (negligible water).

TABLE 5

NUMBER OF TRUCK LOADS* REQUIRED TO COMPLETE SUSTAINABLE SEDIMENT TRUCKING REMOVAL OPTION

Truck Model Number	m^3/Truck Load	Number of Loads (Phase I)	Number of Loads (Phase II)
769D	16.2	N/A	141,696,342
771D	18	N/A	127,526,708
773D	26	N/A	88,287,721
775D	31	N/A	74,047,766
777D	42.1	N/A	54,524,483
785B	57	N/A	40,271,592
789B	73	N/A	31,444,942
793C	96	N/A	23,911,258

*1997. Caterpillar Performance Handbook, Ed. 28. CAT Publication by Caterpillar Inc., Peoria,Illinois, USA. October 1997.

TABLE 6

NUMBER OF DREDGES REQUIRED TO COMPLETE SUSTAINABLE SEDIMENT DREDGING REMOVAL OPTION

Volume Removed per Dredges (m^3/Dredge)	No. of Dredges (Phase I)	No. of Dredges(Phase II)
11,000,000	N/A	13
*Calculated assuming dredging mixture velocity through pipe = 5 m/s, diameter of dredge pipe=0.8 m, reservoir length is <4 km,dam height is <30 m, and dredge runs 70% of time.		

TABLE 7

UNIT COST OF SEDIMENT REMOVAL

	Phase I	Phase II
Unit Cost of Dredgings ($/$m^3$)	N/A	2.62
Unit Cost of HSRS ($/$m^3$)	7.23	

7. REFERENCES

Atkinson, E. 1996. *The Feasibility of Flushing Sediment from Reservoirs.* TDR Project R5839, Rep. OD 137. HR Wallingford.

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Turner, T.M. 1996. *Fundamentals of Hydraulic Dredging, 2nd Ed.* New York: American Society of Civil Engineers.

ANNEX 1. HSRS FEASIBILITY CRITERIA CALCULATIONS

Hydrosuction Pipeline Sizing to Determine Feasibility

Developed from the following paper and direct comments from R. Hotchkiss:

Hotchkiss, Rollin H., Xi Huang. 1995. Hydrosuction Sediment-Removal Systems (HSRS): Principles and Field Test. *Journal of Hydraulic Research*, June 1995, pp. 479-489.

Note:

1. The calculations here are long due to iterations.
2. This method has been found to break down and yield imaginary numbers at pipe diameters less than 1.2 feet. If you are given imaginary number results, try increasing your pipe diameter until the results are real numbers.

Step 1:

Determine the approximate values of available head and pipeline length for your system. Assign pipe material and a trial pipe diameter. Enter values in User Input Sheet for corresponding parameters unless given as assumed below. Note that data should be entered in specified units on the User Input Sheet; units will be converted by program as needed to English units for these calculations.

Assumptions made by program:

E: = 0.00015 ft, (e = ks), assume a pipe material type is steel with this equivalent roughness.

SumKi := 6 Assumed total minor energy loss coefficient. Represents possible minor losses in hydrosuction piping system. Minor losses should include energy losses at entrance, exit, bends, connections, and valves.

Resulting pipe area and velocity from assumed parameters:

$$\text{Apipe} = \frac{\pi \cdot D^2}{4}\ \text{ft}^2$$, trial pipe cross-sectional area

$$V = \frac{Q}{\text{Apipe}}\ \text{fps}$$, trial velocity through pipe

Step 2:

Using sediments from the area of your reservoir that will be subject to hydrosuction, the following parameters should also be input to the User Input Sheet (unless otherwise noted):

$\gamma s: = 80 \text{lb/ft}^3$, density of in-situ reservoir sediments (converted from metric on User Input)

$\gamma s: = 62.4\ \text{lb/ft}^3$ assumed specific weight of water

$$\rho s := \frac{\gamma s}{g}\ \text{slugs}/\text{ft}^3,$$ density of sediments

S: = 2.65 assumed sediment specific gravity (quartz)

$$v := \frac{0.00002}{1.0334 + 0.03672 \cdot T + 0.0002058 \cdot T^2}\ \text{ft}^2/\text{s},$$

Kinematic viscosity, for assumed temperature, T.

For Type = 1 on User Input Sheet, assumed particle size distribution:

d100 := 9.5mm
d90 := 3.6mm
d65 := 1.3mm
d50 := 0.73mm
d35 := 0.42mm

For Type = 2 on User Input Sheet, assumed particle size distribution:

d100 := 75mm
d90 61 := mm
d65 36 := mm
d50 27 := mm
d35 15 := mm

Program calculates drag coefficient for each size fraction & a weighted composite Cd using an iterative process.

Iteration Process:

a) assume Cd, calculate fall velocity,
b) calculate Re using fall velocity,
c) using updated Re,
d) using new Cd, calculate new fall velocity,
e) continue until change in Cd is within acceptable tolerance.

a) Assume Cd for each category of the grain size distribution:

assume: Cd100 := Cd90 := Cd65 := Cd50 := Cd35 :=

The following equation calculates a composite Cd for your sediment sample:

$$Cd := \left(Cd100^{.5}\cdot 0.05 + Cd90^{.5}\cdot 0.175 + Cd65^{.5}\cdot 0.20 + Cd50^{.5}\cdot 0.15 + Cd35^{.5}\cdot 0.4\ Cd\right)^2 =$$

let: Cdold := Cd

Calculate fall velocity for each category of grain size distribution using equation determined from force balance on sediment particle:

$$\omega100 := 8.42\cdot\sqrt{\frac{\left(\frac{d100}{25.4\cdot 12}\right)}{Cd100}} \qquad \omega90 := 8.42\cdot\sqrt{\frac{\left(\frac{d90}{25.4\cdot 12}\right)}{Cd90}}$$

ω100 = fps   ω90 = fps

$$\omega65 := 8.42\cdot\sqrt{\frac{\left(\frac{d65}{25.4\cdot 12}\right)}{Cd65}} \qquad \omega50 := 8.42\cdot\sqrt{\frac{\left(\frac{d50}{25.4\cdot 12}\right)}{Cd50}}$$

ω65 = fps   ω50 = fps

$$\omega35 := 8.42\cdot\sqrt{\frac{\left(\frac{d35}{25.4\cdot 12}\right)}{Cd35}}$$

ω35 = fps

b) Calculate Reynold's Number using fall velocity for each category of grain size distribution:

$$Re100 := \frac{\omega100\cdot\left(\frac{d100}{25.4\cdot 12}\right)}{v} \qquad Re100 =$$

$$Re90 := \frac{\omega90\cdot\left(\frac{d90}{25.4\cdot 12}\right)}{v} \qquad Re90 =$$

$$Re65 := \frac{\omega65\cdot\left(\frac{d65}{25.4\cdot 12}\right)}{v} \qquad Re65 =$$

$$Re50 := \frac{\omega50\cdot\left(\frac{d50}{25.4\cdot 12}\right)}{v} \qquad Re50 =$$

$$Re35 := \frac{\omega35\cdot\left(\frac{d35}{25.4\cdot 12}\right)}{v} \qquad Re35 =$$

c) Equation below calculates updated Cd from Reynold's Number for each category of the grain size distribution.

β := 0.7 assume shape factor for most natural sands applies here

$$Cd100 := 0.84\cdot\left[\frac{33.78}{\left(1+4.5\cdot\beta^{0.35}\right)^{0.7}\cdot Re100^{0.56}} + \left(\frac{Re100}{Re100+700+1000\cdot\beta}\right)^{0.28}\cdot\frac{1}{\left(\beta^4+20\cdot\beta^{20}\right)^{0.175}}\right]^{1.428}$$

$$Cd90 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re90^{0.56}} + \left(\frac{Re90}{Re90 + 700 + 1000 \cdot \beta} \right)^{0.28} \cdot \frac{1}{\left(\beta^4 + 20 \cdot \beta^{20}\right)^{0.175}} \right]^{1.428}$$

$$Cd65 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re65^{0.56}} + \left(\frac{Re65}{Re65 + 700 + 1000 \cdot \beta} \right)^{0.28} \cdot \frac{1}{\left(\beta^4 + 20 \cdot \beta^{20}\right)^{0.175}} \right]^{1.428}$$

$$Cd50 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re50^{0.56}} + \left(\frac{Re50}{Re50 + 700 + 1000 \cdot \beta} \right)^{0.28} \cdot \frac{1}{\left(\beta^4 + 20 \cdot \beta^{20}\right)^{0.175}} \right]^{1.428}$$

$$Cd35 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re35^{0.56}} + \left(\frac{Re35}{Re35 + 700 + 1000 \cdot \beta} \right)^{0.28} \cdot \frac{1}{\left(\beta^4 + 20 \cdot \beta^{20}\right)^{0.175}} \right]^{1.428}$$

$Cd100 =$ $Cd90 =$ $Cd65 =$ $Cd50 =$ $Cd35 =$

The following equation calculates a composite Cd for your sediment sample:

$$Cd := \left(Cd100^{.5} \cdot 0.05 + Cd90^{.5} \cdot 0.175 + Cd65^{.5} \cdot 0.20 + Cd50^{.5} \cdot 0.15 + Cd35^{.5} \cdot 0.425\right)^2 \quad Cd =$$

d) Use new Cd to re-calculate fall velocity:

$$\omega100 := 8.42 \cdot \sqrt{\frac{\left(\frac{d100}{25.4 \cdot 12}\right)}{Cd100}} \qquad \omega90 := 8.42 \cdot \sqrt{\frac{\left(\frac{d90}{25.4 \cdot 12}\right)}{Cd90}}$$

$\omega100 =$ fps $\qquad$ $\omega90 =$ fps

$$\omega65 := 8.42 \cdot \sqrt{\frac{\left(\frac{d65}{25.4 \cdot 12}\right)}{Cd65}} \qquad \omega50 := 8.42 \cdot \sqrt{\frac{\left(\frac{d50}{25.4 \cdot 12}\right)}{Cd50}}$$

$\omega65 =$ fps $\qquad$ $\omega50 =$ fps

$$\omega35 := 8.42 \cdot \sqrt{\frac{\left(\frac{d35}{25.4 \cdot 12}\right)}{Cd35}}$$

$\omega35 =$ fps

e) Continue iteration process until change in Cd is within acceptable tolerance.

Check tolerance on Cd:

$$tol := \frac{Cd - Cdold}{Cd} \cdot 100 \qquad tol =$$

Continue to iterate unit tol <1%

let: Cdold := Cd

b) Calculate Reynold's Number using fall velocity for each category of grain size distribution:

$$Re100 := \frac{\omega100 \cdot \left(\frac{d100}{25.4 \cdot 12}\right)}{v} \qquad Re100 =$$

$$Re90 := \frac{\omega90 \cdot \left(\frac{d90}{25.4 \cdot 12}\right)}{v} \qquad Re90 =$$

$$Re65 := \frac{\omega65 \cdot \left(\frac{d65}{25.4 \cdot 12}\right)}{v} \qquad Re65 =$$

$$Re50 := \frac{\omega50 \cdot \left(\frac{d50}{25.4 \cdot 12}\right)}{v} \qquad Re50 =$$

$$Re35 := \frac{\omega35 \cdot \left(\frac{d35}{25.4 \cdot 12}\right)}{v} \qquad Re35 =$$

c) Equation below calculates updated Cd from Reynold's Number for each category of the grain size distribution.

β := 0.7 assume shape factor for most natural sands applies here

$$Cd100 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re100^{0.56}} + \left(\frac{Re100}{Re100 + 700 + 1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^4 + 20 \cdot \beta^{20}\right)^{0.175}} \right]^{1.428}$$

$$Cd90 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re90^{0.56}} + \left(\frac{Re90}{Re90 + 700 + 1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^4 + 20 \cdot \beta^{20}\right)^{0.175}} \right]^{1.428}$$

$$Cd65 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re65^{0.56}} + \left(\frac{Re65}{Re65 + 700 + 1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^4 + 20 \cdot \beta^{20}\right)^{0.175}} \right]^{1.428}$$

$$Cd50 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re50^{0.56}} + \left(\frac{Re50}{Re50 + 700 + 1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^4 + 20 \cdot \beta^{20}\right)^{0.175}} \right]^{1.428}$$

$$Cd35 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re35^{0.56}} + \left(\frac{Re35}{Re35 + 700 + 1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^4 + 20 \cdot \beta^{20}\right)^{0.175}} \right]^{1.428}$$

The following equation calculates a composite Cd for your sediment sample:

$$Cd := \left(Cd100^{.5} \cdot 0.05 + Cd90^{.5} \cdot 0.175 + Cd65^{.5} \cdot 0.20 + Cd50^{.5} \cdot 0.15 + Cd35^{.5} \cdot 0.425\right)^2 \quad Cd =$$

d) Use new Cd to re-calculate fall velocity:

$$\omega100 := 8.42 \cdot \sqrt{\frac{\left(\frac{d100}{25.4 \cdot 12}\right)}{Cd100}} \qquad \omega90 := 8.42 \cdot \sqrt{\frac{\left(\frac{d90}{25.4 \cdot 12}\right)}{Cd90}}$$

$\omega100 =$ fps $\quad \omega\pi0 =$ fps

$$\omega65 := 8.42 \cdot \sqrt{\frac{\left(\frac{d65}{25.4 \cdot 12}\right)}{Cd65}} \qquad \omega50 := 8.42 \cdot \sqrt{\frac{\left(\frac{d50}{25.4 \cdot 12}\right)}{Cd50}}$$

$\omega65 =$ fps $\quad \omega50 =$ fps

$$\omega35 := 8.42 \cdot \sqrt{\frac{\left(\frac{d35}{25.4 \cdot 12}\right)}{Cd35}}$$

$\omega35 =$ fps

e) Continue iteration process until change in Cd is within acceptable tolerance.

Check tolerance on Cd:

$$tol := \frac{Cd - Cdold}{Cd} \cdot 100 \qquad tol =$$

Continue to iterate until tol<1%

let: Cdold := Cd

b) Calculate Reynold's Number using fall velocity for each category of grain size distribution:

$$Re100 := \frac{\omega100 \cdot \left(\frac{d100}{25.4 \cdot 12}\right)}{v} \qquad Re100 =$$

$$Re90 := \frac{\omega90 \cdot \left(\frac{d90}{25.4 \cdot 12}\right)}{v} \qquad Re90 =$$

$$Re65 := \frac{\omega65 \cdot \left(\frac{d65}{25.4 \cdot 12}\right)}{v} \qquad Re65 =$$

$$Re50 := \frac{\omega 50 \cdot \left(\frac{d50}{25.4 \cdot 12}\right)}{v} \qquad Re50 =$$

$$Re35 := \frac{\omega 35 \cdot \left(\frac{d35}{25.4 \cdot 12}\right)}{v} \qquad Re35 =$$

c) Equation below calculates updated Cd from Reynold's Number for each category of the grain size distribution.

$\beta := 0.7$ assume shape factor for most natural sands applies here

$$Cd100 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re100^{0.56}} + \left(\frac{Re100}{Re100 + 700 + 1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^4 + 20 \cdot \beta^{20}\right)^{0.175}}\right]^{1.4}$$

$$Cd90 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re90^{0.56}} + \left(\frac{Re90}{Re90 + 700 + 1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^4 + 20 \cdot \beta^{20}\right)^{0.175}}\right]^{1.428}$$

$$Cd65 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re65^{0.56}} + \left(\frac{Re65}{Re65 + 700 + 1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^4 + 20 \cdot \beta^{20}\right)^{0.175}}\right]^{1.428}$$

$$Cd50 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re50^{0.56}} + \left(\frac{Re50}{Re50 + 700 + 1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^4 + 20 \cdot \beta^{20}\right)^{0.175}}\right]^{1.428}$$

$$Cd35 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re35^{0.56}} + \left(\frac{Re35}{Re35 + 700 + 1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^4 + 20 \cdot \beta^{20}\right)^{0.175}}\right]^{1.428}$$

$Cd100 =$ $\quad Cd90 =$ $\quad Cd65 =$ $\quad Cd50 =$ $\quad Cd35 =$

The following equation calculates a composite Cd for your sediment sample:

$$Cd := \left(Cd100^{.5} \cdot 0.05 + Cd90^{.5} \cdot 0.175 + Cd65^{.5} \cdot 0.20 + Cd50^{.5} \cdot 0.15 + Cd35^{.5} \cdot 0.425\right)^2 =$$

d) Use new Cd to re-calculate fall velocity:

$$\omega 100 := 8.42 \cdot \sqrt{\frac{\left(\frac{d100}{25.4 \cdot 12}\right)}{Cd100}}$$

$\omega 100 =$ fps

$$\omega 90 := 8.42 \cdot \sqrt{\frac{\left(\frac{d90}{25.4 \cdot 12}\right)}{Cd90}}$$

$\omega 90 =$ fps

$$\omega 65 := 8.42 \cdot \sqrt{\frac{\left(\frac{d65}{25.4 \cdot 12}\right)}{Cd65}}$$

$\omega 65 =$ fps

$$\omega 50 := 8.42 \cdot \sqrt{\frac{\left(\frac{d50}{25.4 \cdot 12}\right)}{Cd50}}$$

$\omega 50 =$ fps

$$\omega 35 := 8.42 \cdot \sqrt{\frac{\left(\frac{d35}{25.4 \cdot 12}\right)}{Cd35}}$$

$\omega 35 =$ fps

e) Continue iteration process until change in Cd is within acceptable tolerance.

Check tolerance on Cd:

$$tol := \frac{Cd - Cdold}{Cd} \cdot 100 \qquad tol =$$

Continue to iterate until tol<1%

let: Cdold := Cd

b) Calculate Reynold's Number using fall velocity for each category of grain size distribution:

$$Re100 := \frac{\omega100 \cdot \left(\frac{d100}{25.4 \cdot 12}\right)}{v} \qquad Re100 =$$

$$Re90 := \frac{\omega90 \cdot \left(\frac{d90}{25.4 \cdot 12}\right)}{v} \qquad Re90 =$$

$$Re65 := \frac{\omega65 \cdot \left(\frac{d65}{25.4 \cdot 12}\right)}{v} \qquad Re65 =$$

$$Re50 := \frac{\omega50 \cdot \left(\frac{d50}{25.4 \cdot 12}\right)}{v} \qquad Re50 =$$

$$Re35 := \frac{\omega35 \cdot \left(\frac{d35}{25.4 \cdot 12}\right)}{v} \qquad Re35 =$$

c) Equation below calculates updated Cd from Reynold's Number for each category of the grain size distribution.

$\beta := 0.7$ assume shape factor for most natural sands applies here

$$Cd100 := 0.84 \cdot \left[\frac{33.78}{\left(1+4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re100^{0.56}} + \left(\frac{Re100}{Re100+700+1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^4+20 \cdot \beta^{20}\right)^{0.175}}\right]^{1.428}$$

$$Cd90 := 0.84 \cdot \left[\frac{33.78}{\left(1+4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re90^{0.56}} + \left(\frac{Re90}{Re90+700+1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^4+20 \cdot \beta^{20}\right)^{0.175}}\right]^{1.428}$$

$$Cd65 := 0.84 \cdot \left[\frac{33.78}{\left(1+4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re65^{0.56}} + \left(\frac{Re65}{Re65+700+1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^4+20 \cdot \beta^{20}\right)^{0.175}}\right]^{1.428}$$

$$Cd50 := 0.84 \cdot \left[\frac{33.78}{\left(1+4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re50^{0.56}} + \left(\frac{Re50}{Re50+700+1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^4+20 \cdot \beta^{20}\right)^{0.175}}\right]^{1.428}$$

$$Cd35 := 0.84 \cdot \left[\frac{33.78}{\left(1+4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot Re35^{0.56}} + \left(\frac{Re35}{Re35+700+1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^4+20 \cdot \beta^{20}\right)^{0.175}}\right]^{1.428}$$

$Cd100 =$ $Cd90 =$ $Cd65 =$ $Cd50 =$ $Cd35 =$

The following equation calculates a composite Cd for your sediment sample:

$$Cd := \left(Cd100^{.5} \cdot 0.05 + Cd90^{.5} \cdot 0.175 + Cd65^{.5} \cdot 0.20 + Cd50^{.5} \cdot 0.15 + Cd35^{.5} \cdot 0.4Cd\right)^2 =$$

d) Use new Cd to re-calculate fall velocity:

$$\omega100 := 8.42 \cdot \sqrt{\frac{\left(\frac{d100}{25.4 \cdot 12}\right)}{Cd100}} \qquad \omega100 = \qquad fps$$

$$\omega90 := 8.42 \cdot \sqrt{\frac{\left(\frac{d90}{25.4 \cdot 12}\right)}{Cd90}} \qquad \omega\pi0 = \qquad fps$$

$$\omega65 := 8.42 \cdot \sqrt{\frac{\left(\frac{d65}{25.4 \cdot 12}\right)}{Cd65}} \qquad \omega65 = \qquad fps$$

$$\omega50 := 8.42 \cdot \sqrt{\frac{\left(\frac{d50}{25.4 \cdot 12}\right)}{Cd50}} \qquad \omega50 = \qquad fps$$

$$\omega 35 := 8.42 \cdot \sqrt{\frac{\left(\frac{d35}{25.4 \cdot 12}\right)}{Cd35}} \qquad \omega 35 = \qquad \text{fps}$$

e) Continue iteration process until change in Cd is within acceptable tolerance.

Check tolerance on Cd:

$$tol := \frac{Cd - Cdold}{Cd} \cdot 100 \qquad tol =$$

Continue to iterate until tol<1%—OK

Step 3:
Program determines parameters needed to calculate the non-flow parameter, α.

First need experimental K and m values for this situation—calculate ψ from Hotchkiss equation (2):

$$\Psi := \frac{V^2 \cdot \sqrt{Cd}}{g \cdot D \cdot (S-1)}; \quad \Psi =$$

Zandi and Govatos (1967), according to Hotchkiss, found:

$$K = 280 \text{ for } \Psi < 10$$
$$K = 6.3 \text{ for } \Psi \geq 10$$

$$m = -1.93 \text{ for } \Psi < 10$$
$$m = 0.354 \text{ for } \Psi \geq 10$$

Non-flow parameter, α, is a combination of non-flow variables from Hotchkiss equation (8):

$$\alpha := \frac{K \cdot Cd^{0.5 \cdot m}}{\left[g \cdot D \cdot (S-1)\right]^m}; \quad \alpha =$$

Step 4:
Program calculates an estimated headloss gradient through the hydrosuction pipe, based on the initial guess for pipe diameter and flowrate and minor loss estimation.

$$Jm := \frac{\left(h - sumKi \cdot \frac{V^2}{2 \cdot g}\right)}{L}; \quad Jm = \ \text{ft/ft}$$

calculated headloss gradient in hydrosuction pipe.

Step 5:
Program calculates trial friction factor and uses results of previous steps to calculate an initial value for sediment transport rate, Qs.

Reynold's number for pipe: $Re := \frac{V \cdot D}{v}; \quad Re =$

Using equation developed from Moody diagram yields trial friction factor value:

$$f := \frac{0.25}{\left(\log\left(\frac{\varepsilon}{3.7 \cdot D} + \frac{5.74}{Re^{0.9}}\right)\right)} \implies f =$$

Maximum sediment transport rate under available headloss gradient, calculated by Mathcad using Hotchkiss (1996) equation (12):

$$Qs := \left[\frac{Jm}{\left[\frac{f \cdot \left[\frac{-\pi \cdot D^2}{2 \cdot \alpha \cdot (1 + 2 \cdot m)}\right]^{\frac{2}{(2 \cdot m - 1)}}}{2 \cdot g \cdot D} + \frac{2 \cdot f \cdot \alpha}{\pi \cdot g \cdot D^3} \cdot \left[\frac{-\pi \cdot D^2}{2 \cdot \alpha \cdot (1 + 2 \cdot m)}\right]^{\frac{1 + 2 \cdot m}{2 \cdot m - 1}}\right]}\right]^{\frac{(1 - 2 \cdot m)}{2}}$$

cfs

$$Qs :=$$

Step 6:
Program calculates trial optimum mixture flow velocity from Hotchkiss equation (11).

$$Vm := \left[\frac{-\pi \cdot D^2}{2 \cdot \alpha \cdot Qs} \cdot \frac{1}{(1+2 \cdot m)}\right]^{\frac{1}{(2 \cdot m - 1)}} ; \; Vm = \; fps$$

Step 7:
Program calculates the Reynold's number.

$$Rm := \frac{Vm \cdot D}{v} ; \; Rm =$$

Step 8:
Program calculates the mixture friction coefficient, fm, using the explicit formula given by Swamee and Jian (Streeter and Wylie, 1985) [Hotchkiss equation (14)].

$$fm := \frac{1.325}{\left(1n\left(\frac{\varepsilon}{3.7 \cdot D} + \frac{5.74}{Rm^{0.9}}\right)\right)^{2^{fm \, =}}} ; \; fm =$$

Step 9:
Using Vm, program will recalculate Jm and fm, and compare with value of fm calculated in step 8. Repeat steps 3 through 8 until the difference between fm values calculated in subsequent steps is within acceptable tolerance (usually 2-3 iterations).

RESULTS SUMMARY

Converting Units:

$$Qs\,[tons/day] = \frac{Qs\,[cfs] \times \gamma s \times 86400}{2000}$$

Mixture Velocity: Vm = fps

Mixture Flowrate: Qm := Vm·Apipe; Qm = cfs

Sediment Concentration through Hydrosuction Pipe:

$$C := \frac{Qs}{Qm} \cdot \frac{\gamma s}{\gamma w} \cdot 10^6 ; \; C = ppm$$

ANNEX 2. FLUSHING FEASIBILITY CRITERIA CALCULATIONS

Developed from:

Atkinson, E. 1996. *The Feasibility of Flushing Sediment from Reservoirs*, TDR Project R5839, Rep. OD 137. HR Wallingford.

SBR Calculations—The sediment balance ratio is the ratio of the sediment flushed annually to the sediment deposited annually:

A representative top width of the reservoir upstream from the dam at the flushing water surface based on the reservoir bathymetry:

$$Wres := Wbot + 2 \cdot SSres \cdot (ELf - ELmin) \quad m$$

The actual flushing width is estimated using a best-fit equation resulting from empirical data (Atkinson, 1996):

$$Wf := 12.8 \cdot Qf^{0.5} \quad m$$

Because the width at the bottom of the reservoir before impoundment may limit the channel width that can be achieved with flushing, Wres and Wf are compared to chose the smaller as the representative width of flow for flushing conditions:

A := Wres Wf ( ) := Wf

W := min A ( ) := A   m, representative width of flow for flushing conditions

The estimated longitudinal water slope during flushing:

$$S := \frac{EL\,max - ELf}{L}$$

The Tsingua University method for sediment load, Qs, prediction is used. This empirical method is based on observations of flushing at reservoirs in China. These Chinese reservoirs usually have annual flushing, yielding little consolidation and fine sediment, usually loess. The empirical equation requires choice of a constant, ψ, determined by sediment type:

1600 for fine loess sediments
650 for other sediments with median size finer than 0.1mm
300 for sediments with median size larger than 0.1mm
180 for flushing with a low discharge (less than 50 m3/s) with any grain size

ψ := <==*User Input sheet choice from above list*

Sediment load during flushing:

$$Qs := \Psi \frac{Qf^{1.6} \cdot S^{1.2}}{W^{0.6}}$$

tonnes/sec, Note that 0.00006 < S < 0.016 according to Morris and Fan (1998) for this equation's development

A qualitative analysis must be made to determine whether the reservoir in question is similar to the Chinese reservoirs studied in Atkinson's report (especially with regards to sediment gradations). The equation below should only be used if the reservoir in question is dissimilar to Chinese reservoirs studied. If reservoirs *are similar, insert 1 for adj below. If reservoirs are not similar, insert 3 for adj below.*

Ans := <== *Determine value for Ans (1 or 3) in User Input Sheet.*

$$Qs := \frac{Qs}{adj} \quad \text{tonnes / sec}$$

Sediment mass flushed annually, Mf:

$$Mf := 86400 \cdot Tf \cdot Qs \quad \text{tonnes}$$

Where Tf = duration of flushing

Trapping efficiency, TE, is the percent of inflowing sediment that is trapped in the reservoir. The Brune curve method of determining TE was used. The ratio between reservoir capacity and water inflow was correlated with TE by Brune in the Brune curve in Figure A4.1 of Atkinson (1996). The Brune curve actually consists of three curves. The sediments at the reservoir in question must be classified as 1) the highly flocculated and coarse sediment curve, 2) the median curve for normal ponded reservoirs and average sediment size, or 3) fine sediment. The highest applicable curve produces the most conservative SBR estimate.

Brune_curve := choose 1, 2, or 3 for reservoir type for Brune Curve on User Input Sheet

Brune-ratio value is calculated below.

$$Brune\_ratio := \frac{Co}{Vin}$$

The result is used in a piecewise fit equation of the Brune Curve to determine the trap efficiency (TE) for cases Brune_curve=1, 2, and 3. Depending on value of Brune_curve, the corresponding value of TE will be chosen.

==> TE

Sediment mass depositing annually wich must be flushed:

$$Mdep := \frac{Min \cdot TE}{100} \quad \text{tonnes}$$

Finally, the sediment balance ratio is the ratio of the sediment flushed annually to the sediment deposited annually:

$$SBR := \frac{Mf}{Mdep}$$

CRITERION: Must have SBR > 1.0

LTRC Calculations—The long term capacity ratio is a ratio of the scoured valley area to the reservoir area for the assumed simplified geometry:

See Figure 10 of Atkinson (1996) for a sketch of the simplified trapezoidal cross section used in approximating the reservoir as a prismatic shape. A section at the dam site is used to determine the ratio of cross-sectional area for the channel formed by flushing to the original reservoir cross-sectional area (LTRC). The LTRC is assumed to be representative of the capacity ratio for the entire reservoir.

Scoured valley width at the top water level based on the representative flow width for flushing conditions:

$$Wtf := W + 2 \cdot SSs \cdot (ELmax - ELf) \quad \text{m}$$

Reservoir width upstream from the dam at top water level for the simplified geometry assumed:

$$Wt := Wbot + 2 \cdot SSres \cdot (ELmax - ELmin) \quad \text{m}$$

When Wtf <= Wt, the reservoir geometry does not constrict the width of the scoured valley; thus the scoured valley cross-sectional area is the average of the reservoir top width and the bottom scour width, multipied by the depth of flow in the scoured area:

$$Afl := \frac{Wt + W}{2} \cdot (El\,max - ELf) \quad \text{m}^2$$

When Wtf > Wt, the scoured valley is constricted as in Figure A4.2 of Atkinson; thus, a more complex geometry must be calculated to determine the scoured valley cross-sectional area:

$$hm := \frac{Wres - W}{2 \cdot (SSs - SSres)} \quad \text{m}$$

$ht := ELmax - ELf - hm$ m

$hf := ELmax - ELf$ m

$Af2 := W \cdot hf + (hf + ht) \cdot hm \cdot SSs + ht^2 \cdot SSres$ m^2

"If"-statement below determines which scoured valley area applies in this situation:

Valley := if (Wtf ≤ Wt, "not constricted", "constricted")

$Af := \text{if } (Wtf \leq Wt, Af1, Af2)$ m^2

The reservoir cross-sectional area is estimated from the average of the reservoir top and bottom widths, multiplied by the total depth of water in the reservoir:

$$Ar := \frac{Wt + Wbot}{2} \cdot (EL\max - EL\min) \quad m^2$$

Finally, the long term capacity ratio is a ratio of the scoured valley area to the reservoir area for the assumed simplified geometry:

$$LTRC := \frac{Af}{Ar}$$

Guideline: Use Caution if LTCR < 0.35.

DDR Calculation—The extent of reservoir drawdown is unity minus a ratio of flow depth for the flushing water level to flow depth for the normal impounding level:

$$DDR := 1 - \frac{ELF - EL\min}{EL\max - EL\min}$$

GUIDELINE: DDR should be ~ 0.7 for drawdown to be sufficient.

FWR Calculation—Flushing width ratio checks that the predicted flushing width, Wf, is greater than the representative bottom width of reservoir, Wbot:

$$FWR := \frac{Wf}{Wbot}$$

GUIDELINE: Preferably have FWR > 1.0, but can have exceptions.

TWR Calculations—TWR checks that the scoured valley width at top water level for complete drawdown is greater than the reservoir top width:

Steep side slopes in the scoured valley will be a constraint when 1) FWR is a constraint, or 2) reservoir bottom widths are small when compared to the top widths at full storage level. The reservoir top width ratio, TWR, quantifies a side slope constraint:

Wbf is the bottom width of the scoured valley at full drawdown. It is the minimum of Wbot and Wf:

$B := (Wbot\ Wf)$

$Wbf := \min(B)$ m

Wtd is the scoured valley width at top water level if complete drawdown is assumed:

$Wtd := Wbf + 2 \cdot SSs \cdot (ELmax - ELmin)$ m

TWR checks that the scoured valley width at top water level for complete drawdown is greater than the reservoir top width:

$$TWR := \frac{Wtd}{Wt}$$

GUIDELINE: If FWR is a constraint, preferably have TWR > 2. If FWR not a constraint, TWR approaching 1 sufficient.

SBRd Calculations—SBRd is the sediment balance ratio based on flushing flows; it is independent of drawdown:

SBRd is calculated the same as SBR, except ELf = ELmin:

$$Wres := Wbot + 2 \cdot SSres \cdot (ELmin - ELmin) \quad m$$

$$Wf := 12.8 \cdot Qf^{0.5} \quad m$$

$$A := (Wres\ Wf)$$

$$W := \min(A) \quad m$$

$$S := \frac{EL\max - ELf}{L}$$

$$Qs := \Psi \frac{Qf^{1.6} \cdot S^{1.2}}{W^{0.6}} \quad m^3/s$$

A qualitative analysis must be made to determine whether the reservoir in question is similar to the Chinese reservoirs studied in Atkinson's 1996 report (especially with regards to sediment gradations).

On the User Input sheet, choose either 3 or 1 for the variable Ans. Ans = 3 if reservoir sediments are significantly larger than median grain size = 0.1mm or if reservoir has been impounded for more than 10 years without sediment removal. Ans = 1 otherwise.

Resulting adjusted Qs:

$$Qs := \frac{Qs}{Ans} \quad m^3/s$$

$$Mf := 86400 \cdot Tf \cdot Qs \quad \text{tonnes}$$

$$Mdep := \frac{Min \cdot TE}{100} \quad \text{tonnes}$$

$$SBRd := \frac{Mf}{Mdep}$$

GUIDELINE: SBRd preferably > 1.0.

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Among the many sessions of the Third World Water Forum, held in Japan, March 2003, there was one titled "Sedimentation Management Challenges for Reservoir Sustainability". Two main messages emerged from that session:

- Whereas the 20th century focused on reservoir development, the 21st century will necessarily focus on sediment management; the objective will be to covert today's inventory of non-sustainable reservoirs into sustainable infrastructures for future generations.
- The scientific community at large should endeavor to devise solutions for conserving existing water storage facilities in order to enable their functions to be delivered for as long as possible, possibly in perpetuity.

These important messages are very much in line with the World Bank's Water Resources Sector Strategy that calls the Institution to address management of existing infrastructure, as well as to develop much needed priority water infrastructure.

In fact, many poor countries facing similar climate variability as rich countries, have as little as 1/100th as much water infrastructure capacity. The result is great vulnerability to the vicissitudes of climate variability, a vulnerability which is exacerbated by climate change. There is much that can and must be done by managing watersheds better, and managing demand.

The present book can assist in making existing reservoirs sustainable, as well as in the sustainable design of new surface storage facilities. The book addresses the issue of reservoir sustainability from an economic angle, a perspective hardly explored so far.

We hope that this initial step will encourage others to follow, both in additional research, and in actions aimed at conserving water storage assets for future generations.

Ian Johnson.

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