RESCON 2

User Manual

Reservoir Conservation Model RESCON 2 Beta

Economic and Engineering Evaluation of Alternative Sediment Management Strategies

Nikolaos P. Efthymiou, Sebastian Palt, George W. Annandale, Pravin Karki

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Flushing operation in Kapichira reservoir, Malaw.

Cover photo: : William W. Liabunya.

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Context

The reduced rate of dam construction throughout the world combined with storage loss due to reservoir sedimentation currently results in more storage being lost annually than is added. This problem is further exacerbated by population growth, which results in a sharply declining storage volume per capita. Climate change will further adversely impact the performance of reservoirs. Given the scarceness of undeveloped new dam sites in watersheds where extensive dam construction has already been undertaken, it will be in the future necessary to focus increasingly on storage preservation. The effects of reservoir sedimentation can be mitigated through implementation of reservoir sedimentation management techniques. In addition, the vulnerability of the existing water infrastructure on the effects of climate change can be also reduced through sediment management which can serve as an adaptation strategy that improves the infrastructure robustness through the preservation of the available reservoir storage.

In 2003, The World Bank published the Reservoir Conservation (RESCON) model. The purpose of the RESCON approach was to assist policy makers in identifying the best way to manage a portfolio of single reservoirs, and to assist water resource developers and engineers in developing a preliminary screening analysis of viable sediment management alternatives. The RESCON approach was developed by Alessandro Palmieri, Farhed Shah, George W. Annandale, Ariel Dinar, Shigekazu Kawashima and Tamara Butler Johndrow.

Since its publication in 2003, the RESCON method has been extensively used worldwide to identify technically feasible reservoir management techniques that have the greatest economic value to design and operate dams and reservoirs in a sustainable way. More than a decade later, other factors influencing sustainability have emerged, including among others the hydrological uncertainties associated with climate change. Furthermore, knowledge of reservoir sedimentation management techniques as well as the economic analysis to identify the most sustainable projects have in the meantime also improved. This prompted the World Bank to revise and upgrade the RESCON approach.

In year 2015, World Bank contracted Fichtner GmbH & Co. KG, Stuttgart, Germany to upgrade the RESCON approach and develop the RESCON 2 model. The most important improvements include:

- Upgrading of the sedimentation calculation through implementation of additional methods for assessment of trap efficiency and consideration of its dependence on the available reservoir storage, consideration of partitioning between bedload and suspended load, allocation of deposits in active and inactive storage.
- Incorporation of additional sediment management approaches based on passing sediment through reservoirs or reduction of sediment yield. Improvement of the assessment of deposit removal techniques.
- Analysis of the impacts of climate change on reservoir sustainability and the implementation of sediment management as an adaptation strategy in order to improve the resilience of the water infrastructure.
- Implementation of the option to conduct an economic appraisal by conventional analysis or by incorporating principles relating to the economics of exhaustible resources.
- Improvement of the user-friendliness through implementation of a Graphical User Interface for data input and for reading of the model output.

RESCON 2 was developed by Nikolaos P. Efthymiou, Sebastian Palt, George W. Annandale and Pravin Karki.

The content of the upgrade was conceptualized by George W. Annandale and Pravin Karki. The RESCON 2 algorithms and the user manual were elaborated by Nikolaos Efthymiou and Sebastian Palt supported by Pawan K. Thapa and Peter Pintz, all from Fichtner. The Graphical User Interface was programmed by Claudius Goroll and Andreas Höfler, both also from Fichtner. George W. Annandale and Pravin Karki from the World Bank supervised and commented on the upgrade works throughout the project execution.

The RESCON 2 model was improved by comments received both during the development and the testing phase. The contribution of the reviewers Gregory Morris, Rollin H. Hotchkiss and Jim Neumann is both acknowledged and highly appreciated.

CHAPTER 1

Introduction

This manual details the methodological background of the RESCON 2 model. The RESCON 2 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 2 model is a computer program designed for use in pre-feasibility studies to rank the economic performance of a selection of sediment management techniques. It should be used for options screening and to rank those most promising. The RESCON 2 model is not a substitute for more detailed studies.

The data input as well as reading of results are performed through a Graphical User Interface (GUI). The calculations are performed in Excel. The following sediment management techniques are considered:

- Flushing
- Hydrosuction (HSRS)
- Traditional dredging
- Trucking
- Sluicing
- By-pass
- Density current venting
- Catchment management
- Sediment management strategies involving multiple techniques applied sequentially.

In addition, net economic benefits of the scenario involving “No intervention” 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 concerns. The program may be used for existing as well as proposed reservoirs. An internal climate change analysis provides the user with an assessment of sediment management as an adaptation strategy to future climate non-stationarity.

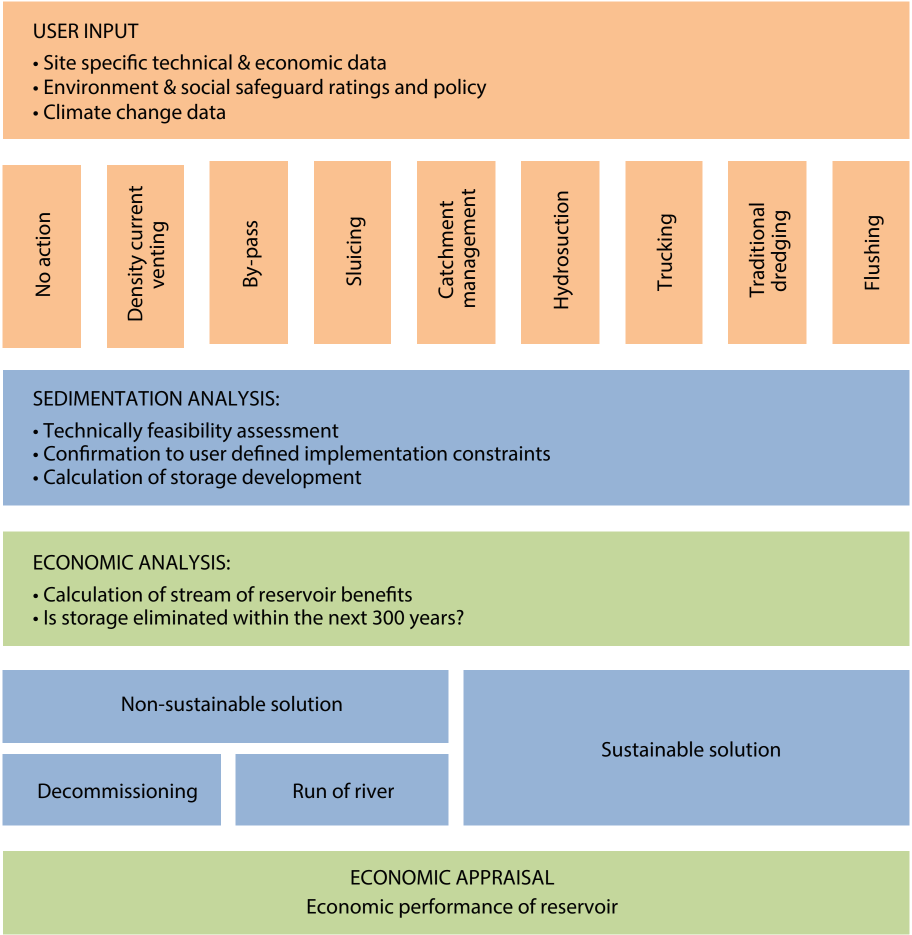
Before using the program the user is encouraged to read Annandale et al. (2016), the World Bank publication on sustainable sediment management for dams and Run-of-River hydropower.

1.1 Structure of Program

The overall goal of the RESCON 2 approach is to select a sediment management strategy that is technically feasible and also maximizes the net economic benefits of the reservoir operation. Figure 2.1 illustrates the main steps involved in this process. These are:

1. Input of site-specific technical data regarding geometry of reservoir, hydrology and sediment transport as well economic input regarding the valuation of revenues and costs associated with reservoir operation. This input is sufficient for the assessment of the "No Action" base case scenario.

Figure 1.1: Program Structure

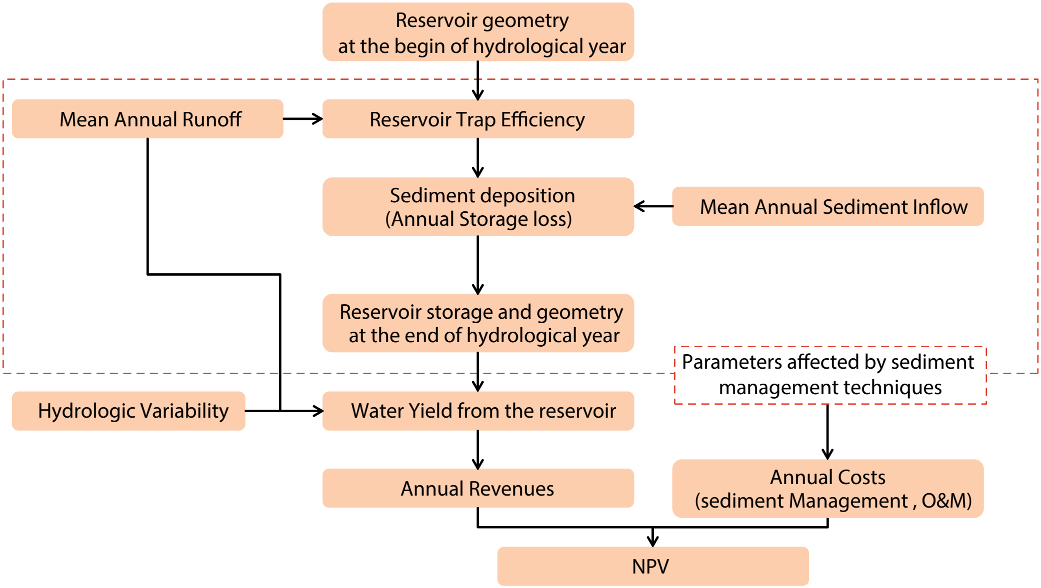


2. Input of sediment management technical data. This includes input such as water level drawdown during sluicing, flushing discharge, etc., i.e. parameters that define the efficiency of sediment management techniques. Furthermore technical constraints with regards the implementation of each sediment management method are also specified such as the maximum allowable storage capacity loss or the maximum duration of application.
3. Testing of the technical feasibility of the selected sediment management techniques under consideration of the user specified constraints.
4. If the techniques pass this test, the temporal and spatial development of reservoir storage as well their economic returns are computed. Based on this calculation it is determined whether the reservoir is sustainable or non-sustainable.
5. The economic performance of the reservoir is calculated throughout its lifetime.

The flow chart of the performed analysis applied for the calculation of the development over time of the reservoir storage and annual benefits is summarized in the Figure 1.2.

The trap efficiency, which is calculated with application of widely used empirical methods (the user here can select among three different methods) and the sediment inflow are the key parameters for calculation of sedimentation, i.e. storage loss rate. Sediment management can reduce the storage loss rate, extending thus the lifetime of the reservoir either by reducing the sediment inflow or removing deposits out of the reservoir or reducing the trap efficiency. This is also considered in the calculation of the temporal development of reservoir storage.

Figure 1.2: Flowchart of performed analysis for determination of annual economic performance of reservoir



The reservoir yield, which is calculated on basis of the remaining reservoir active storage capacity with application of the Gould-Dincer method 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 reservoirs, and capital expenditure costs associated with installing structures required for sediment management, to be included in the Net Present Value (NPV) calculation.

This procedure is repeated under consideration of technical constraints specified by the user during model establishment for every year of reservoir operation. Finally, the aggregate Net Present Value of the benefits stream throughout its lifetime is calculated as a means to express the overall economic performance of the reservoir.

Economic optimization can be performed for each of the sediment management options, except from density current venting, if requested by the user. The objective is to determine the implementation schedule which maximizes the net returns from practicing the given option. Optimal control theory is used to maximize the aggregated net benefits.

Depending on the site and sediment management specific input the solution may take two forms:

1. SUSTAINABLE, where reservoir capacity does not go below the point determined by the user defined capacity loss for characterization of a reservoir as non-sustainable within the first 300 years of reservoir operation.
2. NON-SUSTAINABLE, where the reservoir fills with sediments up to a user defined level (e.g. 95% of pre-impoundment gross storage capacity) in finite time, within a time period of 300 years. This has two sub-solutions:
    2a. the scheme is decommissioned allowing the salvage value (=cost of decommissioning minus any benefits due to decommissioning) to be collected at this time; or
    2b. the scheme is maintained as a "run-of-river" project even after the reservoir is silted, as long as the facility is used for hydropower generation.

Where option 2(a) is the solution, the program calculates and reports 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 outcome is dependent on the calculated or user defined sediment removal or routing capability. If the latter is sufficient, the solution is sustainable. Otherwise, the non-sustainable outcome occurs (in its two possible manifestations). NPV of the "no action" 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 required to take account of these effects in the decision making process. The RESCON 2 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.

Finally, RESCON 2 performs an assessment of the aforementioned sediment management techniques for different future climate change scenarios. The climate change data can be retrieved from the World Bank Climate Knowledge Portal. The analysis allows for an assessment of sediment management as adaptation strategy to climate change.

1.2 Limitations

It is pointed out that RESCON 2 is not intended to replace detailed studies. The RESCON 2 program is based on empirical methods which are not site specific. Therefore sound engineering judgment is required for interpretation of the results.

The main limitations of the performed analysis are:

- The reservoir is considered to be linear. Multiple branches of the reservoir cannot be simulated.
- The calculations are based on a simplified reservoir geometry which considers that the water and sediment inflow to the reservoir takes place at its headwaters. Cases of complicated geometries which might be the reason for model results inconsistencies might include:
  - When an important water and sediment contribution takes place within the inundated area.
  - The existence of training works in the reservoir for manipulation of the deposition processes which might affect the reservoir hydraulics.
- The intra-annual variability in grain size distribution of the sediment inflow is not considered. This might affect the quality of results for reservoirs with very high sediment inflow relative to their storage capacity and the assessment of sediment management methods which might be performed seasonally such as sluicing or density current venting.
- The calculation of the water yield is based on an empirical method, which does not account for the operational rules of the reservoir.
- O&M costs are expressed as percent of the construction cost and remain constant over time. In reality however the O&M costs might increase as the facility ages.
- It is not possible to assess the effect of simultaneous application of different sediment management techniques on storage development.

- The length of the reservoir is constant. Coarse sediments might drop out upstream of the reservoir with result an upstream propagation of the delta and a decrease of the reservoir length over time. Such deposits upstream of the reservoir are not considered in the performed analysis. Based on limited data it can be expected that up to 5% of sediment inflow might settle down before it enters the reservoir.
- The analysis of RESCON 2 similarly to RESCON is mostly focused on reservoirs with storage capacity larger than the mean annual sediment inflow. This does not however exclude the analysis of run-of-river schemes which have reservoirs characterized by small relative hydrologic size. The model results are sensitive for the extreme case of schemes where the sediment inflow is higher than the storage capacity. In that case a calibration of the model is necessary because the calculated trap efficiency of the reservoir might vary significantly depending on the employed equation.
- Synergies due to cascade operation are not considered. This might include among others:
  - Differentiation between water and sediment inflow from the intermediate catchment and the outflow from an upstream reservoir.
  - Impact of sediment management in a reservoir to the reservoirs located downstream.
- RESCON 2 considers that the equipment or hydraulic structures required for the implementation of sediment management techniques will be available by the time of commencement of this activity. Sound engineering judgment is required for assessing the technical feasibility and economic viability of these structures. For example, RESCON 2 will perform an assessment of the effect of sediment by-pass on the development of reservoir storage. The user shall decide whether the construction of the necessary diversion structures is technically feasible. This will depend on the length of the by-pass tunnel and the prevailing topographical and geological conditions. Similar considerations apply to the retrofit of appropriate low level outlets required for performance of flushing or density current venting, the construction of spillways for performance of sluicing, the equipment availability for performance of dredging and trucking and the disposal of removed deposits.

1.3 Analysis steps

The analysis with RESCON 2 involves the following steps:

- Data collection
- Model setup
- Calibration
- Sensitivity analysis

These steps are further explained in the following sections.

1.3.1 Data collection

Data collection and pre-processing includes the gathering and preparation of the data that will be used for:

- Definition of the reservoir geometry.
- The water and sediment inflow.
- The assessment of the effect of different sediment management alternatives on storage development.
- The calculation of the benefits from reservoir operation.

The data that are required for definition of the reservoir geometry include:

- Gross, active and inactive storage of the reservoir. If the project exists, both the current and the pre-impoundment values will be required.
- The normal and the minimum operating pool levels of the reservoir.
- The initial length of reservoir.
- The initial river bed elevation at the dam cross-section.
- The characteristic width of the river bed.

The aforementioned data should be preferably obtained by means of a topographical survey. If this is not possible, public available data sets such as SRTM can be used for an initial assessment of the required data.

The compulsory hydrologic and sediment input includes:

- The mean annual water inflow.
- The hydrologic variability coefficient.
- The statistical distribution of annual water flows.
- The mean annual total sediment (suspended load and bedload) inflow to the reservoir, the % of total sediment load transported as bedload and the time period during which the river bed is morphodynamically active, i.e. the time period during which bedload transport takes place.
- The user has to select the method that will be used for calculation of reservoir trap efficiency.

The coefficient of hydrologic variability and distribution of annual flows can be determined by statistical analysis of flow records. This input is used for the calculation of the reliable water yield supplied by the reservoir based on its storage capacity. The mean annual sediment inflow shall be determined by available suspended load and bedload measurements. If the latter are not available, RESCON 2 incorporates the empirical equation BQART for calculation of the total load, while the bedload can be calculated by an empirical approach which is based on the type of the river and the concentration of suspended load.

Optional data, which are not compulsory for performance of the RESCON 2 analysis are:

- The grain size distribution of suspended sediment inflow.
- The settling velocities of individual grain classes.

This data is required only if the user decides to apply the Borland equation for assessment of reservoir trap efficiency as well for the assessment of the technical feasibility of density current venting.

An important hydrologic input is the intra-annual distribution of water and sediment inflow. This input is required for the assessment of sediment routing techniques, i.e. sediment sluicing, by-pass and density current venting. This input is not used for the assessment of the no action scenario and the sediment management techniques involving reduction of sediment inflow to the reservoir and removal of deposits. Therefore it is not compulsory but the performed analysis will not include the sediment routing techniques.

Finally the user has to define the temperature of impounded water as a necessary input for assessment of technical feasibility of density current venting.

The calculation of the annual benefits from reservoir operation is based on the following compulsory data:

- Unit cost of project implementation expressed as US$/m^3 of reservoir storage capacity.
- Annual Operation and Maintenance Costs (O&M) expressed as % of project cost.
- Unit price value of water yield expressed in US$/m^3.
- Discount rate.

If the unit cost of project implementation is not known it can be estimated on basis of an empirical equation developed from estimated costs for dams in Africa. Guidance is also provided for the selection of the annual O&M costs and the unit price value of water yield. The user can select between the application of a constant discount rate for discounting of the annual benefits and costs or can define a sequence of declining discount rates over time in order to account better for the renewable nature of the reservoir storage as a natural resource.

Optional data for the performed economic appraisal are the costs or benefits obtained from decommissioning of reservoir if it is filled with sediment and the market interest rate for assessment the annual retirement fund that has to be paid annually in order to transfer the burden of project decommissioning to the beneficiaries of the current generation.

The necessary input for assessment of different sediment management alternatives is explained in detail Chapter 3. Generally speaking the user has to provide for each sediment management method the following information:

- The implementation scheduling, including the commencement year, the frequency of its operation and the duration. The parameters for definition of implementation schedule vary from method to method. Alternatively the user can skip the specification of this input. In that case the latter will be calculated automatically by an optimization procedure which maximizes the aggregate Net Present Value of reservoir benefits. The calculated optimal implementation schedule is reported by RESCON 2 as output of the analysis.
- Technical constraints with regards the minimum allowable reservoir storage before implementation of a specific sediment management technique or the maximum amount of deposits that can be removed during each dredging or trucking operation. This will limit the optimum implementation time schedule or will inform the user that the selected implementation schedule is not possible under the given constraints.
- Parameters that will define the efficiency of each sediment management technique. For instance the duration, the water level drawdown and the discharge during flushing will have an impact on the amount of deposits that can be removed out of the reservoir, i.e. on the efficiency of this operation. Similar parameters are defined also for the other sediment management techniques.
- For dredging and trucking the user has to specify if a non-sustainable solution that will just prolong the reservoir lifetime will be acceptable or whether a sustainable solution has to be determined automatically. In the first case the user has to specify the amount of deposits that will be removed during each operation. In the second case the amount that has to be removed in order to convert the reservoir to a sustainable solution will be calculated by the program.

The climate change analysis is based on data that can be downloaded from the World Bank Climate Change Knowledge Portal. The user has to specify:

- Four different combinations of GCM model and emission scenarios as a representative data set of the future climate.
- The expected increase in hydrologic variability.
- Catchment characteristics which will be used for a rapid assessment of the climate change on sediment loads.

1.3.2 Model setup and test run

The model setup is done through the Graphical User Interface using the Project definition and Data input tabs.

The user has access to additional information regarding the input parameters from the help buttons located next to the input boxes. If an input is erroneous, for instance if a negative or non-numeric value is inserted, the text in the input box becomes red to notify the user. A corresponding error message appears at the bottom of the active tab.

When the data input is complete the calculation can commence by pressing the calculate button and selecting the methods that will be assessed. A plausibility check is performed automatically and the user is not allowed to proceed with the assessment of a sediment management technique until the corresponding input is complete and plausible. For example if the user specifies a water level during flushing which is lower than the minimum river bed elevation at the dam site it is not possible to proceed with the assessment of this technique. The possible error messages or warnings are documented in the excel sheet “Plausibility check” included in the workbook of the project.

When the data input is complete and the calculations have been performed the user can see the results in the corresponding tab named “Results.”

1.3.3 Model calibration

Whenever possible the model should be calibrated on basis of available field measurements. The calibration shall aim at adjusting the calculated reservoir storage development or water yield to the measured values. This is usually possible for existing projects which are already in operation and a monitoring program is executed. For Greenfield projects the calibration might be based on data collected for similar reservoirs characterized by comparable hydrological conditions.

If the reservoir is existing, the calibration can be performed as follows:

- Setup and test run of a model with the initial (pre-impoundment) storage capacity and the measured mean annual and water sediment inflows.
- Calibration of the model until the calculated development of reservoir storage is in good agreement with the results of the available bathymetrical surveys.

If the reservoir is greenfield i.e. in the planning stage, it is recommended to setup and calibrate a model for an existing and comparable reservoir following the procedure mentioned above. When the calibration is completed the model has to be setup again for the greenfield project with the previously calibrated parameters such as method for calculation of trap efficiency and number of compartments for definition of reservoir geometry.

The parameters that can be used for the calibration of the calculated sedimentation i.e. the amount of sediment settling in the reservoir and the spatial pattern of the deposits are the following:

- Applied equation for calculation of reservoir trap efficiency. The user can select between the equations of:

  - Brune
  - Churchill
  - Borland
- Grain size distribution of suspended sediment inflow. This parameter can be used only if the trap efficiency is calculated with the equation of Borland. The user can adjust the fractional content of clay, silt and sand in suspended sediment flux entering the reservoir.
- Similarly to grain size distribution, the user can adjust also the settling velocity of the individual grain classes as a means of model calibration. This parameter again can be used only with the Borland equation.
- Percent of total sediment load transported as bedload.
- Number of compartments used for schematization of reservoir geometry.
- Distribution of annual inflows if not already obtained from a previously performed statistical analysis. The user can select between the following options:
  - Gamma
  - Log-normal
  - Normal

Additional parameters that can be used for the calibration of the performance of individual sediment management techniques are:

- Flushing
  - Parameter for calibration of side slope of scoured channel with Mignot equation.
- Sluicing and By-Pass
  - Intra-annual distribution of water and sediment inflow.

1.3.4 Investigation of model sensitivity

For subsequent model setup and calibration it is useful to perform a series of runs that will reveal the sensitivity of the model results to the entered input data. The sensitivities that shall be investigated can be grouped in the following categories:

- Sediment inflow
- Efficiency and cost of sediment management
- Discounting scheme used for calculation of economic performance of reservoir
- Annual O&M costs

The first sensitivity run shall be investigated for a variation of the sediment inflow. This involves test runs with sediment inflows both lower and higher than the current sediment flux. The first scenario of lower sediment inflows is essential if there are plans for construction of a new reservoir upstream of the project location. The reduction of the sediment inflow to be expected will depend on the trap efficiency of the upstream reservoir. Furthermore, the sediment released by the upstream reservoir will be presumably finer than the sediment transported naturally by the river at the current status.

The second scenario will apply in the case of a change in the land uses in the future for instance because of deforestation.

The second group of sensitivity investigations involves the efficiency and cost of sediment management. In that case the user can vary the following parameters:

- Flushing: Flushing discharge and cost of construction of necessary low level outlet.
- Dredging and trucking: Amount of dredging and trucking if it is specified by the user. Unit cost of dredging and trucking if it is specified by the user.
- Hydro Suction Removal System (HSRS): number and diameter of discharge pipelines.
- Sluicing: Cost of construction of new appropriate outlet in existing dam structure.
- By-pass: Cost of construction and annual costs for maintenance of by-pass structure.
- Catchment management: Cost of construction and maintenance costs for catchment management measures in conjunction with variation of the efficiency of catchment management.
- Density current venting: Duration of density current venting and water losses associated with prolonged or shortened duration of this activity.

The third group of model sensitivity involves a variation of the discounting scheme. The user shall compare the model results with a constant discount rate against the corresponding results for a declining discount rate.

A further sensitivity shall investigate the impact of a relatively low constant discount rate, say 3%. This investigation will demonstrate the impact of consideration of intergenerational equity on the preferred solution.

Finally the user shall perform additional runs with increased annual O&M costs because the latter might increase as the facility ages because of equipment deterioration and required extensive rehabilitation or replacement or because of structural problems due to regulatory changes or construction deficiencies.

CHAPTER 2

Reservoir Sedimentation

RESCON 2 allocates the deposits between active and inactive storage. A partitioning of total sediment load in suspended load and bedload is performed and the trap efficiency for these two transport modes is calculated individually. The trap efficiency of fine material transported in suspension is determined by applying the methods of Churchill, Borland or Brune. The trap efficiency of coarse material transported as bedload is considered to be always equal to 100%.

These features allow for an accurate simulation of the reservoir storage loss development in the case of no action as well as in the case of different sediment management techniques. In the subsequent sections the theoretical background of the reservoir sedimentation prediction module is presented and explained in detail.

2.1 Allocation of Deposits between Active and Inactive Storage

One important feature of RESCON 2 is that it is able to differentiate between active and inactive storage and to allocate the deposits in these pools. This allows for a representative determination of the reservoir benefits as well for a correct consideration of the impact of sedimentation on reservoir operation.

2.1.1 Reasoning of method selection

Several empirical methods for prediction of the spatial pattern of sediment deposits have been developed and published in the technical literature, including among others:

- Annandale (1984)
- Borland (1970)
- Borland & Miller (1958)
- Szechowycz & Qureshi (1973)
- Van Rijn (2013).

RESCON 2 applies the method of Van Rijn (2013) for the assessment of the spatial pattern of sedimentation and subsequently for the calculation of the distribution of deposits between active and inactive storage. The reasons for selecting this method are:

- The application of the aforementioned empirical approaches would require additional data, which are difficult to collect or are not generally available during the preliminary phases of the project development, such as Elevation-Storage curves.
- The method suggested by Van Rijn (2013) is characterized by a wider applicability than empirical methods the derivation of which is based usually on limited data sets, rendering thus these methods more bias prone.

2.1.2 Data input and data processing

RESCON 2 allows the specification of two different pools, namely the initial active and inactive storage. Furthermore, the user defines the Minimum Operating Water Level [ELmwl]. Based on the following user defined parameters, the reservoir is schematized into compartments:

- Elevation of normal operating water level [ELowl]
- Elevation of minimum operating water level [ELmwl]
- Reservoir's active storage [St_a_res]
- Reservoir's inactive storage [St_d_res]
- Length of reservoir [L_res]
- Elevation of minimum river bed level, i.e. elevation of river bed at the dam site [ELbim].

Each compartment is characterized by the following automatically calculated parameters:

- Elevation of compartment's bottom ELbi
- Length of each compartment Li
- Compartment's inactive storage width Wdi
- Compartment's active storage width Wai
- Compartment's Inactive storage St_d_i
- Compartment's Active storage St_a_i.

The maximum number of compartments that can be used for discretization of reservoir storage is 10 in order to limit the computational load.

An example of the assumed reservoir longitudinal profile after the schematization in compartments is shown in the Figure 2.1.

Similarly, a plan view of the reservoir geometry showing the calculated average width of active and inactive storage of each reservoir compartment is given in Figure 2.2.

Figure 2.1: Longitudinal profile of reservoir after schematization in compartments

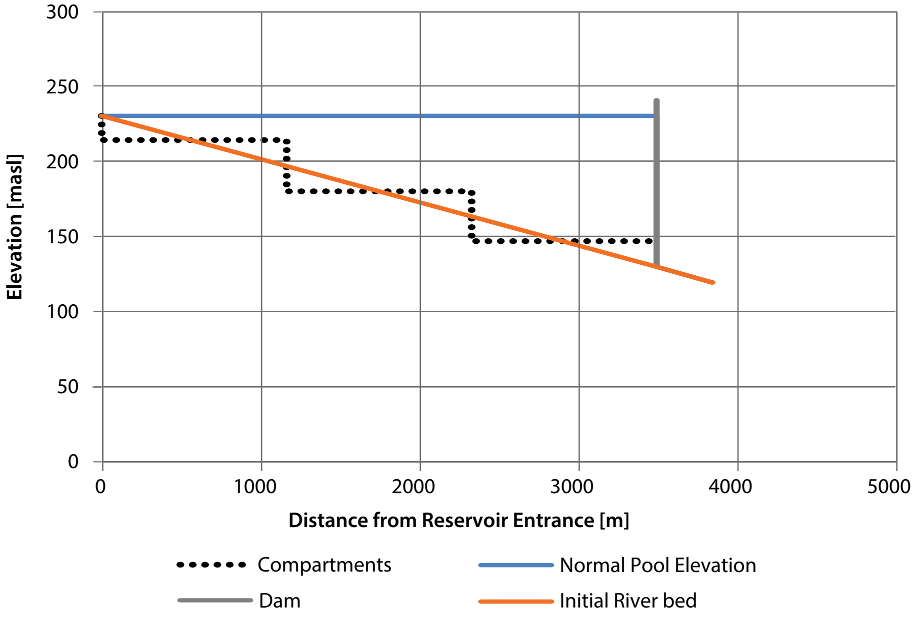
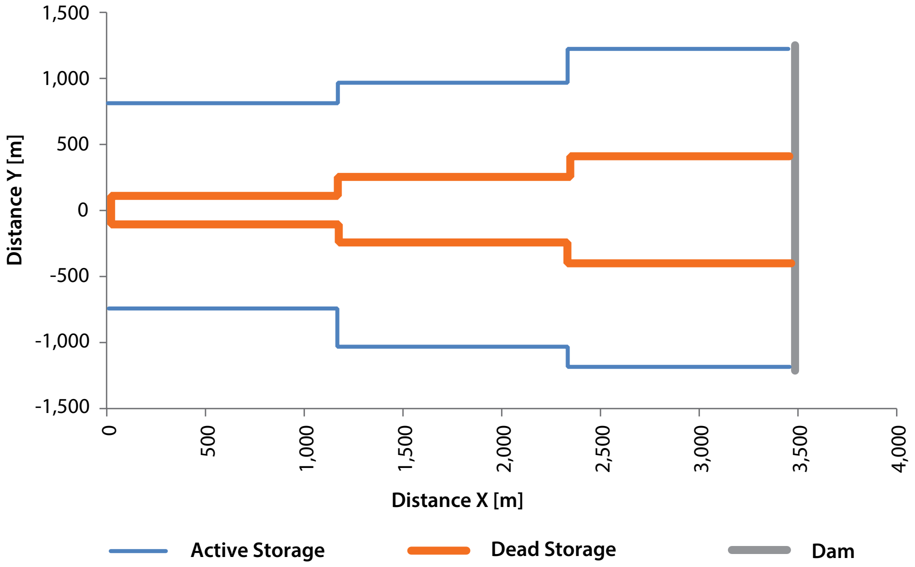


Figure 2.2: Plan view of reservoir after schematization in compartments



The number of the compartments used for schematization of reservoir geometry can influence the calculated reservoir storage development and therefore it can be used as a calibration parameter in the analysis of existing projects. It is recommended to calculate the storage development for the no action scenario for different values of this parameter and to select the one that provides the better agreement with the measured reservoir storage development.

2.1.3 Calculation procedure

The calculation procedure for determination of the distribution of deposits between active and inactive storage is presented schematically in the following depicted in Figure 2.3.

The calculation comprises the following steps.

Step 1: Calculation of reservoir's condition at the beginning of the hydrological year on basis of the reservoir bathymetry.

This involves the determination of available gross, inactive and active storage and mean flow velocity Vres

Input data:
- elevation of compartments bottom
- width of compartment's active storage
- width of compartment's inactive storage
- hydrological input.

Step 2: Calculation of reservoir's trap efficiency.

Input data:
- reservoir gross storage and length
- mean flow velocity in the reservoir.

The calculation is performed only for suspended solids, while the trap efficiency of incoming bedload is considered to be 100%. For fine sediment transported in suspension the user can select one of the following methods for calculation of trap efficiency:
- Churchill (1948)
- Brune (1952)
- Borland (1971)

Step 3: Calculation of potential suspended and bedload deposits in reservoir during the hydrological year

Input data:
- mean Annual Sediment Inflow (MAS)
- % of bedload in total suspended load
- reservoir's suspended and bedload Trap efficiency.

Step 4: Calculation of compartment's i condition.

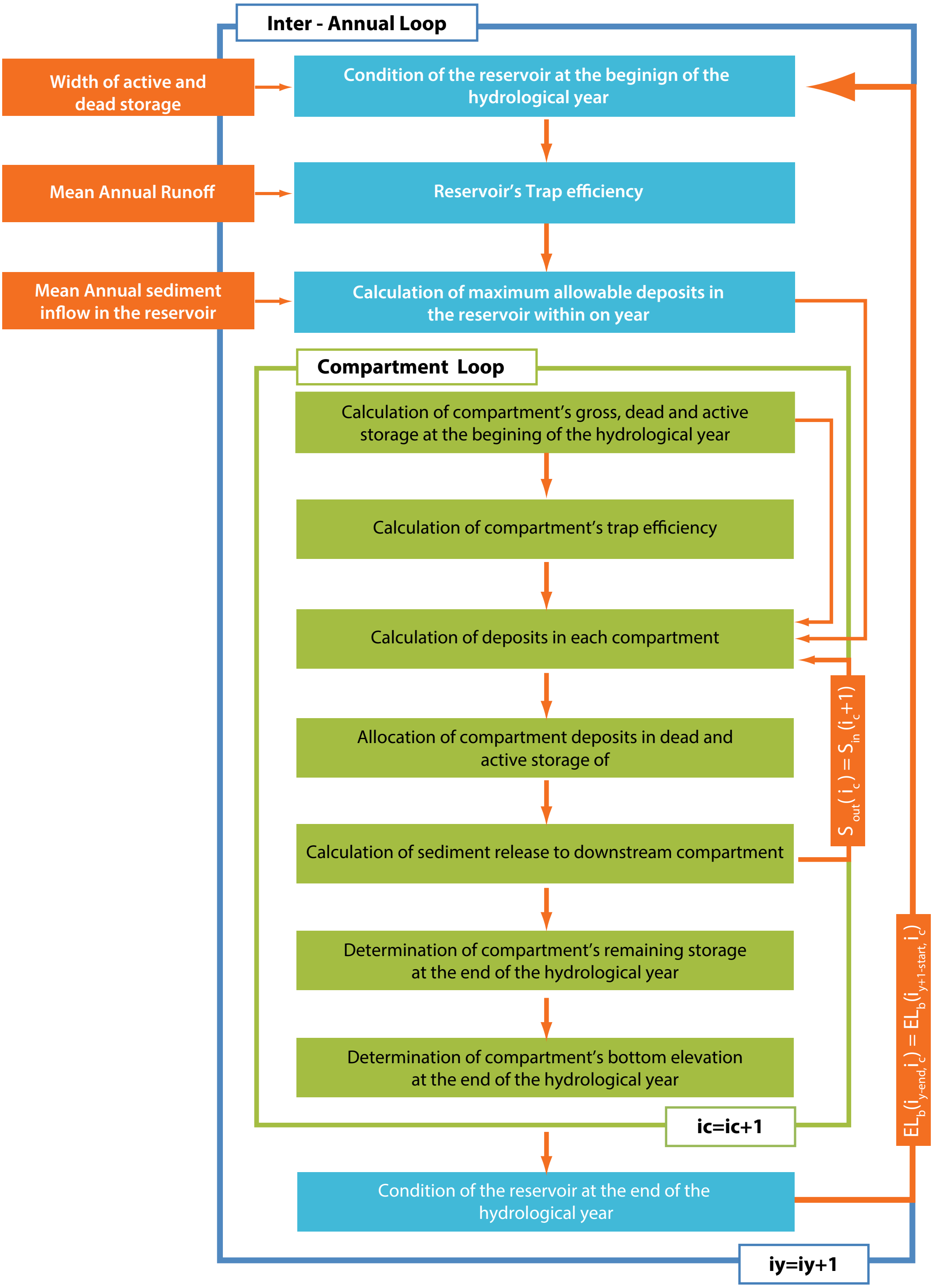
Input data:
- compartment's gross storage
- mean flow velocity in the compartment

Step 5: Calculation of compartment's i trap efficiency.

Input data:
- compartment's gross storage
- mean flow velocity in the compartment

When the method of Borland is selected, the trap efficiency of clay, silt and sand suspended load is individually calculated for each fraction, depending on the settling velocities defined by the user.

Figure 2.3: Flow chart showing the sequence of performed calculations for allocation of deposits between active and inactive pools



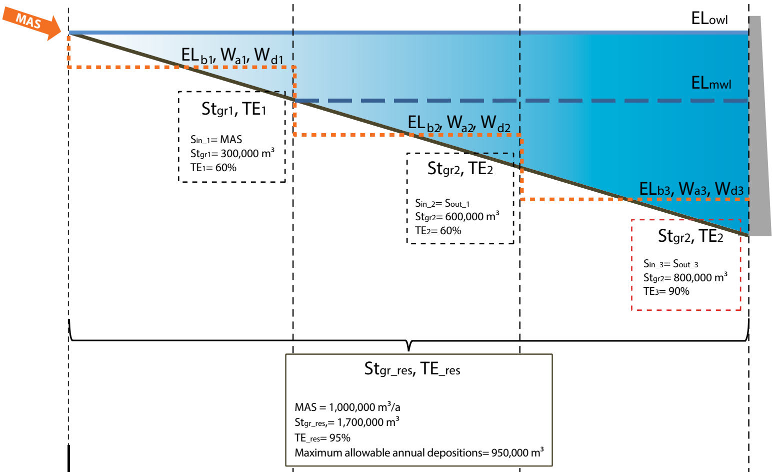
Step 6: Calculation of deposits in compartment i.

The deposits in compartment i are subject to three limitations imposed by the available storage in the under consideration compartment, the compartment's trap efficiency and the upper limit of allowable deposits in the reservoir determined previously in Step 3. Therefore, the deposits in compartment i are considered as the minimum of the following values.

- Available gross storage of compartment
- Product of compartments Trap Efficiency and sediment inflow in this compartment (i.e. sediment outflow from the upstream compartment when i > 1)
- Total reservoir deposits potential (calculated in Step 3) after excluding the deposits in the upstream compartments.

The method used for calculation of deposits in each compartment is illustrated in the Figure 2.4 accompanied by a simplifying example

Figure 2.4: Applied method for determination of sediment deposits in reservoir compartments (fictional example for illustration purposes)



Compartment		①	②	③	
Sediment Inflow in Compartment	S_{in_i}	1,000,000 m^3 (Mean Annual Sediment inflow in reservoir)	700,000 m^3 (Sediment release from compartment 1)	210,000 m^3 (Sediment release from compartment 2)	
Compartment's Trap Efficiency	$TE_{\_i}$	60%	70%	90%	
Potential deposits in the compartment	$Dep_{\_pot\_i}$	600,000 m^3 (S_{in_1} x $TE_{\_1}$)	490,000 m^3 (S_{in_2} x $TE_{\_2}$)	189,000 m^3 (S_{in_3} x $TE_{\_3}$)	
Total deposits limitation	$Dep_{\_max\_i}$	950,000 m^3 ($TE_{\_res}$ x MAS)	650,000 m^3 ($TE_{\_res}$ x MAS-$dep_{\_1}$)	160,000 m^3 ($TE_{\_res}$ x MAS-$dep_{\_1}$-$dep_{\_2}$)	
Compartment Storage limitation	St_{gr_i}	300,000 m^3 (available compartment storage St_{gr1})	500,000 m^3 (available compartment storage St_{gr2})	800,000 m^3 (available compartment storage St_{gr3})	
Deposits in compartment i	$Dep_{\_i}$	300,000 m^3 Min {$Dep_{\_pot\_i}$, $Dep_{\_max\_i}$, St_{gr_i}}	490,000 m^3 Min {$Dep_{\_pot\_i}$, $Dep_{\_max\_i}$, St_{gr_i}}	160,000 m^3 Min {$Dep_{\_pot\_i}$, $Dep_{\_max\_i}$, St_{gr_i}}	950,000 $\Sigma Dep_{\_i}$
Sediment Release from compartment i	S_{out_i}	700,000 m^3 (S_{in_i}–S_{out_i})	210,000 m^3 (S_{in_i}–S_{out_i})	50,000 m^3 (S_{in_i}–S_{out_i})	50,000 (Sediment release from reservoir)

with fictional figures, which allows following the above described considerations.

Step 7: Calculation of sediment release to downstream compartment.
It is calculated as the difference between sediment inflow and sediment deposits occurring in compartment i.
Within the compartment loop, the sediment release from compartment i-1 is considered to be the sediment inflow in the downstream compartment i. If the sediment deposits are higher than the available storage, it is considered that the sediment release includes also the part of sediment inflow that could not be deposited due to available storage limitation.

Step 8: Calculation of compartment's storage at the end of hydrological year.
It is calculated by extracting the calculated deposits from the compartment storage of the previous year. The available active and inactive storage is calculated by comparing the sediment deposits occurring this year with the available active and inactive storage at the end of the previous year.

Step 9: Calculation of compartment's bottom elevation at the end of hydrological year.
It is calculated by dividing the calculated volume of deposits, with the average width of the pool, where the deposits occur and the length of the reservoir.

Step 10: Calculation of reservoir's condition at the end of hydrological year.
It is calculated by adding the compartments storages. The reservoir active storage is used for determination of the annual benefits from reservoir operation.

2.2 Partitioning of Total Sediment Load into Bedload and Suspended Load

The partitioning of the total sediment load into bedload and suspended load is important because the trap efficiency of particles can vary significantly depending on the mode of transport. Namely, all incoming bedload will be trapped providing that there is storage available, while the retention of suspended solids depends greatly on the hydraulic conditions prevailing in the reservoir. For this reason the differentiation between bedload and suspended load increases significantly the representativeness of the model results.

For this purpose, a partitioning method based on a rule-of-thumb approach, whereby the bedload is defined as a percent of the total load depending on the suspended load concentration and the river type, has been implemented in RESCON 2. The user is asked to provide as input the Mean Annual Sediment

Table 2.1: Partitioning between bedload and suspended load according to Lane & Borland (1951). [Retrieved from Turowski et al. (2010)]

Concentration of suspended load [p.p.m.]	*Type of bed material forming the channel of the stream*	*Texture of suspended material*	*Percent bedload in terms of measured suspended load*
low[1]	Sand	Similar to bed material	25% - 150%
	Gravel, rock or consolidated clay	Small amount of sand	5% - 12%
medium[2]	Sand	Similar to bed material	10% - 35%
	Gravel, rock or consolidated clay	25% sand or less	5% - 12%
high[3]	Sand	Similar to bed material	5% - 15%
	Gravel, rock or consolidated clay	25% sand or less	2% - 8%

1 *Low:* suspended load concentration < 1000 p.p.m.

2 *Medium:* suspended load concentration 1000 - 7500 p.p.m.

3 *High:* suspended load concentration > 7500 p.p.m.

Inflow (MAS) in the reservoir, which corresponds to the total sediment load, i.e. comprises both bedload and suspended load. In addition, the user is asked to provide an assessment of bedload expressed as a percentage of the total sediment load. The user is supported by having easy access to the so called Maddock Table as modified and extended by Lane & Borland (1951). The incorporated Lane and Borland (1951) partitioning method is shown in the Table 2.1.

2.3 Trap Efficiency

2.3.1 Available methods and selection criteria

The reservoir trap efficiency is an important parameter for the determination of the storage loss rate. On these grounds the following concept is incorporated in RESCON 2 for the calculation of its trapping efficiency:

- Partitioning of total load into bedload and suspended load.
- Accounting for a bedload trap efficiency of 100% until the storage is depleted.
- Calculation of a varying over time trap efficiency of fine material transported in suspension.

RESCON 2 provides the following options with regards to calculation of trap efficiency of fine material:

- Brune (1952)
- Churchill (1948)
- Borland (1971).

Brune (1952) curve provides a reasonable assessment of the average trap efficiency to be expected in the long term. This method however is not appropriate for relatively short time intervals, whereby the flow conditions in the reservoir are altered significantly. Therefore this method should only be used for normally ponded reservoirs because it accounts only for the average retention time of the water in the reservoir, ignoring however the flow conditions in the reservoir (Versraeten et al. (2000)).

The trap efficiency of reservoirs regularly sluiced, semi dry or desilting reservoirs as well of reservoirs serving for flood retention, i.e. reservoirs characterized by shallow water depths and/or relatively high flow velocities should be calculated with application of Churchill (1948) and Borland (1971) methods, which are more appropriate for short term predictions of a variable over time trap efficiency.

2.3.2 Suspended load trap efficiency

The derivation of Churchill (1948) curves was based on measurements of suspended sediment and therefore it has been considered that this method provides an assessment of the trap efficiency of suspended solids (and not of total sediment load, i.e. bedload and suspended load). This method has been included because it relates the reservoir trap efficiency to a sedimentation index, which accounts for the period of retention as well for the mean flow velocity in the reservoir, describing thus better the prevailing hydraulic conditions in the reservoir. On these grounds it is considered that the Churchill curve will provide a better assessment of the trap efficiency for a wider range of reservoir types, as well as for reservoirs where sediment management is applied.

The trap efficiency of suspended sediment originating from the catchment draining to the reservoir according to Churchill (1948) is calculated in RESCON 2 by the following equation, which was retrieved by Maniak (2010).

The release efficiency, i.e. the % passing of inflowing suspended sediment is given by the equation:

$$100 - TE_{Churchill} = (1600(SI\, g)^{-0.2} - 12$$ **Equation 2.1**

Hence, the trap efficiency is:

$$TE_{Churchill} = 100 - (1600(SI\ \ g)^{-0.2} - 12$$ **Equation 2.2**

Where:

TE Trap Efficiency (%)

g gravitational acceleration (9.81 m/s^2)

SI Sedimentation Index (s^2/m)

The Sedimentation Index (SI) expresses the ratio of retention time to mean flow velocity in the reservoir.

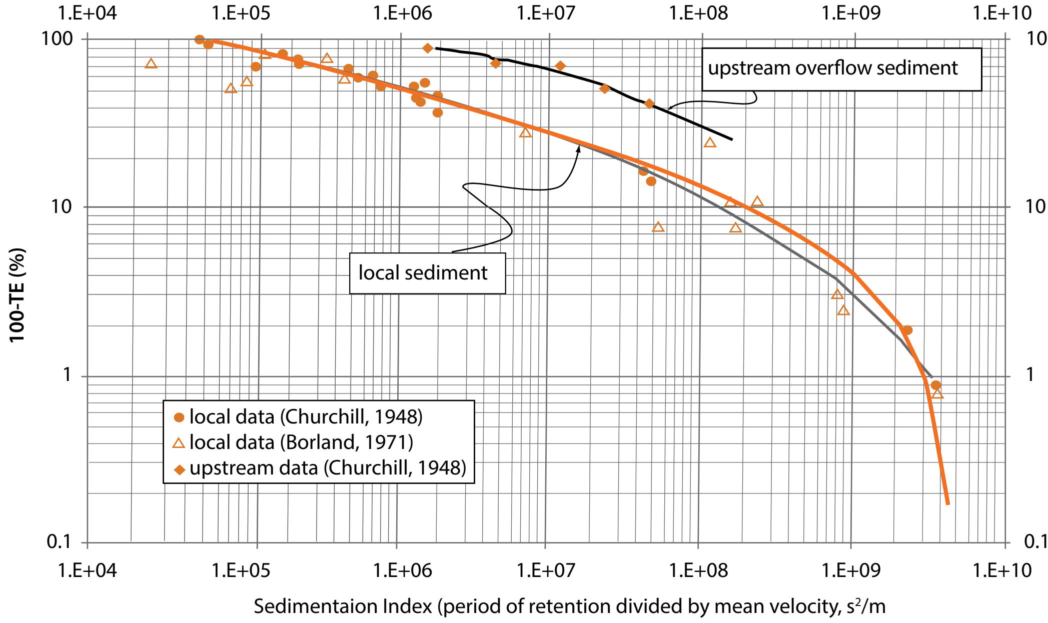
$$SI = \frac{{St_{gr\,res}}/{MQ}}{{MQ}/{\left({St_{gr\,res}}/{L}\right)}} = \frac{St_{gr\,res}^{2}}{MQ^{2}L} \qquad \textbf{Equation 2.3}$$

Where:

Stgr res	gross storage capacity of the reservoir (m^3)
MQ	Mean annual water inflow in the reservoir (m^3/s)
L	Reservoir length

Equation 2.1 provides a reasonable good fit to the curve initially suggested by Churchill (1948) for local sediments. The curve for upstream overflow sediment applies to the case of a cascade of reservoirs and is not implemented in RESCON 2.

Figure 2.5: Churchill (1948) measured data and curves for calculation of trap efficiency of local and upstream overflow sediment. [Retrieved from Borland (1971)]



RESCON 2 provides the user with the option to calculate the trap efficiency with application of the Borland (1971) equation. This second option has the following advantages:

- It is derived from a theoretical model based on the principles of particle sedimentation in water. This widens the applicability range to all types of reservoirs.
- It allows for a fractionwise calculation of trap efficiency, i.e. different trap efficiencies are calculated for clay, silt and sand particles in suspension.
- The former allows for an indication of the reduction of deposits grain size as we move toward the dam.
- It allows for an assessment of the grain size distribution of the material passing through the reservoir. This will allow for an enhanced calculation of reservoir trap efficiency in case of a cascade system.

The equation of Borland (1971) as reported by Van Rijn (2013) is shown below:

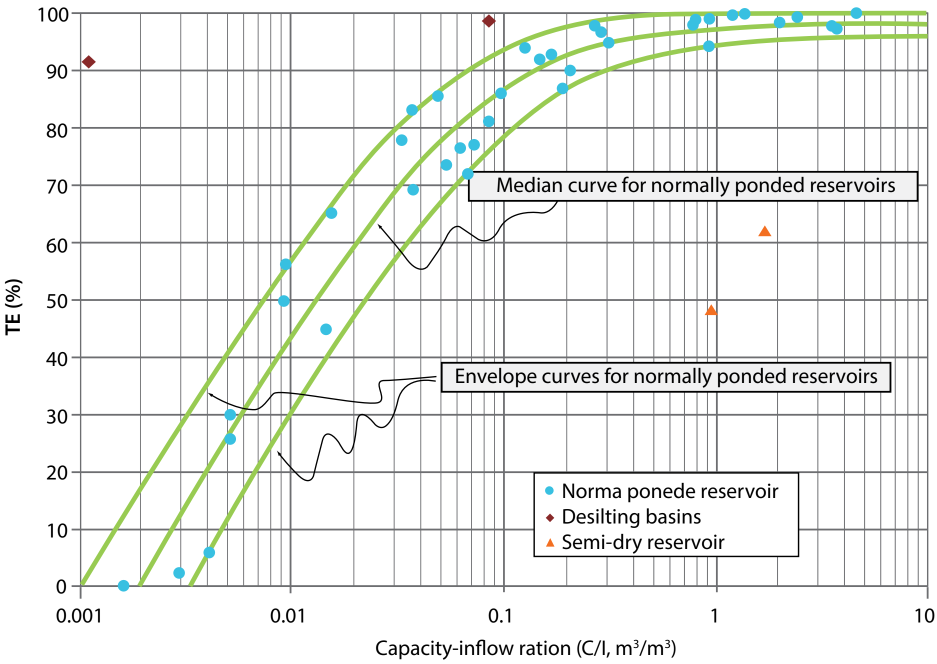
$$TE_{Borland} = 100\left(1 - e^{-1.055\left(\frac{L}{h}\right)\left(\frac{w_s}{u}\right)}\right)$$

Equation 2-4

Where:

TE	Trap Efficiency (%)
L	reservoir (or section of reservoir) length (m)
h	mean flow depth of reservoir (or section of reservoir) (m)
w_s	settling velocity of sediment (m/s).
u	mean flow velocity in reservoir (or section of reservoir) (m/s)

Figure 2.6: Brune curve for estimating the trap efficiency of reservoirs



Source: Brune (1953

Finally, the trap efficiency can be calculated with the Brune curve, which is shown in the figure below.

The equations used for calculation of the trap efficiency with the Brune method are:

Median envelope curve for normally ponded reservoirs:

$$TE_{Brune} = \begin{cases} 23.546\ \ln\left(\frac{C}{I}\right) + 150.67, & 0.0018 \le C/I < 0.07 \\ 7.5422\ \ln\left(\frac{C}{I}\right) + 104.13, & 0.07 \le C/I < 0.5 \\ 0.5995\ \ln\left(\frac{C}{I}\right) + 97.028, & 0.5 \le C/I < 10 \end{cases}$$

Equation 2.5

High envelope curve for normally ponded reservoirs:

$$TE_{Brune} = \begin{cases} 23.357\ \ln\left(\frac{C}{I}\right) + 163.31, & 0.001 \le C/I < 0.05 \\ 10.096\ \ln\left(\frac{C}{I}\right) + 116.78, & 0.05 \le C/I < 0.2 \\ 1.3428\ \ln\left(\frac{C}{I}\right) + 100.04, & 0.2 \le C/I < 10 \end{cases}$$

Equation 2.6

Low envelope curve for normally ponded reservoirs:

$$TE_{Brune} = \begin{cases} 23.099\ \ln\left(\frac{C}{I}\right) + 136.02, & 0.0032 \le C/I < 0.2 \\ 6.0515\ \ln\left(\frac{C}{I}\right) + 96.807, & 0.2 \le C/I < 1 \\ 0.7192\ \ln\left(\frac{C}{I}\right) + 95.072, & 1 \le C/I < 10 \end{cases}$$

Equation 2.7

2.4 Intra-annual Distribution of Water and Sediment Inflow

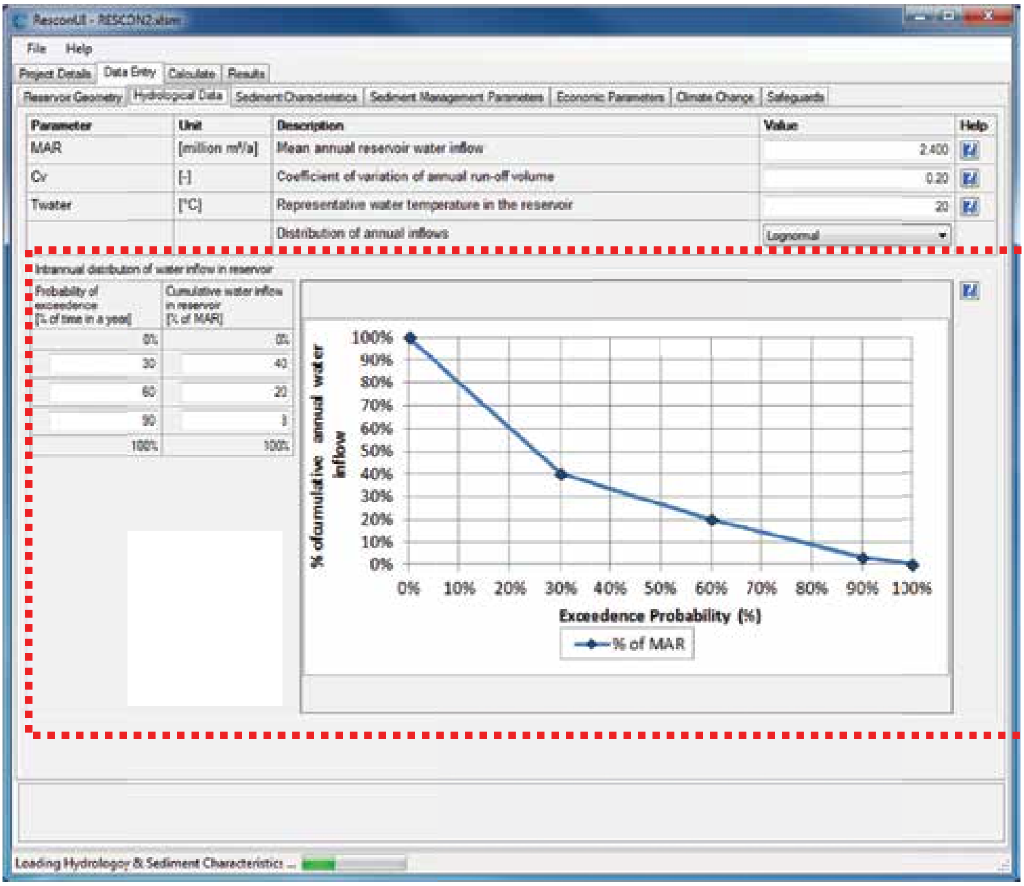
The assessment of sediment routing techniques, namely sluicing, by-pass and density current venting requires the knowledge of the intra-annual distribution of water and sediment inflow into the reservoir. The latter is specified by the user in the GUI tabs Data Entry > Hydrological Data and Data Entry > Sediment Characteristics respectively. An example is given in Figure 2.7.

The derivation of the necessary input can be based on mean monthly values of water inflow or on regional empirical approaches if the former input is not available.

The following steps should be followed:

1. Determination of mean monthly water inflows as % of the mean annual water inflow.

Figure 2.7: Tab Data Entry > Hydrological Data, Input boxes for specification of intra-annual distribution of water inflow and graphical plot



Parameter	Unit	Description	Value	Help
MAR	[million m³/a]	Mean annual reservoir water inflow	2.400	
Cv	[-]	Coefficient of variation of annual run-off volume	0.20	
Twater	[°C]	Representative water temperature in the reservoir	20	
		Distribution of annual inflows	Lognormal	

Intrannual distribution of water inflow in reservoir

Probability of exceedence [% of time in a year]	Cumulative water inflow in reservoir [% of MAR]
0%	0%
30	40
60	20
90	3
100%	100%

Loading Hydrologoy & Sediment Characteristics ...

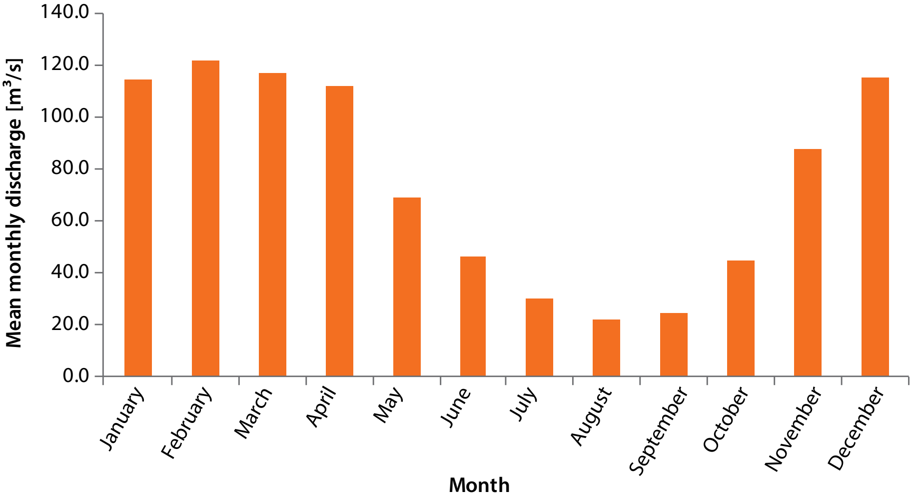
Next to example (Figure 2.8):

- Input: The mean monthly discharges are shown in the figure below. In the given example the mean monthly discharge of January is 114 m³/s and the mean annual discharge is 75 m³/s.
- The mean monthly water inflow in January is 114 x 31 x 86400 = 306 million m³ and the mean annual water inflow is 75 x 365 x 86400 = 2366 million m³.
- The mean annual water inflow in January is 306/2366 = 12.9% of the mean annual water inflow.

2. Sorting of the mean monthly fractions of the mean annual water inflow starting the first month of wet season and determine the cumulative water inflow as % of the mean annual water inflow. (see Figure 2.9).
   Example:

- Input: The first month of wet season is November.

Figure 2.8: Plot of mean monthly discharges (example illustrating the derivation of intra-annual water inflow distribution required for assessment of sediment routing techniques)



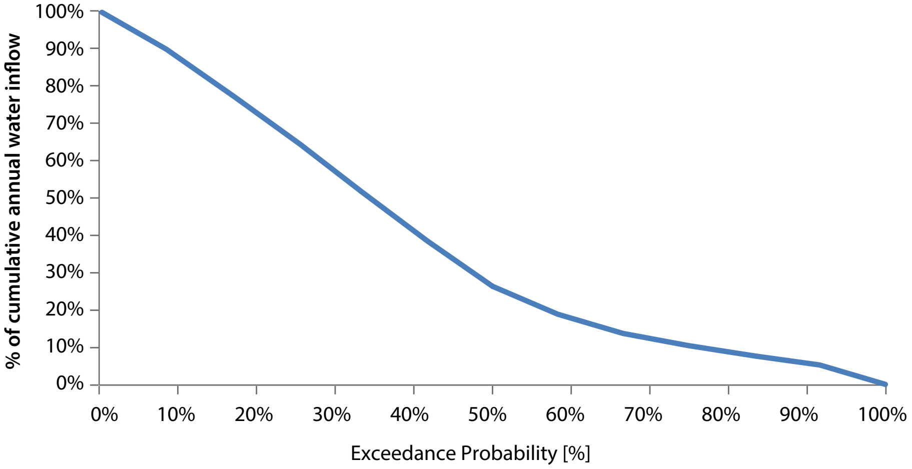
Month	*Mean monthly discharge [m³/s]*	*Mean monthly water inflow [million m³/month]*	*Mean monthly water inflow as % of mean annual water inflow*
1	114.2	305.9	12.9%
2	121.5	293.9	12.4%
3	117.0	313.3	13.2%
4	111.8	289.9	12.3%
5	69.0	184.9	7.8%
6	46.8	121.2	5.1%
7	29.8	79.9	3.4%
8	22.4	60.1	2.5%
9	24.1	62.6	2.6%
10	44.6	119.3	5.0%
11	87.6	227.1	9.6%
12	115.0	308.0	13.0%
		2366.2	100.0%

3. Plot the cumulative mean monthly fractions of annual water inflow in a descending order starting from 100%.

The interpretation of this input, on basis of the above presented example is as follows:

- 25% of the annual time, i.e. approximately 2 months after commencement of the wet season, the water inflow in the reservoir corresponds to 20% (100%-80%, i.e. the value read from the plot) of the mean annual water inflow.

Figure 2.9: Plot of intra-annual distribution of water inflow



	Month	*Percent of annual time*	*Cumulative percent of annual time*	*Mean monthly water inflow as % of mean annual water inflow*	*Cumulative water inflow as % of mean annual water inflow*
			0.0%		100.0%
1st Month of wet season	11	8.2%	8.2%	9.6%	90.4%
	12	8.5%	16.7%	13.0%	77.4%
	1	8.5%	25.2%	12.9%	64.5%
	2	7.7%	32.9%	12.4%	52.0%
	3	8.5%	41.4%	13.2%	38.8%
	4	8.2%	49.6%	12.3%	26.5%
	5	8.5%	58.1%	7.8%	18.7%
	6	8.2%	66.3%	5.1%	13.6%
	7	8.5%	74.8%	3.4%	10.2%
	8	8.5%	83.3%	2.5%	7.7%
	9	8.2%	91.5%	2.6%	5.0%
	10	8.5%	100.0%	5.0%	0.0%

- Similarly the last 2 months of the dry season, i.e. by 80% of the mean annual time, occurs 10% of mean annual water inflow.

2.5 Sustainability of Reservoir Storage Time Path

A reservoir storage time path is characterized as sustainable in RESCON 2 analysis when the reservoir storage remains above a user specified storage threshold within a sufficiently long user specified time period of reservoir operation. Accordingly, the storage time path is considered to be non-sustainable when the reservoir storage drops permanently below the user specified storage threshold within a long but finite time period of reservoir operation. Hence, the characterization of a reservoir as non-sustainable or sustainable depends on the calculated development of reservoir storage, the duration of the analysis defined by the parameter i_ymax and the Non-sustainability storage threshold St_NS.

The non-sustainability storage threshold is defined as:

$$St_{NS} = f(x) = \begin{cases} (1 - CL_{NS})\ So_{gr}, & \text{greenfield projects} \\ (1 - CL_{NS})\ Se_{gr}, & \text{existing projects} \end{cases}$$

Where:

StNS: when the available storage drops permanently below this threshold value, the reservoir is characterized as non-sustainable. This threshold storage value depends on the user specified parameter CLNS which is explained below and the currently available reservoir storage.

CLNS: The maximum allowable capacity loss for characterization of a reservoir as non-sustainable.

The default value of the parameter CLNS is 95%. This means that the reservoir will be characterized as non-sustainable if the reservoir storage looses permanently 95% of its current gross storage capacity due to sedimentation. The value of this parameter can be adjusted in the economic appraisal input tab in the graphical user interface. It is strongly recommended to use values in the range of 90% -100%.

Sogr: Pre-impoundment gross storage capacity.

Segr: Current gross storage capacity for reservoirs that were impounded in the past.

It is considered that the reservoir gross storage converges to a constant value, when the annual storage loss rate drops below 0.2%, i.e. when the following condition is satisfied.

$$\frac{St_{gr}(i_y - 1) - St_{gr}(i_y)}{St_{gr}(i_y - 1)} < 0.2\%$$

The aforementioned threshold storage loss rate corresponds to a reservoir lifetime of 500 years.

2.5.1 Sustainable time paths

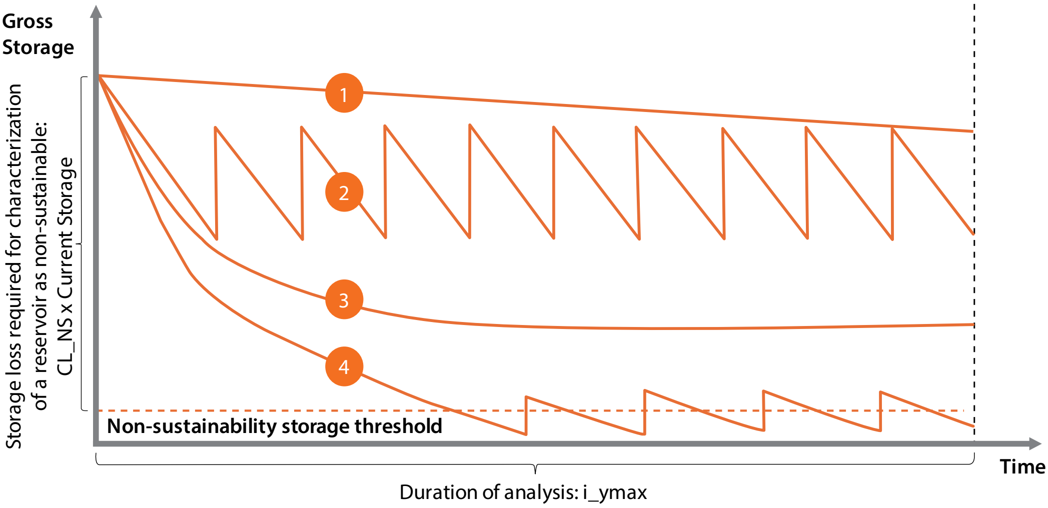
The four possible time paths of reservoir storage development, which when followed will result in the characterization of the reservoir as sustainable are given in Figure 2.10.

The four possible time paths are differentiated as follows:

1. Continuous reservoir storage during the user specified time period of i_ymax years. At the end of this time period, the available reservoir storage is larger than the non-sustainability storage threshold StNS.
2. The reservoir storage will converge to a constant value, i.e. the sedimentation stops, within the user specified time period. This convergence might occur due to applied sediment routing techniques or because the reservoir trap efficiency drops to zero.
3. The applied deposit removal technique such as dredging or flushing has as result that the reservoir storage remains always larger the threshold value.
4. The applied deposit removal technique has as result that the reservoir storage drops only periodically below the threshold value. As soon as the deposit removal operation is completed, the reservoir storage is larger than the non-sustainability threshold. Hence, the reservoir storage does not drop permanently below the threshold rather only periodically.

The default value of the duration of the analysis is 300 years and it can be changed by the user only in the template excel spreadsheet RESCON2 Default.xlsm, in the worksheet Input (Economic Parameters) and the cell E30.

Figure 2.10: Possible time paths of sustainable storage development



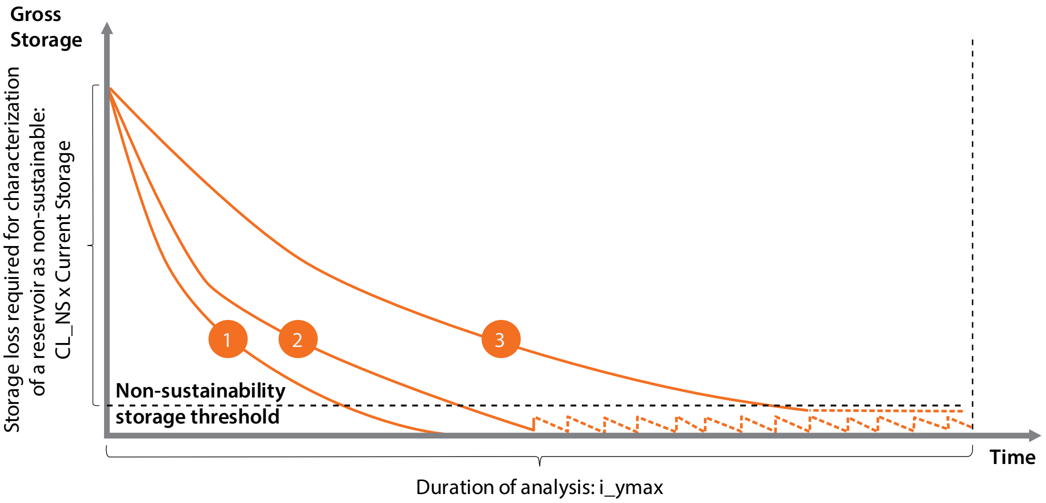
2.5.2 Non-sustainable time paths

The four possible time paths of reservoir storage development, which when followed will result in the characterization of the reservoir as sustainable in Figure 2.11.

The three possible non-sustainable time paths are differentiated as follows:

1. Continuous reservoir storage which has as result the full storage elimination before the end of the user specified time period with duration of i_ymax years. This time path might be observed for the no action scenario, or for catchment management and by-pass when the bedload inflow into the reservoir is not fully eliminated. The lifetime of the reservoir is defined by the year the reservoir storage is eliminated.
2. Despite the application of deposit removal methods, the reservoir storage drops below the non-sustainability threshold and subsequently does never exceed the threshold storage value. This scenario might be realized if the amount of deposits removed by means of dredging for instance is very small and the trap efficiency of the reservoir is also accordingly low. In that case it is considered that the deposit removal operation will be ceased as soon as the storage after a deposit removal does not manage to exceed the non-sustainability threshold. Therefore, in the figure above the "sustainably" maintained reservoir storage which is below the non-sustainability threshold is annotated by a dashed line. This symbolizes the storage that could be potentially preserved by means of the user specified deposit removal operation but it is however not realized because it is considered that this operation will seize as soon as it is confirmed that the reservoir storage can't return in a value above the non-sustainability threshold.

Figure 2.11: Possible time path of non-sustainable storage development



3. The reservoir storage will converge to a constant value which is lower than the user specified non-sustainability threshold, within the user specified analysis time period. This convergence might occur due to the applied sediment routing techniques or because the reservoir trap efficiency drops to zero before the storage is fully eliminated. That year will cease the operation of any sediment management method applied beforehand. In that case it is considered that the lifetime of the reservoir is defined by the year the convergence occurs for the no action scenario or the year the storage will be eliminated assuming that sediment routing will be stopped the year of convergence. Therefore, in the figure above the "sustainably" maintained reservoir storage which is below the non-sustainability threshold is annotated by a dashed line. This symbolizes the storage that could be potentially preserved by means of the user specified sediment routing operation but this is however not realized because it is considered that this operation will seize as soon as it is confirmed that the reservoir storage has converged to a storage value lower than the non-sustainability threshold.

CHAPTER 3

Economic Appraisal

3.1 Elements of Economic Appraisal

The purpose of the economic analysis is to find out whether investment or measures taken for the implementation of sedimentation management are a viable undertaking from a societal point of view. If several technical solutions for sedimentation management exist, the economic analysis identifies the one with the highest net benefits, i.e. the most viable option. This is expressed in the RESCON 2 model by the Net Present Value (NPV).

When the user carries out the economic analysis, i.e. the ex-ante assessment of investment and other measures for sedimentation management and the calculation of the NPV, it is required to address and clarify, in broad terms, three general issues:

- The benefits that result from reservoir operation with or without implementation of sedimentation management. It will be necessary to clearly identify the benefits, to value them appropriately and to determine over which time horizon the benefits can be expected to occur.
- An appropriate estimate of the costs associated with the reservoir construction and operation and the investment in measures for sedimentation management.
- The discount rate to be applied. Here, the discussion of an efficiency-oriented (also called "finance-equivalent") discount rate vs. a social (or "social-welfare") discount rate is required on the one hand and of the issue of a constant discount rate vs. a discount rate that declines over time on the other hand.

The first issue of cost estimation is dealt with in connection with the analysis of the different sedimentation techniques and measures in the previous chapters of the report and, therefore, it is not further included in this chapter. In the following, the user will be acquainted with some background information on the issues of discounting and benefit calculation. Suggestions are made for the way in which the model and its inputs are to be handled by the user concerning these two elements.

3.2 Benefit Calculation in Economic Models

The benefits from reservoir operation are calculated in RESCON 2 similar to RESCON as the product of reservoir yield (water available for use) with a given reliability (probability of providing yield) and a user specified unit price (economic value of water yield). In this chapter is explained how the water yield is calculated in RESCON 2 analysis and information is provided regarding its economics.

3.2.1 *Water yield estimation*

The RESCON 2 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 the quantity of water that can be given economic value.

McMahon et al. (2007) showed that the water yield calculated by the Gould-Dincer method is in close agreement with the results of conventional simulation approaches. Therefore the yield analysis performed by RESCON 2 for assessment of the reservoir benefits adopts the Gould-Dincer equations for the calculation of the water yield. According to this approach, the dimensionless water yield can be expressed as a function of available reservoir storage, reliability and annual inflows assuming normally distributed and independent annual flows by the following equation:

$$\alpha_{storage} = 1 - \frac{z_p^2 C_v^2}{4\tau}$$

Where:

$\alpha_{storage}$: dimensionless water yield for storage schemes (–) defined as a ratio of mean of annual water inflow (water yield/mean annual water inflow).

z_p: standardized normal variate (–) at 100 p% non exceedance probability of failure. This parameter depends on the user specified reliability of water yield supply.

C_v: coefficient of variation of annual water inflows to the reservoir (–), which is calculated by the following equation:

$$C_v = \frac{s_d}{MAR}$$

Where:

s_d: standard deviation of the annual flows (m^3)

MAR: mean annual water inflow in reservoir (m^3)

τ: dimensionless reservoir active storage (–) defined as a ratio of mean of annual water inflow (reservoir active storage/mean annual water inflow)

The calculated water yield and consequently the reservoir benefits depend on the user specified reliability of water supply. Users are enjoined against changing the reliability level in search of a higher economic benefit.

The firm water yield is calculated with the aforementioned method until the calculated water yield reaches a low limit as calculated by the following equation:

$$\alpha_{ror} = 1 + z_p C_v$$

Where:

α_{ror}: dimensionless water yield for run of river schemes (–) defined as a ratio of mean of annual water inflow (water yield/mean annual water inflow)

z_p: standardized normal variate (–) at 100p% non exceedance probability of failure. This parameter depends on the user specified reliability of water yield supply.

C_v: coefficient of variation of annual water inflows to the reservoir (–),

At that time it is considered that the available storage does not provide any benefits with regards to the firm water yield and the reservoir enters the run-of-river operation mode. The storage at which the transition from storage to run-of-river operation occurs is the characterized as the cross-over storage.

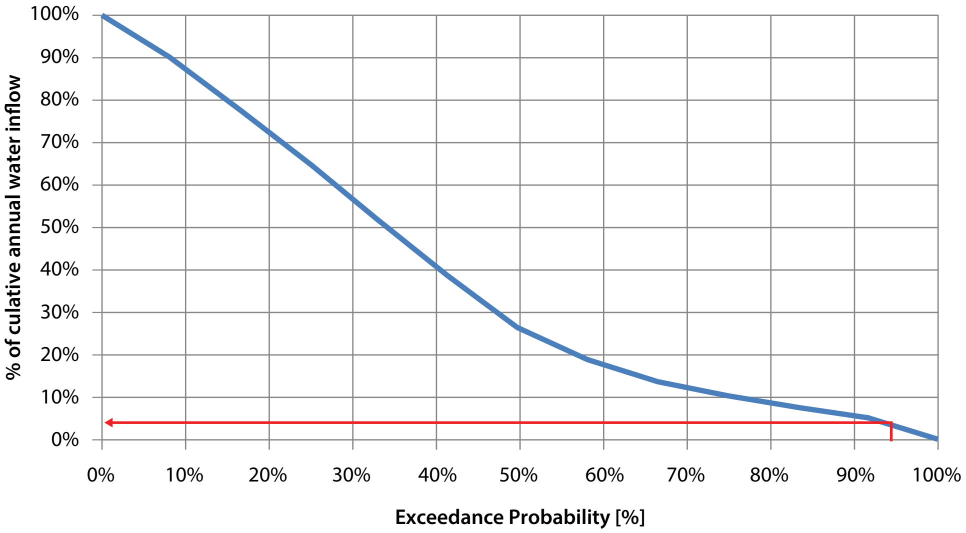
When the reservoir storage ranges between 0 and the cross-over storage value the run-of-river firm water yield is calculated through linear interpolation between the following two values:

- For storage equal with the cross-over threshold the corresponding water yield is given by the equation αror = 1 + zpCv
- When the storage is zero it is considered that the water yield depends on the user specified required reliability and the also user specified intra-annual distribution of water inflow.

  For instance if the required reliability is 95% then the firm water yield corresponding to zero storage conditions is the water inflow entering the reservoir the last 5% of the annual time during the dry season. According to the example that has been presented in section 2.4 this would be approximately 4% of the mean annual water inflow (see figure 3.1).

The user can select between gamma, log-normal and normal distribution for the annual flows.

Figure 3.1: Determination of firm water yield with reliability 95% for zero storage conditions



If the annual inflow obeys the gamma distribution, z_p in the previous equations is replaced by the gamma variate z_g which is calculated based on the Wilson-Hilferty transformation for flows that are not auto correlated and not characterized by skewness.

$$z_g = \frac{2}{\gamma}\left\{\left[1 + \frac{\gamma}{6}\left(z_p - \frac{1}{6}\right)\right]^3 - 1\right\}$$

Where:

γ: skewness

RESCON 2 incorporates an empirical approach according to which skewness is equal to 2.5 times the coefficient of hydrologic variability, i.e.

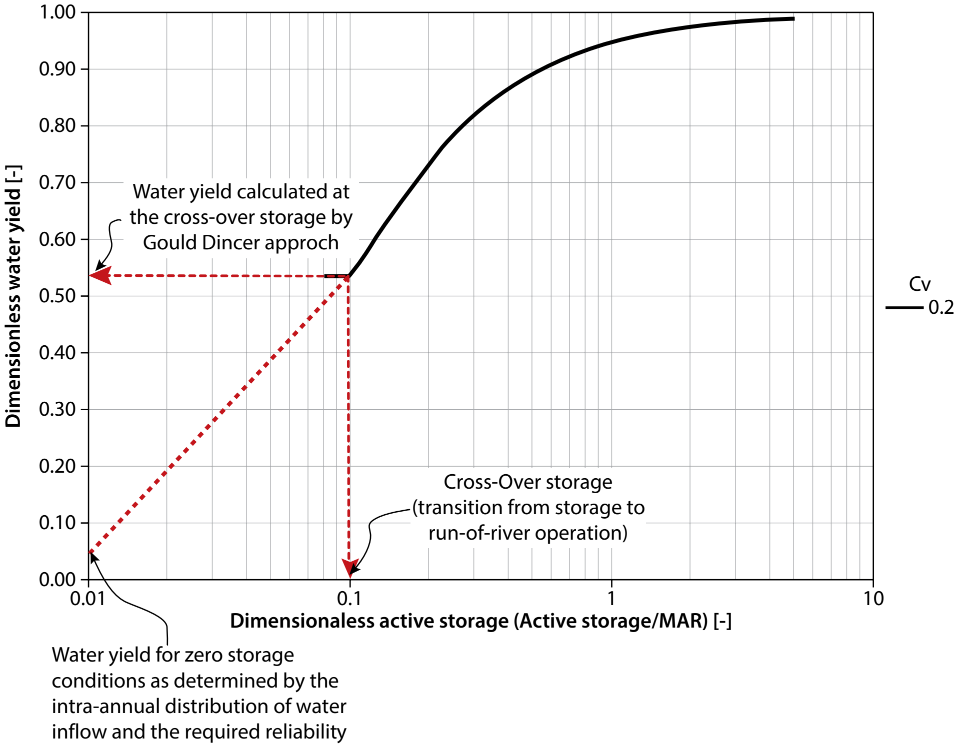
$$\gamma = 2.5\ C_v$$

If the annual inflow obeys the log-normal distribution, z_p in the previous equations is replaced by the log-normal variate z_{ln} which is calculated based on the following equation (Chow 1964).

$$z_{ln} = \frac{1}{C_v}\left[e^{z_p\sqrt{ln\left(1+C_v^2\right)}-0.5ln\left(1+C_v^2\right)} - 1\right]$$

A plot of the reservoir yield against available active storage is shown schematically in Figure 3.2. As reservoir volumes decrease due to sedimentation, the reliable yield also decreases.

Figure 3.2: Reservoir Capacity/Yield Relationship



It is pointed out that the water yield calculated with the aforementioned equations does not incorporate any water losses caused by sediment management activities. The reduction of the water yield due to sediment management is explained by the description of each individual method in chapter 4. Detailed information on how the water losses due to sediment management is incorporated in RESCON 2 analysis can be found in sections 4.3.6, 4.4.1.6, 4.4.2.6, 4.4.3.6, 4.4.4.6, 4.5.1.6, 4.5.2.6 and 4.5.3.6.

3.2.2 Unit price of water yield

The calculation of benefits from reservoir operation is based on the user specified unit price of water yield, expressed in US$/m^3.

If the value of this parameter is not available at the time of the model setup the user can find relevant methodologies for this assessment in Gibbons (1986) and Young (1996 and 2003). Thoughts on the valuation of benefits from reservoir operation are also presented at the last section 3.5 of the present chapter.

A range of water prices in various sectors and uses is included in the following sources: Dinar and Subramanian (1997), Ahmad (2000), OECD (1998a), OECD (1998b), OECD (1999), Jones (2000) and Savedoff and Spiller (1999), Dinar (2000).

Finally a compilation of observed prices from various countries and sectors, expressed in 1997 US$ values is provided in the table included in Annex 6. It should be emphasized that the values in the Table do not necessarily represent the true worth of water but are based on water prices that have been observed in various countries. Therefore, appropriate care and caution should be exercised when making use of these numbers.

3.3 Cost Calculation in Economic Models

Unit cost of reservoir construction c

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

$$c = \begin{cases} 11.835\ So_{gr}^{-0.519}, & So_{gr} < 2000 \\ 0.15, & So_{gr} \geq 2000 \end{cases}$$

Where:

c: unit cost of construction [US$/m^3 storage capacity (2010 estimates)]

So$_{gr}$: Pre-impoundment gross storage capacity of the reservoir [million m^3]

The calculated unit cost of construction (c) decreases as the original capacity (So) increases.

Cost of reservoir construction C2

The cost of reservoir construction is determined as the product of the user specified or internally calculated unit cost of reservoir construction and the pre-impoundment gross storage capacity of the reservoir.

Annual operations and maintenance cost C1

The annual operations and maintenance cost, C1 is specified by the user. If the exact value is not known at the time of model setup it can be assumed that the regular O&M cost is a function of the original construction cost of the dam. Thus, the annual operations and maintenance cost can be calculated as:

C1 = omc x C2

where:

C1: annual operations and maintenance cost, US$

omc: operations and maintenance coefficient is entered by the user. This coefficient usually varies between 1% and 3%

C2: cost of reservoir construction

Cost of sediment management

The incorporation of the cost associated with the application of sediment management in RESCON 2 analysis is described individually for each technique in sections 4.3.6, 4.4.1.6, 4.4.2.6, 4.4.3.6, 4.4.4.6, 4.5.1.6, 4.5.2.6 and 4.5.3.6 of the present manual.

Decommissioning cost

If the reservoir is non-sustainable and decommissioning is required the user can define the associated cost. If the provided value is positive, this means that the cost of dam decommissioning is higher than the benefits obtained from this activity. If contrary the provided value is negative this means that the costs associated with dam decommissioning are lower than the corresponding benefits.

For non-sustainable outcomes, the terminal year T is also determined by the program and is sensitive to sediment management parameters. In case decommissioning is required and salvage value is positive, i.e. an amount of money has to be paid at the end of reservoir lifetime for decommissioning, the annual retirement fund contribution is calculated as:

$$k = \frac{-m\ V}{(1+m)^T - 1}$$

Where:

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

V: salvage value of reservoir at its retirement. If V is positive this means than this amount of money has to be paid at the end of reservoir lifetime for decommissioning.

T: Terminal year of reservoir, i.e. year of decommissioning

RESCON 2 reports the calculated annual retirement fund that has to be paid by the generation that benefits the reservoir operation. It is pointed out however that the annual retirement fund is not part of the economic analysis, i.e. it is not considered as an annual cost associated with the reservoir operation.

3.4 Selection of Discount Rate

The discount rate is that interest rate with which future streams of costs and benefits are discounted to the present. The actual value of the discount rate is thus of great importance for projects with a very long time horizon, such as for example sediment management measures that extend the lifetime of a reservoir, as the Present Value (PV) of a future benefit (or cost) is lower the higher the discount rate is. Due to the way the PV is calculated, this effect is greater the further in the future the benefit occurs that is discounted. As a consequence, the level of the discount rate has a substantial impact on the economic viability of investment and measures for sedimentation management.

For a long time the selection of the discount rate for the economic analysis of International Financing Institutions (IFI), such as the World Bank, Asian Development Bank and others, has been carried out on the basis of efficiency considerations without taking into account inter-generational implications. This led to the use of so-called "efficiency" or "finance-equivalent" discount rates. It was based on the understanding that the project whose viability is assessed has a lifetime that stretches no longer than to the end of the current generation, which means a lifetime, dependent on the concrete (infrastructure) project, of 15-30, or 40 years at the most. Therefore, the finance-equivalent discount rate, represented by the investment rate of interest, which is the marginal rate of return on capital and reflects the opportunity costs of capital, usually formed the basis for the discount rate applied.

As a consequence, comparatively high discount rates have hitherto been used for economic project appraisal. Due to the many difficulties to precisely determine the exact level of the discount rate for a specific national economic environment, IFI usually used a fixed discount rate on the order of magnitude of 10%-12% for discounting in the economic analysis across all countries and all projects. In the case of the World Bank this rate is also understood as a kind of rationing device.

More recently, such a level of economic discount rates has been considered too high and generally questioned as a single parameter for all cases of economic appraisal of projects. This also relates to the World Bank and the Asian Development Bank. A lower discount rate is primarily advocated in connection with investment for combating long-term problems, mostly related to environmental impacts, such as global climate change etc., which have substantial impacts on future generations. Such a lower discount rate is known as the "social", "social-welfare" or "intergenerational" discount rate, as it takes into account a comparatively long time horizon and thus the impacts of a project on future generations.

There is, however, no common understanding or consensus of what the level or order of magnitude of this social or intergenerational discount rate should be. Neither is there a common understanding in literature as to whether a low constant discount rate should be used or a discount rate that declines over time. Therefore, both possible approaches are provided in the model.

Concerning a low intergenerational discount rate, often a prescriptive or normative determination of the rate is pursued, be it through direct prescriptive determination of the discount rate or by attributing prescriptive values to variables in the Ramsey formula, notably the pure time preference and the elasticity of the marginal utility of consumption (ibid., 6-13). Therefore, many studies also apply two different levels of an intergenerational discount rate.

In this context a brief word on a value of 0% for the intergenerational discount rate, which is occasionally also under discussion, might be required. As some of the intergenerational projects are considered providing infinite benefits (primarily projects preventing environmental hazards from climate warming; also the impact on reservoir volume from sedimentation management might be seen as an infinite impact, as discussed above), a zero discount rate "*could require the current generation to impoverish itself. ….Indeed, a zero discount rate implies that even a policy which costs $ 100 million now and gives just $1 to each future generation should be adopted*" (Harrison, 2010, 20), as there might be a potentially infinite number of future generations. Therefore, it does not seem appropriate to take a zero discount rate for economic analysis.

The World Bank has recently prepared and circulated a technical note on discounting costs and benefits in economic analysis.[1] Based on a welfare analysis of projects and with the assumption of a pure rate of time preference of zero, the World Bank now recommends using a 6% discount rate in the evaluation of World Bank projects. In addition the Bank also recommends carrying out a sensitivity analysis in order to identify the discount rate at which the project's Net Present Value (NPV) would become negative. Furthermore, the Bank also concedes that there might be cases in which a lower or a higher discount rate might be justified, but the usage of such rates would need to be supported by its rational.

Based on these considerations, in the model a 6% discount rate has been set as default value. In addition, the user shall carry out one or several sensitivity analyses with another (or other) discount rate(s). We recommend a 3% discount rate for the main sensitivity case.

For projects with a time horizon that stretches over more than one generation, a declining discount rate might be applied as an alternative to a low constant discount rate.

The issue of a discount rate declining over time has been substantially discussed in literature over the past 10-15 years. Declining discount rates are based on the assumption of uncertain future discount rates and can be calculated as certainty-equivalent discount rates. Various concrete series of declining discount rates have been worked out so far by different authors and also by national authorities, such as the UK Treasury. It is, however, practically impossible to consider one of the schedules as more "reliable" or "accurate" than any other.

Johnson and Hope present two declining discount rate schedules, one applied by UK Treasury, based on the assumption of a zero rate of pure time preference, and the other developed by Weitzman in a 2009 publication (Johnson and Hope 2012, 2014). As the Weitzman schedule includes a zero discount rate from year 300 onwards, this schedule is discarded for the reasons

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[1] World Bank (2016): Technical Note on Discounting Costs and Benefits in Economic Analysis of World Bank Projects.

discussed above. Therefore, it is suggested applying the series of declining discount rates as used by UK Treasury. This includes the following sequence:

0–30 years	3.0%
31–75 years	2.57%
76–125 years	2.14%
126– 200 years	1.71%
201–300 years	1.29%
301+ years	0.86%

The user can specify a different declining discount rate sequence if required.

It is recommended that the user of the RESCON 2 model carries out the economic analysis in addition to the 6% discount rate with a sequence of declining discount rates. The model, to this end, foresees a switch between a constant discount rate and the declining discount rate.

3.5 Guidelines for valuation of benefits from reservoir operation

Reservoirs generate various types of benefits, depending on the purpose for which the reservoir and the related dam have been constructed. The major direct benefits thus are:

- Supply of drinking water to the water supply system.
- Supply of water for irrigation.
- Flood control.
- Hydropower generation.

In the case of multi-purpose reservoirs, two or more of these benefits are obtained. The type of benefits listed is the same no matter which technique of sedimentation management is applied and independent of the fact whether sedimentation management is applied or not. The difference lies in the level or quantity of annual benefits and the time horizon during which the benefits can be harvested.

The user will thus have to identify all the direct benefits that are created by the reservoir for each of the various techniques for sedimentation management on an annual basis and over the technical lifetime of the reservoir. The quantity of the benefits will depend on the capacity of the reservoir and the quantity of water yield from the reservoir, which will differ from one technique for sedimentation management to the other. The identified physical benefits will then be valued in line with the price at which a specific output is sold.

For reservoirs that are constructed for the supply of water, the price for the sale of water represents the value of the benefit. This is applicable for both reservoirs that supply water for irrigation and reservoirs that supply water to final domestic, industrial and commercial customers. In the case of drinking water supply it is again not the price that is paid by the final customers, as this includes the costs for transport and distribution of the water. Therefore, it is the price paid by the bulk water off-taker that then transports and distributes the water to the final customers. Should the entity that operates the water reservoir also supply the final customers (so that there is no bulk water off-taker and thus no price that such a bulk water off-taker pays), the relevant costs for water transport and distribution have to be deducted from the water price that the final customers pay to obtain the correct value of the benefit of the water yield from the reservoir.

In the case of reservoirs for flood control, the benefit consists in the damages that are avoided by the dam and the reservoir. The calculation or estimate of these benefits are not as straightforward as for reservoirs for hydropower generation and water supply. The benefits actually depend on the area covered in the case of inundation, the amount of dwellings and industrial and public infrastructure affected, their values, the severity of flooding and the likelihood of occurrence.

In the case of hydropower generation, the benefit is determined by the sales price for electricity from the hydropower plant. In the case of hydropower, the sales price from the hydropower plant might vary over time and might be higher at times of peak demand.

It is necessary to keep in mind, when calculating the benefits in the way just outlined, that only the net benefit can be assigned to the reservoir and to sedimentation management. This means that the costs for the operation and maintenance of the reservoir on the one hand and the additional costs for producing the final goods or services beyond the cost of water on the other hand need to be deducted from the gross benefits (in particular the cost of the power generator needs to be deducted from the revenues from the sale of power). These costs need to be deducted in addition to and above the deduction of the costs of power and/or water transmission and distribution, as described above.

The net benefits in the no action case and the different sediment management cases will need to be included in the economic analysis over the entire time horizon over which the reservoir actually provides the said outputs. The respective time horizon for each type of sediment management is determined as an element of the model.

A final effect that also needs to be included in the economic analysis occurs at the end of the project's time horizon. This effect results from decommissioning of the reservoir and can be positive or negative. One can usually expect a negative value, as decommissioning in the sense of removing the existing (civil) structures incurs costs. Occasionally, however, a salvage value of the leftovers and a possible value of the land gained through decommissioning might lead to a positive benefit. The user, thus, has to make reasonable assumptions as to what might happen with the area of the reservoir after its decommissioning.

The RESCON 2 model operates, as was the case for RESCON, on the value side with the quantity of water yield from the reservoir under different sediment management techniques. The benefit value that is entered into the model is thus the value per cubic meter of water yield. It will therefore be necessary to convert the monetary benefits as derived from the sale of electricity generated, water supplied, etc. into a value per cubic meter of water yield. This can easily be done by dividing total annual benefit from the reservoir for the different measures for sedimentation management by total annual water yield from the reservoir, which leads to the unit value per cubic meter.

Two more aspects need to be taken into account by the user in the process of determining and valuing the benefits. The first is related to a possible valuation on the basis of opportunity cost considerations, the second concerns other, indirect benefits from sediment management. Both these issues are outlined in the following.

Economic analysis often applies opportunity cost approaches when valuing the benefits of a project. The values proposed above for benefit calculation that are taken from the market are thus only an approximation, proposed for the sake of simplicity of calculation. The problem with values based on opportunity cost considerations is that, although in theory various economic concepts exist for the determination of opportunity costs, in practice these opportunity costs can mostly not be realistically calculated due to a lack of empirical data and information. This leads, therefore, often, if not usually to the consequence that opportunity cost concepts can actually not be applied to this end. Their results would not be accurate enough or would lead to an ambiguous value.

However, if the user of the RESCON 2 model is of the opinion that the available empirical data can ensure a proper accuracy of results, he or she might prefer to apply such an opportunity cost approach to the approach outlined above. In practice in particular two concepts for the determination of opportunity costs can be seen as potentially applicable for the user. One is the willingness-to-pay and the other the depletion premium approach. Furthermore, for reservoirs used for irrigation a third concept based on the value of agricultural outputs is conceivable.

The willingness-to-pay concept is based on the notion that, for some consumers, the actual benefit from the consumption of a good (this could be electricity from the hydropower plant or water for irrigation or drinking purposes) is higher than its sales price, so that these consumers would be willing to pay more for electricity or water than they are actually required to pay on the market. The difference between the sales price in the market and the willingness-to-pay is the so-called “consumer surplus”. The theoretical background of the existence of such a consumer surplus is the fact that the demand curve of the good considered is negatively sloping. In practice, however, it is rather difficult to determine the exact location and slope of the demand curve and thus the exact level of the consumer surplus and the willingness-to-pay, so that in reality this concept is likely to be applicable only in a limited number of cases, if at all. Also alternative means to determine the willingness-to-pay, for example through contingent valuation, based on surveys, might not help much in the situation at hand here. If, however, a user is able to apply the willingness-to-pay concept, the results would replace the sales prices mentioned above for the valuation of the benefits.

The concept of the depletion premium is based on the notion that, if the capacity of a water reservoir is depleted due to the fact that no sedimentation management is conducted, the scarcity of reservoir capacity would make the erection of new reservoirs necessary that compensate the depleted one. This could be done only at higher costs. Therefore, these additional avoided future costs would have to be added to the benefits from the sale of the output from the reservoir in the case the reservoir capacity (or part of it) is maintained through sedimentation management measures. Again, also here the application of such a depletion premium concept will hardly be possible in practice, as the necessary empirical information on potentially new reservoirs and the costs for their erection cannot be expected to be available to the user of the model. It is also conceivable that, if the reservoir is used for the supply of drinking water and will be exhausted due to the lack of sediment management, the depletion premium is calculated on the basis of the costs for the provision of drinking water from other sources. This can be expected to be drinking water from desalination plants, so that the incremental costs of producing drinking water in desalination plants form the basis for the depletion premium. Such calculation, too, would be very difficult for the user to perform in practice.

For reservoirs for irrigation, the actual benefits can also be valued on the basis of the value of the crops grown on the irrigated area. This can be assumed to be above the price of water for irrigation, as an added value is generated that is caused by the irrigation water. In practice, however, it might also for this concept be difficult to obtain the necessary empirical data and properly forecast future quantities and prices of agricultural products and the pattern of agricultural production. If such an approach is pursued by the user, also here it has to be kept in mind that only the net benefits can be attributed to the reservoir and all other types of costs for producing the final agricultural products need to be deducted from the sales revenues, such as seeds, fertilizer, human labor, animal labor, etc.

Reservoirs, depending on the purpose they are used for, can also create important secondary effects. One such indirect effect, in the case of use of the reservoir for hydropower generation, is related to the avoidance of adverse environmental impacts. Sedimentation management in reservoirs that are used for the production of hydropower as a renewable energy source leads to the avoidance of emissions of CO_2, NOx, SO_2, particulate matters and other hazardous substances that would be emitted by alternative forms or power generation based on fossil fuels, if the additional water yield was not available for hydropower generation. It is, therefore, recommended that the user of the Model takes these benefits into account in the economic analysis by, first, identifying the quantities of avoided hazardous environmental substances (at least for the most important one, CO_2) and, secondly, attributing an appropriate monetary value to the avoided quantities. The user shall also take into account that the impoundment of a shallow reservoir in a location with dense vegetation may increase the output of CO_2, at least in the first years of operation.

Concerning the avoidance of CO_2 emissions it is suggested that the estimate of avoided quantities is based on the most recent approved CDM methodology for grid-connected electricity generation from renewable sources. This would mean that the baseline emissions are therefore calculated by multiplying the expected additional electricity fed into the grid (i.e. from the reservoir as a result of the sedimentation management) by the grid emission factor of the country in which the reservoir is located. The grid emission factor represents the CO_2 emissions that are released on average by generating 1 MWh of electricity fed into the grid. The grid emission factor shall be taken from baseline studies carried out for the specific country (and, if possible, validated in line with UNFCCC requirements).

Concerning the value of one ton of avoided CO_2 emissions ("the social cost of carbon") an intensive discussion can be found in literature, together with a wide range of actual values proposed. A 2014 Working Paper of the International Monetary Fund (IMF) finds that the nationally efficient CO_2 price among the top twenty emitters averages US-$57.5 per ton, and a US government study (US IAWG 2013) puts the global damage from CO_2 emissions at US-$35 per ton.[2] Earlier, IMF had suggested a lower value of US-$25 per ton of CO_2 emission reduction.[3] We recommend that the user of RESCON 2, if including the benefits from the avoidance of CO_2 emissions resulting from sedimentation management, clarifies whether recent national values are available for this parameter in the country where the reservoir is located and then uses this specific value for benefit calculation. Should such a national value not be available, we recommend using a conservative value, best in the order of magnitude of some US-$25 per ton of CO_2 in line with earlier IMF suggestion.

3.6 Economic Optimization Framework

If the User does not explicitly explicitly the implementation schedule of sediment management RESCON 2 determines the implementation schedule that maximizes the economic performance of the reservoir through an internal economic optimization procedure.

The following optimization is performed for each technique with exception density current venting.

$$\textit{Maximize} \sum_{t=0}^{T} NB_t \, d^t - C2 + V \; d^T$$

Subject to: $S_{t+1} = S_t - M + X_t$

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[2] Parry, Ian/Veung, Chandara/Heine, Dirk: How Much Carbon Pricing is in Countries' Own Interests? The Critical Role of Co-Benefits, *IMF Working Paper 14/174*, September 2014; p. 5. In needs to be seen, however, that the IAWG value depends on the chosen discount rate.

[3] Litterman, Bob (2013): "What is the Right Price for Carbon Emissions?", *Regulation*, Vol. 36 No. 2, p. 38.

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 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 for calculation of the net benefits are provided in chapters 3.2 and 3.3.

CHAPTER 4

Sediment Management Alternatives

4.1 Introduction

This chapter presents the methodology applied by RESCON 2 for the assessment of different sediment management techniques. This assessment provides answers to the following questions:

- What is the reservoir storage development if a specific sediment management technique is applied?
  - Is this sediment management technique technically feasible?
  - Can the reservoir become sustainable?
    - If yes, what is the long term sustained reservoir storage capacity and when is it reached?
    - If no, what is the prolonged reservoir lifetime?
- What is the economic performance of the reservoir if this sediment management technique is applied?
  - What is the aggregate Net Present Value of the reservoir
  - How is the economic performance of the reservoir maximized for this specific sediment management method.

RESCON performed an evaluation of methods belonging only in the family of sediment deposit removal. This involved an evaluation of the technical feasibility as well an assessment of the economic performance of the reservoir for the following sediment management techniques:

- Flushing
- Dredging
- Hydrosuction removal
- Trucking

RESCON 2 incorporates the possibility to evaluate an extended palette of sediment management methods. The analysis performed by RESCON 2 is not limited only to the possibility to remove sediment deposits in order to restore lost storage, rather it is expanded to additional options involving the reduction of sediment inflow as well the reduction of sediment deposition. The added methods are:

- Catchment management
- Sediment routing
  - Sluicing
  - Sediment by-pass
  - Density current venting.

Although there are broad similarities, each management option has a few distinguishing characteristics that merit attention. For each sediment management technique incorporated in RESCON 2 the following points are herein presented.

- Short technical description of the sediment management technique.
- A preliminary screening tool.
- How is the technical feasibility assessed by RESCON 2.
- Parameters involved in the assessment and how they affect the development of reservoir storage.
- The economic formulation used for determination of the net present value of annual revenues and costs and optimization framework for maximization of the aggregate net present value.

Possible time paths of usable storage capacity vary by sediment management option and are presented below. For a more detailed presentation of the available techniques the interested reader is referred to Annandale et al. (2016), which provides an outline of the available sediment management alternatives.

4.2 No Action

Under this management alternative there is no sediment management plan implemented. The reservoir storage is reduced as sediment accumulates and eventually one of two possible outcomes will occur:

- Decommissioning of the facility.
- Use of the facility as a run-of-river scheme.

In the case of decommissioning, the dam is removed the year after the gross reservoir storage is fully eliminated. This year the salvage value of the reservoir is discounted. The program also calculates an annual retirement fund based on the salvage value and the timing of the dam removal with use of the especially dedicated for this purpose discount rate. The annual retirement fund shall be considered only if the economic analysis is performed with a fixed discount rate higher than 3%. If the declining discount rate or a low fixed discount rate is used, it shall be considered that the issue of intergenerational equity is covered by the application of the two aforementioned discounting concepts.

In the case of run-of-river operation, it is assumed that the entire reservoir capacity is depleted by sedimentation before such operation begins. It is also assumed that run-of-river benefits are available only if the reservoir has a power generation facility. An annual retirement fund is not calculated as the facility is maintained forever under run-of-river operations.

4.3 Catchment Management

4.3.1 Technical description

Catchment management can be used with the purpose to reduce the sediment inflow in the reservoir and hence the prolongation of its lifetime due to the reduced annual sediment deposits. The catchment management methods comprise the following two groups of techniques:

- Watershed management with the aim to reduce the surface soil erosion, which is one important sediment source. This can be achieved with the implementation of:
    - improved agricultural practices
    - reforestation
    - de-intensification of land use practices
- Implementation of check structures on mountainous streams upstream of the reservoir.

The first group of methods, i.e. watershed management has an impact on suspended sediment inflows. Larger catchments are characterized by lower sediment delivery ratios. Therefore the effect of soil erosion control measures in large catchments on sediment inflow in a reservoir might only become apparent after many years.

The second group i.e. the implementation of check structures, such as sabo dams or small retention basins, has a larger impact on coarse grained bedload transport, while it is not possible to reduce essentially the suspended load because the storage capacity of the basins impounded behind these structures is usually limited and it is characterized by a low trap efficiency for suspended particles. The reason for this is that these structures will normally be constructed in steep mountainous streams with a torrential character. This group of catchment management methods is usually characterized by an immediate impact on bedload transport. The sustainability of this method depends on the accessibility of the structures and their regular maintenance, i.e. the restoration of their capacity in order to trap the incoming bedload. If the small retention basins are not regularly cleared from deposits, they will be filled within few years and the bedload inflow will return to the pre-catchment management values or eventually to slightly lower values due to a reduction of the average longitudinal river bed gradient.

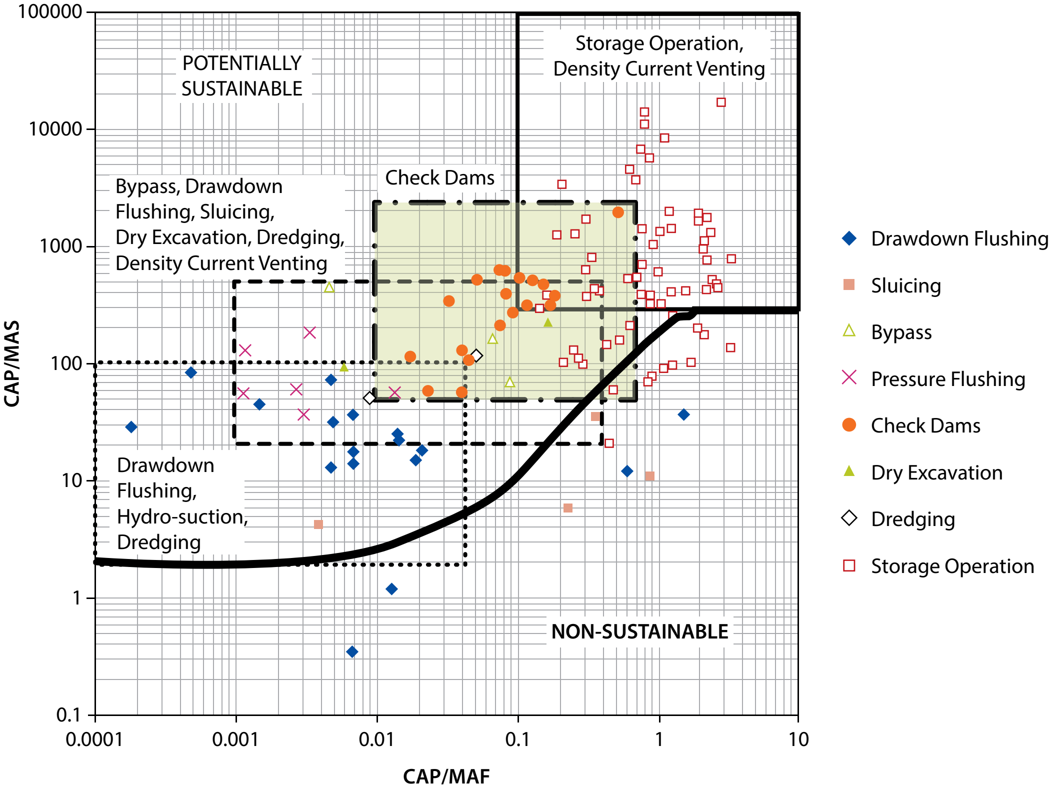
RESCON 2 incorporates a screening method to evaluate the potential of catchment management to reduce the storage loss rate of a reservoir. The developed screening tool accounts for the method that will be applied, the individual impact on suspended and bedload transport and the time lag between the implementation of catchment management measures and the appearance of their effect on sediment inflows in the reservoir.

4.3.2 Preliminary assessment

A preliminary assessment of the suitability of catchment management and specifically the case of construction of check dams for retention of bedload upstream of the reservoir can be performed by the diagram published by Annandale (2013). In this figure, CAP annotates the reservoir gross storage capacity expressed in m³, MAS expresses the mean annual sediment inflow expressed in m³/a and MAF the mean annual runoff expressed also in m³/a.

Catchment management by check dams is considered to be potentially effective when the following pre-requisites are fulfilled:

Figure 4.1: Preliminary assessment of catchment management suitability



Source: Annandale (2013)

- The hydrologic reservoir size defined as the ratio of reservoir capacity to mean annual runoff ranges between 0.01 and 0.7.
- The ratio of reservoir capacity to mean annual sediment inflow, which provides an indicator of the reservoir life span lies between 50 and 2,500.

The boundaries of the aforementioned indicators within which the implementation of check dams is considered to be a sediment management method worth to be investigated are shown schematically in the figure above.

4.3.3 Parameters in RESCON 2 analysis

The parameters provided in the Table 4.1 are used for the calculation of the reservoir storage development and the economic performance of the facility if catchment management is applied.

Table 4.1: Parameters used for assessment of the impact of catchment management on storage development and economic performance of the reservoir

Parameters specifying efficiency of catchment management		
CM_Method	[-]	Catchment management method
MASb reduction	[%]	Expected reduction of bedload inflow in reservoir due to catchment management
MASs reduction	[%]	Expected reduction of suspended load inflow in reservoir due to catchment management
Year MAS reduction Start	[Years]	How many years after its implementation will catchment management affect sediment inflow in reservoir?
Costs for implementation of catchment management		
C_CM	[US$]	Costs for implementation of catchment management measures
OMC_CM	[US$/a]	Annual operation and maintenance costs of catchment management
Scheduling of catchment management implementation		
Shall the implementation year of catchment management be determined through economic optimization?		
Year CMstart	[years]	Implementation year of catchment management
User defined constraints in application of catchment management		
CL_CM	[%]	Maximum allowable storage loss before implementation of catchment management

4.3.4 Technical feasibility and implementation constraints

Catchment Management with the aim of reducing sediment inflows into a reservoir is considered to be always technically feasible. This means that it is possible to construct the necessary structures such as check dams or implement improved catchment management practices that will lead to a reduction of the bedload and suspended load inflow to a reservoir. This assumption however should be confirmed by the user on basis of specialized engineering judgment.

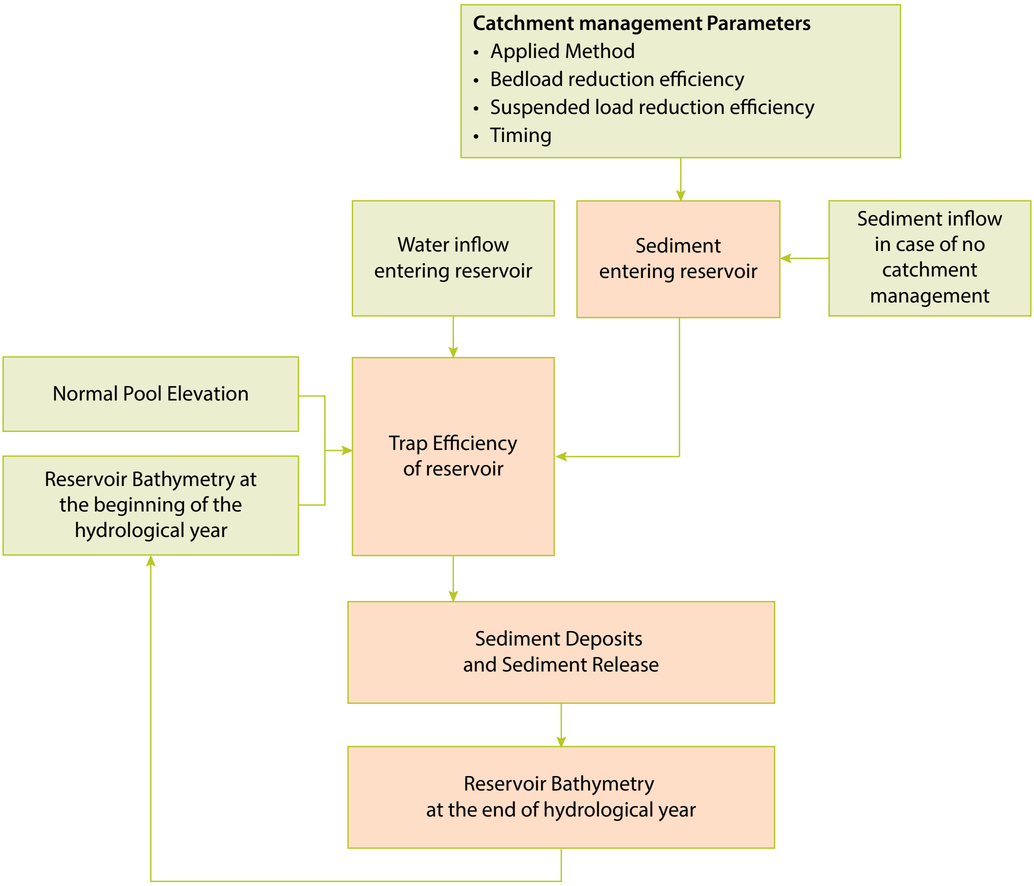
The user can either define explicitly the catchment management implementation year or let RESCON 2 find the optimal timing which maximizes the economic performance of the reservoir. At the same time it is possible to specify a constraint regarding the latest possible implementation year. This constraint is expressed as the maximum allowable reservoir capacity loss before implementation of catchment management and is specified by the parameter CL_CM. RESCON 2 will calculate the development of reservoir storage if no sediment management is applied and will determine the year by which the maximum allowable storage loss is reached. This year is the latest possible catchment management implementation year.

If the user defines explicitly the timing of implementation of this sediment management method and the specified implementation year is later than the previously calculated latest possible implementation year, the calculations will stop and the user will be accordingly informed.

4.3.5 Sedimentation development

The reduction of reservoir storage is estimated by RESCON 2 by application of the procedure which is summarized in Figure 4.2.

Figure 4.2: Computational procedure incorporated in RESCON 2 for the assessment of reservoir storage development when catchment management is applied



The computational procedure comprises the following steps:

Step 1: Calculation of reduced sediment inflow in reservoir in case of catchment management

The user will provide the necessary input that will allow the calculation of sediment inflow in reservoir after implementation of the catchment management. This includes the following parameters:

- The method that is intended to be applied for the purpose of reducing the sediment inflow into the reservoir. The following options are available:
  - Construction of Check Dams
  - Reforestation
  - Implementation of improved agricultural management practices
  - De-intensification of land use practices
  - Combination of methods
- The expected bedload reduction expressed as percentage of the pre-catchment management bedload inflow.
- The expected suspended load reduction expressed as percentage of the pre-catchment management suspended load inflow.
- The expected timing of appearance of the impact of catchment management on the sediment inflows in the reservoir.

General and not binding guidance for the selection of the aforementioned parameters is shown in Table 4.2.

These values are only general recommendations derived from the review of relevant case studies published in the literature (Alatorre et al. (2012), Keesstra et al. (2009), Lakel et al. (2010), Quiñonero-Rubio (2014), Wang et al. (2011), Wark & Dixon (2012) a.o.) and are intended to provide only a general guidance in case no relevant data or studies are available. The quantification however of catchment management efficiency is a task depending strongly on site specific data input and requiring numerical modeling of surface erosion and sediment transport in the catchment upstream of the reservoir. Therefore

Table 4.2: Suggestions implemented in RESCON 2 regarding the impact of different catchment management methods on suspended load inflow in reservoir

Catchment Management Method	*Reduction of bedload*	*Reduction of suspended load*	*Timing of appearance of impact*
Check Dams	up to 100%	0%	Immediate
Reforestation	10%	30%	> 3 years after implementation
Improved agricultural management practices	10%	30%	>3 years after implementation
De-intensification of land use practices	10%	30%	>3 years after implementation
Combination of methods	50%	30%	Immediate

specialized engineering judgment should be consulted before model set-up for the selection of the parameters specifying the efficiency of catchment management. For instance, the time lag between implementation of catchment management and realization of reduction of sediment loads in the case of the Yellow River or Mangla dam was essentially longer than three years. The expected reduction in sediment load and timing of impact appearance provided by the user will be used for the calculation of bedload and suspended sediment inflow in the reservoir even if they deviate from the aforementioned recommendations. Finally, the sediment inflow to the reservoir after implementation of catchment management will be internally calculated on basis of the provided expected percent reduction and the user defined sediment inflow in the reservoir in the pre-catchment management era. It is assumed that the water inflow to the reservoir will not be affected from the implementation of catchment management techniques.

Step 2: Trap efficiency and sediment deposition

The calculations in this step are performed with the previously determined reduced sediment inflow if the year considered is later than the first year of appearance of impact of catchment management on sediment inflow. The mean velocity calculation is based on the user defined mean discharge and the water depth corresponding to the normal operating water level. The trap efficiency can be calculated either with the method of Brune or Churchill or Borland.

The sediment deposits and associated sediment release are computed according to the method already presented in chapter 2.1.3. The reduced sediment inflow as calculated in the previous step is used in this calculation. Finally the bottom elevation of the reservoir compartments at the end of the hydrological year is calculated and used as data input for the hydrological year to follow, until the storage is eliminated or reaches an equilibrium between sediment inflow and reduced trap efficiency due to storage reduction.

4.3.6 Economic formulation

The benefits from the reservoir use are calculated on basis of the water available for use (yield) and the user defined unit price of one cubic meter of water yield.

The water yield from the reservoir and hence the benefits for a given reliability and inflow variability are reduced as the reservoir capacity is also reduced due to sediment deposits. This relationship is implemented in the model with the Gould-Dincer method. According to this relationship, the volumetric reservoir yield at time t is a function of the remaining reservoir active storage capacity at that time, statistical parameters relative to reliability and inflow variability as well the mean annual water inflow to the reservoir expressed as a volume.

In case of catchment management, as explained in the previous chapter, the water inflow in the reservoir is not affected by the implementation of measures for control of surface soil erosion and bedload transport in the hydrographic network of the catchment upstream of the reservoir. For this reason it is assumed that the water yield from the reservoir will not be reduced due to the implementation of catchment management measures. The lack of water losses in accordance with the slower rate of storage loss due to catchment management results in higher and prolonged benefits compared to the case of no sediment management.

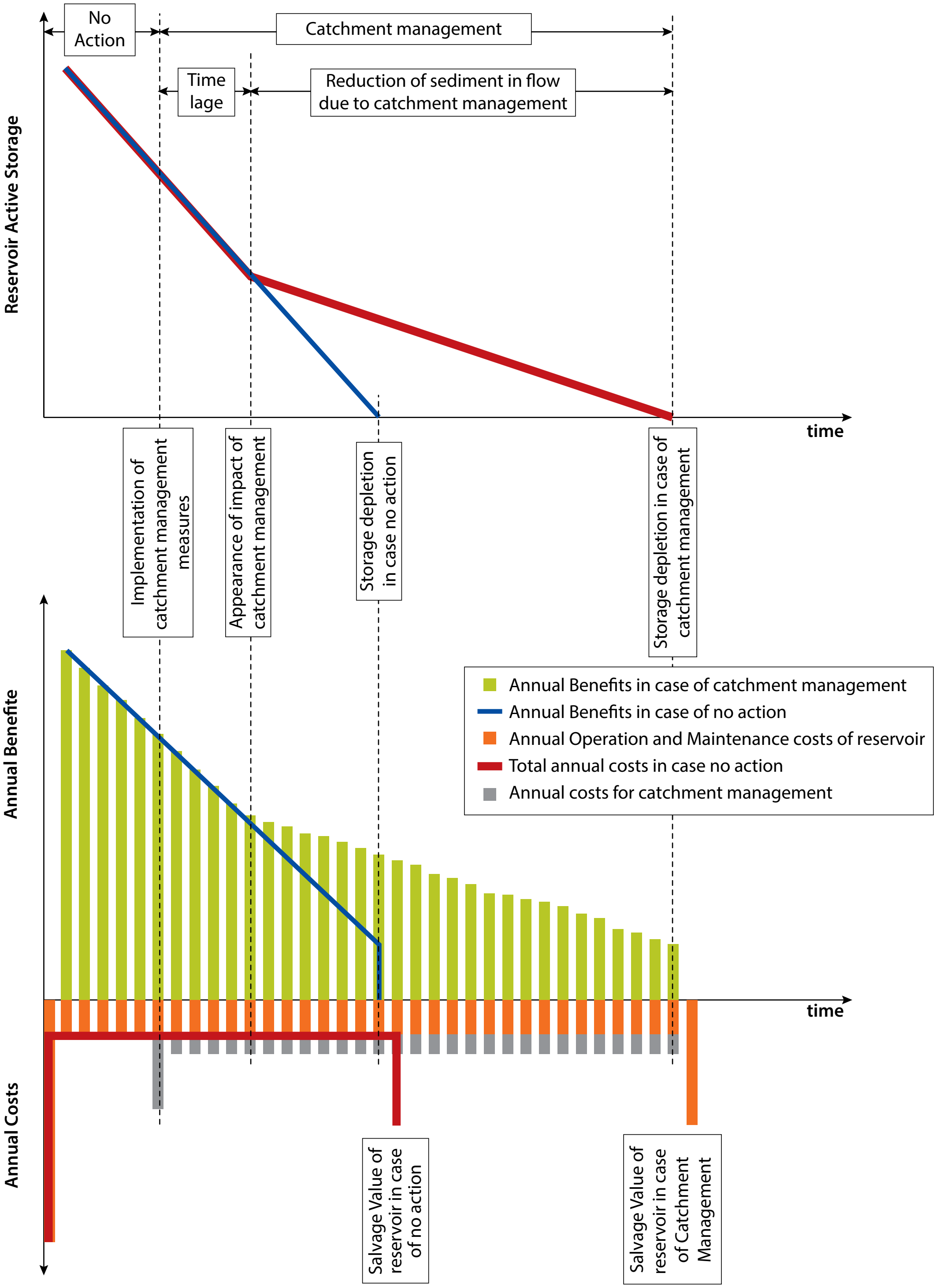
The implementation of catchment management is associated with additional costs for the implementation of these measures as well as with additional annual maintenance costs. The extent of these costs depends on several parameters such as the implemented method, the extent of the area where these measures will be implemented, accessibility and others. The planning of catchment management measures and the determination of their costs shall be the outcome of a detailed study performed by water resources specialists. Considering the rapid analysis character of RESCON 2, the user is asked to insert these costs, i.e. the capital expenditures for implementation and the annual costs for maintenance optionally in order to be accounted in the discounting with the purpose to determine the net present value.

A comparison of the development of annual benefits and costs over time for the cases of no action and catchment management is shown in Figure 4.3. In the lower part of the figure, the bars represent the annual benefits and costs for the case of catchment management and the blue and red lines represent the annual benefits and costs for the case of no action respectively.

At year 0, i.e. prior the first year of reservoir operation the investment cost of the reservoir is considered. This cost is neglected if the user declares that the reservoir is existing and we do not have a green field project. One year after the reservoir storage elimination, the salvage value of the reservoir is included in the annual costs. The salvage value includes any costs or benefits might occur as soon as the reservoir is totally filled with sediment. This might include the costs for dam removal and associated costs for mitigation of environmental impacts. It may include also any benefits which might be involved in the decommissioning of the reservoir, such as benefits from the dismantled equipment, the agricultural land that might replace the reservoir pool and similar. The determination of the salvage value should be determined by a separate study. In RESCON 2, this value is directly inserted by the user and it shall be positive if the costs of dam decommissioning are higher than the according benefits when the storage is fully depleted. The salvage value shall be negative when the decommissioning costs are lower than the benefits.

The second scenario investigated by RESCON 2 with regards to costs and benefits after full siltation of the reservoir is the case of Run of River operation of the hydropower plant. This scenario is studied only when the reservoir is used for generation of hydroelectricity.

Figure 4.3: Comparison of development of storage and annual benefits and costs for the case of no action and the case of catchment management



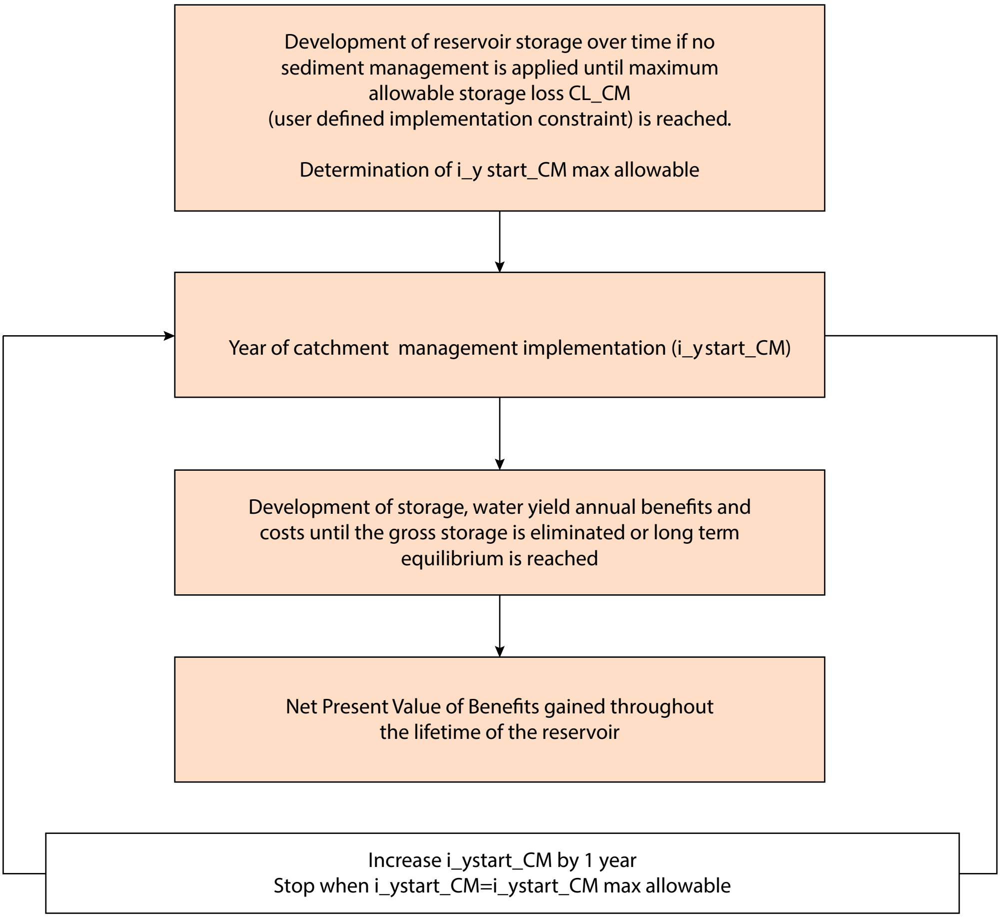
4.3.7 Optimization framework

RESCON 2 provides the user with the possibility to determine the timing of implementation of catchment management through economic optimization.

The procedure of economic optimization comprises one computation loop during which the year of catchment management implementation is varied. For each value of this parameter the reduction of reservoir storage is calculated until it is eliminated or until equilibrium between sediment inflow and sediment release is achieved. The knowledge of the temporal development of storage capacity allows the calculation of annual costs and benefits from reservoir use. When discounted over time they lead to the Net Present Value of Benefits gained from reservoir use if catchment management is applied for the tested timing. The value of the commencing year of implementation that maximizes the Net Present Value of Benefits is selected as the optimum catchment management strategy.

The internal optimization is summarized in Figure 4.4.

Figure 4.4: Economic optimization procedure for selection of optimum catchment management strategy



The user is able to limit the range within which the subject to optimization parameter is varied. This is achieved by a technical constraint on the capacity loss allowable before implementation of catchment management. This is realized through the parameter CLCM (maximum percentage of allowable capacity loss in case of catchment management). For instance, if the user specifies CLCM as 30%, RESCON 2 will determine after how many years the reservoir loses 30% of its initial capacity if no sediment management is performed. Catchment management has to be implemented prior to this year, i.e. before 30% of the initial storage capacity is lost. Therefore, the optimization procedure will vary the implementation year until this constraint is reached in order to determine the optimum strategy.

4.4 Deposition Removal

4.4.1 Flushing

4.4.1.1 Technical description

Flushing involves the remobilizing of deposited sediments by increasing te flow velocity in the reservoir. The entrained deposits are discharged downstream of the reservoir through low-level outlets. The flow velocity is increased by drawing down the reservoir water level through a suitably designed outlet structure. There are typically two approaches:

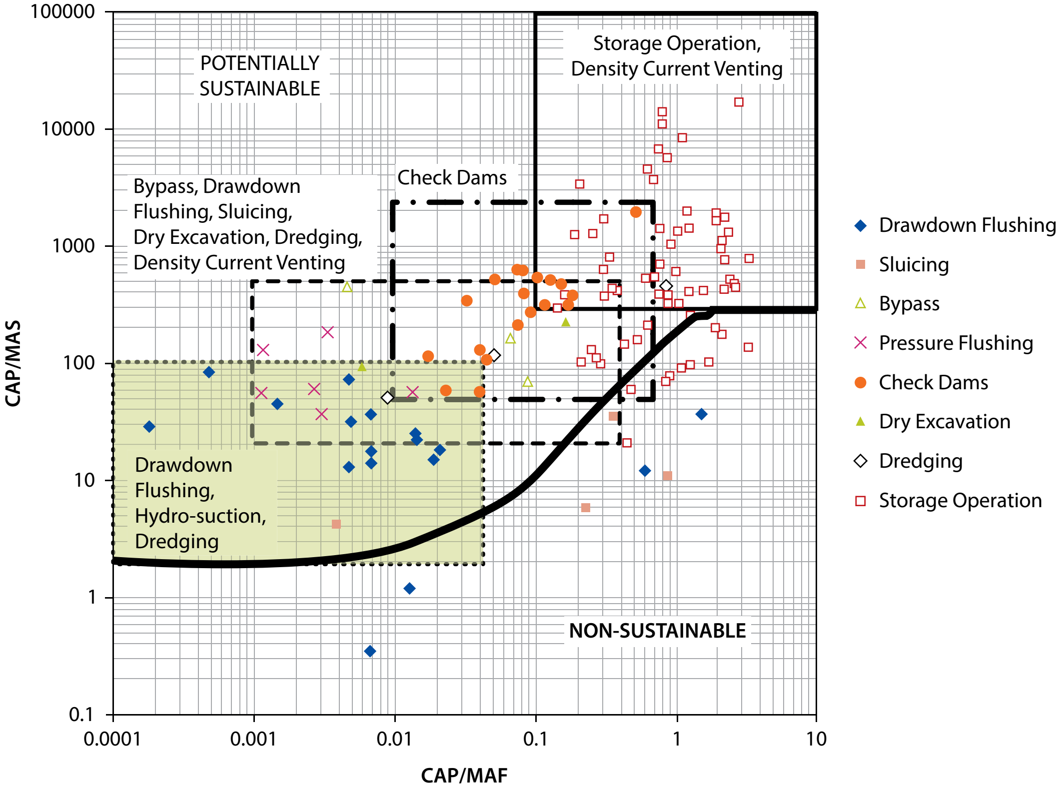
- Complete drawdown, where the reservoir is emptied completely.
- Partial drawdown, where the reservoir is partially emptied (pressure flushing).

During flushing with complete drawdown, a river channel is eroded through the sediment deposits. Usually, the width and slope of the scoured channel will approach the slope and width of the main channel existing before the reservoir impoundment. These original regime conditions can be maintained with periodic complete drawdown flushing operations.

Flushing without or with partial water level drawdown (pressure flushing) has only local effect and therefore aims at protecting hydraulic structures located in the vicinity of the outlet structure from blockage due to sedimentation. During flushing with partial or no water level drawdown, a funnel-shaped crater develops. The spatial extent of the crater is determined by the angle of repose of the sediment and the elevation of the outlet.

RESCON 2 performs an assessment of the full water level drawdown case. It is considered that flushing is implemented by opening low-level outlets and drawing down the water surface elevation behind the dam almost completely 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 depending on the reservoir shape and slope.

Figure 4.5: Preliminary assessment of flushing suitability



Source: Annandale (2013).

4.4.1.2 Preliminary assessment

Based on observations of flushing operations in reservoirs of different sizes, flushing will be eventually effective when the following pre-requisites are fulfilled:

- The hydrologic reservoir size defined as the ratio of reservoir capacity (CAP) to mean annual runoff (MAF) ranges between 0.0001 and 0.04.
- The ratio of reservoir capacity (CAP) to mean annual sediment inflow (MAS), which provides an indicator of the reservoir life span lies between 2 and 100 years.

The boundaries of the aforementioned indicators of effective flushing are shown schematically in the Figure 4.5.

4.4.1.3 Parameters in RESCON 2 analysis

The parameters provided in the Table 4.3 are used for the calculation of the reservoir storage development and the economic performance of the facility if flushing is applied.

Table 4.3: Parameters used for assessment of the flushing efficiency and the economic performance of the reservoir

Parameters determining efficiency of flushing		
Y	[-]	Indicator of deposits type
Ans	3 or 1	Sediment removal difficulty
Elfl_dam	[masl]	Water elevation at dam during flushing
Qf	[m^3/s]	Representative flushing discharge
Tf	[days]	Duration of flushing after complete drawdown
Cal_SSfl	[-]	Calibration parameter for Mignot equation used for estimation of side slopes of scoured channel
Water losses and costs for implementation of flushing		
s1	[%]	Fraction of run-of-river water yield the year flushing is performed
s2	[%]	Fraction of storage water yield the year flushing is performed
FI	[US$]	Cost of capital investment
OM_FL	[US$/a]	Annual operation and maintenance costs of flushing
Scheduling of flushing implementation		
Shall the implementation strategy of flushing be determined through economic optimization?		Yes No
CycleNS	[Years]	Time interval between flushing events during the 1st phase (Reservoir storage = sustainable long term reservoir capacity)
CycleS	[Years]	Time interval between flushing events during the 2nd phase (Reservoir storage = sustainable long term reservoir capacity)
User defined constraints in application of flushing		
CLF	[%]	Maximum percent of capacity loss allowable

The reservoir storage development if flushing is applied depends on the following parameters:

- The annual deposits occurring during the normal operation of the reservoir.
- The efficiency of flushing, i.e. the amount of deposits that can be removed during a flushing event.
- The implementation strategy of flushing, i.e. how often is flushing applied.

The efficiency of flushing depends on the type of the deposits and the hydraulic conditions prevailing in the reservoir due to the water level drawdown. Increasing the flushing discharge, the flushing duration and the water level drawdown has as result that larger volumes of deposits will be removed by flushing, i.e. flushing will be more effective.

Higher annual deposits have as result that a higher flushing efficiency or a more frequent flushing operation is required in order to maintain sustainably the reservoir storage capacity.

4.4.1.4 Technical feasibility and implementation constraints

The basis of the technical model for assessment of flushing technical feasibility is Atkinson (1996), which quantifies aspects of reservoirs that are likely to be successful in flushing at complete drawdown. The two major criteria Atkinson developed are the Sediment Balance Ratio (SBR) and the Long-Term Capacity Ratio (LTCR). The RESCON 2 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 the 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. LTCR is calculated as the ratio of the scoured valley area to the assumed typical reservoir area at the dam location. The area of the scoured valley depends on the side slope of the deposits exposed during flushing, which is calculated by the following empirical equation, known as Migniot equation.

$$SS_s = \frac{Cal\_SS_{FL}}{\frac{31.5}{5}\rho_d^{4.7}}$$

Where:

SSs	is the side slope of scoured channel [V:H]
Cal_SS_{FL}	Calibration parameter for adjustment of the calculated side slope of scoured channel. The adjusted Migniot's equation often overestimates the side slopes by 10 times and therefore a value of 10 is used as default.
ρd	is the specific weight of in-situ reservoir sediment (bulk density) [t/m^3]

Atkinson develops four more criteria to assess flushing feasibility. The RESCON 2 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 the DrawDown Ratio, (DDR) should be greater than 0.7 for sufficient drawdown conditions.

- Because SBR is affected by incomplete drawdown, SBR is also calculated for conditions of full drawdown, as an indicator of the potential for flushing if low-level gates would be installed to allow full drawdown (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).

A summary of the applied feasibility criteria and guidelines is given in the Table 4.4:

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

The program assumes there are two phases to the flushing operation. The two phases are independent of each other because the transition point is predetermined 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.

The implementation schedule of flushing is defined as the cycle length during the first non-sustainable phase and the cycle length during the second sustainable phase of reservoir operation. Cycle length is the time interval between two flushing events. The user can either define explicitly the implementation schedule, i.e. the cycle lengths of flushing, or let RESCON 2 find the

Table 4.4: Criteria and guidelines applied for assessment of technical feasibility of flushing

	Criterion	*Requirement*
SBR	SBR is the ratio of the sediment flushed annually to the sediment deposited annually.	> 1
	Guidelines	*Recommendation*
LTCR	LTCR is the 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	preferably > 0.35
DDR	DDR is the ratio of the extent of reservoir drawdown to flow depth for the normal impounding level:	> 0.7
FWR	Flushing width ratio checks that the predicted flushing width, Wf, is greater than the representative bottom width of reservoir, Wbot:	> 1
TWR	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 constrain	> 1
SBR_d	SBR_d is the sediment balance ratio based on flushing flows; it is independent of drawdown. SBRd is calculated the same as SBR, except ELf = Elmin	> 1

optimal scheduling that maximizes the economic performance of the reservoir. In both cases the frequency of flushing performance is subject to site specific and user defined constraints.

The maximum allowable cycle length during the first phase is the time required for reaching the LTCR capacity if no sediment management is applied. If it is an existing reservoir, whereby the current reservoir storage is below the LTCR capacity the maximum cycle length in the first phase is one year.

The maximum allowable cycle length in the second phase is the time required to reach the minimum allowable capacity as defined by the CLF technical constraint and the calculated maximum amount of deposits that can be removed by one flushing event.

If the user has specified explicitly the implementation schedule, i.e. the cycle lengths for both phases of reservoir operation, he is alerted to increase the CLF constrain or alter the parameters determining the LTCR, for example the flushing discharge, if one or both of the provided values exceed the maximum allowable cycle lengths. In that case the calculations will stop and the user can try to repeat them after the necessary modification of data input. If the implementation schedule is determined through economic optimization the two maximum allowable cycle lengths function as upper bounds for the values of cycle lengths tested during the optimization procedure.

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 LTCR capacity. When the reservoir capacity cannot go below the site's long-term capacity because of the specified technical lower bound, the calculation will stop and the user will be alerted to increase CLF.

If the reservoir is existing and the current storage capacity is below the minimum allowable defined by the constrain CLF and the maximum amount of deposits that can be removed by a flushing event, the calculations will stop and the user will be alerted.

4.4.1.5 Sedimentation development

The program assumes there are two phases to the flushing operation. 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 4.6 below). The solution depicted in Figure 4.7 also holds for an existing dam if the remaining reservoir capacity is larger than the dam's long-Term Capacity (LTC).

If the initial storage capacity of the reservoir is lower than the calculated site specific long-term capacity for flushing, the first non-sustainable phase does not exist and the reservoir operation enters immediately the second non-sustainable phase. The possible time path for this case is shown in the Figure 4.7.

Figure 4.6: Possible time path of remaining capacity for flushing if the initial storage capacity is higher than the site specific Long-Term Capacity (LTC)

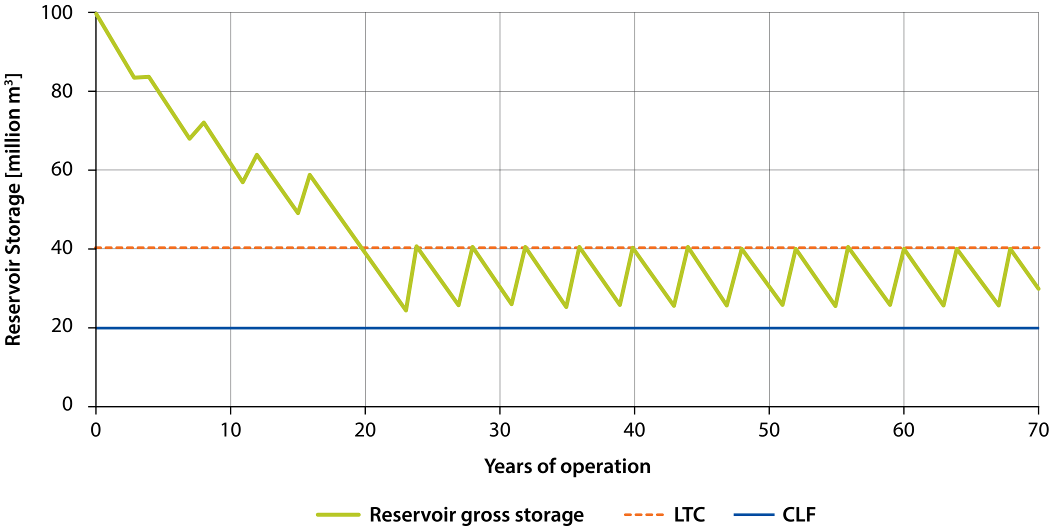
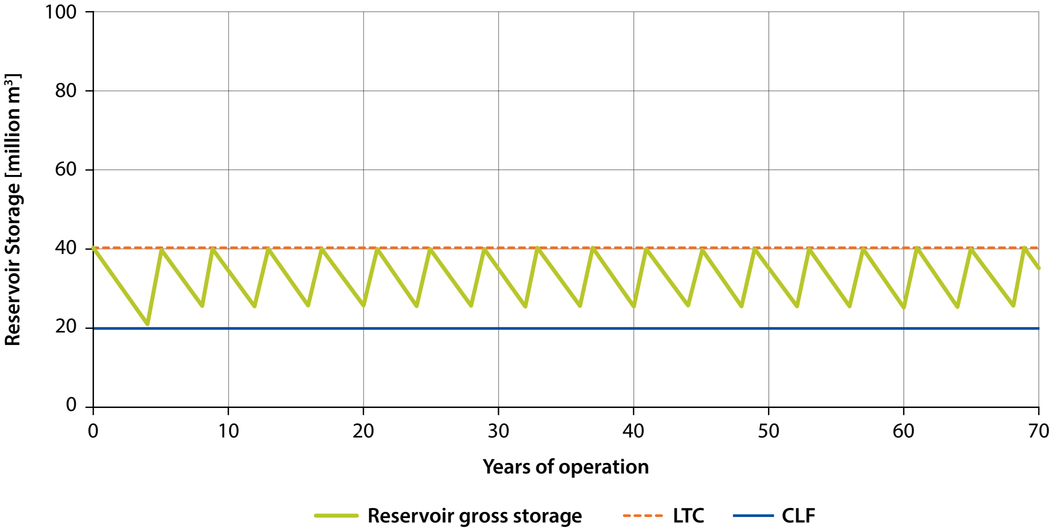


Figure 4.7: Possible time path of remaining capacity for flushing if the initial storage capacity is lower than the site specific Long-Term Capacity (LTC)



If the initial reservoir storage capacity is lower than the minimum allowable capacity defined by the constraint CLF or the maximum amount of deposits that can be removed during one flushing event, it is considered that flushing cannot be implemented due to excessive sedimentation.

During Phase I flushing occurs at intervals specified either by the user or determined by the program by means of an optimization procedure which aims at maximizing the aggregate net benefits. The duration of Phase I for the case of an existing dam will be shorter than the duration of this phase if 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 I 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 2 program, however, eliminates such cases from consideration.

In Phase II, the amount of sediment removed is determined by the cycle length of flushing events and the sediment deposits accumulating in the reservoir during the time interval corresponding to one flushing cycle. The remaining capacity after each flushing event always goes back to the Long-Term Capacity (LTC), which is site specific.

4.4.1.6 Economic formulation

Reservoir revenues

When flushing is carried out, the reservoir is emptied down to the user specified water level during flushing. Therefore the reservoir water yield is reduced compared to the water yield when no flushing is performed. This reduces the revenues from reservoir operation.

During the year in which flushing occurs, the water yield (Wt) is determined as follows,

$$W_{t\_FL} = s1 \cdot W(0) + s2 \cdot (W(St) - W(0))$$

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(St): is water yield from storage capacity the year of flushing.

The revenues therefore are:

Flushing is performed

$$B(t\_FL) = P1 \cdot [s1 \cdot W(0) + s2 \cdot (W(St) - W(0))]$$

Where:

B(t_FL):	Revenues from reservoir operation the year flushing occurs
P1:	Unit price of water yield [US$/m^3]

Flushing is not performed

$$B(t) = P1 \cdot W(St)$$

Cost of flushing

The year the first flushing operation is performed the cost of flushing is determined by the sum of construction costs Fl of the bottom outlet used for this sediment management activity and the annual operation and maintenance costs associated with the flushing performance OM_FL.

If the project is greenfield, the construction costs of the outlet structure used for flushing are usually comprised in the overall project construction costs.

It is most likely that the Fl costs will occur for the case of retrofitting a bottom outlet in an existing reservoir in order to perform flushing.

The year the subsequent flushing events are carried out the annual operation and maintenance costs are increased due to flushing performance by the user defined amount of OM_FL.

Net benefits

Flushing is performed

$$NB(t) == \begin{cases} P1\left[s1\ W(0) + s2\ \left(W(St) - W(0)\right)\right] - C1 - Fl - OM\_FL, & \textit{first flushing} \\ P1\left[s1\ W(0) + s2\ \left(W(St) - W(0)\right)\right] - C1 - OM\_FL, & \textit{subsequent flushing} \end{cases}$$

Where:
C1: regular annual operation and maintenance costs of reservoir
Fl: construction costs of bottom outlet used for flushing
OM_FL: annual operation and maintenance costs associated with performance of flushing

Flushing is not performed
NB(t) = P1 · W(St) - C1

4.4.1.7 Optimization framework

The implementation schedule can be either explicitly specified by the user or can be determined by an economic optimization procedure. If the determination of implementation schedule by means of economic optimization is selected, RESCON 2 calculates the economic performance of the reservoir for all possible constellations of cycle lengths of Phase I and II and protrudes as optimal scheduling the constellation of flushing cycle lengths that maximizes the aggregate net present value of reservoir benefits under the technical assumption that the pre-determined long-term capacity has to be reached. This means that the cycle lengths during non-sustainable phase that lead to a convergence to a storage capacity higher than the site specific LTCR will be ignored. 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 2 program calculates NPV for all possible cycle lengths in this phase and determines the optimal cycle.

The program reports the optimal cycle lengths and the amount of flushed sediment for Phase I and II respectively.

4.4.2 Hydrosuction Sediment Removal System (HSRS)

4.4.2.1 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.

4.4.2.2 Preliminary assessment

Experience shows that HSRS is generally appropriate for small reservoirs because the efficiency of this method depends largely on the transport distance of the removed material. A preliminary assessment of HSRS suitability can be obtained on basis of the following criteria:

- The hydrologic reservoir size defined as the ratio of reservoir capacity (CAP) to mean annual runoff (MAF) ranges between 0.0001 and 0.04.
- The ratio of reservoir capacity (CAP) to mean annual sediment inflow (MAS), which provides an indicator of the reservoir life span lies between 2 and 100 years.

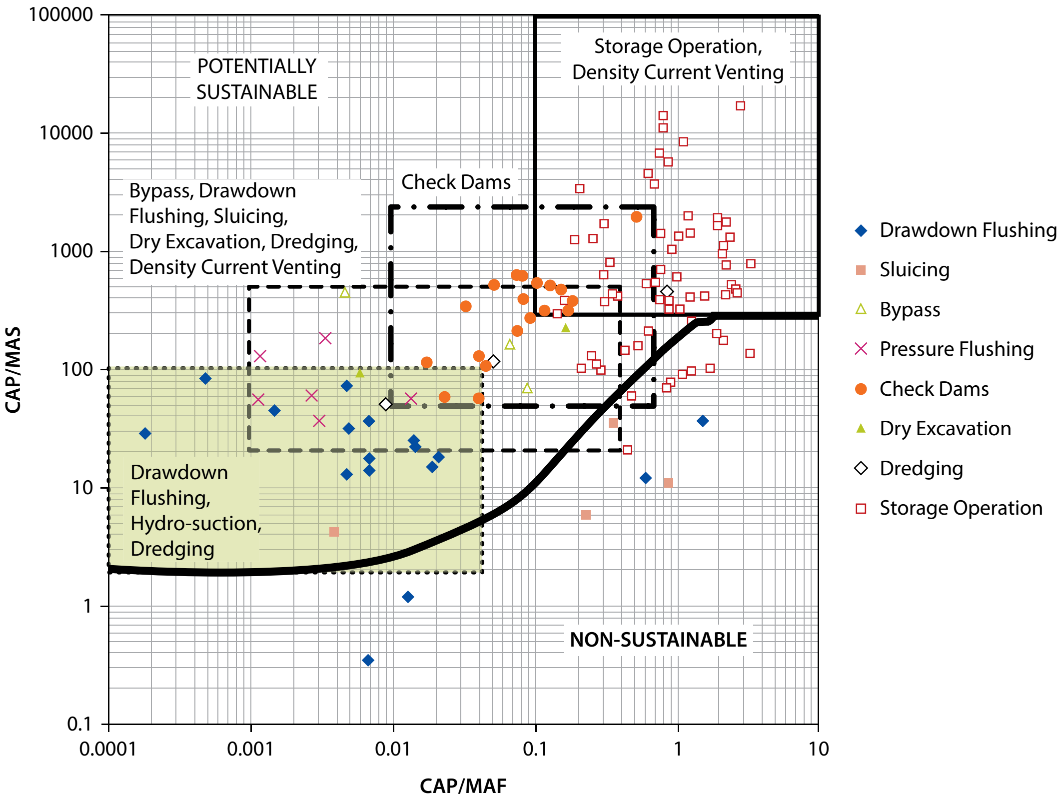
The boundaries of the aforementioned indicators of effective flushing are shown schematically in the Figure 4.8.

4.4.2.3 Parameters in RESCON 2 analysis

The parameters provided in the Table 4.5 are used for the calculation of the reservoir storage development and the economic performance of the facility if HSRS is applied.

An additional parameter that can be adjusted in order to fit better the site specific conditions is the gradation curve of the deposits in the reservoir. This can be done only in the Excel template file in the cells O52 : S54 of the

Figure 4.8: Preliminary assessment of flushing suitability



Source: Annandale (2013)

Table 4.5: Parameters used for assessment of storage development and the economic performance of the reservoir if HSRS is applied

Parameters determining efficiency of HSRS		
Type	1 or 2	Sediment type category to be removed by Hydrosuction Sediment Removal System (HSRS)
D	[m]	Assume a trial pipe diameter for HSRS
NP	1, 2, or 3	Number of pipes for HSRS
Water losses and costs for implementation of HSRS		
PH	[$/m^3]	Unit value of water released downstream of dam in river by HSRS operations
HI	[US$]	Cost of capital investment to install HHSRS
DU	[Years]	The expected life of HSRS
Scheduling of HSRS implementation		
Shall the implementation strategy of HSRS be determined through economic optimization?		• Yes • No
Year HSRS start	[Years]	Timing of HSRS installation
User defined constraints in application of HSRS		
CLH	[%]	Maximum percent of capacity loss that is allowable at any time in reservoir for HSRS
YA	[%]	Maximum fraction of total yield that is allowed to be used in HSRS operations

spreadsheet: Input (Sediment Management). Please note that the GUI must be closed at the time of modification of the deposit gradation curve, as well as that any changes will be applied also in future software application, unless the default values are re-entered.

4.4.2.4 Technical feasibility and implementation constraints

The technical feasibility is tested with application of the method published by Hotchkiss and Huang (1995). Furthermore, the technical feasibility of implementation of HSRS depends on the length of the pipeline, which as worst case is assumed to be equal to the length of the reservoir. If the length of reservoir is larger than 5000 m it is considered that HSRS cannot be implemented because the hydraulic losses will be very high, prohibiting thus the performance of hydrosuction.

It is considered that hydrosuction will be performed annually hence the implementation scheduling comprises only the timing of installation of the equipment. The latter can be either explicitly specified by the user or can be determined by means of economic optimization which is explained in detail in chapter 4.4.2.7. In both cases the user can insert a technical constraint which limits the latest possible implementation of HSRS. This constraint is specified by the parameter CLH, which defines the maximum allowable storage loss at any time if HSRS is applied. 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. It is pointed out that this constrain applies only to the case of sustainable reservoir solutions, i.e. when the amount of deposits that can be removed by HSRS is equal or higher than the amount of annual sedimentation.

RESCON 2 will calculate the reservoir storage development for the case of no sediment management and will determine by which year the maximum allowable storage loss (CLH) is reached. Furthermore, the maximum and the minimum amount of annual deposits (maximum and minimum annual sedimentation) occurring the first and last year of the reservoir lifetime respectively for the no action scenario will be calculated too.

If the minimum annual sedimentation is higher than the removal capacity of the reservoir, the user is informed that only a non-sustainable solution is possible. This solution will extend the lifetime of the reservoir but it will not prevent the elimination of storage capacity. In that case the CLH constraint is not considered. The extent of reservoir lifetime prolongation depends on the timing of HSRS installation. The sooner HSRS is installed the longer the lifetime of the reservoir.

If the removal capacity of the HSRS system is higher than the maximum annual deposits the reservoir will be sustainable. The long term capacity of the reservoir depends on the timing of HSRS installation. The sooner the installation the higher the long term capacity of the reservoir. If HSRS is installed the first year of reservoir operation, the initial capacity can be maintained. In that case the timing of HSRS installation is subject to CLH constraint. The latest possible implementation year is the year the maximum allowable capacity loss as defined by the parameter CLH is reached.

If the removal capacity of the HSRS system is between the minimum and maximum annual deposits expected to occur during the lifetime of the reservoir, then the reservoir will be sustainable. If the annual deposits the year specified by the user as first year of HSRS operation are more than the capacity of the system, the reservoir storage will continue to drop until an equilibrium is reached between deposition and removal later on. If the capacity loss this year is more than the CLH capacity loss, the user is informed that the technical constraint cannot be kept and the program reports the minimum capacity loss by which a sustainable solution is possible.

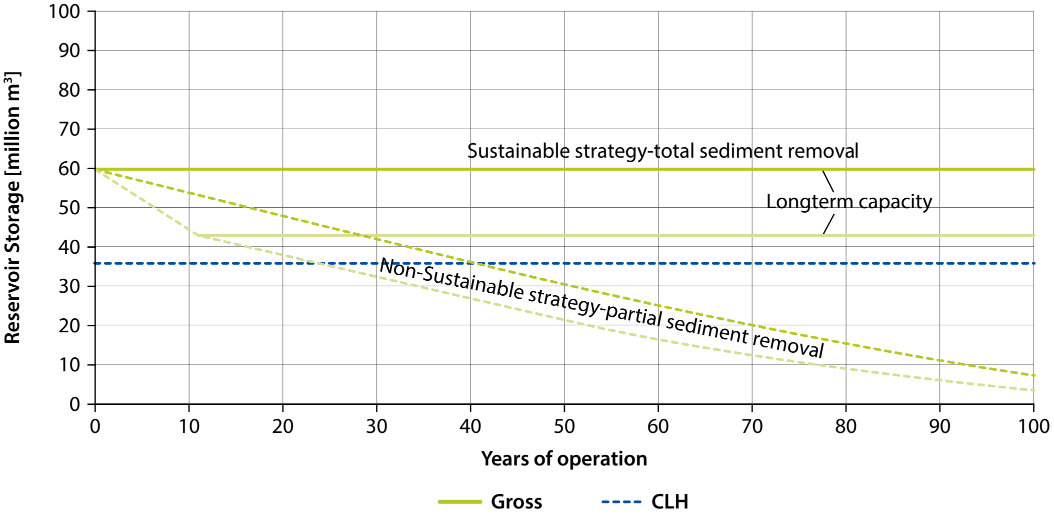
If the annual deposits the specified implementation year are more than the removal capacity of the HSRS the user is informed that the CLH constraint will not be kept.

4.4.2.5 Sedimentation development

Hydrosuction is assumed to occur annually and the timing of HSRS installation is either specified by the user or determined through economic optimization. If the entire amount of sediment retained in the reservoir is removed each year, then the solution is sustainable. In that case, the long-term capacity is determined by the remaining storage capacity at which HSRS is installed.

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. Possible

Figure 4.9: Possible Time Path of Remaining Capacity for Hydrosuction



time paths of remaining capacity by hydrosuction are presented in Figure 4.9. 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.

4.4.2.6 *Economic formulation*

Reservoir revenues

B(t) = P1 · W(St) – (P1 – PH) · Yt

Where:

W(St): Reservoir water yield corresponding to available active storage capacity at year t. [m^3/a]

P1: Unit price of water yield [US\$/m^3]

PH: Unit price of water released downstream of dam by HSRS operations [US\$/m^3]

Y_t: the water needed for sediment removal. It is calculated as:

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

Where:

Qm: mixture flowrate (m^3/s), calculated according to Hotchkiss and Huang (1995)

Qs: sediment flowrate (m^3/s), calculated according to Hotchkiss and Huang (1995)

Xt: sediment removed in year t (m^3).

Cost of HSRS

The unit cost of hydrosuction is determined as follow,

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

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

Qs: is the technical maximum sediment transport rate (annual).

Net benefits

NBt = P1·W(St) – (P1–PH)·Yt–C1–CH·Xt

4.4.2.7 *Optimization framework*

Similar to RESCON, RESCON 2 provides the possibility to determine the HSRS timing that maximizes the economic performance of the reservoir. In that case it is not necessary to define explicitly the installation year of the system because it will be calculated by the program.

The economic optimization is performed if the user answers the question:

"Shall the implementation strategy of dredging be determined through economic optimization?" with "Yes".

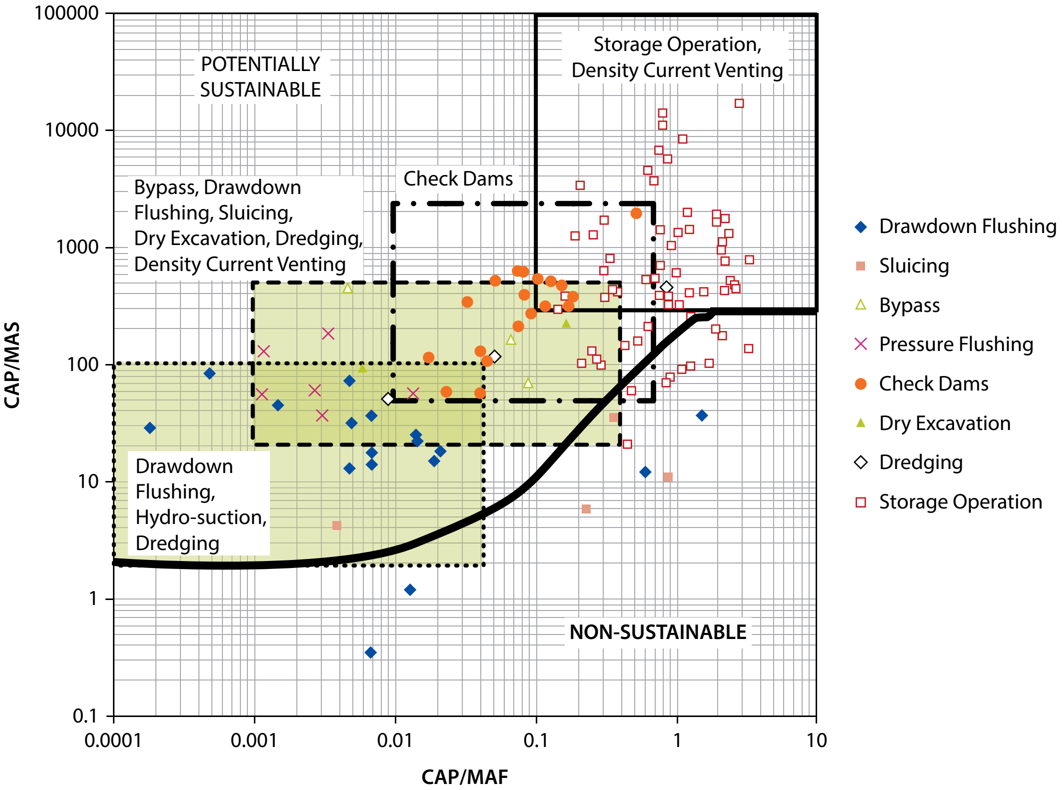
The aggregate Net Present Value of reservoir benefits is calculated for all possible duration of the first phase of no HSRS operation. The tested values are limited by the maximum allowable value, i.e. the latest possible implementation of HSRS which depends on the user defined constraint CLH. Hence the optimal solution conforms to the limitation imposed by the user with regards the maximum allowable capacity loss at any time in the reservoir.

4.4.3 Dredging

4.4.3.1 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

Figure 4.10: Preliminary assessment of dredging suitability



Source: Annandale (2013)

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.

4.4.3.2 Preliminary assessment

Based on observations in reservoirs of different sizes, dredging is more appropriate for relatively small and middle sized reservoirs. A first preliminary assessment is that dredging will be a good option for sediment management when the following pre-requisites are fulfilled:

- The hydrologic reservoir size defined as the ratio of reservoir capacity (CAP) to mean annual runoff (MAF) ranges between 0.0001 and 0.4.
- The ratio of reservoir capacity (CAP) to mean annual sediment inflow (MAS), which provides an indicator of the reservoir life span lies between 2 and 500 years.

Experience has shown that for larger reservoir, whereby the hydrologic reservoir size ranges between 0.001 and 0.4 and the ratio of reservoir capacity (CAP) to mean annual sediment inflow is between 20 and 500 years, partial

Table 4.6: Parameters used for assessment of storage development and the economic performance of the reservoir if dredging is applied

		Parameters determining dredging amount	
Shall a sustainable solution be determined automatically?			• Yes • No
MD	[m^3]	Maximum amount of sediment removed per dredging event	
Where do you want to perform dredging?			• Active storage • Both active and inactive storage
		Water losses and costs for implementation of dredging	
Cw	[%]	Concentration by weight of sediment removed to water removed by traditional dredging	
Shall the unit cost of dredging be determined automatically?			• Yes • No
CD	[\$/m^3]	Unit cost of dredging	
PD	[\$/m^3]	Unit value of water used in dredging operations	
		User defined constraints in application of dredging	
CLD	[%]	Maximum percent of capacity loss that is allowable at any time in reservoir for dredging	
ASD	[%]	Maximum allowable percent of accumulated sediment removed per dredging event	
		Scheduling of dredging implementation	
Cw	[%]	Concentration by weight of sediment removed to water removed by traditional dredging	
Shall the implementation strategy of dredging be determined through economic optimization?			• Yes • No
Cycle 1DR	[years]	Duration of Phase 1 (No dredging)	
Cycle 2DR	[years]	Cycle length in Phase 2 (Frequency of dredging operation)	

dredging will be predominantly applied. The boundaries of the aforementioned indicators are shown schematically in the Figure 4.10.

4.4.3.3 Parameters in RESCON 2 analysis

The parameters provided in the Table 4.6 are used for the calculation of the reservoir storage development and the economic performance of the facility if dredging is applied.

The economic performance of the reservoir depends on the time path of reservoir storage development as well the water losses and costs associated with application of dredging. The time path of reservoir storage depends on the amount of deposits removed per dredging event and the implementation schedule of dredging, i.e. the commencement year and the frequency of dredging events. The aforementioned parameters provide control over the amount of deposits that will removed during each dredging event, the implementation schedule and the cost associated with this sediment management activity.

Dredging is practiced at intervals that are either user defined or are computed internally by means of economic optimization. There are two phases for each technique: Phase I and II. No sediment removal is practiced in Phase I, while periodic sediment removal is practiced in Phase II. If the user wants to specify the implementation schedule explicitly, the question: "Shall the implementation strategy of dredging be determined through economic optimization?" must be answered with "No". If it answered contrary with "Yes", the implementation schedule that maximizes the economic performance of the reservoir will be calculated by RESCON 2.

The user can either specify the amount of deposits that will be removed in every dredging event or can request to have a sustainable solution which fulfills specific prerequisites. In this case the amount of deposits that has to be removed in order to achieve the requested solution will be calculated by RESCON 2. This will happen if the user selects the answer "yes" in the question "Shall a sustainable solution be determined automatically?", the amount of dredged material that leads to a sustainable solution conforming to the user specified constraints will be automatically calculated. More information on the user defined constraints that can limit the sustainable solution is provided in the following sub-chapters. If the provided answer to the aforementioned question is "No", the user has to specify with parameter MD the amount of deposits that will be removed by each dredging event. This can lead to non-sustainable solutions if the specified amount of dredging is smaller or larger than the deposits occurring between dredging events.

The user can also specify whether dredging will remove deposits only from the active storage or both storage pools, i.e. the active and the inactive storage.

If the user has specified the amount of deposits that will be removed per dredging event through the parameter MD, and has specified as location of dredging activity both storage pools, deposits from inactive storage will be removed only if the specified amount of dredging MD is higher than the accumulated deposits in active storage. Contrary if the user specifies as location of dredging activity only the active storage and the specified amount of dredging is higher than the accumulated deposits in active storage, the dredged amount will be limited by the availability of deposits in active storage.

4.4.3.4 Technical feasibility and implementation constraints

The program assumes dredging is 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 over-riding the recommendations of the program where applicable.

The highest sediment volume removal by dredging that can be expected from a typical system over a year is approximately 11 million m^3. This is 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. Note that the approximated removal per dredge is very crude; site specific analysis must be done to confirm the volume of sediment removal per dredge per year.

To remove more sediment, additional dredges could possibly be installed on a reservoir, but this would increase the overall cost of the project. Based on this gross estimate of sediment removal capability, the number of dredges to remove the required amount of sediment annually can be calculated.

The implementation schedule of dredging, i.e. the installation year and the time interval between dredging events can be either specified explicitly by the user or can be determined by RESCON 2 by means of an optimization procedure which aims at maximizing the economic performance of the reservoir. In both cases, the duration of the first phase of no dredging and the frequency of dredging events is subject to user defined constraints with regards the minimum allowable storage capacity of the reservoir and the maximum amount of deposits that can be removed during each dredging event.

The duration of the first phase of no dredging is limited by the parameter CLD which determines the maximum allowable storage loss at any time in the reservoir if dredging is applied. Hence, the latest possible implementation year of dredging is determined as the year the capacity loss reaches this limit if no sediment management is applied. This applied also for an existing reservoir as long as the current reservoir storage is higher than the minimum allowable storage. If the current storage capacity is lower than the minimum allowable, the duration of the first phase is one year, i.e. the dredger will be installed at the end of the first year.

The cycle length, i.e. the time interval between dredging events is limited by the constraint ASD, which expresses the maximum allowable amount of deposits that can be removed during each dredging event. It is expressed as percent of pre-impoundment gross storage capacity. Hence the maximum allowable time interval between dredging events is the time required for accumulation of deposits equal with the ASD percent of pre-impoundment gross storage capacity.

If the user defined implementation schedule can't be applied due to the CLD and ASD constraints, the user is notified accordingly to modify either the implementation schedule or the technical constraints. For example if the user specified duration of Phase I, i.e. the commencement year of dredging is longer than the time period required to reach the maximum allowable reservoir storage capacity loss as determined by the constrain CLD, the user is notified to reduce the duration of Phase I or to increase the CLD parameter. The same happens also with the cycle length of Phase II and the constrain ASD.

It is pointed out that the aforementioned constraints apply only for the case of sustainable solutions. If the user determines explicitly the amount of deposits removed during each dredging event, through parameter MD, the implementation schedule of dredging is not subject to the CLD and ASD technical constraints.

4.4.3.5 Sedimentation development

The solution is sustainable when the amount removed at any time is equal to the additional accumulation since the previous event. In that case the reservoir storage will not decline continuously over time, rather it will fluctuate between an upper and lower bound, which in turn are controlled by the implementation schedule and the user specified CLD and ASD technical constraints. Contrary, when the removed amount of deposits is smaller than the sedimentation occurring between dredging events, the solution is non-sustainable and the reservoir lifetime is just prolonged compared to the no action scenario. It is assumed that the amount of sediment removed per event is constant over time. It is only limited by the availability of deposits in the reservoir.

For the case of sustainable solutions, the duration of Phase I determines the lower bound of remaining reservoir capacity (Smin) and the cycle length in Phase II determines the sustained remaining reservoir capacity, LTC. A typical time path for this case is shown in Figure 4.11.

The determined lower bound (Smin) is always higher than technical lower bounds that is given by users (through CLD: maximum percent of reservoir capacity loss allowable). Thus, the time path of remaining capacity satisfies technical requirements imposed by the user. The determined amount of sediment removed is the observed difference between the LTC and the optimally determined lower bound (Smin). The determined amount of sediment removed per event also satisfies the technical requirement imposed by the ASD constraint.

The time path of sediment management obtained in the above manner also applies to an identical existing dam if the current capacity of this dam is larger than the minimum allowable capacity, which is determined by the constraint CLD. On the other hand, if the current capacity of the existing dam is below the minimum allowable storage capacity, the first sediment removal event occurs immediately. In that case, the amount of sediment removed during the first event is allowed to be different from the amount of deposits removed

Figure 4.11: Possible Time path of remaining capacity for dredging (SE>Smin)

Figure 4.12: Possible Time path of remaining capacity for dredging (SE<Smin)

during the subsequent events. The amount of sediment removed by initial dredging determines LTC and the subsequent cycle determines lower bound (Smin), which is again limited by the CLD constrain.

The program reports the optimally determined cycle length, the amount of sediment removed and the LTC. Parameter values specified by the user, such as CLD and ASD, are used as constraints and optimally determined values within these constraints are reported. The user also specifies unit costs of dredging. 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.

If the user will specify explicitly the amount of deposits that will be removed during each dredging event, this will lead presumably to non-sustainable solutions. If the specified amount is higher than the sedimentation taking place between two subsequent dredging events, this will lead in reservoir storage restoration depending on the year of dredging implementation. The restoration upper bound is the pre-impoundment storage capacity. An example is shown in the Figure 4.13.

Figure 4.13: Possible Time path of remaining capacity for dredging (user defined amount of dredging, deposit removal > sedimentation)

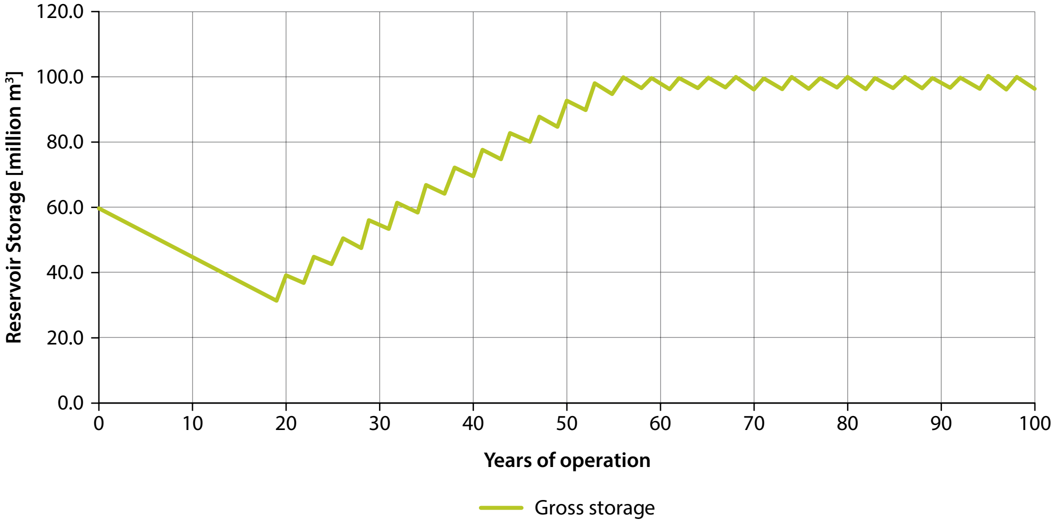
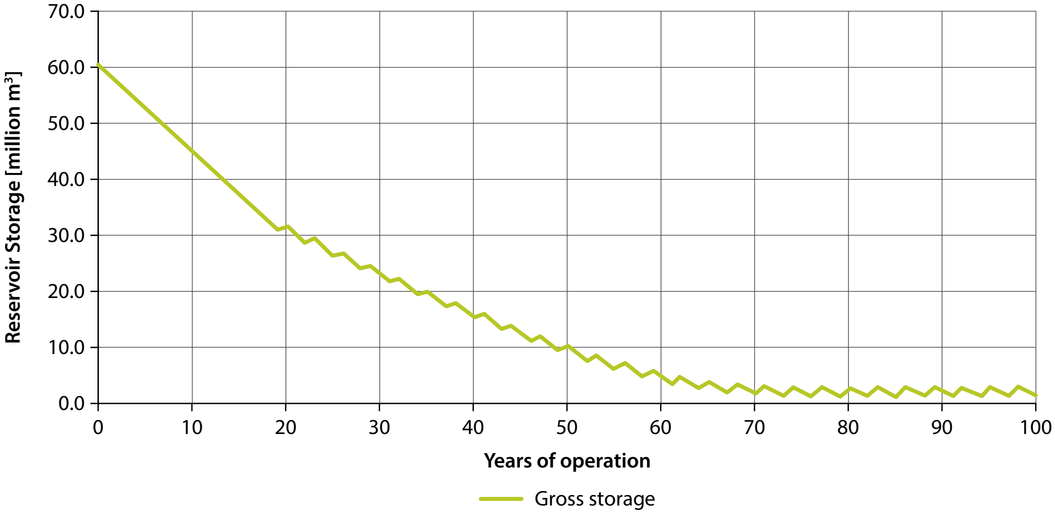


Figure 4.14: Possible Time path of remaining capacity for dredging (user defined amount of dredging, deposit removal < sedimentation)



If the specified amount of deposits removed during each dredging event is lower than the sedimentation occurring between two dredging events, the reservoir storage will continue to decline and finally it will be eliminated. The lifetime of the reservoir in this case will be longer than the lifetime for the case of the no action scenario.

4.4.3.6 Economic formulation

Reservoir revenues

The reservoir revenues differentiate depending on the performance of dredging this year or not.

dredging is performed

$B(t\_DR) = P1 \cdot W(St) - (P1 - PD) \cdot Yt$

Where:

W(St): Reservoir water yield corresponding to available active storage capacity at year t. [m^3/a]

P1: Unit price of water yield [US$/$m^3$]

PD: Unit price of water used in dredging operations [US$/$m^3$]

Yt: the water needed for sediment removal [m^3]. It is calculated as follow:

$Yt = 2.65 \cdot X/Cw$

Where:

X: the volume of deposits removed by dredging

Cw: the concentration by weight of sediment removed to water removed by dredging [%]

Dredging is not performed

$B(t) = P1 \cdot W(St)$

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:

$$CD(X) = \begin{cases} 15, & X < 150{,}000\, m^3 \\ 6.61588728\left(X/10^6\right)^{-0.43148367}, & 150{,}000\, m^3 < X < 16{,}000{,}000\, m^3 \\ 2, & X \geq 16{,}000{,}000\, m^3 \end{cases}$$

Where:

X: amount of sediment dredged per cycle [m^3)]

CD: unit cost of dredging [US$/m^3]

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

Net benefits

dredging is performed

$NB(t) = P1 \cdot W(St) - (P1 - PD) \cdot Yt - C1 - CD(X) \cdot X$

Where:

C1: annual operation and maintenance costs of reservoir

dredging is not performed

$NB(t) = P1 \cdot W(St) - C1$

4.4.3.7 Optimization framework

Similar to RESCON, RESCON 2 provides the possibility to determine the dredging implementation schedule that maximizes the economic performance of the reservoir. In that case it is not necessary to define explicitly the installation year and the frequency of dredging operation because they will be calculated by the program.

The economic optimization is performed if the user answers the question:

“Shall the implementation strategy of dredging be determined through economic optimization?” with “Yes”.

The aggregate Net Present Value of reservoir benefits is calculated for all possible constellations of implementation year and time interval between dredging events. The tested values are limited by the maximum allowable values which are depending on the user defined constraints CLD and ASD. Hence the optimal solution conforms always to the limitations imposed by the user with regards the maximum allowable capacity loss and the maximum amount of deposits that can be removed during each dredging event.

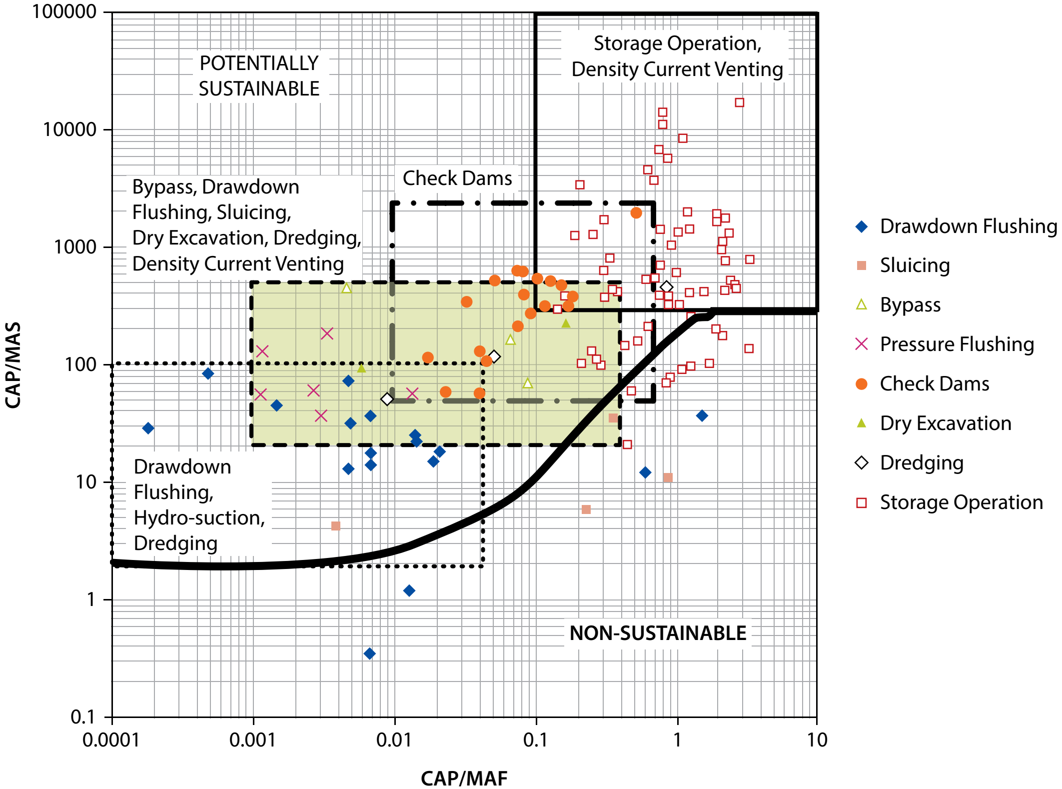
4.4.4 Trucking

4.4.4.1 Technical description

Trucking is the removal of accumulated sediment from a drained reservoir using heavy equipment.

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.

Figure 4.15: Preliminary assessment of trucking suitability



Source: Annandale (2013).

4.4.4.2 Preliminary assessment

Based on observations in reservoirs of different sizes, trucking is more appropriate for middle sized reservoirs. A first preliminary assessment is that trucking will be a good option for sediment management when the following pre-requisites are fulfilled:

- The hydrologic reservoir size defined as the ratio of reservoir capacity (CAP) to mean annual runoff (MAF) ranges between 0.001 and 0.4.
- The ratio of reservoir capacity (CAP) to mean annual sediment inflow (MAS), which provides an indicator of the reservoir life span lies between 20 and 500 years.

The boundaries of the aforementioned indicators are shown schematically in the Figure 4.15.

4.4.4.3 Parameters in RESCON 2 analysis

The parameters provided in the Table 4.7 are used for the calculation of the reservoir storage development and the economic performance of the facility if trucking is applied.

Table 4.7: Parameters used for assessment of storage development and the economic performance of the reservoir if trucking is applied

		Parameters determining trucking amount	
Shall a sustainable solution be determined automatically?			• Yes • No
MT	[m^3]	Maximum amount of sediment removed per trucking event	
Where do you want to perform trucking?			• Active storage • Both active and inactive storage
		Water losses and costs for implementation of trucking	
CT	[\$/m^3]	Unit cost of trucking	
sTR	[%]	Fraction of reservoir water yield the year trucking occurs	
		User defined constraints in application of trucking	
CLT	[%]	Maximum percent of capacity loss that is allowable at any time in reservoir for trucking	
AST	[%]	Maximum allowable percent of accumulated sediment removed per trucking event	
		Scheduling of trucking implementation	
Shall the implementation strategy of trucking be determined through economic optimization?			• Yes • No
Cycle1TR	[years]	Duration of Phase 1 (No trucking)	
Cycle2TR	[years]	Cycle length in Phase 2 (Frequency of trucking operation)	

Similarly to dredging, the user can either specify the amount of deposits that will be removed in every trucking event or can have this parameter calculated with objective the transformation of the reservoir from a non-sustainable to a sustainable facility. If the user selects the answer “yes” in the question “Shall a sustainable solution be determined automatically?”, the amount of deposits that has to be removed in order to have a sustainable solution will be automatically calculated. The sustainable solution will be subject to the user specified constraints CLT and AST. More information on the available constraints that can limit the sustainable solution are provided in the following sub-chapter.

If the provided answer to the aforementioned question is “No”, the user has to specify with parameter MT the amount of deposits that will be removed by each trucking event. This will lead presumably to non-sustainable solutions if the specified amount of removed deposits is smaller or larger than the sedimentation occurring between trucking events.

The user can also specify whether trucking will remove deposits only from the active storage or both storage pools, i.e. the active and the inactive storage. If the user has specified the amount of deposits that will be removed per trucking event through the parameter MT, and has specified as location of trucking activity both storage pools, deposits from inactive storage will be removed only if the specified amount of trucking MT is higher than the accumulated deposits in active storage. Contrary if the user specifies as location of trucking activity only the active storage and the specified amount of trucking is higher than the accumulated deposits in active storage, the dredged amount will be limited by the availability of deposits in active storage.

4.4.4.4 Technical feasibility and implementation constraints

Technical feasibility of trucking 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 trucking is 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 Table 4.8 shows the possible range of truck loads in m^3 depending on the truck model. This can provide a first indication regarding the number of truck loads required for removing the calculated amount of deposits. If the determined number of truck loads can be accommodated at the project site in the time allowed (the maximum is one year), trucking can be considered as technically feasible.

The implementation time schedule of trucking and finally the timepath of reservoir storage is subject to the same user defined constraints as dredging. The technical constrain regarding the maximum allowable storage loss CLT corresponds to the constraint CLD for dredging and the constraint AST regarding the maximum allowable amount of deposits removed during each trucking event corresponds to the constraint ASD for dredging. Please refer to section 4.4.3.4 for a detailed explanation.

4.4.4.5 Sedimentation development

The timepath of reservoir storage capacity is calculated in the same manner as for dredging. For detailed explanation please go back to chapter 4.4.3.5.

Table 4.8: Truck loads in m^3 for different truck models

Truck Model Number	*m^3/Truck Load*
769D	16.2
771D	18.0
773D	26.0
775D	31.0
777D	42.1
785B	57.0
789B	73.0
793C	96.0

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

4.4.4.6 *Economic formulation*

Reservoir revenues

Although the reservoir is emptied during the years in which trucking occurs, trucking itself does not use any significant volume of water. Therefore, during the year in which trucking occurs, the water yield (Wt) is assumed to be lower than the water yield during a year where no trucking is performed. The reduction of the water yield has to be specified explicitly by the user and it depends on the time needed to empty the reservoir, the duration of works and the time needed to fill again the reservoir.

During the year trucking occurs, the water yield (Wt) is determined as follows,

$W_{t\_TR} = sTR \cdot W(St)$

where:

sTR: is the fraction of water yield available in the year trucking occurs.

W(St): is water yield corresponding to the available active storage capacity the year trucking is performed.

The revenues therefore are:

Trucking is performed

$B(t\_TR) = P1 \cdot [sTR \cdot W(St)]$

Where:

B(t_TR): Revenues from reservoir operation the year trucking occurs

P1: Unit price of water yield [US$/m^3]

Flushing is not performed

$B(t) = P1 \cdot W(St)$

Cost of trucking

Wherever possible users are encouraged to enter their own values.

A default value of 13 US$/m^3 is recommended if it is not possible to insert a project specific estimation.

Net benefits

Trucking is performed

$NB(t) = P1 \cdot sTR \cdot W(St) - C1 - CT(Xt) \cdot Xt$

Where:

C1: annual operation and maintenance costs of reservoir [US$/a]

CT(Xt): unit cost of deposit removal with trucking [US$/m^3]

Xt: Volume of deposits removed by trucking the year t [m^3]

Trucking is not performed

$NB(t) = P1 \cdot W(St) - C1$

4.4.4.7 Optimization framework

Similar to dredging the user can let RESCON 2 calculate the optimal implementation time schedule for trucking on basis of an optimization procedure which aims at maximizing the aggregate Net Present Value of reservoir benefits.

The optimal solution will conform to the user specified technical constraints CLT and AST.

4.5 Sediment Routing

Sediment routing around or through storage involves the change of hydraulic conditions in the reservoir or upstream of the reservoir with the aim to minimize the sediment deposition and hence the extension of reservoir lifetime. The following methods are considered to belong to the family of sediment routing strategies:

- Pass-through
  - Drawdown Routing (Sluicing)
  - Density Current Venting

- By-pass
  - Diversion of sediment laden water
  - Diversion of clear water (Off-Stream Reservoir).

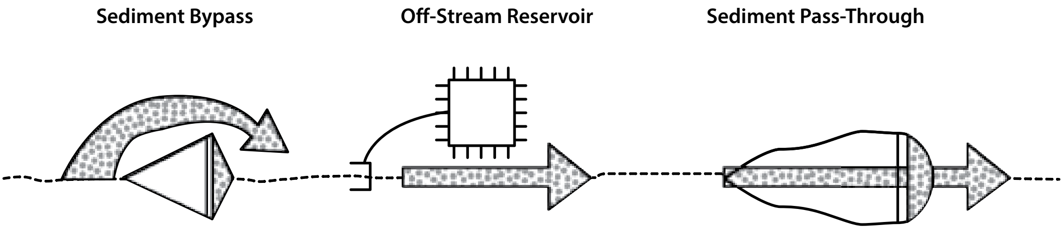
The concepts of sediment by-pass and sediment pass-through are schematically illustrated in the figure below.

4.5.1 Sluicing

4.5.1.1 Technical description

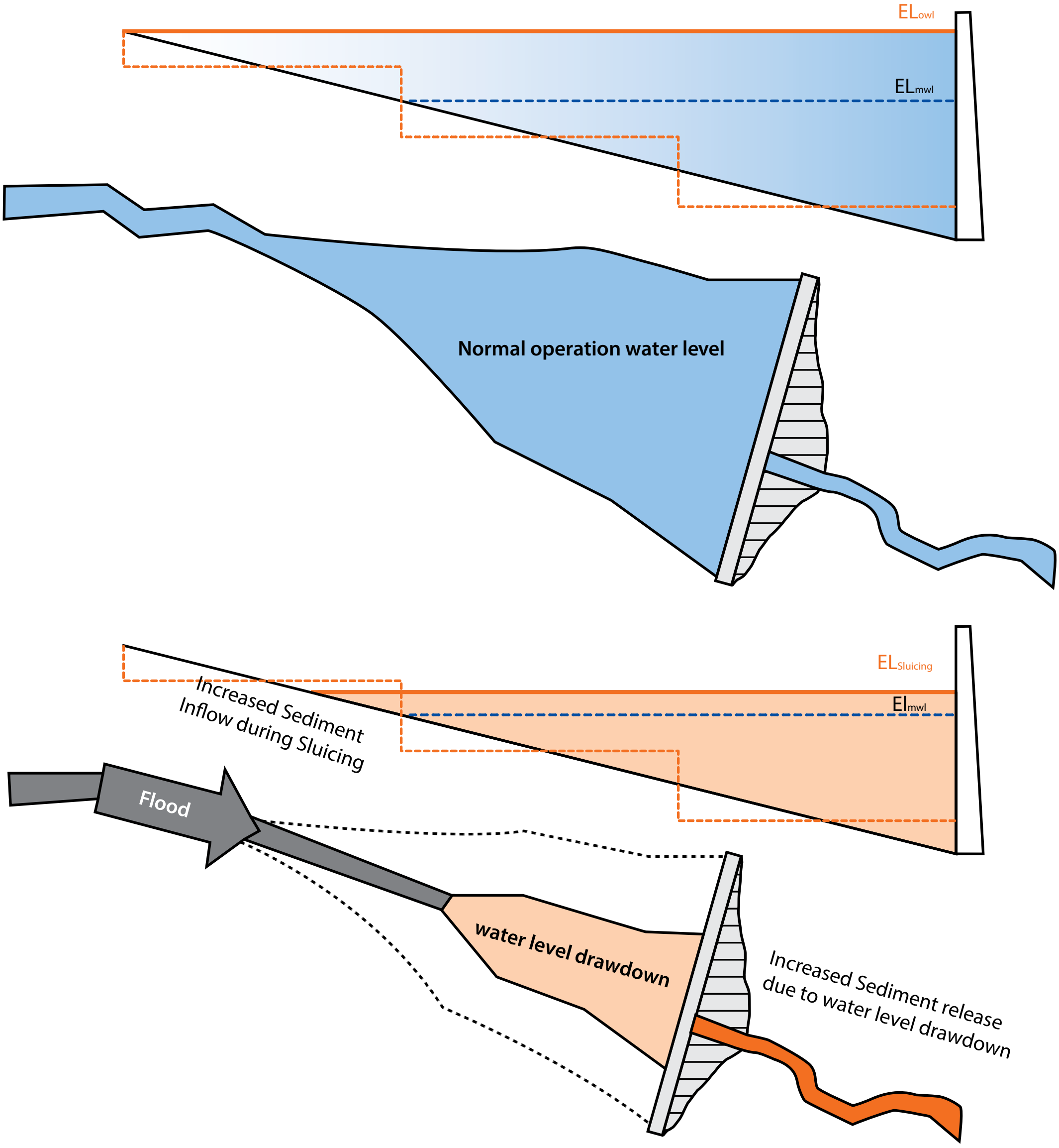
In order to achieve a reduction of sediment deposits, the reservoir volume is partially reduced during the flood season, when the bulk of sediment transport takes place. The pool level drawdown results in the increase of the flow velocities as well the reduction of retention time. Therefore, the trap efficiency of the reservoir during sluicing is essentially reduced. Thereby, a large amount or even the total sediment inflow can pass through the reservoir and can be

Figure 4.16: Definition sketch of sediment routing strategies



[Source: Morris & Fan (1998)]

Figure 4.17: Schematic illustration of sluicing operation

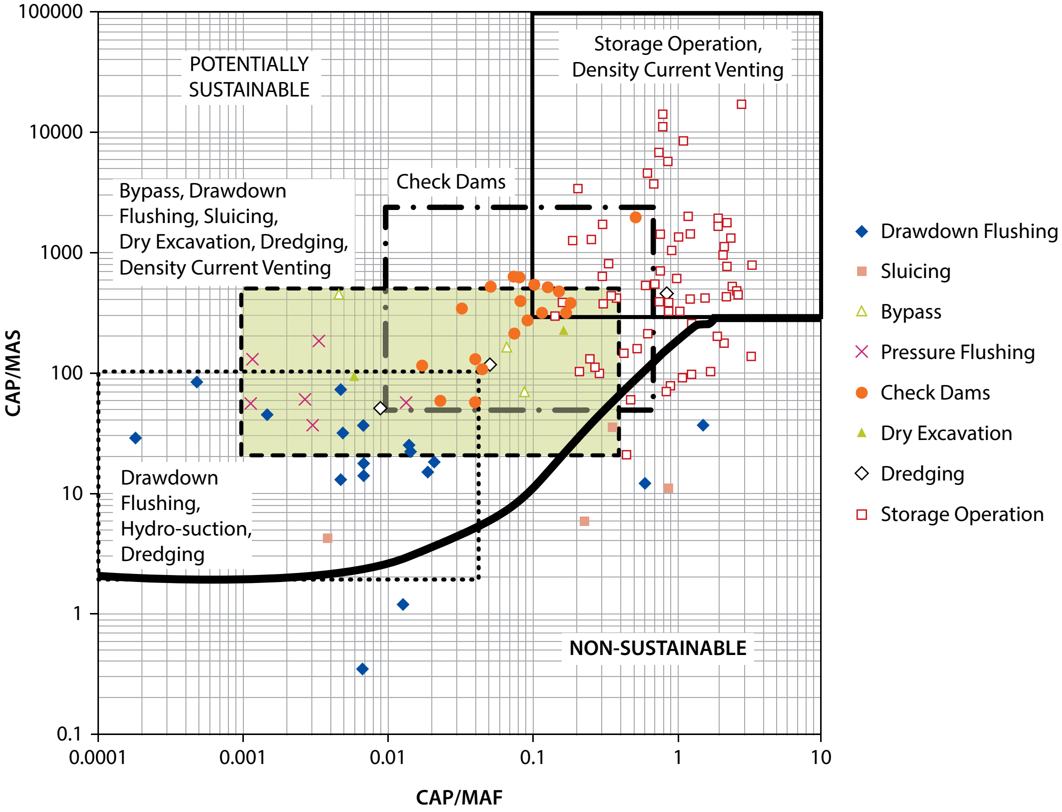


discharged downstream of the reservoir, minimizing or totally eliminating thus the sediment deposits and accordingly the storage loss.

Morris & Fan (1998) report that sluicing might be applied with the following water level drawdown strategies:

- Seasonal drawdown
- Flood drawdown by hydrograph prediction
- Flood drawdown by rule curve
- Venting of turbid density currents (combined with sluicing).

Figure 4.18: Preliminary assessment of sluicing suitability



Source: Annandale (2013)

4.5.1.2 *Preliminary assessment*

Sluicing will be eventually effective when the following pre-requisites are fulfilled:

- The hydrologic reservoir size defined as the ratio of reservoir capacity (CAP) to mean annual runoff (MAF) ranges between 0.001 and 0.4.
- The ratio of reservoir capacity (CAP) to mean annual sediment inflow (MAS), which provides an indicator of the reservoir life span lies between 20 and 500.

The boundaries of the aforementioned indicators of effective sluicing are shown schematically in the figure below.

4.5.1.3 *Parameters in RESCON 2 analysis*

The parameters provided in the Table 4.9 are used for the calculation of the reservoir storage development and the economic performance of the facility if sluicing is applied.

Table 4.9: Parameters used for assessment of storage development and the economic performance of the reservoir if sluicing is applied

	Parameters determining sluicing efficiency	
EL_{SL}	[masl]	Reservoir pool elevation during sluicing
T_{SL}	[months]	Duration of sluicing operation
	Costs associated with sluicing operation	
C_{SL}	[US$]	Cost for implementation of sluicing structure
OMC_{SL}	[US$/a]	Annual operation and maintenance costs of sluicing structures
	Scheduling of sluicing implementation	
Shall the duration and implementation year be defined through economic optimization?		• Yes • No
$Year_{SL\ Start}$	[years]	Implementation year of sluicing
	User defined constraints in application of sluicing	
CL_{SL}	[%]	Maximum allowable storage loss before implementation of sluicing
$T_{SL\ max}$	[months]	Maximum allowable duration of sluicing

4.5.1.4 Technical feasibility and implementation constraints

Sluicing is considered to be technically feasible if appropriate low level outlets allow the reservoir level drawdown to release sediment laden inflows downstream of the reservoir. If such low level outlets are not available and have to be retrofitted in the dam structure, engineering judgment is required for determination of the technical feasibility of this necessary technical intervention for implementation of sluicing.

The implementation schedule of sluicing regardless if it is explicitly specified by the user or determined through economic optimization is limited by two technical constraints, the allowable capacity loss before implementation of sluicing and the maximum allowable duration of sluicing operation.

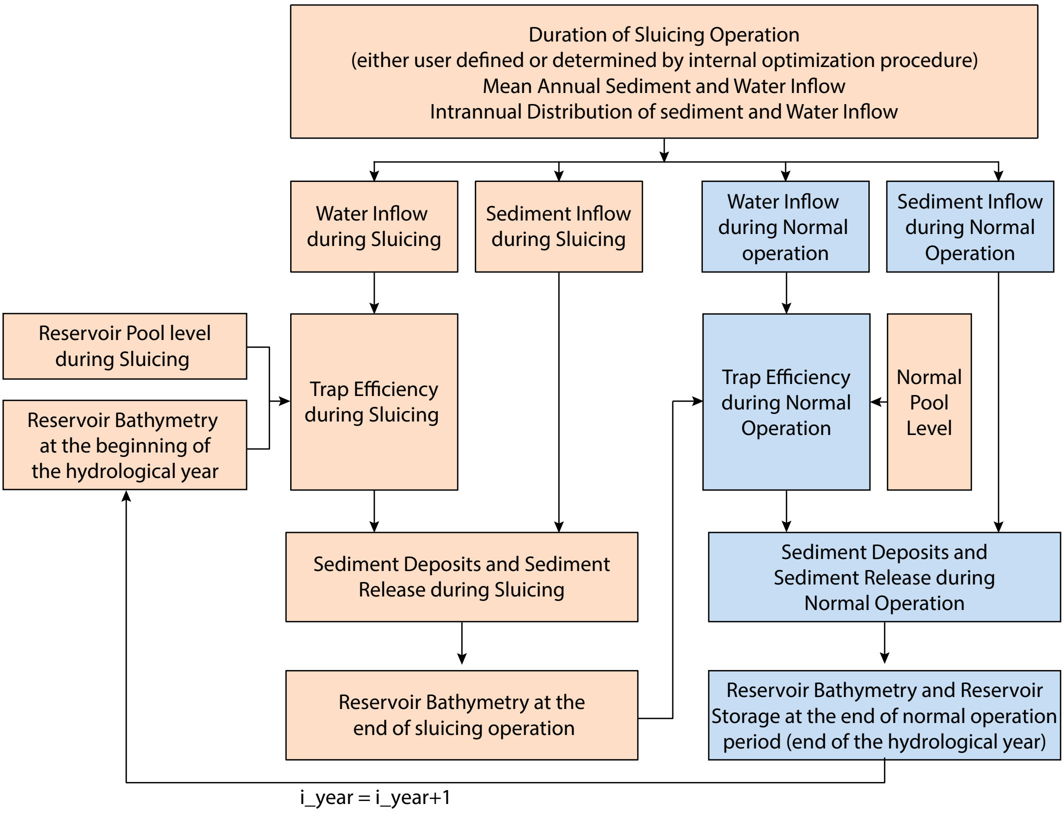
The first constraint is realized through the parameter CLSL (maximum percentage of allowable capacity loss for sluicing). For instance, if the user specifies CLSL as 30%, RESCON 2 will determine after how many years the reservoir loses 30% of its initial capacity if no sediment management is performed. Sluicing shall be implemented before this year, i.e. before 30% of the initial storage is permanently lost.

The second constraint is realized through the parameter TSLmax, which expresses the maximum allowable duration of sluicing. This parameter is provided explicitly by the user. Through this parameter the user can control the maximum allowable water losses for sediment management by means of sluicing.

4.5.1.5 Sedimentation development

The difference between flushing and sluicing is that flushing requires complete drawdown. Sluicing is implemented during floods (high flow). The drawdown

Figure 4.19: Computational procedure for assessment of reservoir storage development when sluicing is applied in RESCON 2



of the reservoir water level is less than during flushing and enough to maintain a high sediment transport capacity to pass sediment through the reservoir.

The effectiveness of sediment sluicing is assessed by RESCON 2 by following the procedure which is summarized in Figure 4.19.

The procedure comprises the following steps:

Step 1: Sluicing Operating Rules

The determination of sluicing operating rules is based on the mean annual water inflow in the reservoir, its intra-annual variation and the duration of sluicing. The first two are defined by the user, while the latter can be either explicitly defined by the user or can be automatically determined by RESCON 2 by means of an internal optimization procedure. The year is separated in two distinct phases, namely:

- The sluicing period during which the water level is lowered and the low level outlets are opened.
- The normal operation period, when the pool level is at the normal operating water level and the reservoir outlets are closed.

The mean discharge and sediment inflow for these two distinct periods are calculated on basis of the duration of sluicing operation and the user defined intra-annual variation of water and sediment inflow.

In the Figure 4.20:

- MQ is the mean annual discharge.
- Qsl is the mean discharge the time period of sluicing, which is higher than the MQ because it is considered that sluicing is performed during high flow season.
- Qowl is the mean discharge the rest of the year, i.e. during normal operation of the reservoir.
- ELowl is the normal operating water level of the reservoir.
- ELsl is the reservoir water level during sluicing operation.

Finally, the sediment inflow in the reservoir during sluicing as well during normal operation is calculated on basis of the duration of sluicing and the user defined intra-annual distribution of sediment inflow.

The amount of sediment and water that enters the reservoir during the time period of the year during which sluicing is performed and the amount of water and sediment entering the reservoir the rest year, when the reservoir water level is at the normal operating level are determined as follows.

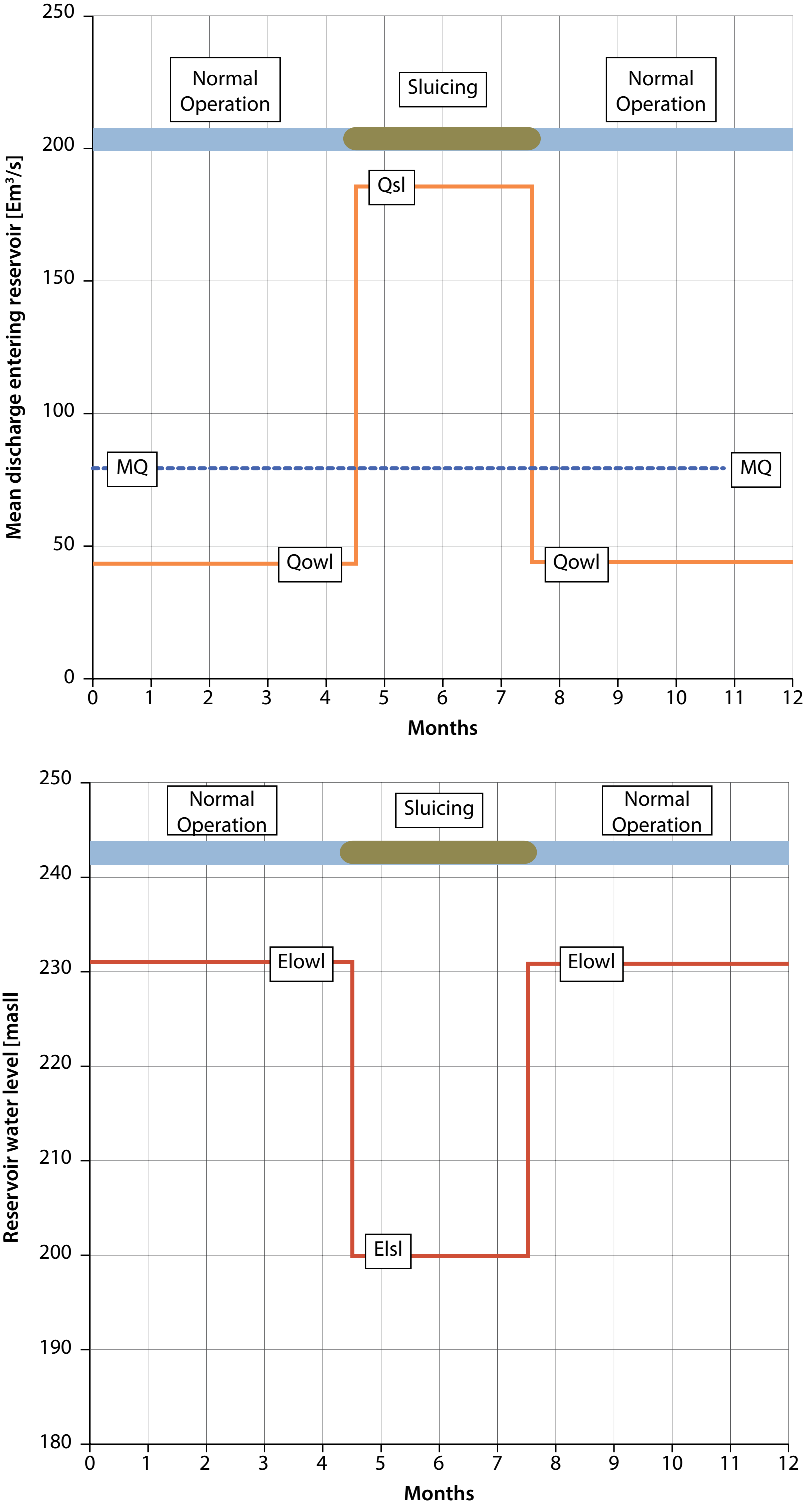
Depending on the duration of sluicing operation and the intra-annual variation, the mean annual water and sediment inflow is divided in water and sediment inflow during sluicing operation and water and sediment inflow during normal operation.

Example

The partitioning of water and sediment inflow is demonstrated in the following fictional example according to which the user has provided as input the intra-annual distribution of water and sediment inflow shown in the figure below and has specified a duration of sluicing operation of three months, i.e. 25% of annual time. Bedload is 10% of total sediment inflow and bedload transport takes place 15% of the annual time. The mean annual water inflow is 2500 million m^3/a and the mean annual sediment inflow is 6.2 million t/a.

Based on this input it is determined that 59% of the mean annual water inflow arrives at the reservoir during sluicing, i.e. during water level drawdown. This corresponds to 59% x 2500 million m^3 = 1475 million m^3 water inflow in a time period of three months. Hence, the average discharge during the sluicing operation is 190 m^3/s. Contrary 41% of the mean annual water inflow, i.e. 49% x 2500 million m^3 = 1225 million m^3 arrives at the reservoir when the water level is at the normal operating level, the remaining nine months of the year. Hence

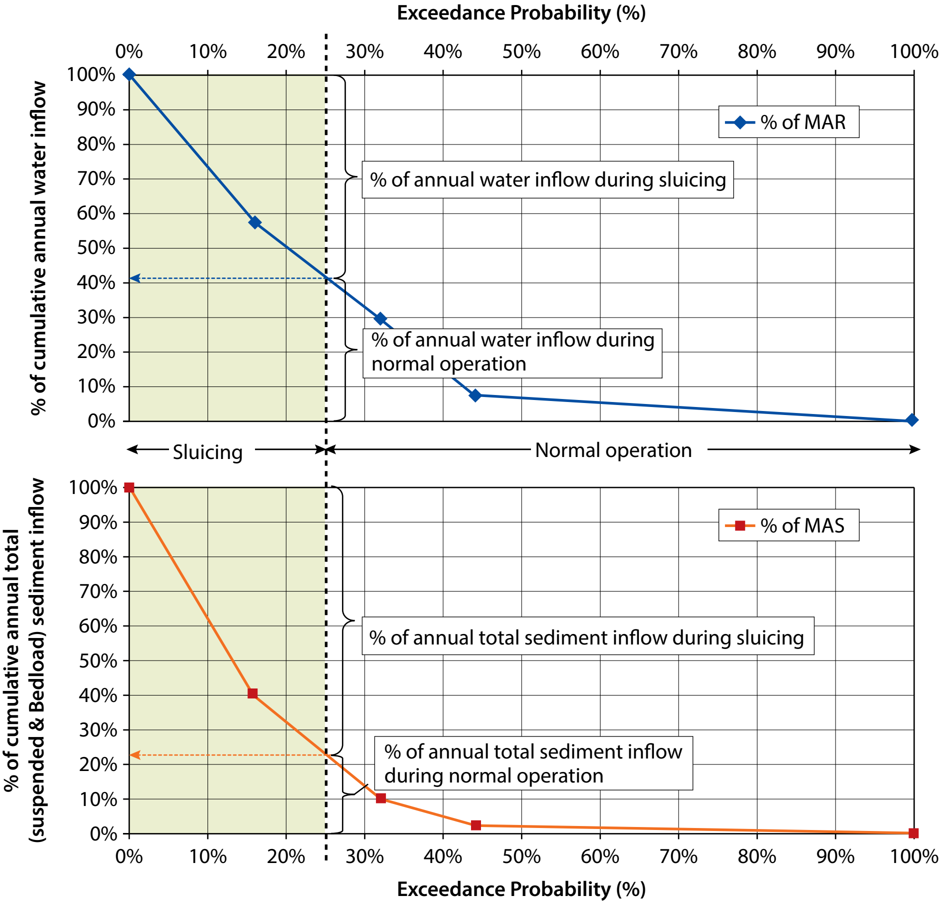
Figure 4.20: Operating Rules of Sluicing



the average discharge during normal operation of the reservoir is 52 m³/s.

Similarly, it is determined that 78% of the mean annual total sediment inflow arrives at the reservoir when sluicing is performed and the remaining 22% of mean annual sediment inflow takes place during normal operation of the reservoir. Hence the sediment inflow in the reservoir during sluicing will be 4.84 million tons. 100% of the annual bedload inflow will enter the reservoir during sluicing, because the duration of sluicing (25% of the year) is longer than the duration of bedload transport (15% of annual time). Hence the 4.84 million tons of sediment entering the reservoir will comprise 0.62 million tons of bedload (10% of 6.2 million tons total load) and 4.22 million tons of suspended load. The sediment inflow during normal operation will be only suspended load and it will be equal to 22% x 6.2 million tons = 1.36 million tons.

Figure 4.21: Partitioning of mean annual water and sediment inflow in parts occurring during sluicing and during normal operation



Step 2: Trap efficiency and sediment deposition during sluicing

This step is performed only if the considered year is later than the first year of sluicing implementation.

The mean flow velocity in the reservoir during sluicing is calculated by taking into account the lowered water level ELsl and the water inflow Qsl in the reservoir during the sluicing period. The trap efficiency shall be calculated either with the method of Churchill or Borland in order to account for the reduced detention time and the increased flow velocities in the reservoir during sluicing. The user will be warned if he attempts to apply the Brune method for calculation of trap efficiency during sluicing.

The sediment deposits and according sediment release during sluicing are computed according to the method already presented in chapter 2.1.3, on basis of the increased trap efficiency corresponding to the lowered water level ELsl and the increased water discharge Qsl during sluicing and the sediment inflow entering the reservoir during this time period.

The mean flow velocity in the reservoir during slucing is considerably higher than the corresponding velocity during normal operation due to the higher mean discharge and the lower average water depth. Therefore, the trap efficiency during sluicing is essentially lower than the trap efficiency during normal operation.

The duration of sluicing determines the sediment inflow in the reservoir during this period as previously explained. The bulk of sediment inflow however occurs during sluicing and therefore the sediment deposits are reduced compared to the continuous normal operation of the reservoir.

Finally the bottom elevation of the reservoir compartments at the end of the sluicing period is calculated.

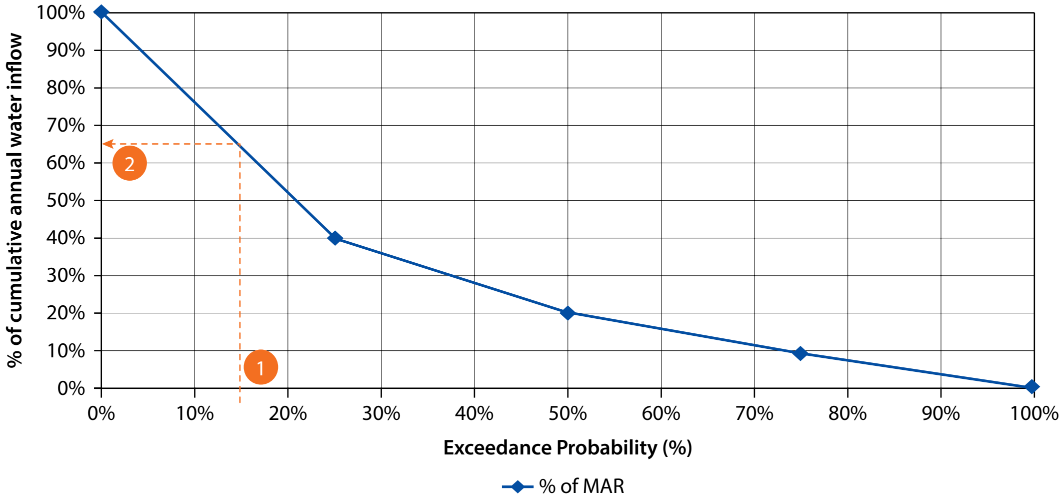
Step 3: Trap efficiency and sediment deposition during normal operation period

The mean flow velocity in the reservoir during normal operation is calculated for the previously calculated reservoir bottom elevation at the end of the sluicing operation, the normal operation water level ELowl and the mean flow velocity during normal operation is considerably lower than the corresponding velocity during sluicing due to the lower mean discharge Qowl and the higher average water depth. Therefore, the trap efficiency during normal operation is also much higher than the trap efficiency during sluicing. The bulk of sediment inflow however occurs during sluicing and therefore the sediment deposits during normal operation are not very high.

4.5.1.6 Economic formulation

In the case of sluicing, as explained in the previous chapter, the water yield from the reservoir that can be used for hydropower generation, irrigation or other uses is essentially reduced because one part of water inflow in the reservoir cannot be used for this purpose because it exits the reservoir during the water level drawdown from the low level outlets. Therefore the benefits from reservoir operation in the years where sluicing is performed are lower than the corresponding benefits in a year where no water level drawdown takes place. The water yield for the case of sluicing is calculated with the Gould-Dincer approach whereby the annual volumetric water inflow in the reservoir is reduced by the volume of water sluiced out of the reservoir. The latter is calculated by the average discharge during sluicing and the duration of this operation. An example regarding the water yield calculation during sluicing is provided below.

1. Reading of the duration of sluicing. For instance the user has specified a sluicing operation duration of 15% of annual time (approx. 8 weeks).
2. Determination of % of annual flow entering the reservoir during sluicing operation.
   In the given example approximately 35% of mean annual water inflow enters the reservoir during the specified duration of sluicing operation.



3. Determination of water yield the year sluicing occurs as follows.

- **Water level during sluicing >= Minimum operating water level**
  Sluicing does not affect the water yield. The latter is calculated with the Gould Dincer approach as a function of available storage and MAR.
- **Water level during sluicing < Minimum operating water level.**
  Sluicing reduces the water yield. The latter is calculated with the Gould Dincer approach as a function of available storage and MAR – sluiced water (as calculated in step 2).

The implementation of sluicing might require additional costs for the incorporation of additional low level outlets in the existing structures. It is assumed that no additional annual maintenance costs will be required. If it is a green field project the cost of implementation of the low level outlets is incorporated in the user defined capital expenditures for implementation of the reservoir.

A comparison of the development in time of the reservoir storage as well as the annual benefits and costs for the cases of no action and sluicing are shown in Figure 4 22. In the lower part of the figure the annual benefits and costs for sluicing are annotated by bars and the corresponding figures for the no action scenario are illustrated by straight lines.

Further explanations on the construction costs and salvage value have been previously provided in chapter 4.3.6.

4.5.1.7 Optimization framework

Sluicing is considered that it will be performed annually. One of the parameters having an important impact on the efficiency of sluicing is the duration of this operation, because it determines the amount of sediment entering the reservoir when its trap efficiency is essentially reduced due to the water level drawdown. Therefore, the duration of sluicing operation can be determined by RESCON 2 through economic optimization. A second parameter that can affect the efficiency of sluicing operation is the timing of implementation. This can be also determined by RESCON 2 through economic optimization.

The procedure of economic optimization comprises two computation loops, where the year of sluicing implementation and the duration of sluicing is varied. For each pair of values of these two parameters the development of reservoir storage is calculated. This allows the calculation of annual costs and benefits from reservoir use and the Net Present Value. The pair of values that maximizes the Net Present Value of Benefits is selected as the optimum sluicing strategy. The internal optimization is summarized in Figure 4.23.

The user is able to limit the range within which the aforementioned two parameters are varied with the purpose to determine the optimum combination. This is achieved with the two technical constraints described in section 4.5.1.4.

4.5.2 By-pass

4.5.2.1 Technical description

Sediment by-pass for instream reservoirs implies the diversion of sediment laden flows before the transported sediment load is deposited within the reservoir storage. The implementation of sediment by-pass requires the construction of a weir for the diversion of flood flows and the construction of a by-pass tunnel or open channel together with the necessary inlet and outlet portals that will discharge the diverted flows to the planned location, usually downstream of the reservoir.

Figure 4.22: Comparison of development of storage and annual benefits and costs for the case of no action and the case of sluicing

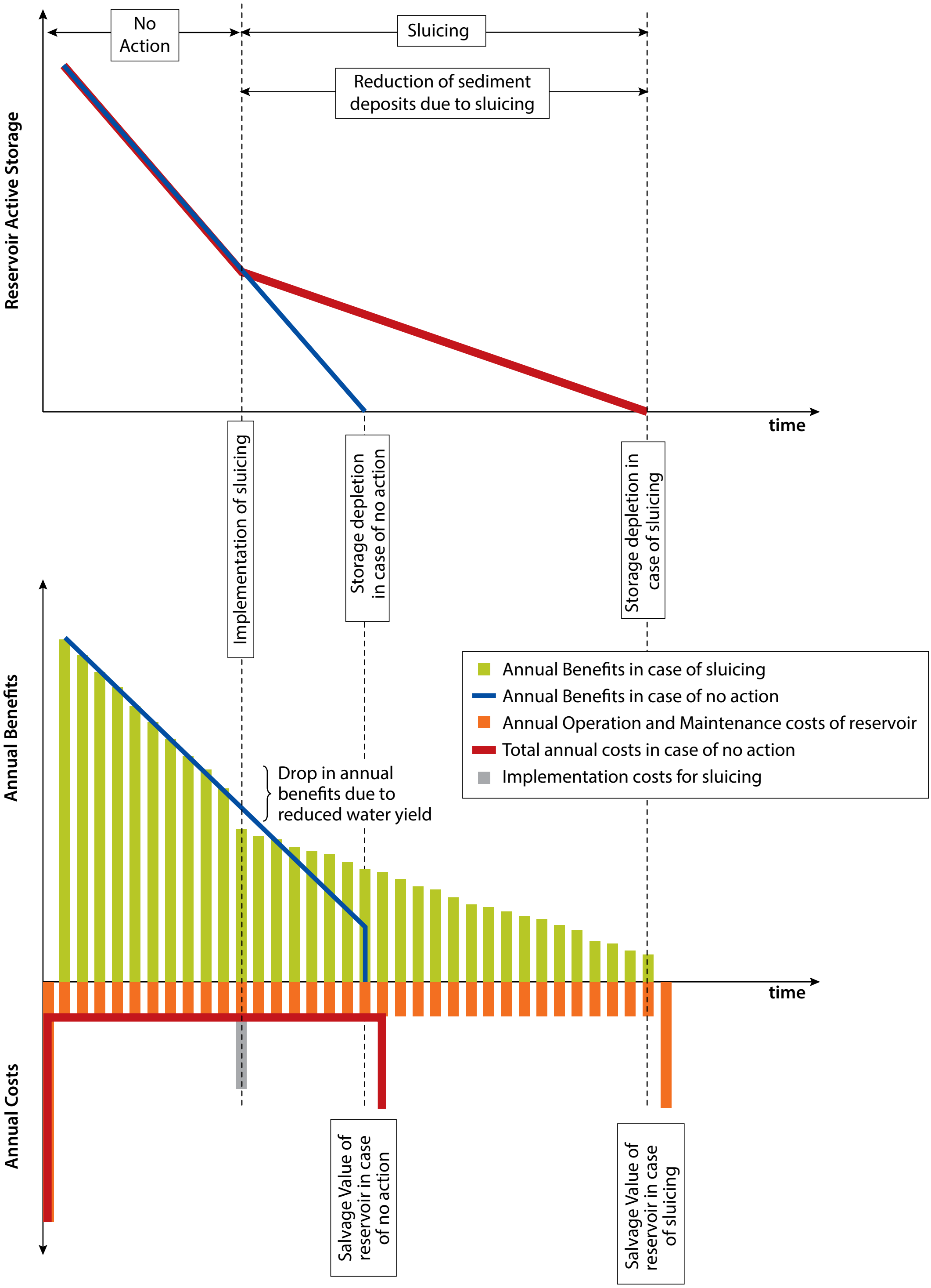
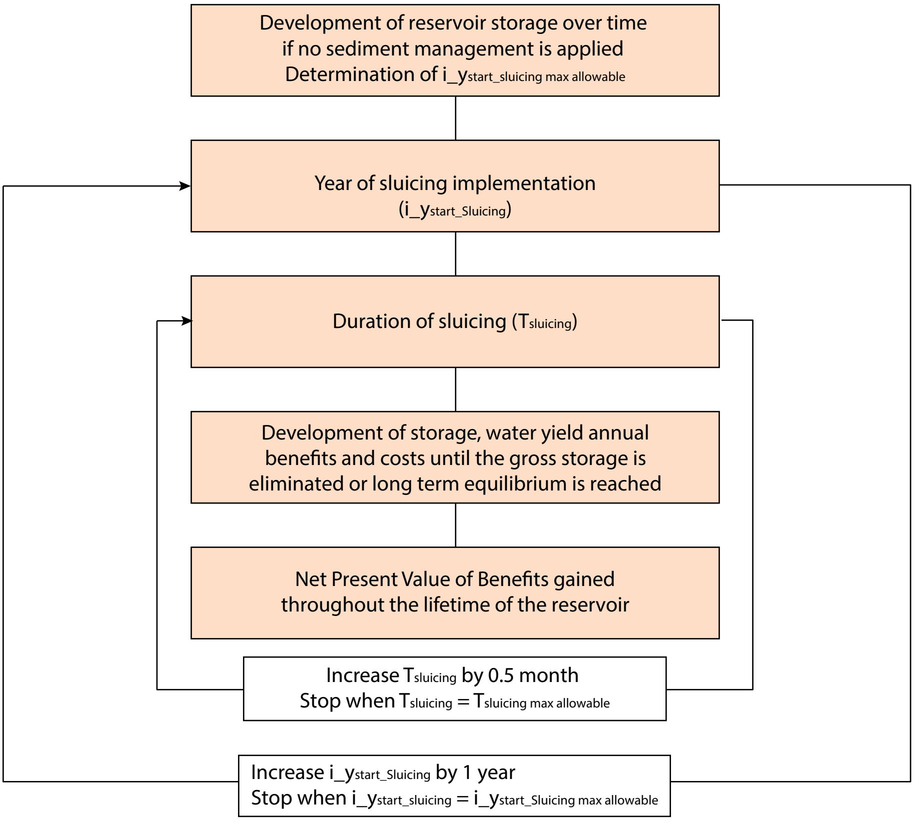


Figure 4.23: Internal economic optimization procedure for selection of optimum sluicing strategy



An example of sediment by-pass configuration is illustrated in the Figure 4.25, which shows the Nagle Reservoir in South Africa and the used sediment diversion scheme as documented by Annandale (1987).

The advantage of sediment by-pass is that the coarse part of total sediment load is diverted downstream of the reservoir mitigating thus the environmental impact of sediment transport continuity interruption which is usually triggered by the impoundment of a reservoir. This has as result that the river bed degradation downstream of the dam is essentially smaller than the erosion observed in the case of retention of sediment laden flows and release of clear “hungry for sediment” water. Another advantage of a sediment by-pass is that it does not interfere with the normal reservoir operation as it does not require a water level drawdown. Finally, the size of the spillway at the dam can be reduced considering that the sediment diversion structure is used for the discharge of flood flows.

4.5.2.2 Preliminary assessment

The preliminary assessment of suitability of sediment by-pass is performed by following the same criteria as for sluicing, which are mentioned in chapter 4.5.1.2 and specifically in Figure 4.18.

Figure 4.24: Definition sketch of sediment management in instream reservoirs with sediment by-pass

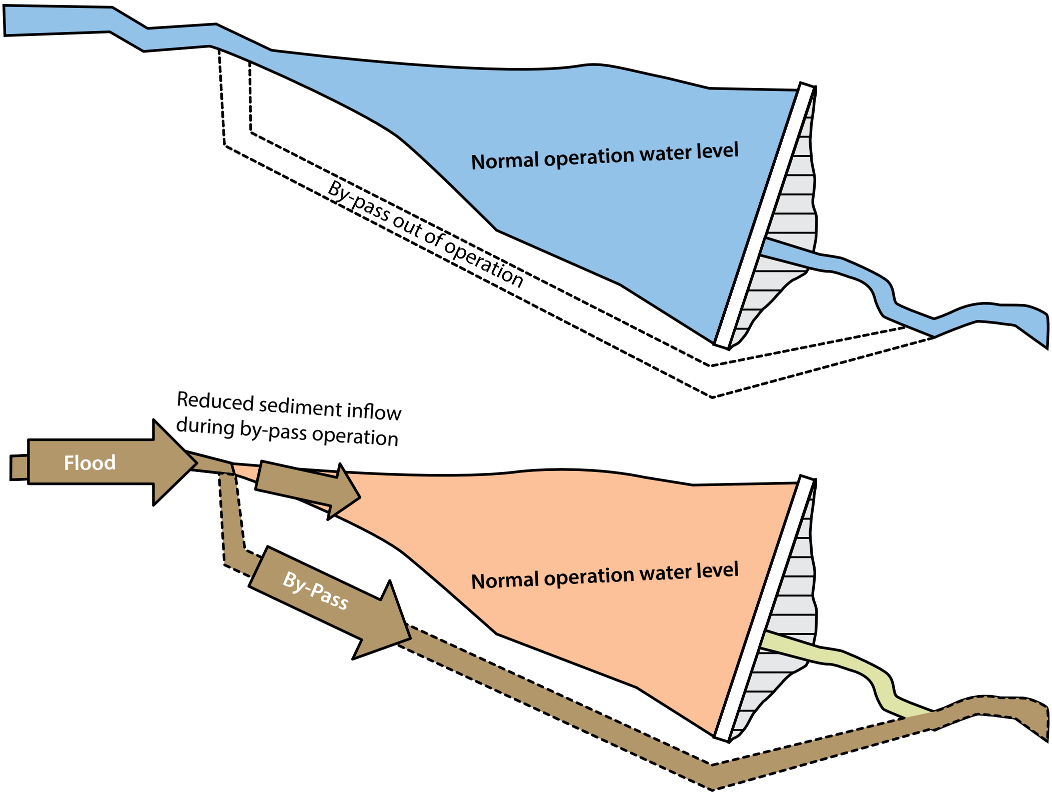
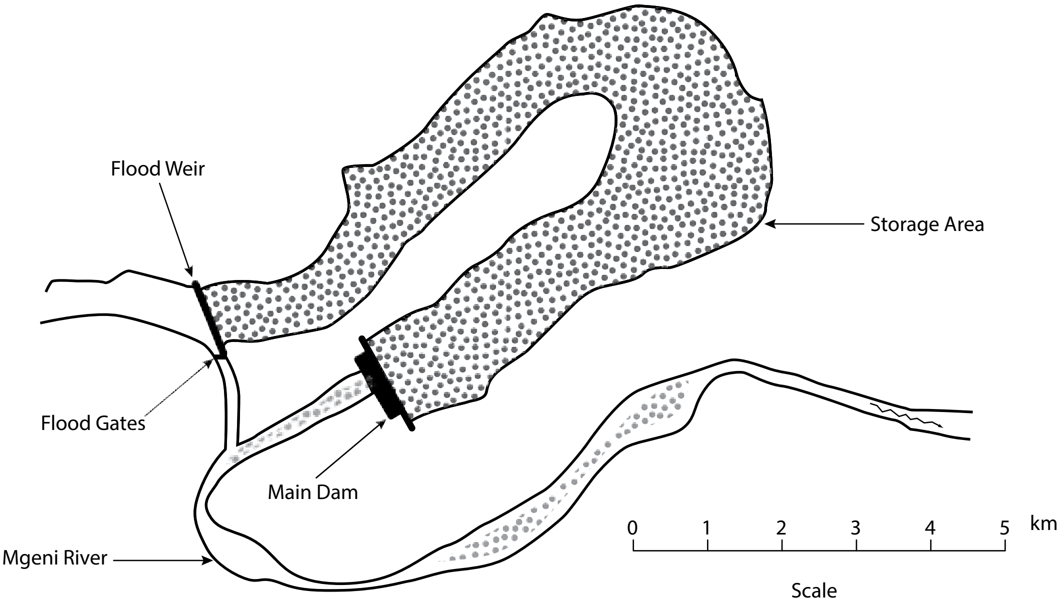


Figure 4.25: Sediment by-pass configuration at Nagle reservoir in South Africa



Source: Annandale (1987)

That means that sediment by-pass might be an appropriate option for sediment management in reservoirs characterized by:

- Hydrologic reservoir size lying between 0.001 and 0.4.
- Ratio of reservoir capacity to mean annual sediment inflow, ranging between 20 and 500.

Therefore sediment by-pass is usually not indicated for reservoirs in arid countries where the demand is high due to water scarcity.

4.5.2.3 Parameters in RESCON 2 analysis

The parameters provided in the Table 4.10 are used for the calculation of the reservoir storage development and the economic performance of the facility if sediment by-pass is applied.

Table 4.10: Parameters used for assessment of storage development and the economic performance of the reservoir if sediment by-pass is applied

		Costs associated with sluicing operation	
$C_{B\text{-}P}$	[US$]	Cost for implementation of by-pass structure	
$OMC_{B\text{-}P}$	[US$/a]	Annual operation and maintenance Costs of by-pass structures	
		Scheduling of sluicing implementation	
Shall the duration and implementation year be defined through economic optimization?			• Yes • No
$Year_{BP\ Start}$	[years]	Implementation year of by-pass	
T_{BP}	[months]	Duration of sediment by-pass	
		User defined constraints in application of sluicing	
$CL_{B\text{-}P}$	[%]	Maximum allowable storage loss before implementation of sediment by-pass	
$T_{B\text{-}P\ max}$	[months]	Maximum allowable duration of by-pass operation	
		Parameters determining by-pass efficiency	
BP_Efficiency	[%]	Water by-pass efficiency	
BP_bedload_Efficiency	[%]	Bedload by-pass efficiency	
BP suspended load_ Efficiency	[%]	Suspended load by-pass efficiency	

4.5.2.4 Technical feasibility and implementation constraints

Sediment by-pass is assumed always technically feasible. This means that appropriate structures, i.e. diversion weir and diversion tunnel or open channel have to be available or have to be designed accordingly. If such structures are not available and have to be retrofitted in the reservoir, engineering judgment is required for determination of the technical feasibility of this necessary technical intervention for implementation of by-pass. The technical feasibility depends on the length of the by-pass structure, the prevailing geological conditions, and the topography among others. It is noted from a practical point of view that by-pass tunnels seldom exceed a length of four to five km. The construction of longer tunnels is usually uneconomic.

The following assumptions are used:

- Sediment by-pass will be performed annually.
- The inlet to by-pass structure (tunnel or open channel) and the necessary diversion works are located upstream of the reservoir.

The implementation schedule of by-pass regardless if it is explicitly specified by the user or determined through economic optimization is limited by two technical constraints, the allowable capacity loss before implementation of by-pass and the maximum allowable duration of by-pass operation.

The first constraint is realized through the parameter CLBP (maximum percentage of allowable capacity loss for by-pass). For instance, if the user specifies CLBP as 30%, RESCON 2 will determine after how many years the reservoir loses 30% of its initial capacity if no sediment management is performed. By-pass shall be implemented before this year, i.e. before 30% of the initial storage is permanently lost.

The second constraint is realized through the parameter Tbpmax, which expresses the maximum allowable duration of by-pass. This parameter is provided explicitly by the user. Through this parameter the user can control the maximum allowable water losses for sediment management by means of by-pass.

4.5.2.5 Sedimentation development

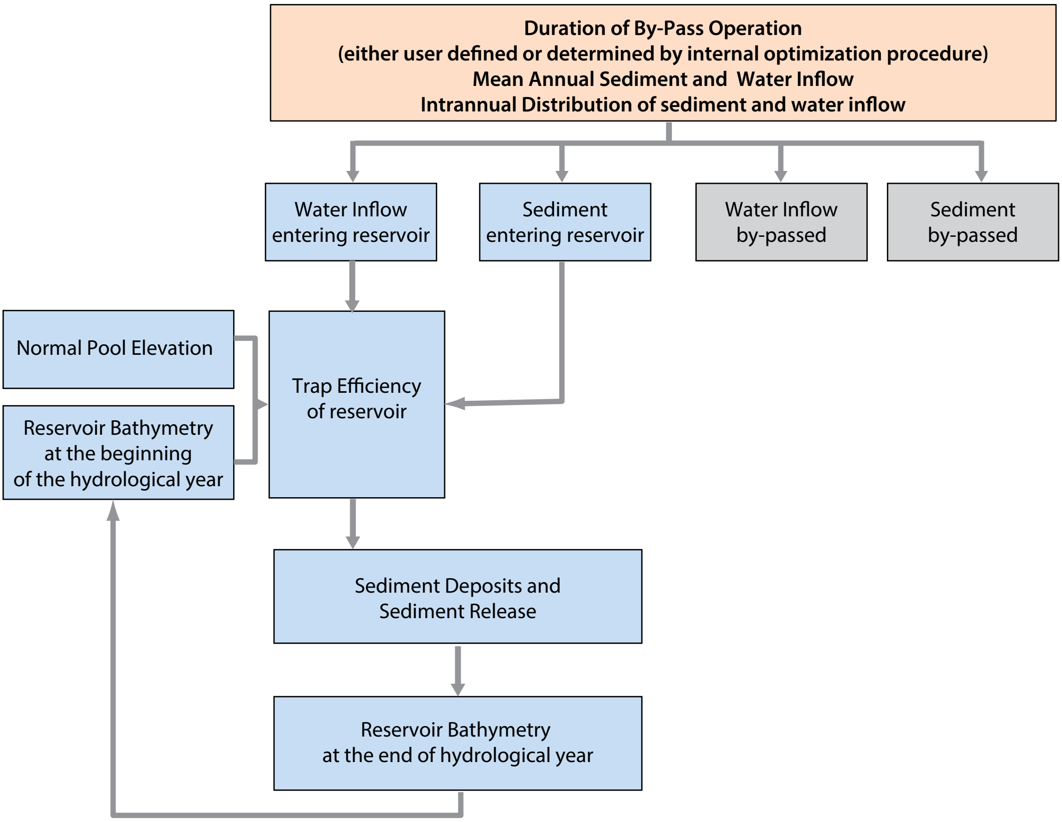
The effectiveness of sediment by-pass for instream reservoir is assessed by RESCON 2 by following the procedure which is summarized in Figure 4.26.

The computation procedure comprises the following steps:

Step 1: By-pass Operating Rules

The hydrological year is divided into two distinct phases. During the first phase, which takes place during the high flow season, sediment by-pass occurs. During this phase one part of the water and sediment runoff is diverted and the rest enters the reservoir. The distribution of runoff and sediment inflow occurring during by-pass operation between diversion structure and reservoir depends on the discharge capacity of the diversion structure and the operation rule of the submerged weir if existing. It is defined explicitly by the user. The rest of the time, i.e. when the by-pass structure is out of operation no water is diverted and the runoff and sediment inflow occurring during this time of the season enter the reservoir.

Figure 4.26: Computational procedure incorporated in RESCON 2 for assessment of reservoir storage development when sediment by-pass is applied



The determination of by-pass operating rules, or in other words the distribution of water and sediment inflow between diversion and reservoir, is based on the following parameters:

- Mean annual water and sediment inflow in the reservoir.
- Intra-annual variation of annual water and sediment inflow.
- The duration of the time period during which the river bed is active, i.e. bedload transport takes place.
- The percentage of the water and sediment inflow during by-pass operation, which is not diverted and enters the reservoir.
- The duration of by-pass operation.

The first four parameters are defined by the user, while the latter can be either explicitly defined by the user or can be automatically determined by RESCON 2 by means of an internal optimization procedure.

The following steps are carried out in order to determine the amount of sediment and water which is diverted and the amount entering the reservoir within one hydrological year.

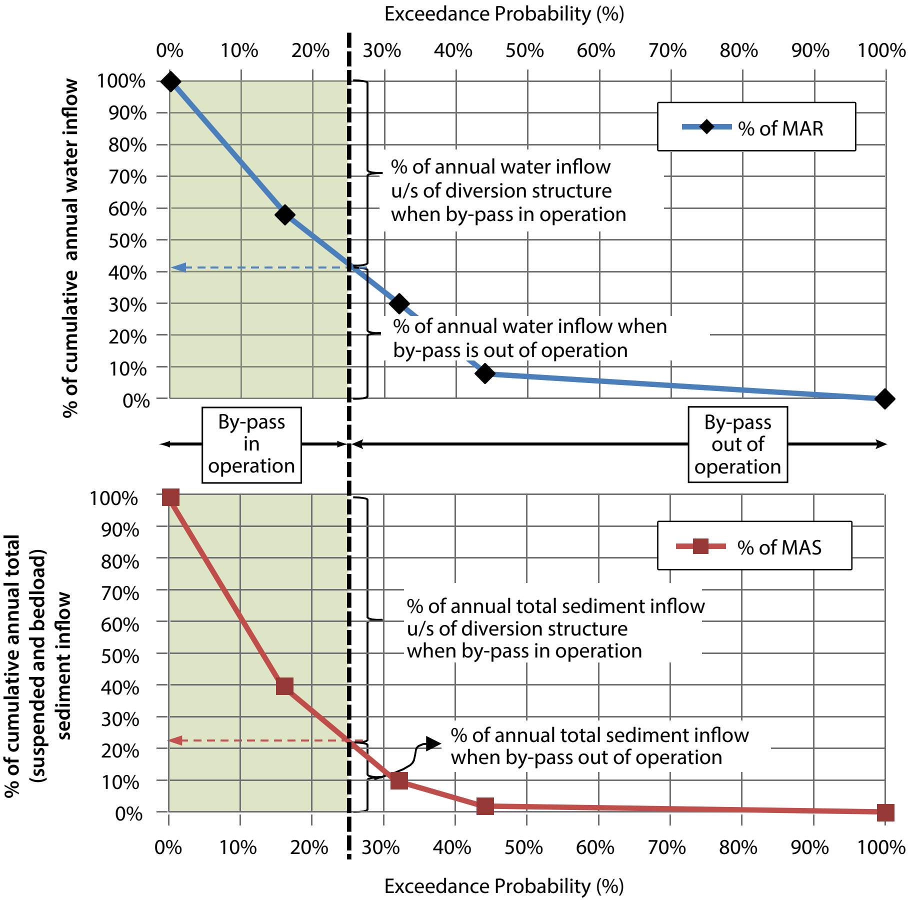
Step a: Partitioning of mean annual water and sediment inflow in parts occurring during by-pass operation and when by-pass is out of operation

Depending on the duration of by-pass operation and the intra-annual variation, the mean annual water and sediment inflow is divided in water and sediment inflow during by-pass operation and water sediment inflow when the by-pass is not diverting flow, i.e. it is out of operation.

Example

The partitioning of water and sediment inflow is demonstrated in the following fictional example according to which the user has

Figure 4.27: Partitioning of mean annual water and sediment inflow in parts occurring during by-pass operation and when by-pass is out of operation



provided as input the intra-annual distribution of water and sediment inflow shown in the figure below and has specified a duration of by-pass operation of three months, i.e. 25% of annual time. Bedload is 10% of total sediment inflow and bedload transport takes place 15% of the annual time.

Based on this input it is determined that 59% of the mean annual water inflow arrives upstream of the inlet of diversion structure when the by-pass is in operation. Contrary 41% of the mean annual water inflow arrives at the aforementioned location when the by-pass is out of operation.

Similarly, it is determined that 78% of the mean annual total sediment inflow arrives upstream of the diversion structure inlet when by-pass is in operation and the rest 22% of mean annual sediment inflow takes place when the by-pass is out of operation.

Step b: Water and sediment inflow in reservoir during by-pass operation

The previously determined water and sediment inflow arriving upstream of the by-pass structure inlet during by-pass operation is further partitioned into the amount of water and sediment diverted around the reservoir and the amount of water and sediment entering the reservoir during by-pass operation. This partitioning is performed on the basis of the user specified efficiency of water, suspended load and bedload by-pass. This is done by the parameters:

- BP_Efficiency: % of water inflow during by-pass operation which is diverted.
- BP_bedload_Efficiency: % of bedload arriving during by-pass operation upstream of by-pass structure inlet which is diverted.
- BP_suspended load_Efficiency: % of suspended load arriving during by-pass operation upstream of by-pass structure inlet which is diverted.

Example

Assuming that the user specified water by-pass efficiency is 80% and the bedload and suspended load efficiency is 90% based on the results of the fictional example described in Step a it is concluded that the diverted amount of water is 59% MAR x 90% = 53% of the mean annual water inflow MAR. Similarly it is calculated that the diverted amount of bedload load is 10% MAS x 90% = 9% of the total sediment inflow MAS and the diverted suspended load is 90% MAS x 78% x 90% = 63% of the total sediment inflow MAS.

Step c: Annual water and sediment inflow into the reservoir

The mean annual water and sediment inflow in the reservoir is deducted after adding the water sediment entering the reservoir during by-pass operation to the water sediment inflow into the reservoir when by-pass is out of operation.

A schematic illustration of the aforementioned by-pass operating rules is shown in the Figures 4.28-4.30.

Figure 4.28: Distribution of annual water inflow in water entering the reservoir (blue color) and water diverted through by-pass structure (red color)

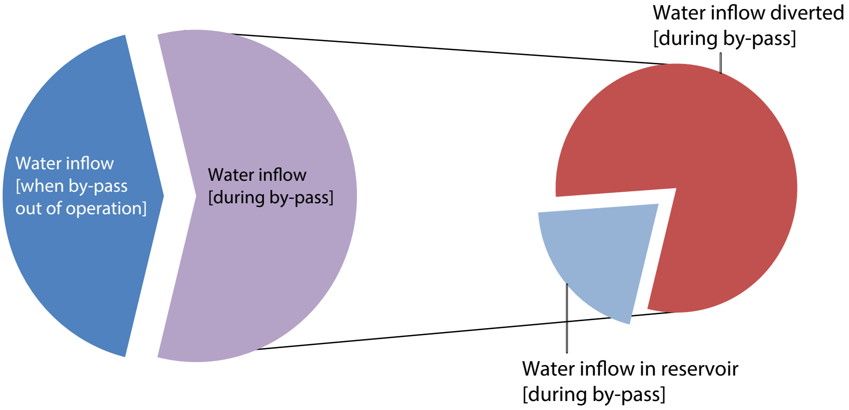


Figure 4.29: Comparison of water inflow to the reservoir when by-pass is applied and the case of no sediment management

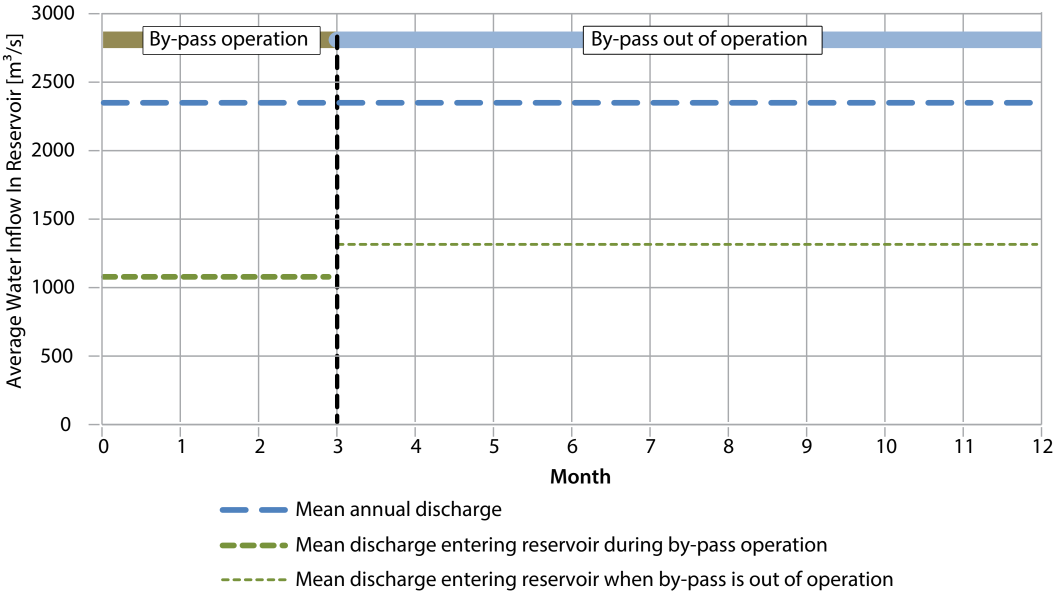
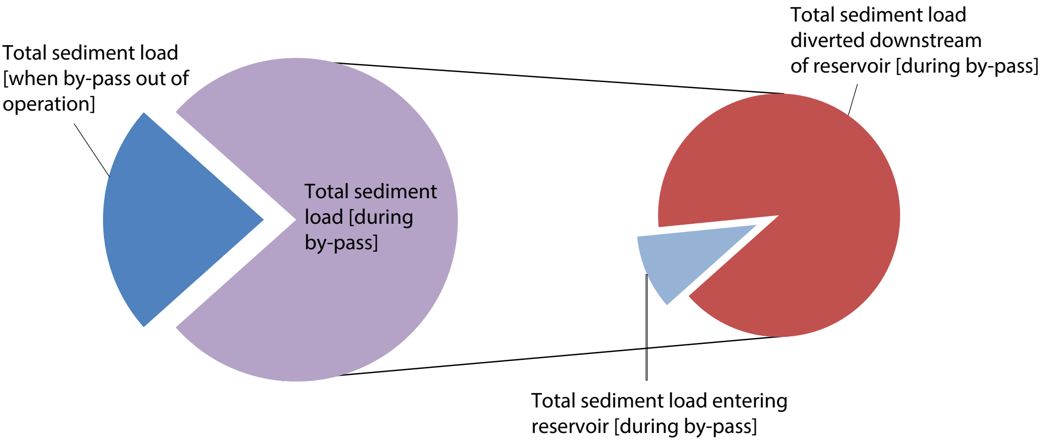


Figure 4.30: Distribution of annual sediment inflow in sediment entering the reservoir and sediment diverted through by-pass structure



Step 2: Trap efficiency and sediment deposition

The calculations in this step are performed with the previously determined reduced water and sediment inflow if the year considered is later than the first year of by-pass implementation.

The mean flow velocity in the reservoir is calculated for the reduced mean annual water inflow and under the assumption that the reservoir is operated always at the normal operating water level. The trap efficiency shall preferably be calculated either with the method of Churchill or Borland.

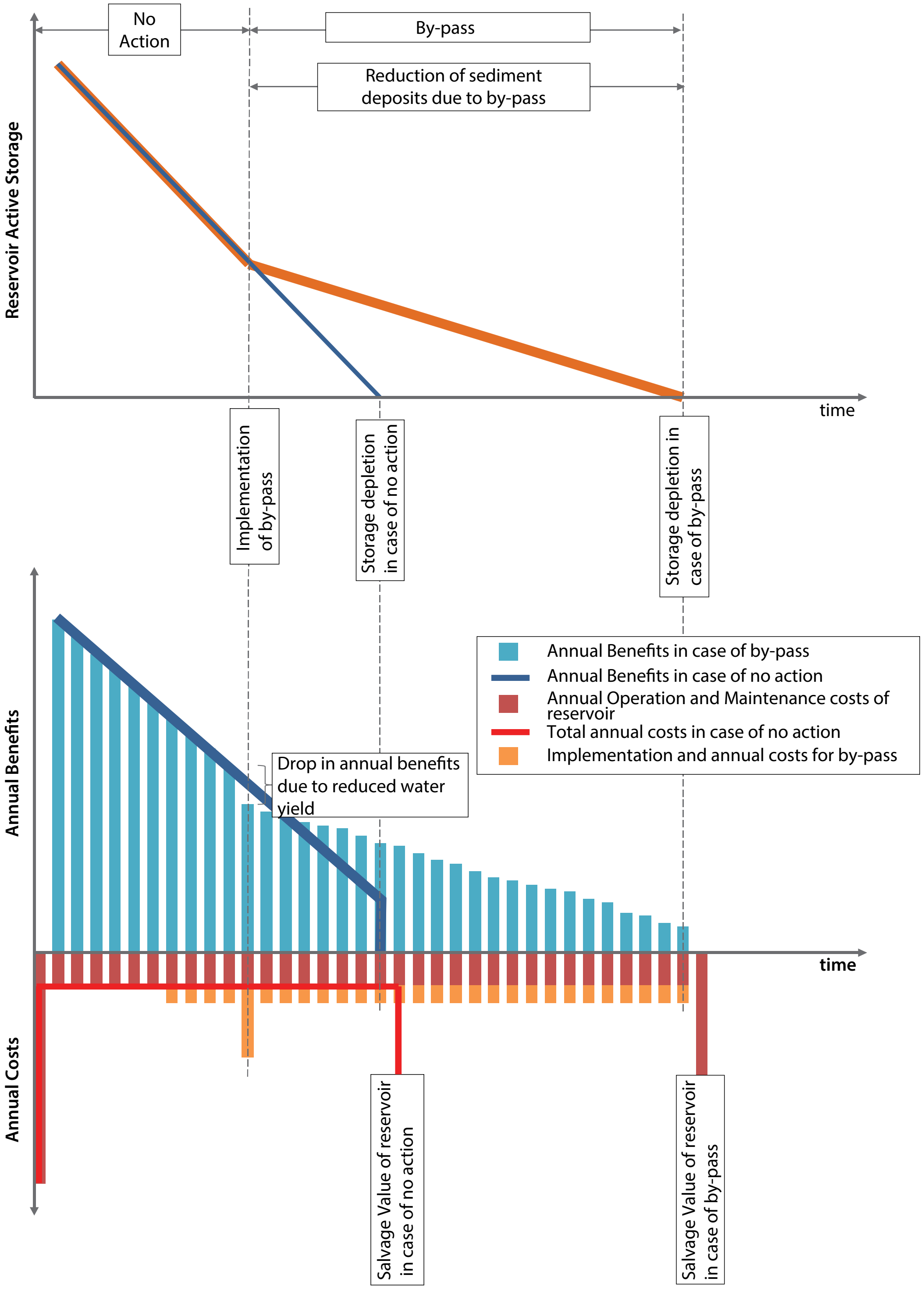
The sediment deposits and sediment release are computed according to the method already presented in chapter 2.1.3. The reduced sediment inflow is used during this calculation.

4.5.2.6 Economic formulation

In case of sediment by-pass, as explained in the previous chapter, the water yield from the reservoir that can be used for hydropower generation, irrigation or other uses is essentially reduced because one part of water inflow is diverted around the reservoir. Therefore the benefits from reservoir operation in the years where by-pass is performed are lower than the corresponding benefits in a year where no by-pass takes place. The water yield for the case of by-pass is calculated with the Gould-Dincer approach whereby the annual volumetric water inflow to the reservoir is reduced by the volume of water diverted. The latter is calculated as explained in chapter 4.5.2.4, Step 1.

The implementation of by-pass might require additional costs for the construction of the necessary diversion structures, i.e. diversion weir and by-pass tunnel or open channel. If it is a green field project the cost of implementation of the necessary structures is incorporated in the user defined capital expenditures for implementation of the reservoir. Furthermore, additional annual

Figure 4.31: Comparison of development of storage and annual benefits and costs for the case of no action and the case of by-pass



maintenance costs are considered because regular maintenance works for rehabilitation of the tunnel or open channel lining due to wear caused by hydro-abrasive erosion is usually required. The user inserts both implementation and annual maintenance cost as input.

A comparison of the development of the reservoir storage as well as the annual benefits and costs over time for the cases of no action and by-pass is shown in Figure 4.31. In the lower part of the figure the annual benefits and costs for by-pass are annotated by bars and the corresponding figures for the no action scenario are illustrated by straight lines.

4.5.2.7 *Optimization framework*

RESCON 2 provides the user with the option to perform an economic optimization, which aims at determining the constellation of the following parameters that maximizes the economic performance of the reservoir if by-pass is applied.

- Optimal timing of sediment by-pass implementation
- Optimal duration of sediment by-pass operation.

If the user does not want to determine the first implementation year and the duration of by-pass through economic optimization but rather prefers to perform the calculations for a predefined constellation of these parameters, RESCON 2 provides the possibility to insert as direct input the values of the first year of by-pass implementation and the duration of this sediment management operation.

The procedure of economic optimization comprises two computational loops during which the year of by-pass implementation and the duration of this operation is varied. For each pair of values of these two parameters the development of reservoir storage is calculated until it is eliminated or until equilibrium between sediment inflow and sediment release is achieved. The knowledge of the temporal development of storage capacity allows the calculation of annual costs and benefits and the NPV from reservoir use. The pair of values that maximizes the Net Present Value of Benefits is selected as the optimum by-pass strategy.

The user is able to limit the range within which the aforementioned two parameters are varied during the optimization procedure with the two technical constraints described in section 4.5.2.4.

4.5.3 *Density current venting*

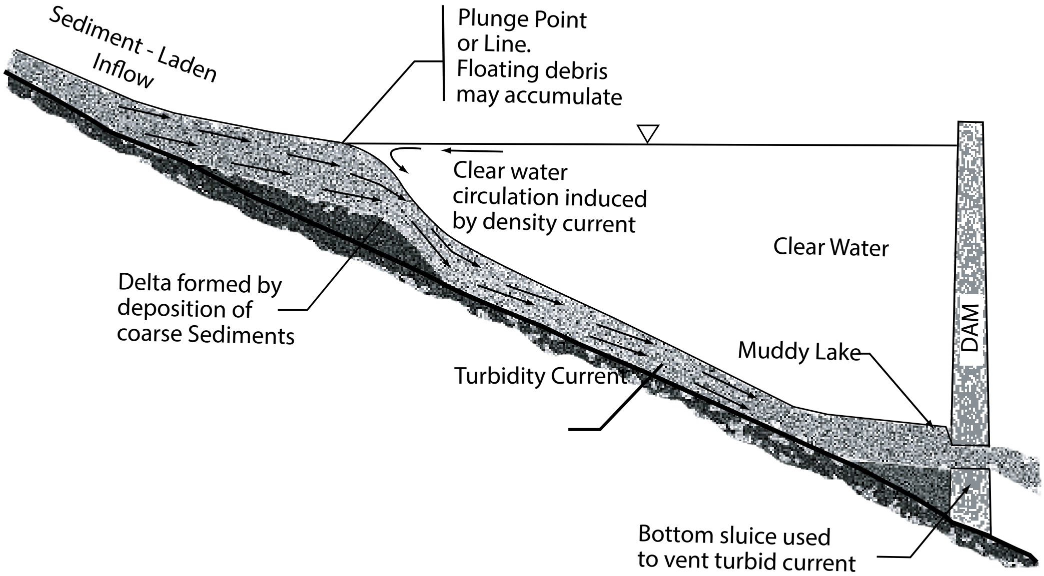
4.5.3.1 *Technical description*

Turbid density current is defined as the turbidity transported in reservoirs by means of density currents. These currents involve the gravity induced movement of one fluid mass under, through or over another fluid mass. The density currents are caused by differences between the denser river inflow and the water already impounded in the reservoir which is characterized by a slightly lower density than the water inflow (Morris & Fan (1998)).

The density difference between water inflow and impoundment water depends on the temperature difference between river flow and impounded water as well as the sediment load carried in suspension by the river. A turbidity current will be observed when a highly sediment-laden water inflow enters the reservoir and the density difference between impounded water and river flow will cause the latter to plunge beneath the water surface and travel downstream along the thalweg of the river valley.

The density current during its travel along the reservoir will dissipate due to the gradual deposition of the coarser initially and the finer consequently, particles in transport. The transport capacity of the current depends on its velocity. The latter will be higher the steeper the reservoir longitudinal bottom gradient and the larger the density difference between turbid water and stationary clear water is. If the density current is not fully dissipated until it reaches the dam, i.e. its transport load is not fully depleted due to deposition, the sediment load remaining in transport at the dam site can be fully or partially vented out of the reservoir via a suitable low-level outlet at the dam. Turbidity current venting can remove up to 50% of the sediment inflow in the reservoir during a high flood event. The efficiency of turbidity current venting depends on the characteristics of reservoir and sediment inflow and can vary considerably throughout the lifetime of the reservoir due to alteration of the reservoir bottom geometry.

Figure 4.32: Passage of a turbid density current through a reservoir and venting through a low level outlet



Source: Morris & Fan (1998)

4.5.3.2 *Preliminary assessment*

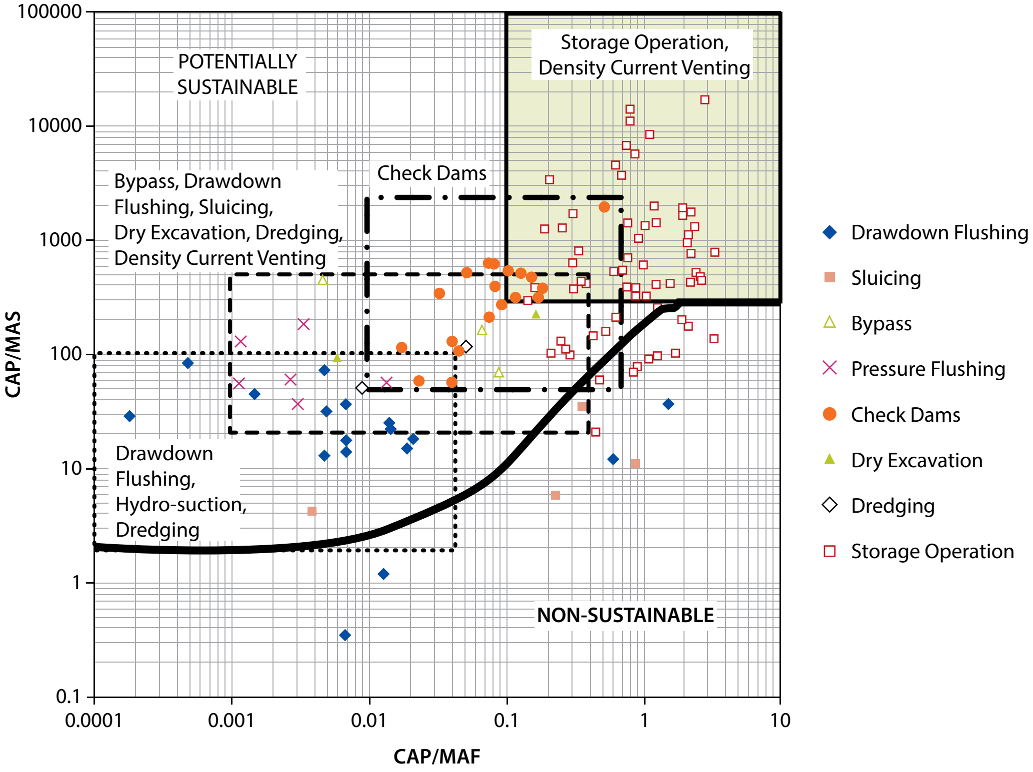
According to ICOLD Bulletin 67 (1989), density differences play an important role in deposition procedure through the formation of turbid density currents in cases of:

- Large density differences between impounded and inflowing water, i.e. when the sediment concentration of inflowing water is high.
- Large flow depths
- Steep bed slopes
- Low flow velocities.

A preliminary assessment based on the diagram published by Annandale (2013) shows that density current venting might be effective when the following pre-requisites are fulfilled:

- The hydrologic reservoir size defined as the ratio of reservoir capacity to mean annual runoff ranges between 0.1 and 10.
- The ratio of reservoir capacity to mean annual sediment inflow, which provides an indicator of the reservoir life span lies between 300 and 100,000.

Figure 4.33: Preliminary assessment of density current venting suitability



Source: Annandale (2013)

The boundaries of the aforementioned indicators are shown schematically in the Figure 4.33.

It is noted that density currents also appear in smaller reservoirs not indicated on Figure 4.33.

4.5.3.3 *Parameters in RESCON 2 analysis*

The parameters provided in the Table 4.11 are used for the calculation of the reservoir storage development and the economic performance of the facility if sluicing is applied.

Table 4.11: Parameters used for assessment of storage development and the economic performance of the reservoir if density current venting is applied

		Parameters determining density current venting efficiency
T_{DCV}	[months]	Duration of density current venting
		Scheduling of density current venting implementation
Year DCV_{start}	[years]	Implementation year of density current venting
		User defined constraints in application of density current venting
CL_{DCV}	[%]	Maximum allowable storage loss before implementation of density current venting
		Costs associated with sluicing operation
S_{DCV}	[%]	Fraction of reservoir benefits the year density current venting occurs
DCVI	[US$]	Cost of capital investment

4.5.3.4 *Technical feasibility and implementation constraints*

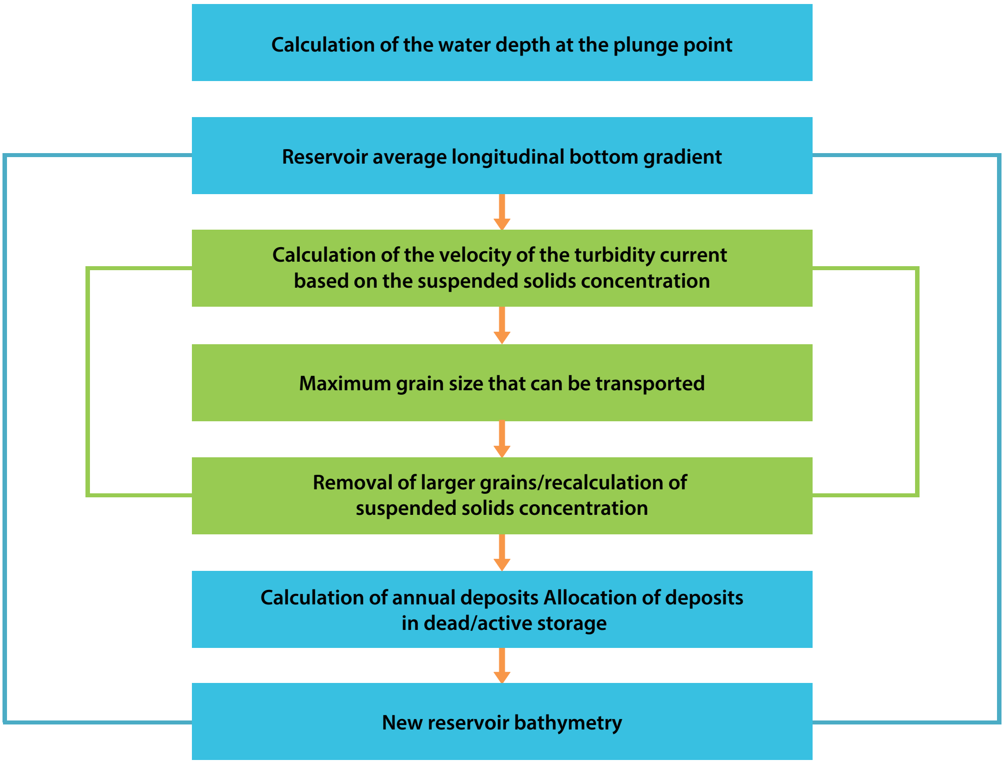
The technical feasibility of density current venting is assessed by applying the methodology of Morris & Fan (1998), which is describe in Annex 3. Initially it is cross-checked if a density current will be formed in the reservoirs. This is done by calculating the required water depth at the plunge point for the average concentration of sediment inflow during the user defined high flow period. If the required flow depth at the plunge point is smaller than the maximum available flow depth in the reservoir this means that density currents might occur in the reservoir. If not then density current formation is not possible and consequently venting is not feasible too.

The user defined implementation year of density current venting is limited by the technical constraint CLDCV regarding the maximum allowable capacity before implementation of this sediment management method. For instance, if the user specifies CLDCV as 30%, RESCON 2 will determine after how many years the reservoir loses 30% of its initial capacity if no sediment management is performed. Density current venting shall be implemented before this year, i.e. before 30% of the initial storage is permanently lost as long as it is technically feasible.

4.5.3.5 *Sedimentation development*

The timepath of reservoir storage development is assessed by applying the computational strategy shown in the figure below, which is based on the

Figure 4.34: Computational procedure for assessment of reservoir trap efficiency and sediment deposits if turbid density current venting is performed in RESCON 2



Morris & Fan (1998) methodology. The sequence of the performed calculations for estimating the reservoir trap efficiency and development of reservoir storage if density current venting is performed is shown in the Figure 4.34.

This method is adopted to the reservoir discretization scheme as described in chapter 2.1.2 in order to allow the allocation of the material that the turbid density current is not able to transport in the active and inactive storage as long as reservoir conditions favor the appearance of density current. Furthermore, the development of the reservoir bottom longitudinal slope over time, driven by the horizontal progress of the deltaic deposits and vertical lift of the reservoir bottom at the deeper sections of the reservoir bottom as a result of sediment accumulation is also accounted during the calculation of transport capacity of the density current. The equations applied during the assessment of feasibility of appearance of density currents and the efficiency of venting are provided in Annex 3.

It is pointed out that the formation of density currents depends on the geometry of the reservoir and density differences between sediment laden inflows and sediment free impounded water. Therefore, RESCON 2 calculates every year the required water depth at the plunge point for the average concentration of sediment inflow during a user defined high flow period. If the required flow depth at the plunge point is smaller than the maximum available flow depth in the reservoir this means that density currents might occur in the reservoir. Subsequently it is calculated the maximum grain size that the turbid current can keep in suspension and its fractional content in the user defined grain size distribution. The latter determines the efficiency of density current venting and is considered in the annual trap efficiency of the reservoir, which in the case of efficient density current venting is smaller than the trap efficiency in the case of no action.

4.5.3.6 Economic formulation and optimization

The storage development if density current venting can be applied is comparable to the storage development in the case of sluicing. It is considered that density current venting can prolong the reservoir lifetime due to reduction of the annual trap efficiency but it cannot eliminate totally the deposits rendering thus the reservoir sustainable.

The assessment of the economic performance of the reservoir for the case of effective density current venting is based on the user defined fraction of reservoir benefits available the year of effective density current venting operation. This depends on the duration of the bottom outlet opening and the percent of discharged water relative to water inflow. This is something that has to be determined by detailed investigations with purpose the minimization of the water losses and the maximization of the venting efficiency.

It is considered that density current venting will be performed annually while the user can define the first year of implementation of this technique. This is subject to a technical constraint relevant with the maximum allowable reservoir storage loss prior to implementation.

The scheduling of this method cannot be optimized by RESCON 2 because the economic performance of the reservoir depends mostly on the user defined percent of benefits available when this technique is applied. The latter is directly correlated with the duration of the high flow season and the timing of bottom outlet opening which depend from site specific conditions.

4.6 Multiple Methods

The user can define a sediment management strategy comprising up to five different techniques, which will be applied sequentially. The available techniques have been described in detail in the previous chapters.

The methods involved in the sediment management strategy are subject to the same technical constraints as if they were applied as standalone methods. The only difference is that the sediment routing and catchment management techniques are considered to be applied instantly, i.e. the user cannot define an initial time period during which no sediment management will be performed.

It is recommended to perform the multiple methods analysis separately than the analysis of the individual methods.

CHAPTER 5

Climate Change Analysis

5.1 Introduction

A vast body of scientific evidence indicates that the climate in the future will be different than the climate observed in the past. According to the fifth assessment report of the Inter-governmental Panel on Climate Change (IPCC), the average global surface temperature has increased 0.85 °C since the year 1880. It is expected that the surface temperature will continue increasing also in the future (IPCC (2013a and b)). This change of Earth's climate will alter among other parameters the availability and variability of runoff as well the sediment flux of rivers worldwide. The water sector infrastructure however, is usually designed and operated under the assumption of a natural system fluctuating within an unchanging envelope of variability, i.e. it is assumed that the climate will not change in the future. As Milly et al. (2008) however eloquently stated "Stationarity is dead". It is expected that the climate non-stationarity will trigger challenges and additional risks with regards to water resources planning.

Climate change in the planning and design phase of long-lived infrastructure in the water sector can be addressed through the development of adaptation strategies which shall aim at reducing the vulnerability of the infrastructure to a differentiated climate future. A recent analysis of the climate resilience of Africa's infrastructure in the power and water sector has shown that the benefits in terms of reduced risks for a climate change adapted design significantly exceeded the cost of modifying the baseline investments in order to perform the adaptation (Cervigni et al. (2015).

The potential adaptation strategies to the climate change effects shall allow mitigating the negative impacts of a potentially harsher climate future or taking advantage of the positive effects of a potentially wetter future. Climate change adaptation strategies might comprise measures such as increase or reduction of the turbine capacity, increasing the mean conveyance irrigation efficiency and others. Most of these adaptation strategies for infrastructure projects in the water sector aim at adjusting the project design to a varying future reservoir water yield, which can be either lower or higher than the one determined on basis of historical hydrological data.

Annandale (2013, 2015) has clearly illustrated that the extent of the impact of climate change on the water yield supplied from a reservoir with a specific reliability depends largely on the storage capacity available for regulation of water inflows and outflows. Consequently the physical and economic performance of hydropower and water supply infrastructure under different climate scenarios is also dependent on the available reservoir storage. The larger the increase of hydrologic variability in the future, the larger the reduction of firm water yield from the reservoir. The reduction in firm water yield due to increased hydrologic variability will be more profound the smaller the available storage. Therefore RoR facilities will be more vulnerable to climate change than storage facilities. The larger the storage capacity the less profound is the effect of variability change and hence the bigger the resilience of infrastructure to climate change.

Accepting that the hydrological variability will unavoidably increase due to climate change, leads to the conclusion that the continuous loss of reservoir storage capacity due to sedimentation will increase the vulnerability of infrastructure in the water sector. Therefore, sediment management, which can decelerate the storage loss rate and can lead to a sustainable conservation of a residual reservoir storage, might prove to be a very important part of an effective adaptation strategy to climate change. Therefore, the analysis and design of any adaptation strategy shall take into account the potential impact of sediment management on the resilience of designed infrastructure to climate change.

It is important to note that the quantification of the probability of appearance of a specific climate future is not possible due to the lack of agreement between climate change scientists. Therefore, the climate change effects cannot be predicted and quantified in a deterministic manner, rather they are associated with high uncertainty. Furthermore, it is not the intent of RESCON 2 analysis to perform a detailed assessment of climate change impacts on the economic and physical performance of long-lived infrastructure in water sector. The incorporated tool/approach shall demonstrate the effect of climate change on the economic performance of the investment for different sediment management configurations over a representative range of potential climate futures. This analysis shall aid the decision making process in a preliminary phase of project development.

The climate change incorporated in RESCON 2 facilitates a sensitivity analysis which has the following objectives:

- Climate "stress test"
  Indication of how vulnerable different project configurations might be across a sensible range of potential climate change effects. The project configurations are differentiated by the applied sediment management method.
- Robust Decision Making (RDM).

Identification of one or more robust project configurations (i.e. design capable of delivering acceptable performance under a wide range of climate scenarios).

The analysis performed by RESCON aims to provide a rapid assessment of sediment management as adaptation strategy to climate change of infrastructure in water sector which includes a reservoir. The advantage of the performed analysis is that it takes into account the continuous loss of storage and the increase of hydrologic variability.

5.2 Effect of Climate Change and Sedimentation on Performance of Infrastructure in Water Sector

The benefits gained from infrastructure projects in the water sector depend on the water yield, i.e. the water available to key productive uses such as hydropower or irrigation, supplied with a given reliability by a reservoir, which is constructed with purpose the regulation of water inflows and outflows. The water yield and its corresponding reliability depend on available reservoir storage, river runoff availability and variability. The hydrologic indicators, i.e. water availability and variability controlling the reservoir water yield and its reliability are sensitive to climate change. In addition, the available storage is continuously reduced by sediment deposits. The storage loss rate is determined by the sediment inflow which is also affected by climate change. This shows that the water yield from the reservoir and its reliability, i.e. two parameters which have an important impact on the economic performance of the infrastructure will depend largely on the future climate.

In this section is described first the impact of climate change on hydrologic parameters. Subsequently, is presented the interrelation between water yield and hydrologic indicators as well as available reservoir storage. This section aims at providing a description of how climate change increases the vulnerability of a water sector infrastructure and how the impact of climate change is magnified by continuous storage loss due to sedimentation.

5.2.1 Impact of climate change on hydrologic indicators and water yield

Climate change will have as result a change of the total amount of annual precipitation and its inter-annual distribution as well the amount of evaporation and consequently the contribution of precipitation to runoff. It is therefore generally expected that climate change will have over time an impact on the following basic hydrologic indicators, which control the water yield supplied by a reservoir:

- Mean annual runoff
- Annual runoff variability
- Mean annual sediment inflow

The response of river runoff to future climate change will be different from place to place. It is expected that the annual average river runoff will increase as a result of climate change at high latitudes and in some wet tropical areas and decrease over some dry regions at mid-latitudes and in the dry tropics. (Bates et al. 2008). According to Milly et al. (2005) it is expected that the mean river flow will decrease by 10-30% in the Middle East, southern Europe, North and Southern Africa, mid-latitude western part of North America, Mexico, Central America and in northern and southern parts of South America. It is expected that mean river flow will be increased by 10-40% in eastern equatorial Africa, the La Plata basin and high-latitude North America and Eurasia.

The aforementioned climate projections describe unfortunately only a very geographical pattern of future change. The projection of water availability in the future is characterized by large and persistent uncertainty. The models used for prognosis of climate often disagree whether the future climate in a specific location will be wetter or drier than the observed historic climate. According to some models or emission scenarios the water availability expressed by the mean annual runoff in a specific location might be smaller than the historic observations, while some other models or emission scenarios might show that this hydrologic parameter will increase in the future. Hence, both options, i.e. a lower or a higher water availability in the future are possible and no clear trend with regards to the impact of climate change on water availability is apparent.

It is generally accepted that the precipitation intensity and variability will increase due to climate change. This will result in increased risks with regards to flooding and longer multiple-year droughts in many areas of the planet. Therefore, it is considered that the hydrologic variability will likely increase globally although it is difficult to determine the extent of this potential change. The hydrologic variability can be expressed by the annual coefficient of variation of river flow, which is determined as the ratio of standard deviation to mean annual runoff. This parameter takes usually values between 0.2 and 0.8. A Cv equal with 0.2 describes a low variability of water inflows, while a value of 0.8 applies to a high hydrologic variability.

The impact of climate change on the sediment load transported by the river, which will finally enter the reservoir is difficult to be assessed because it depends on many different parameters. For instance, changes of temperature due to climate change are related to actual evapotransporation which directly influences sediment loading. This effect is magnified when reforestation or deforestation occurs in the catchment area of the river. Zhu et al. (2007) reported that a climate change driven increase in precipitation will increase the sediment flux to a given stream.

Generally, studies indicate that sediment loads in rivers are more likely to increase due to the climate change. For instance, according to Asselman et al. (2003), soil erosion in the Rhine River Basin in Central Europe will increase by

12% for the UKHI climate change scenario. The aforementioned increase of soil erosion considers also a change in land uses. Yang et al. (2003) calculated that soil erosion will increase by 14% globally. Almost one third of the aforementioned global increase of soil erosion rate will be driven by changes in land uses and two thirds by climate change. Shrestha et al. (2013) assessed the future changes in sediment flux attributable to climate change in the Nam Ou basin, in northern Laos. The predicted changes in annual sediment yield ranged from a 27% decrease to 160% increase. They concluded that the projected climate change impact on sediment varies remarkably between the different climate models and therefore the uncertainty should be taken into account in both sediment management and climate change adaptation.

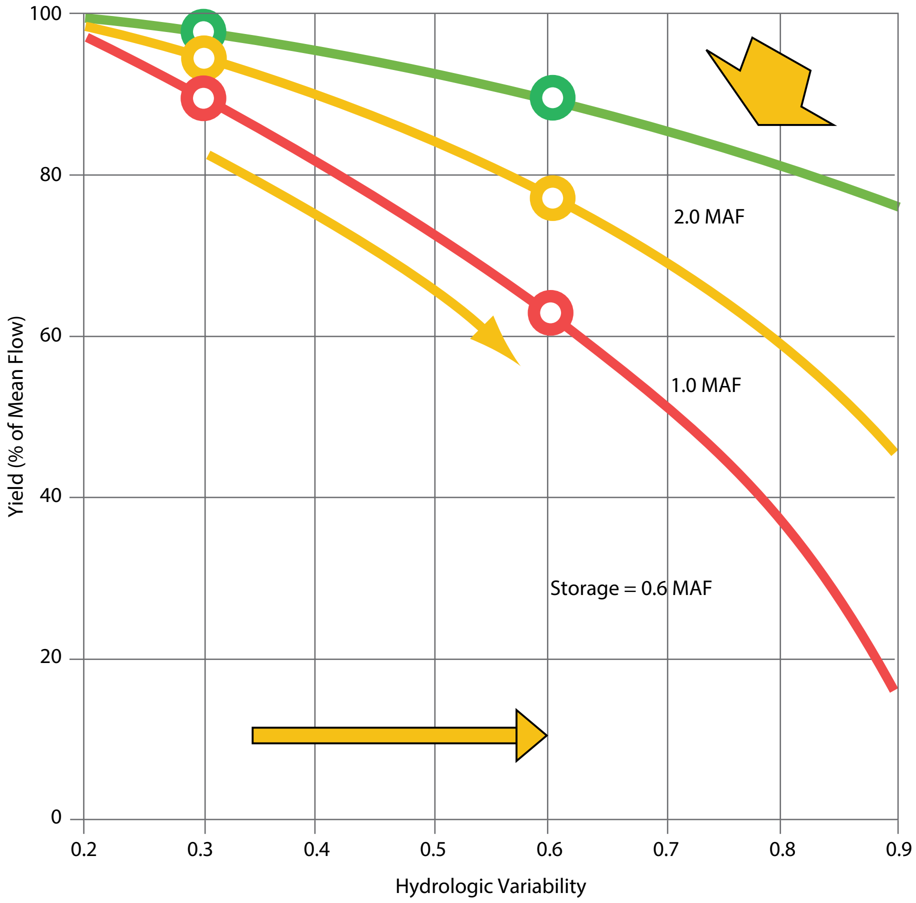
5.2.2 Impact of sedimentation on reservoir water yield

The available reservoir storage will be continuously reduced due to deposition of sediment transported by the impounded river. The reservoir storage loss due to sedimentation has as result the reduction of the water yield from the reservoir for a given reliability. Similarly it is concluded that the continuous storage loss results in a reduction of the reliability of a given water yield.

It is generally accepted that climate change will result in an increase of hydrologic variability in the future, which will be revealed through the occurrence of larger floods as well as longer dry periods (Bates et al. (2008)). Annandale (2013, 2015) has clearly illustrated that the combination of hydrologic variability increase due to climate change with continuous storage loss due to sedimentation will intensify the drop of reliability of water supply over time. This leads to the conclusion that in the future a given demand will remain unsatisfied more frequently than in the observed historic climate case. This might become evident faster than expected, due to an increase in sediment flux, which will be also driven by climate change.

The Figure 5.1 shows the variation of dimensionless water yield for a given reliability (expressed as the ratio of yield to mean annual water inflow) with hydrologic variability for different dimensionless reservoir storages. It is assumed that the reservoir storage volume is equal to two times the mean annual water inflow (green line) and it is expected to be reduced to 0.6 times the mean annual water inflow due to sedimentation (red line) within a given time period. If the hydrologic variability throughout this time period remains constant, e.g. at 0.3, the sedimentation will have as result that the water yield from the reservoir with a given reliability will drop from 98% to 88% of mean annual inflow. If the storage loss during this time period however is accompanied by an increase of hydrologic variability due to climate change, the water yield from the reservoir for a given reliability will drop now from 98% to 61% of water inflow. Hence, the combination of climate change expressed as increase in hydrologic variability and storage loss due to sedimentation intensifies the reduction of infrastructure resilience.

Figure 5.1: Impact of variation of hydrologic variability to reservoir firm yield



Source: Annandale, G. (2015)

In the previous example it was illustrated the impact of the increase of hydrologic variability driven by climate change on the water yield provided by a reservoir for a given reliability in conjunction with the storage loss due to sedimentation. Climate change is expected however to have an impact not only on the hydrologic variability but on other hydrologic characteristics such as water availability and sediment inflow. The impact of these parameters might magnify the effect of climate change on reservoir performance.

5.3 Sediment Management as Adaptation Strategy to Climate Change

Climate Change might lead to infrastructure underperforming if the reservoir water yield is reduced if a drier future is realized or if insufficient installed capacities are available. In the first scenario the impact of climate change expressed in economic terms, i.e. its cost will appear as revenue losses. In the second scenario the cost of climate change will be expressed as foregone revenues. Adapting to the climate change aims at reducing any negative impacts (threats) and seizing any positive consequences (opportunities). Adaptation strategies therefore shall aim at adjusting the design of the infrastructure in a manner that will allow the reduction of potential foregone revenues or the reduction of revenue losses due to climate change.

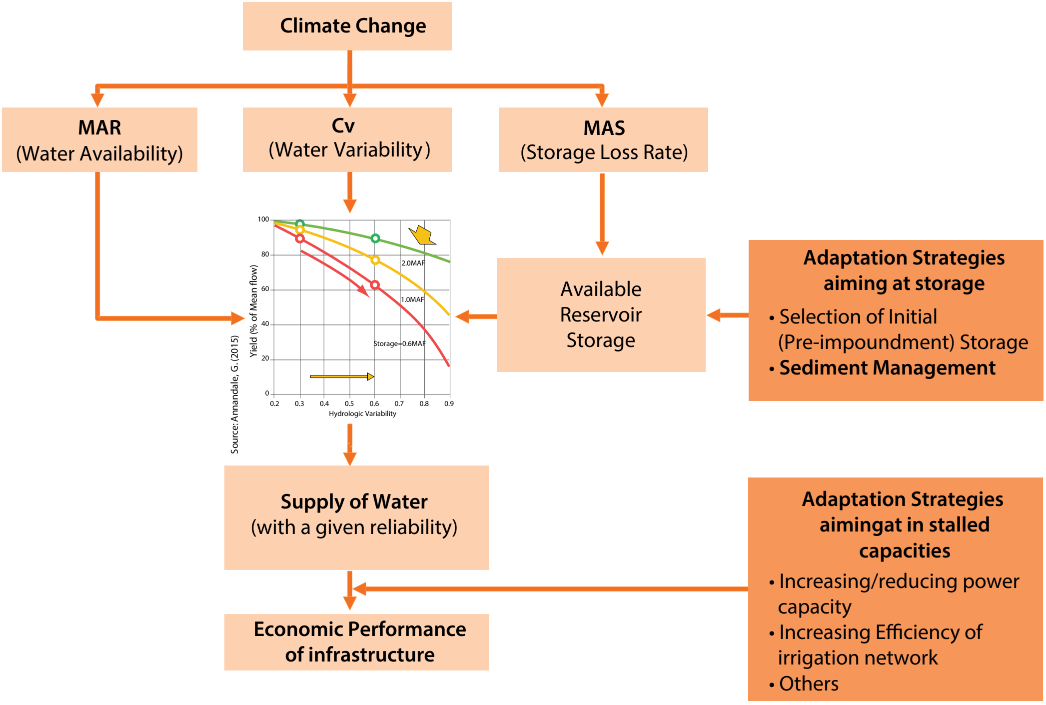
Considering the large and persistent uncertainty associated with the site specific climate projections it is important to develop a robust adaptation strategy i.e. an adaptation strategy able to deliver an acceptable performance of the infrastructure for a wide range of climate scenarios.

The adaptation strategy can have the following objectives:

- Adjusting the infrastructure design to adapt to altered water yield due to climate change.
- Reducing the impact of climate change on water yield.
- Combination of the aforementioned two methods.

This interrelation between climate change adaptation strategies and economic performance of the infrastructure is shown in the Figure 5.2. Climate change will affect the water availability and variability as well the sediment inflow. Sediment inflow will determine the temporal variation of reservoir storage. Water inflow availability, variability and reservoir storage determine the

Figure 5.2: Impact of climate change and potential adaptation strategies on economic performance of infrastructure in water sector



Source: Annandale, G. (2015)

water yield of the reservoir. Climate change will hence alter the water yield supplied by the reservoir.

Climate change adaptation strategies belonging to the first group might comprise measures such as increase or reduction of the turbine capacity, increasing the mean conveyance irrigation efficiency and others. Most of these adaptation strategies for infrastructure projects in the water sector aim at adjusting the installed capacities, which have been designed according to business as usual for the historic climate, for utilization of a future reservoir water yield, which can be either lower or higher than the one determined on basis of historical hydrological data.

Annandale (2013, 2015) showed that the extent of the impact of climate change on the firm water yield supplied from a reservoir with a specific reliability depends largely on its storage capacity available for regulation of water inflows and outflows. Consequently the physical and economic performance of hydropower and water supply infrastructure under different climate scenarios is also dependent on the available reservoir storage. The larger the storage capacity the less profound is the impact of climate change on water yield and hence the bigger the resilience of infrastructure to climate change.

It is deducted that sediment management can reduce essentially the project vulnerability to climate change, because it can reduce the storage loss rate. This becomes easily evident with the help of Figure 5.2. For instance, if the application of sediment management measures has as result a milder reduction of available storage to one time the mean annual inflow (yellow line) instead of 0.6 times the mean annual inflow (red line), the increase of hydrologic variability to 0.6 from 0.3 due to climate change will cause a drop of firm water yield to 78% of mean annual water inflow from the initial value of 98% of mean annual inflow. The drop of firm water yield for the inaction (no sediment management) scenario would be from 98% to 61%. That means that the application of sediment management limited the storage loss, which in turn reduced the impact of climate change on water yield, i.e. on economic performance of infrastructure.

5.4 Ensemble of Possible Future Climates

In order to perform a sensitivity analysis it is necessary to identify first the full range of possible impacts of future climate change on hydrologic indicators influencing the water yield from a reservoir. Therefore it is necessary to determine the impact of climate change on the following parameters:

- Mean runoff percent change
- Runoff Variability
- mean annual sediment inflow.

There are different internet sources available for obtaining model projections regarding future climate and hydrologic indicators but they differ widely in the access-complexities and data format.

In the following is presented a methodology for retrieving climate change data as well the associated processing that will allow the use by RESCON 2.

5.4.1 Future runoff availability

5.4.1.1 Data source

The World Bank has recently developed a concept for the assessment of the impact of climate change on six hydrological indicators for more than 8,000 river basins across the world. Strzepek et al. (2011) provide a thorough description of the developed basin scale indicator approach. One of the assessed future hydrological indicators is mean annual runoff, which affects essentially the water yield supplied by a reservoir and at the same time it is one of the necessary input data for the RESCON 2 analysis. Therefore it is strongly recommended to retrieve the future runoff from the Climate Change Knowledge Portal for Development Practitioners and Policy Makers that was developed by the World Bank Group because alternative data portals provide only projections of precipitation, temperature and evaporation and the calculation of runoff entering the reservoirs requires the application of a hydrologic model or empirical equations. The portal can be found at the following internet address:

http://sdwebx.worldbank.org/climateportal/

This portal provides directly runoff and temperature data for the following options:

- Emission Scenarios (Future Climate Scenario)
  - A1b
  - A2
  - B1

- Ground Circulation Models (GCM)

The portal utilizes results of 22 GCMs in order to perform an analysis that leads to the percentual changes of runoff. The user can select between at least one and maximum all 22 GCMs.

- Time Period
  - 2030-2039
  - 2050-2059.

It is recommended to download the runoff and temperature data for all three emission scenarios A1b, A2 and B1, for all 22 GCMs and for the time period 2050-2059.

5.4.1.2 Data acquisition procedure

The user has to follow the steps described below in order to retrieve the data required for the sensitivity analysis performed by RESCON 2:

Step 1: Select the project location (country) in the Combo box at the upper right corner of the climate change portal home page. (Figure 5.3).

Figure 5.3: Step 1 for retrieving climate change data from World Bank knowledge portal

The Climate Change Knowledge Portal (CCKP) Beta is a central hub of information, data and reports about climate change around the world. Here you can query, map, compare, chart and summarize key climate and climate-related information. Read More

Click on an area of the map to get started >

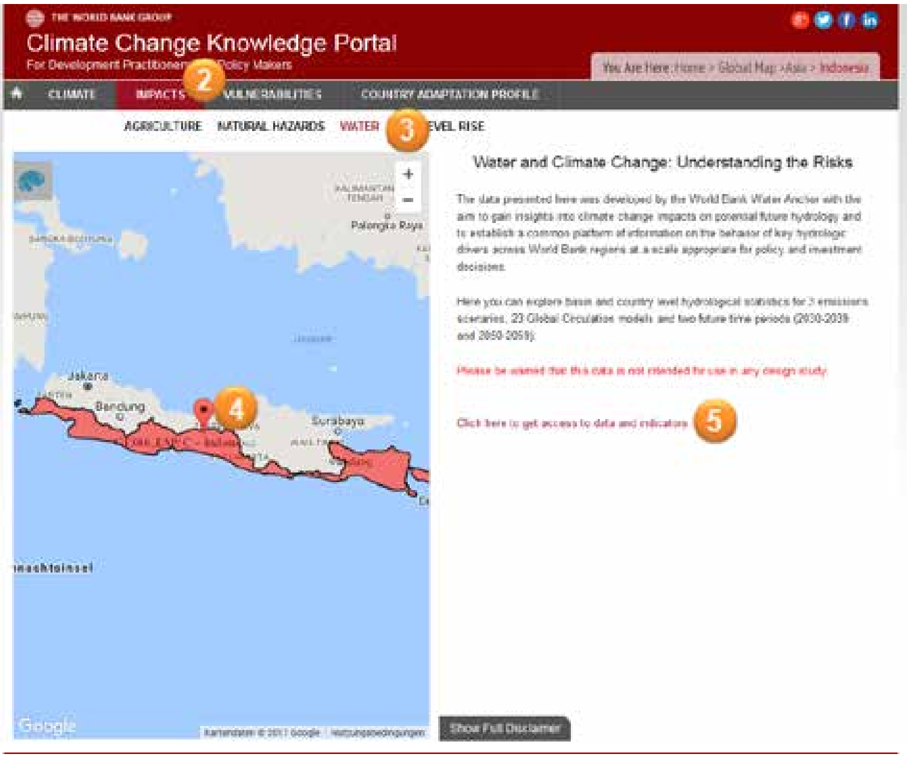
The Climate and Disaster Risk Screening Tools can be used by development practitioners at an early stage of national level planning processes or project design. The tools provide a structured and systematic way to undertake due diligence.

Climate Adaptation Country Profiles provide a quick reference source for development practitioners to better integrate climate resilience into development planning and operations.

Explore the Climate Smart Agriculture (CSA) Country Profiles to learn about CSA terminology, components, relevant issues, and how to contextualize it under different country conditions.

Use your creativity to integrate, visualize, and synthesize climate and development data.

Figure 5.4: Steps 2-5 for retrieving climate change data from World Bank knowledge portal



Water and Climate Change: Understanding the Risks

The data presented here was developed by the World Bank Water Anchor with the aim to gain insights into climate change impacts on potential future hydrology and to establish a common platform of information on the behavior of key hydrologic drivers across World Bank regions at a scale appropriate for policy and investment decisions.

Here you can explore basin and country level hydrological statistics for 3 emissions scenarios, 22 Global Circulation models and two future time periods (2030-2039 and 2050-2059).

Please be advised that this data is not intended for use in any design study

Click here to get access to data and indicators

Step 2: In the next screen select the tab IMPACTS. (Figure 5.4).
Step 3: Select the tab WATER.
Step 4: Select the exact location of the project by moving the red cursor. This way the basin is selected and appears now in red color.
Step 5: Click on the link that provides access to data and indicators.
Step 6: Select the tab View and Download Data in the next screen. (Figure 5.5).
Step 7: Select all three future climate scenarios a1b, a2 and b1 (multiple selections are possible by holding Ctrl key pressed during selection).
Step 8: Select the hydrologic indicators of Mean Temp (it is the first available choice) and Mean Annual Runoff (fifth available choice in the list).
Step 9: Select all 22 GCM climate models. This can be done by clicking on the first and last item of the list while holding the Shift key.
Step 10: Select time period 2050-2059.
Step 11: Click on button Download Data.
Step 12: Save on a hard drive the file WaterBasinData.xls

The downloaded excel file should comprise of one worksheet which includes the requested data in the form shown in Figure 5.6.

The selected percent change of runoff and absolute change of temperature can be entered now directly in RESCON 2.

5.4.1.3 *Alternative data sources*

The recommended portal provides climate change runoff data for the countries shown in the Figure 5.7:

Figure 5.5: Steps 6 - 11 for retrieving climate change data from World Bank knowledge portal

Future Climate Scenario: a1b, a2, b1
Indicators: Drought Indicator, Mean Annual Runoff, Annual Base Flow, Storage
GCM: ncar_ccsm3_0, ncar_pcm1, ukmo_hadcm3, ukmo_hadgem1
Time Period: 2030 - 2039, 2050 - 2059

Figure 5.6: Retrieving Excel worksheet containing climate change data from World Bank knowledge Portal

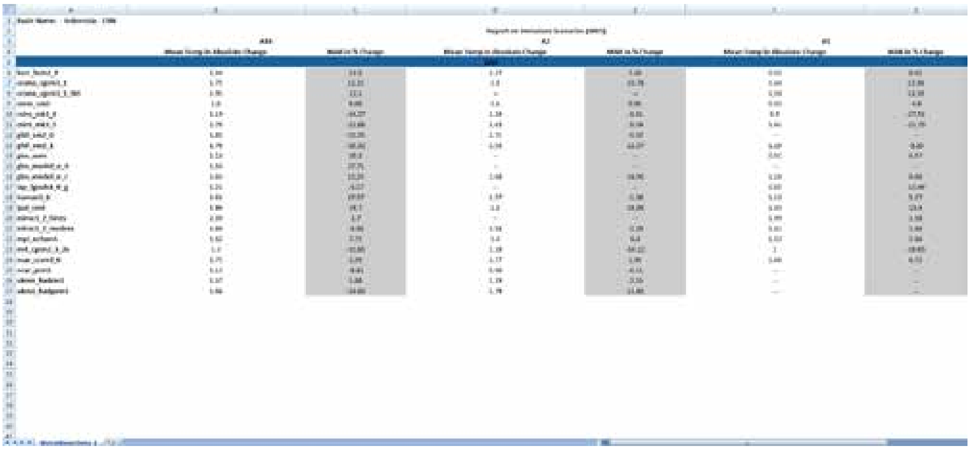
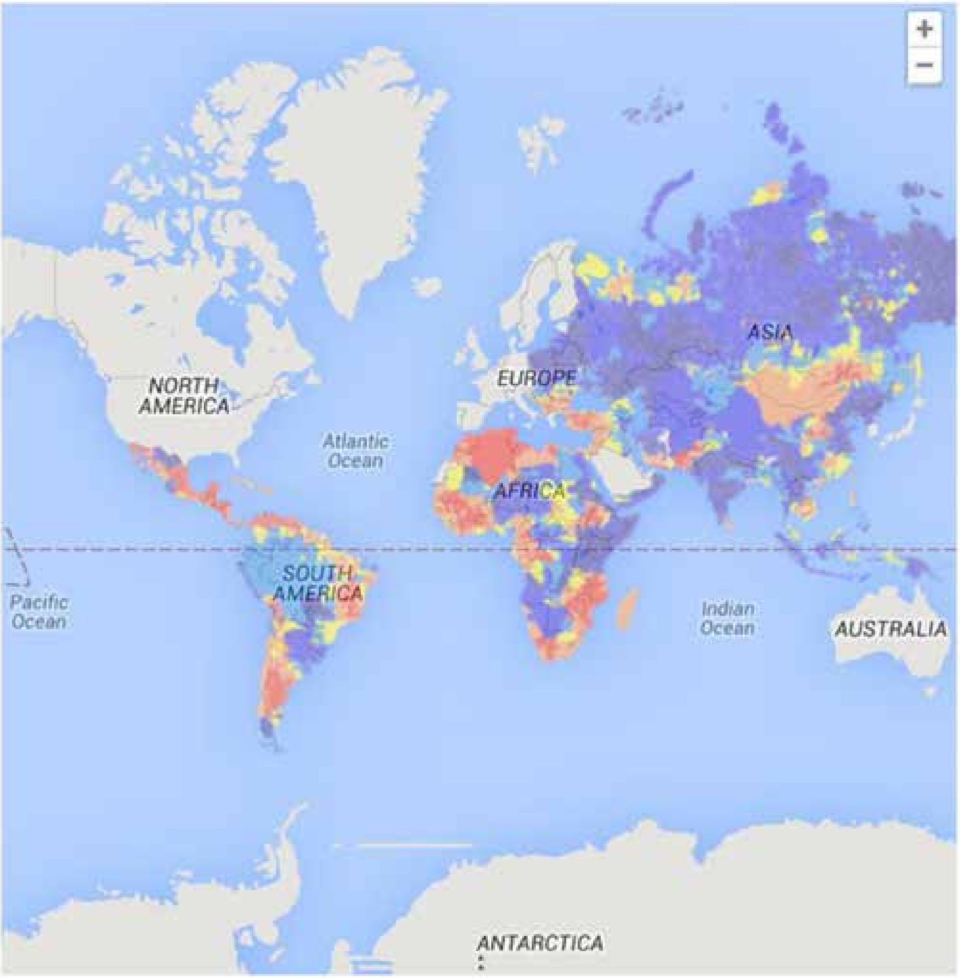


Figure 5.7: Countries with available climate change runoff data in World Bank knowledge Portal



If the project is located in a country which is not included in the data base of the recommended portal, alternative data sources are:

- UNDP Climate Change Country Profiles
- KNMI Climate Explorer
- Climate Wizard.

The disadvantage of these portals is that they do not provide assessments of future projections for mean annual runoff. In that case, this hydrologic indicator, which is necessary for the analysis performed by RESCON 2, has to be calculated from the future projections of precipitation, evaporation and temperature. This can be accomplished with application of the Turc-Pike equations, which can easily be incorporated in an Excel spreadsheet.

5.4.2 Future Runoff variability

It is generally accepted that the hydrologic variability will increase in the future due to climate change. For this reason it is considered that a sensible range of annual coefficients of variation, which can represent adequately the uncertainty associated with climate change, will vary from the observed historic value up to a coefficient of variation equal with 0.8. A Cv value of 0.8 represents an unusually high variability of annual water inflow, i.e. an annual series which accounts for frequent and intense flood events and long, multiple year dry periods. It is noted that by the calculation of water yield, the gamma transformation starts to break down from Cv values 0.8 and onwards.

5.4.3 Future sediment flux

The recommended portal for climate change data acquisition does not provide an assessment of the future percent change of soil erosion or sediment flux. Therefore, the impact of climate change on mean annual sediment inflow is assessed internally by RESCON 2 by following the procedure described below:

Step 1: Calculation of base case mean annual sediment inflow according to Syvitski and Milliman (2007)

The mean annual sediment inflow for the base case is calculated by applying the empirical equation BQART, which was developed by Syvitski and Milliman (2007). The necessary input for application of this equation comprises the following user defined parameters:

- Catchment area draining to reservoir.
- Maximum basin relief.
- Historic average basin surface temperature.
- Historic mean annual runoff.
- Basin averaged lithology class.
- Ice cover as percentage of total drainage area.

- Basin trap efficiency, i.e. existence of reservoirs upstream of the reservoir under consideration.
- Basin human-influence soil erosion class.

Step 2: Calculation of future mean annual sediment inflow according to Syvitski and Milliman (2007) for individual GCM predictions

The mean annual sediment inflow for the climate change scenario is recalculated by applying again the BQART equation, only this time with the runoff and temperature input as calculated by an individual climatic model for a specific emission scenario. The data that characterize the catchment topography and geology such as maximum basin relief and lithology class remain the same. The user, however, can redefine the basin human-influence soil erosion class and the basin trap efficiency. This way, future changes with regards to land uses, impoundment of large reservoirs or socio-economic conditions can be also accounted.

Step 3: Calculation of percent change of MAS (according to BQART equation)

The percent change of Mean Annual Sediment Inflow relative to historic conditions is calculated for each specific climate model and emission scenario on the basis of the past and future MAS values calculated in step 1 and 2 respectively. It is pointed out that the BQART equation does not capture the impact of wind conditions on sediment flux. Climate change might affect the locally prevailing wind conditions which in turn might affect the sediment flux. This is something that will not be accounted when using the method and is left to the judgment of the user if it is necessary to apply a correction.

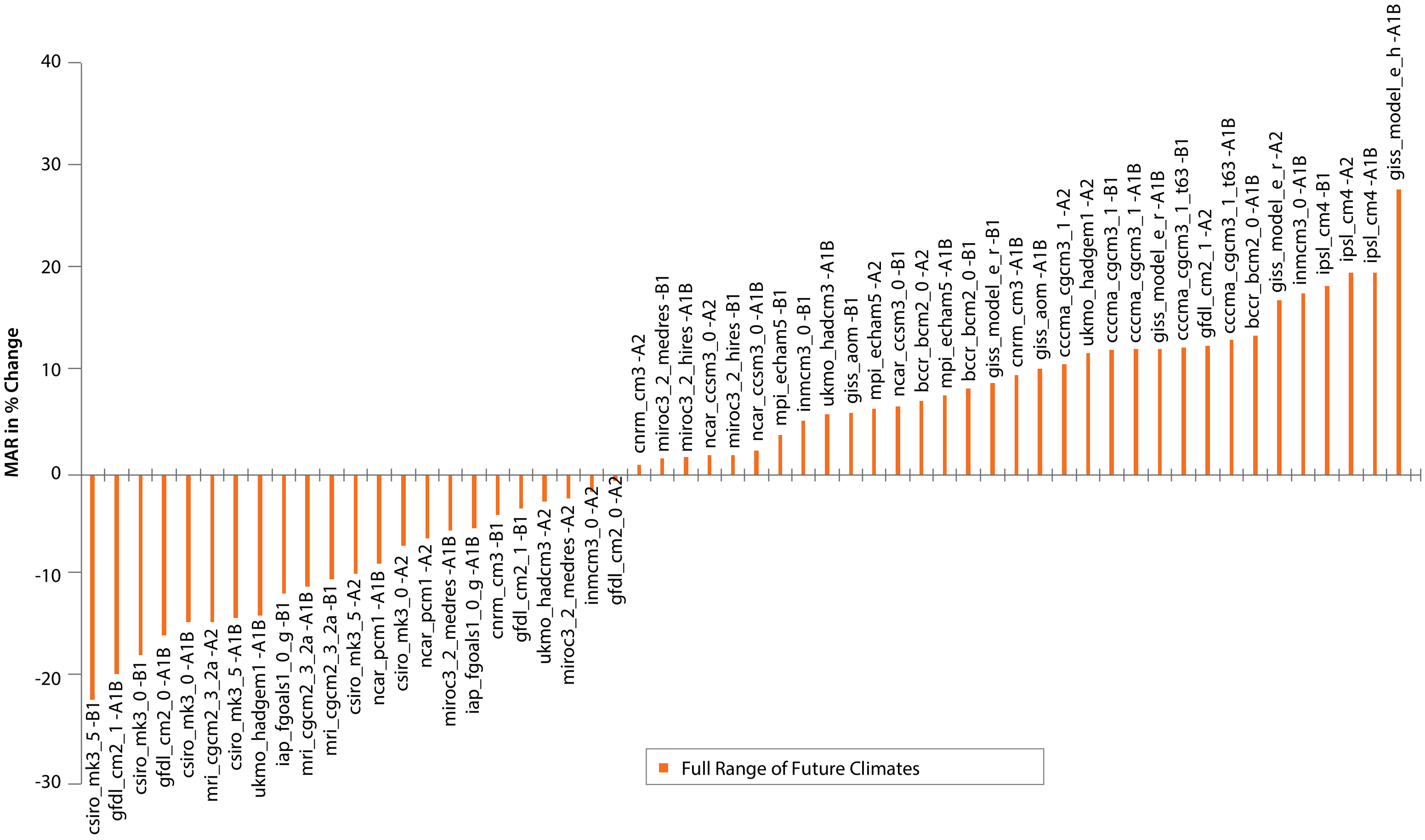
Step 4: Calculation of absolute MAS value

The user defined base case total sediment inflow is increased or reduced by the percent change calculated in step 3 in order to determine the absolute value of mean annual sediment inflow to be expected for the investigated climate change scenario.

5.4.4 Representative data set

The user will retrieve different projections of future runoff from the Knowledge Portal of the World Bank. RESCON 2 will provide the user with a plot of the available GCM predictions regarding Mean Annual Runoff for the selected greenhouse gas emission scenarios. This will give a clear picture of the full range of climate change impact on water availability. An example plot of the possible percent changes in Runoff due to climate change, as predicted by 22 GCMs for three emission scenarios is shown in the Figure 5.8.

Figure 5.8: Full range of possible percent changes in mean annual runoff due to climate change



According to the example given above, the model predictions showed that the mean annual runoff might decrease up to 20% compared to the historic observations or contrary it might increase up to 30% in the wettest future scenario.

The climate change analysis incorporated in RESCON 2 will focus on a representative user defined subgroup of model predictions, which shall describe efficiently the full range of possible future climates. The creation of the user defined representative future climate data set, which will be used for performing the sensitivity analysis in RESCON 2 comprises the following steps.

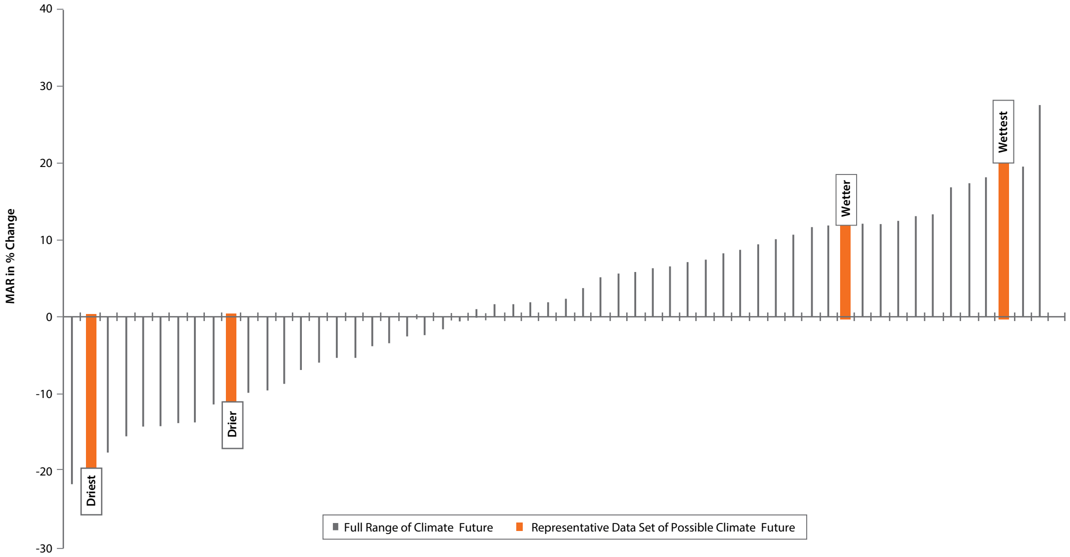
Step 1: The user will select four climate futures representing the following water availability scenarios (Figure 5.9):

- Future MAR < Historic MAR
  - Driest Scenario
  - Drier Scenario
- Future MAR > Historic MAR
  - Wetter Scenario
  - Wettest Scenario

Step 2: Calculation of Mean Annual Sediment Inflows for the selected, driest, drier, wetter and wettest scenarios.

The MAS corresponding to the four representative climate futures selected in the previous step is calculated by applying the procedure described in section 5.4.3.

Figure 5.9: Selection of driest, drier, wetter and wettest futures with regards to water availability for reliable representation of the full range of future climates in the sensitivity analysis performed by RESCON 2



Step 3: The selected future water and sediment availability scenarios are further expanded by considering two different hydrologic variability scenarios. The hydrologic variability scenarios are namely

- Scenario 1: Low increase of water inflow variability
  This is considered through an increase of 10% of the user defined historic coefficient of variability.
- Scenario 2: High increase of water inflow variability
  In this case it is considered that the coefficient of variability will be increased by 100%. The maximum possible value of a future coefficient of hydrologic variability for the scenario of high increase of variability due to climate change is capped at a value of 0.8, which expresses an unusually high hydrologic variability.

The sensitivity analysis can be performed for the following four future climate scenarios with regards to possible water availability and variability:

- Driest Future, High Variability Increase
- Drier Future, High Variability Increase
- Wetter Future, Low Variability Increase
- Wetter Future, Low Variability Increase.

5.5 Framework of Climate Change Analysis in RESCON 2

The key elements of the analysis performed by RESCON 2 are the following:

- Setting the reference scenario, which considers that climate will not change in the future and no sediment management will be applied in the reservoir.
- Assessment of the impact of different future climates on the performance of the infrastructure for the case of no adaptation through incorporation of sediment management.
- Determination of the sediment management alternative providing best possible adaptation in each future climate, under the assumption of perfect foresight.
- Identification of a “robust” adaptation sediment management strategy.

The climate change analysis performed by RESCON 2 comprises the following steps:

Step 1: Ensemble of possible future climate scenarios:
- Acquisition of climate change data for the project area.
- Determination of potential climate change domain.
- Selection of a representative set of climate futures which spans the full range of climate futures.

Table 5.1: Framework of climate change tool incorporated in RESCON 2

Case description	*Project Configuration (sediment management)*	*Climate*	*Performance metrics*	*Adaptation strategy*	*Cost of climate change impacts*
Case A: Reference Case	• No Action (NA)	Historical climate (H) (no climate change)	$NPV_{NA\text{-}H}$	None	0
Case B: Climate Change no adaptation	• No Action (NA)	Representative set of future climates (CCi) that spans the full range of climate futures	$NPV_{NA\text{-}CCi}$	None	$NPV_{NA\text{-}CCi}$ $NPV_{NA\text{-}H}$
Case C: Climate change, perfect foresight adaptation	Varies across future climates among the following: • No Action (NA) • Catchment Mgmt (CM) • Removal of Depositions (RD) • Sediment Routing (SR)	Representative set of future climates (CCi) that spans the full range of climate futures	max $NPV_{NA\text{-}CCi}$, max $NPV_{CM\text{-}CCi}$, max $NPV_{RD\text{-}CCi}$, max $NPV_{SR\text{-}CCi}$ for each future climate	Sediment management method that maximizes the NPV for each representative future climate	max $\{NPV_{NA\text{-}CCi}$, $NPV_{CM\text{-}CCi}$, $NPV_{RD\text{-}CCi}$, $NPV_{SR\text{-}CCi}\}$ $NPV_{NA\text{-}H}$
Case D: Climate change, robust adaptation	Does not vary across future climates. It can be one of the following: • No Action (NA) • Catchment Mgmt (CM) • Removal of Depositions (RD) • Sediment Routing (SR)	Representative set of future climates (CCi) that spans the full range of climate futures	Regrets across climate futures	Selection among the four	

Step 2: Cost of ignoring climate change (inaction), in case of absence of adaptation with sediment management.
Step 3: Benefits of adaptation with sediment management under the assumption of perfect foresight of future climate.
Step 4: Acknowledging the uncertainty in climate change through identification of a robust sediment management alternative.

The framework of the performed analysis is summarized in the Table 5.1:

5.5.1 Case A: Reference stationary case

Starting point for the analysis performed by RESCON 2 is the economic analysis of the reference scenario, which involves the following assumptions:

- No sediment management will be applied in the future.
- Historical climate will continue unchanged in the future.

The calculated NPV for this case will provide the basis for monetization of the impacts of climate change and the costs and benefits of adaptation by means of sediment management.

It is pointed out that the reference case refers to the no action scenario and not to the historic optimum scenario. The reason is that the analysis aims at revealing the advantages associated with application of sediment management.

5.5.2 Case B: No adaptation to climate change

The second stage of RESCON 2 analysis is to determine the economic performance of the infrastructure for a wide range of future climates assuming that no adaptation to climate change via sediment management will be applied.

Hence, this provides an indication of the range within which the impact of climate change expressed in economic terms will move if no countermeasure is applied, i.e. if climate change is ignored. In other words this calculation will indicate how vulnerable the investment is to climate change when no adaptation via sediment management is performed.

The cost of climate change will be calculated by comparing the aggregate NPV of the reference case with the aggregate NPV of the infrastructure for the following conditions:

- No sediment management.
- Representative data set of future climates presented in section 5.4.4.

The results of this calculation will reflect the range and not the distribution of the cost of climate change in case of inaction expressed in terms of the selected metric of economic performance of the infrastructure across the possible future climates. That means that the aggregate NPV of the infrastructure will be calculated for the case of the maximum increase as well the maximum reduction of reservoir water yield due to climate change.

Hence, this calculation presents the maximum cost of climate change to be expected with regards to both possible appearance forms, i.e. either revenue losses in case of a drier future or foregone revenues in case of a wetter future.

5.5.3 Case C: Adaptation under perfect foresight

This step aims at providing an estimation of the potential for adaptation of the infrastructure to differentiated climatic conditions by means of sediment management. The evaluated adaptation strategies comprise different sediment management strategies which have been optimized on basis of the historic conditions. In total four sediment management adaptation strategies are evaluated, namely:

- No Action (NA)
- Catchment Management (CM)
- Sediment Routing (SR)
- Deposition Removal (DR).

The sediment routing technique evaluated as possible adaptation strategy can be one of the techniques belonging to this specific group of methods i.e. sluicing, density current venting and by-pass. The technique, that maximizes the performance of the infrastructure for the historic conditions is selected to represent the sediment routing family. Similarly is selected the technique that will be evaluated as deposition removal adaptation strategy. It can be either flushing, dredging, trucking or HSRS and the applied criterion considers the technique that maximizes the performance of the infrastructure for the historic conditions.

The selected techniques are applied for the different hydrologic indicators included in the data set that has been defined by the user to represent the range of plausible climate futures, i.e. from the wettest with low increase in hydrologic variability scenario to the driest with high increase in hydrologic variability climate future. For each one of the representative climate futures, the sediment management method that maximizes the aggregate NPV is selected as the best sediment management adaptation strategy for this specific climate future. In other words, in this step a range of different project configurations with regards to the method of sediment management to be applied is evaluated with purpose the identification of the sediment management method that optimizes the design for a specific plausible future climate. This way it is determined which sediment management strategy minimizes the cost of climate change for each individual climate change scenario included in the representative data set of future climates. This is based on the important assumption that the future climate is known in advance.

5.5.4 Case D: Adaptation under acknowledgement of uncertainty in prediction of future climate

The risk of inaction, i.e. assuming that the future climate will not change and therefore neglecting any adaptation strategy is not the only one risk associated with climate change. Obviously, the assumption of a perfect foresight of climate future is not realistic, i.e. the development of climate in the future is not known in advance. This creates an additional risk of adapting to the climate change in the wrong way. In the case of sediment management as adaptation strategy, this would involve selecting the optimum sediment management technique based on the expectation of a drier future and in fact the climate future turns out to be wetter. A different sediment management might have been more appropriate for the finally materialized climate. Therefore each of the four identified sediment management strategies identified as optimum adaptation response to a particular climate future might generate regrets if a different climate is realized in the future.

In order to assess the risk of misadaptation the aforementioned regrets for any given climate have to be calculated. The regrets are defined as the difference of the infrastructure performance under the evaluated project configuration, i.e. sediment management strategy and tested future climate with the optimum performance of the infrastructure, i.e. the best performing sediment management strategy for that future climate.

A robust sediment management adaptation strategy is selected on the basis of decision making criterion which minimizes the maximum calculated regrets.

CHAPTER 6

Environmental and Social Safeguards

This chapter has been adopted by the documentation of the first version of RESCON published in 2003 by the World Bank.

6.1 Consequences of implementing sediment management on the downstream environment

Dams have serious environmental and social impacts which require mitigation actions. Some of the more important aspects are outlined in Annex 5. Dam decommissioning and the implementation of sediment management techniques outlined Annandale et al. (2016) and chapter 3 of the present manual also have impacts that need to be taken into consideration. This book does not purport to detail these, but merely to draw the reader's attention to some of the key aspects.

Dam decommissioning and many of the sediment management techniques that involve the release of reservoir sediments downstream need to be appraised within the framework of environmental and social impacts. Downstream impacts may include:

- Geomorphological changes to the downstream river channel.
- Increases in turbidity.
- Changes in flooding frequency and patterns.
- Reduction of dissolved oxygen in the river.
- Poisoning of the ecosystem especially where toxic sediments are released.

All of the above will have an impact on the natural environment as well as on human activity.

Sediment management can both mediate and exacerbate some of the negative effects caused by dams. Some sediment management alternatives involve moving sediments downstream. This can be environmentally positive or negative depending on the strategy used. In the San Gabriel River in southern California, United States, both facets were ob-served. In an upstream area studies on flow assisted sediment transport to remove sediment from behind Cogswell Dam suggested that using flow assisted sediment transport that depended on a more natural hydrograph could have beneficial effects on the native fish fauna, while sediment removal by trucking would maintain the status quo, with a temporary reduction in ecosystem services due to the escape of fine sediments into the stream reach below the dam during the cleanout operation. For Morris Dam, further downstream in the San Gabriel River sys- tem, sediments had been managed by sluicing. As a result of the sluicing (and dam management procedures governing water release) the downstream riverine habitats have been destroyed and no longer support the native aquatic fauna. It should be noted in this case that the cost of the environmental mitigation required as a condition of permitting sluicing was lower, at least in the short term, than alternative sediment management options.

A study undertaken by Zhou and Donnelly (2002) cites numerous occasions where insufficient consideration of the ecological effects of dam removal have resulted in serious impacts downstream. Impacts depend on whether sediments are suspended in the river flow or are deposited in the river bed. Released sediments may fill pools and interrupt mussel reproduction, as well as kill adult fish, mussels, and other aquatic wildlife by clogging gills and causing suffocation. Some species may be very sensitive to even small increases in turbidity. Kundell and Rasmussen, 1995 noted that occasional substantial increases in river turbidity (e.g., caused by the release of sediments from a dam) may eliminate up to 75 percent of some fish species.

Damages to the downstream ecosystem may also have wider ranging consequences on human activities. An example would be the loss of artisan fisheries in a developing country. This would not only deprive a society of its livelihood but may also destroy a way of life. Such indirect consequences need to be considered when appraising alternatives.

Where substantial changes to the water and sediment releases from a dam are being considered (such as would occur with flushing or sluicing) particular care needs to be exercised. Large increases in flows and sediment concentrations in addition to damaging the ecosystem may result in large scale geomorphological changes to the river regime. Such changes may include changes to meander patterns, scouring or infilling of river beds, deposition of sediments at manmade intakes, undermining of flood defense works and blockage of bridges or culverts. Such effects in addition to having far ranging social and economic impacts may have safety implications also. If sediment removal measures are employed from the start of a project, the impacts are likely to be less than if measures are introduced late in the project's life. If no removal is practiced and the dam is ultimately decommissioned, impacts may be severe. An example of this was observed when the Fort Edwards dam was removed in New York. The process released over 4,00,000 m^3 of sediment and resulted in partial blockage of the east channel of the Hudson River as well as increased risk of flooding of the town of Fort Edward. See Zhou and Donnelly, 2002.

Any method of sediment management that results in the return to a more natural hydrograph or incorporates an environmental flow requirement will probably yield positive environmental results or at least a mix of positive and negative impacts. Use of release flows for environmental reasons or sediment management may result in a short-term reduction in financial returns from the project, but will likely lead to increased sustainability and a re-distribution of the benefits of the dam.

Large reservoirs sited closely upstream of estuaries and deltas have in some cases caused wide- spread environmental, social and economic impacts by reducing the flow of sediments. The release of sediments from such a reservoir due to the implementation of sediment management may have positive impacts on the estuary or delta downstream.

Creative sediment management options such as watershed management directed to the upper reaches of the watershed may have direct environmental benefits. Recent studies on headwater streams throughout North America indicate that these streams exert control over nutrient exports to rivers, lakes and estuaries. Thus, restoration and preservation of small stream ecosystems could not only reduce sediment loads delivered to reservoirs, but would improve the quality of water delivered to downstream areas. This could have the additional benefit of reducing eutrophication.

The degree to which sediment management can yield positive environmental impacts is largely a function of its ability to mitigate some of the negative effects of the storage project. Combining sediment management with environmental flows to restore downstream ecosystem services will yield the greatest positive result. Environmental flows can enhance fisheries, support flood recession agriculture, stabilize riparian vegetation, maintain biodiversity, etc. Other approaches such as restoring or preserving portions of the watershed to reduce sediment yield can also have positive environmental effects.

6.2 A Safeguard Approach

In previous decades, relatively little importance was attached to the environmental and social impacts of development projects. Today much greater emphasis is placed on such considerations. Not surprisingly, sediment management plans for reservoirs are now expected to include environmental and social impact analyses.

A complete impact analysis is rarely justifiable at the pre-feasibility level due to lack of appropriate information. The intention of the RESCON approach, on the other hand, is to identify, already at pre-feasibility level, the reservoir sedimentation management techniques that will maximize economic benefits without conflicting with technical feasibility requirements and environmental/social acceptability. When conducting investigations at pre-feasibility level, it is usually necessary to employ approximate evaluation techniques and use the answers as a basis for detailed further investigation. Unfortunately, such preliminary methods have not been fully developed for assessment of aquatic environments. In other words, despite scientific progress in environmental science, no generic cause-effect relationships exist between changes in sediment flows and environmental quality that can be incorporated in a pre-feasibility level mathematical model such as RESCON.

It is expected that improved methods based on the principles of ecohydrology may become available in the future. Ecohydrology is a new concept that was postulated in 1992 during the Dublin International Conference on Water and Environment. It is defined as "the science of integrating hydrological processes with biota dynamics over varied spatial and temporal scales." Ecology as a science appeared at the end of the nineteenth century and was devoted initially to the description of the structure of ecosystems, leading to the first observations and descriptions of succession, predator/prey relationships and other phenomena that drive the dynamics of the ecosystem. However, the science lacked the predictive capability to manage aquatic systems.

As a result, two extremes have appeared in literature: over-engineered management of aquatic environments on the one hand and restrictive environmental conservation, with the general assumption that the aquatic environment should be maintained in its pristine condition, on the other. The former approach sometimes results in unsatisfactory management of the environment and the latter is unrealistic. The integration of ecology and hydrology promises to accelerate the process of moving ecology and environmental sciences from a descriptive stage to an analytical, functional, operational stage. Once this has been accomplished, the chances of successfully managing water resources in a manner that concurrently benefits humanity and the environment will be improved.

Until such methods have been developed for implementation in quantitative computer models, however, the following approach is proposed to assive environmental assessments as necessary. The procedure detailed below may be used for decision making at the pre-feasibility level. The results that emerge should be reviewed in detail during subsequent feasibility studies, prior to implementation of the optimal management approach.

6.3 Application of Safeguard Policies

Outlined in Table 6.1 are the relevant safeguard policies of the World Bank, as they would apply to a generic reservoir conservation program. For more information visit: http://lnweb18.worldbank.org/ESSD/essdext.nsf/52ByDocName/SafeguardPolicies

Table 6.1: Safeguard ratings

Safeguard	*Value*	*Descriptor*	*Discussion of Assignment Criteria*
Natural Habitats	1	Potential Enhancement	Potential enhancement of natural ecosystems due to flushing of sediments, restoration of over bank flows, downstream movement of nutrient, etc.
	2	Minor Impact	Either minor permanent impacts to natural functioning ecosystems, or temporary impacts.
	3	Moderate Impact	Permanent impacts to natural ecosystems, unavoidable significant conversion or degradation of natural habitats.
	4	Significant Impact	Significant conversion or degradation of critical natural habitat.
Human Uses	1	Potential enhancement	Benefits to floodplain agriculture/grazing, downstream or coastal fisheries, preservation of beaches, etc.
	2	Minor Impact	Minor or temporary impacts to floodplain agriculture, downstream fisheries, etc.
	3	Moderate Impact	Permanent impacts to downstream fisheries, loss of agriculture/grazing, short term impacts to potable water, etc.
	4	Significant Impact	Significant loss of agricultural or fisheries potential, long term impacts to potable water, etc.
Resettlement	1	No Resettlement	No resettlement necessary.
	2	Minor Resettlement	Limited population impact, and impacted population will not suffer loss of income or assets.
	3	Moderate Resettlement	Significant numbers of individuals displaced, no social disruptive; but some potential for loss of income, assets, or means of livelihood.
	4	Significant Resettlement	Displaced population is likely to suffer loss of assets, income, and/or means of livelihood. Resistance to resettlement or cultural/social displacement as a result of resettlement.
Cultural Assets	1	None Affected	No cultural assets affected by project (assets with archaeological, paleontological, historical, religious, or unique natural values, including remains left by previous human inhabitants).
	2	Minor Impact	Cultural assets can be protected, salvaged, or translocated, without significant loss of cultural value.
	3	Moderate Impact	Minor to moderate loss of cultural assets, or significant diminution of cultural value due to salvage.
	4	Significant Impact	Significant loss of cultural assets, or devaluation of assets due to translocation.
Indigenous Peoples	1	No Impact	Indigenous peoples may derive direct, socially or culturally appropriate, benefit from the project, or indigenous peoples are not impacted by the project.
	2	Minor Impact	Temporary impacts to land or resources, owned, occupied or used by indigenous peoples.
	3	Moderate Impact	Permanent impacts to land or resources, owned, occupied or used by indigenous peoples, not recompensable in type.
	4	Significant Impact	Physical relocation of households, or permanent loss of access to resources.

Safeguard	*Value*	*Descriptor*	*Discussion of Assignment Criteria*
Trans-boundary Impacts	1	No Issues	Project will not affect any river, lake, or body of water that forms a boundary or flows between two states. All states will be beneficiaries of the project.
	2	Minor Impacts	The project may have minor or transient impacts to one or more impact aspects of a state other than the beneficiary state.
	3	Moderate Impacts	The project may have moderate and/or permanent impacts to one or more impact aspects of a state other than the beneficiary state.
	4	Significant Impacts	The project will likely have significant impacts to one or more of the impact aspects of a state other than the beneficiary state.

Each of the concerns mentioned in the first column have values ranging from one (1) to four (4). In all cases, the value of one (1) is assigned to no impact or to possible benefits and the value four (4) is assigned to the worst condition. The safeguards are assessed when a RESCON investigation is executed and values (1 to 4) are assigned to each concern. The final score is determined by adding the safeguard values. Decisions pertaining to the potential environmental and social feasibility of the project are based on the recommendations in Table 6.2.

Table 6 2: Interpretation of sum of safeguard ratings

Sum of Ratings	*Interpretation*
6	No impact and potential benefit
6 to 12, with no 3's	Minor impact
12 to 15 or at least one 3	Moderate impact
16 or higher, or at least one 4	Significant impact

The RESCON program is used to calculate the economic Net Present Value (NPV) of each sediment management alternative and report the rankings. It also reports the highest ranked management alternative that meets the safeguards standard of acceptability. This standard is specified by the user and is based on the final score in Table 6.2.

6.4 Conclusions

In addition to technical and economic feasibility, environmental and social impacts of sediment management play pivotal roles in determining project selection. Studies of such impacts could use a normative approach, in which the monetary consequences of implementing different levels of safeguard compliance are compared with one another. If the economically and technically optimal strategy is rejected because it does not meet the safeguards standard, the RESCON program results for the case with no safeguards imposed are used to calculate the financial opportunity cost of implementing the safeguard approach. This cost is the difference between the NPVs of the environmentally and socially constrained and unconstrained alternatives.

In order to implement a normative approach, cause-effect relationships for the specific cases would be needed and typically these are not readily available. The insights provided by the safeguard rating method described in this chapter permit outlining of the terms of reference of feasibility level studies required for moving the process forward.

When selecting options for sediment management, emphasis should be placed on estimating and mitigating against the environmental and social impacts a particular option may have and on building this into the decision making process. However, as discussed above, some alternatives for managing sediments have positive impacts as well as negative ones and these need to receive attention also. Furthermore, when outlining the options an opportunity exists for identifying environmental and social enhancement measures which if possible should be included in the option.

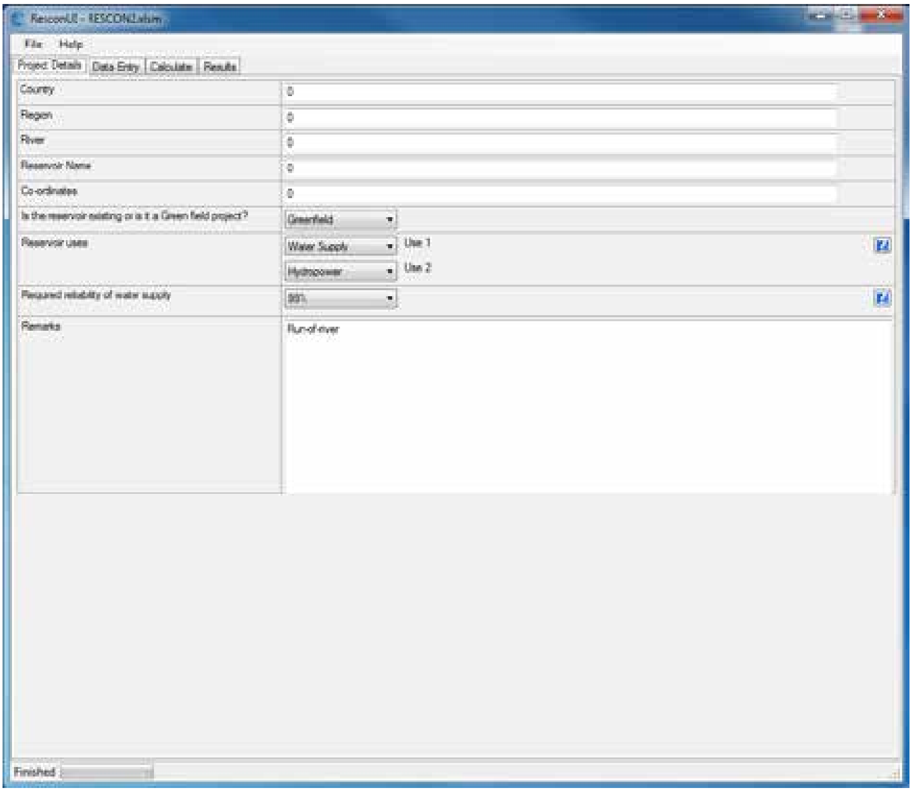
CHAPTER 7

User Interface

This chapter provides an example of the model setup for a specific case study.

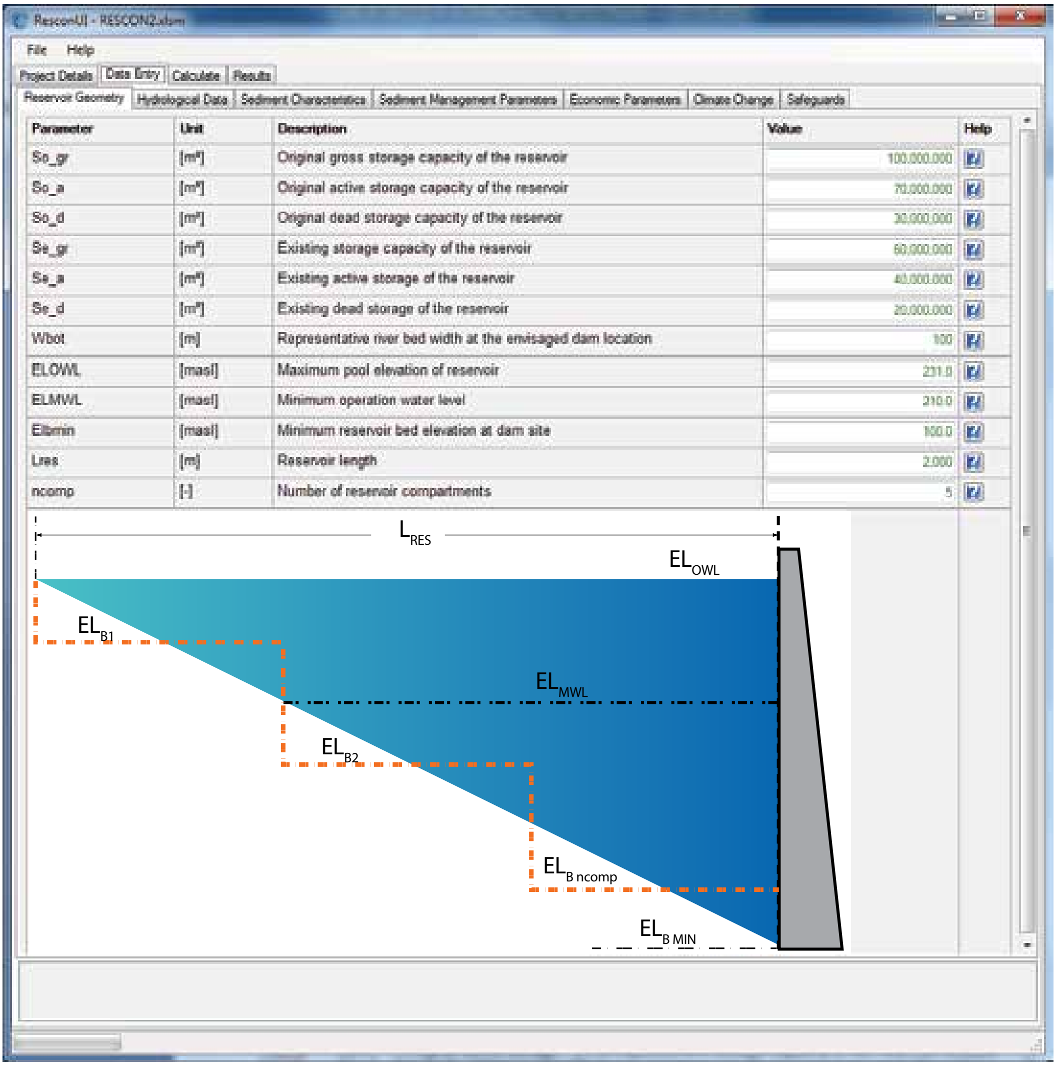
7.1 Data Input

7.1.1 Project definition



Country	0
Region	0
River	0
Reservoir Name	0
Co-ordinates	0
Is the reservoir existing or is it a Green field project?	Greenfield
Reservoir uses	Water Supply – Use 1 Hydropower – Use 2
Required reliability of water supply	95%
Remarks	Run-of-river

7.1.2 Reservoir geometry



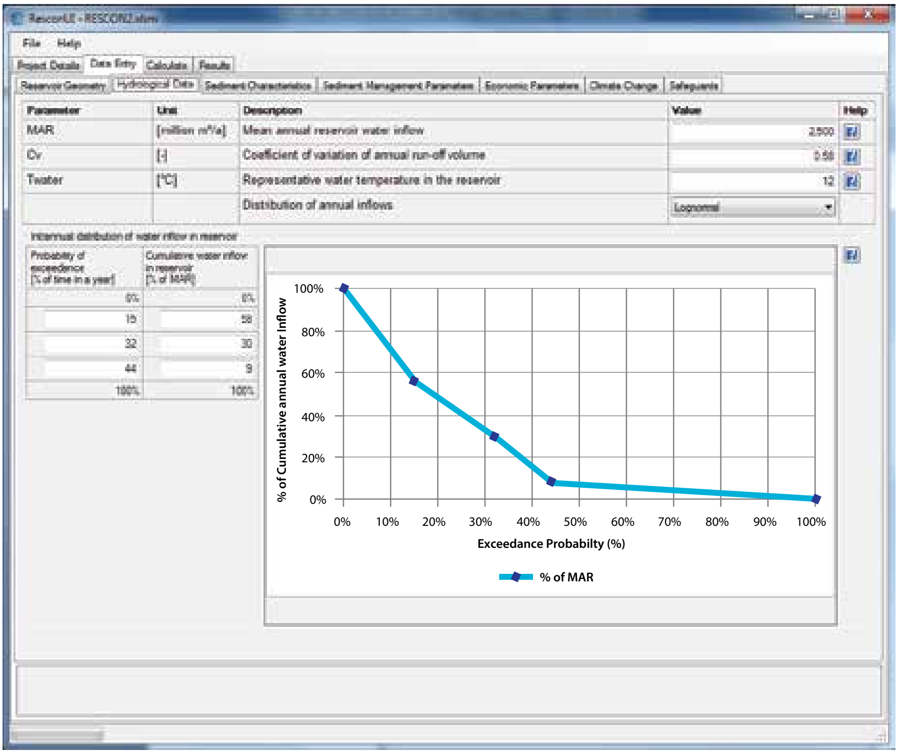
Parameter	Unit	Description	Value	Help
So_gr	[m³]	Original gross storage capacity of the reservoir	100,000,000	
So_a	[m³]	Original active storage capacity of the reservoir	70,000,000	
So_d	[m³]	Original dead storage capacity of the reservoir	30,000,000	
Se_gr	[m³]	Existing storage capacity of the reservoir	60,000,000	
Se_a	[m³]	Existing active storage of the reservoir	40,000,000	
Se_d	[m³]	Existing dead storage of the reservoir	20,000,000	
Wbot	[m]	Representative river bed width at the envisaged dam location	100	
ELOWL	[masl]	Maximum pool elevation of reservoir	231.0	
ELMWL	[masl]	Minimum operation water level	210.0	
Elbmin	[masl]	Minimum reservoir bed elevation at dam site	100.0	
Lres	[m]	Reservoir length	2,000	
ncomp	[-]	Number of reservoir compartments	5	

So_gr	[m^3]	Original gross storage capacity of the reservoir	Pre-impoundment gross storage capacity of the reservoir. If the reservoir is existing, the current gross storage capacity will be smaller than the original. The specified gross storage must be equal with the sum of active and inactive storage. Allowable values: So_gr > 0 (0 m^3 is not allowable) So_gr >= Se_gr So_gr = So_a + So_d

So_a	$[m^3]$	Original active storage capacity of the reservoir	Pre-impoundment storage capacity of the reservoir located between minimum and normal operating level. The water stored in this part of the reservoir can be utilized for beneficial uses such as hydropower production or irrigation or water supply. If the reservoir is existing, the current active storage capacity will be presumably smaller than the original. ___ Allowable values: So_a > 0 (0 m^3 is not allowable) So_a > = Se_a So_a = So_gr - So_d
So_d	$[m^3]$	Original inactive storage capacity of the reservoir	Pre-impoundment storage capacity of the reservoir located lower than the minimum operating water level. The water stored in this part can't be used for beneficial uses. It is intended to be used for storage of incoming sediment without interrupting the operation of the facility. If the reservoir does not have an inactive storage pool then please specify here 0 m3 and use the same value for minimum operating water level (ELMWL) and minimum reservoir bed elevation at dam site (ELbmin). ___ Allowable values: So_d > = 0 (0 m^3 is allowable if ELMWL = ELbmin) So_d > = Se_d So_d = So_gr - So_a
Se_gr	$[m^3]$	Existing storage capacity of the reservoir	If the reservoir is existing please specify here the current gross storage capacity. This must be smaller than the pre-impoundment gross storage capacity specified above. The current gross storage capacity must be equal with the sum of the current active and inactive storage capacities specified below. ___ Allowable values: Se_gr > 0 (0 m^3 is not allowable) Se_gr < So_gr Se_gr = Se_a + Se_d
Se_a	$[m^3]$	Existing active storage of the reservoir	If the reservoir is existing please specify here the current active storage capacity. ___ Allowable values: Se_a > 0 (0 m^3 is not allowable) Se_a < So_a Se_a = Se_gr - Se_d
Se_d	$[m^3]$	Existing inactive storage of the reservoir	If the reservoir is existing please specify here the current inactive storage capacity. ___ Allowable values: Se_d > = 0 Se_d < So_d Se_d = Se_gr - Se_a

Wbot	[m]	Representative reservoir bottom width at the dam location	It corresponds to initial river bed width prior to reservoir inundation. Allowable values: W_bot > 0
ELOWL	[masl]	Maximum pool elevation of reservoir	The maximum elevation which water level in a reservoir generally reaches during normal operating conditions. Allowable values: ELOWL > 0 ELOWL > ELMWL ELOWL > Elbmin
ELMWL	[masl]	Minimum operation water level	Minimum elevation of active storage pool, i.e. the minimum water level elevation which allows normal operating conditions of the reservoir. The minimum operating water level has to be equal with the minimum reservoir bed elevation at dam site if the specified pre-impoundment inactive storage is 0 m^3. Allowable values: ELMWL > 0 ELMWL < ELOWL ELMWL > = ELbmin
Elbmin	[masl]	Minimum reservoir bed elevation at dam site	It represents the pre-impoundment river bed elevation at the dam site. If the reservoir is existing, the reservoir bottom elevation at this location shall be used instead. Allowable values: ELbmin > 0 ELbmin < = ELMWL ELbmin < ELOWL
Lres	[m]	Reservoir length	The distance from dam structure up to the head of reservoir. It can be determined from the longitudinal profile of the reservoir bottom or from satellite images. Allowable values: Lres > 0
ncomp	[-]	Number of reservoir compartments	The geometry of the reservoir is partitioned in compartments in order to represent better the bathymetrical and hydraulic conditions, which determine the reservoir trap efficiency. Furthermore this allows the allocation of deposits between active and dead storage. The maximum number of compartments that can be used for schematization of reservoir storage is limited to 10. A value between 3 to 5 is recommended. Allowable values: 1 <= ncomp <= 10

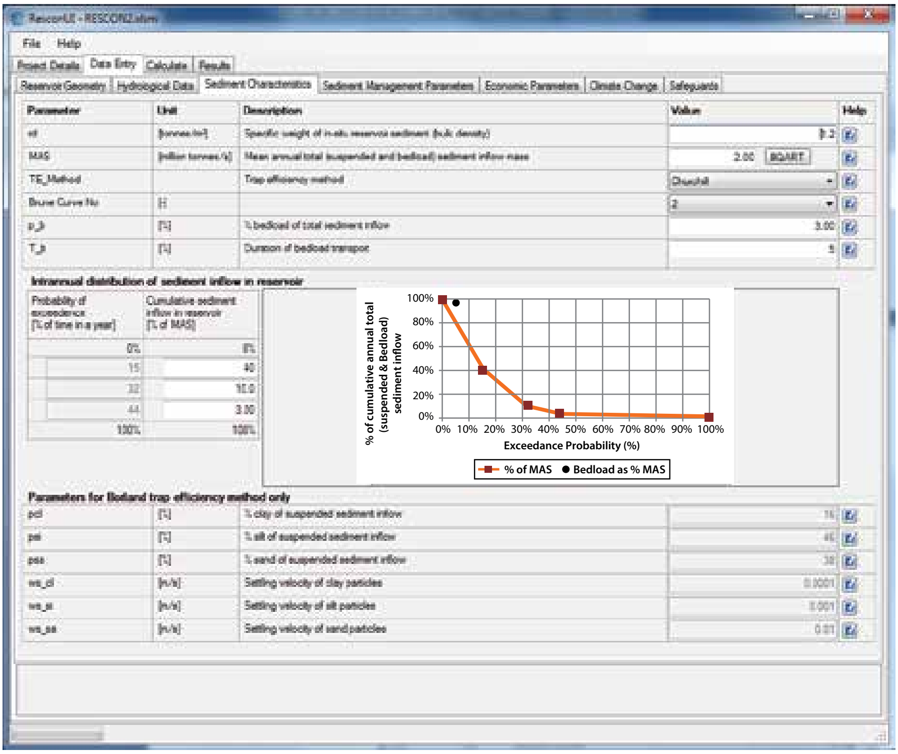
7.1.3 Hydrology and sediment



Parameter	Unit	Description	Value	Help
MAR	[million m³/a]	Mean annual reservoir water inflow	2,500	
Cv	[-]	Coefficient of variation of annual run-off volume	0.58	
Twater	[°C]	Representative water temperature in the reservoir	12	
		Distribution of annual inflows	Lognormal	

Intrannual distribution of water inflow in reservoir

Probability of exceedence [% of time in a year]	Cumulative water inflow in reservoir [% of MAR]
0%	0%
15	58
32	30
44	9
100%	100%



Parameter	Unit	Description	Value	Help
γd	[tonnes/m³]	Specific weight of in-situ reservoir sediment (bulk density)	1.2	
MAS	[million tonnes/a]	Mean annual total (suspended and bedload) sediment inflow mass	2.00	
TE_Method		Trap efficiency method	Churchill	
Brune Curve No	[-]		2	
p_b	[%]	% bedload of total sediment inflow	3.00	
T_b	[%]	Duration of bedload transport	5	

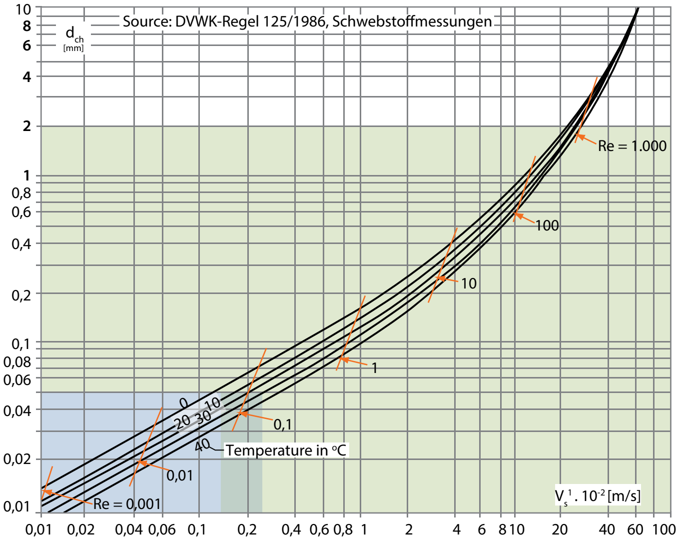
Intrannual distribution of sediment inflow in reservoir

Probability of exceedence [% of time in a year]	Cumulative sediment inflow in reservoir [% of MAS]
0%	0%
15	40
32	10.0
44	3.00
100%	100%

Parameters for Borland trap efficiency method only

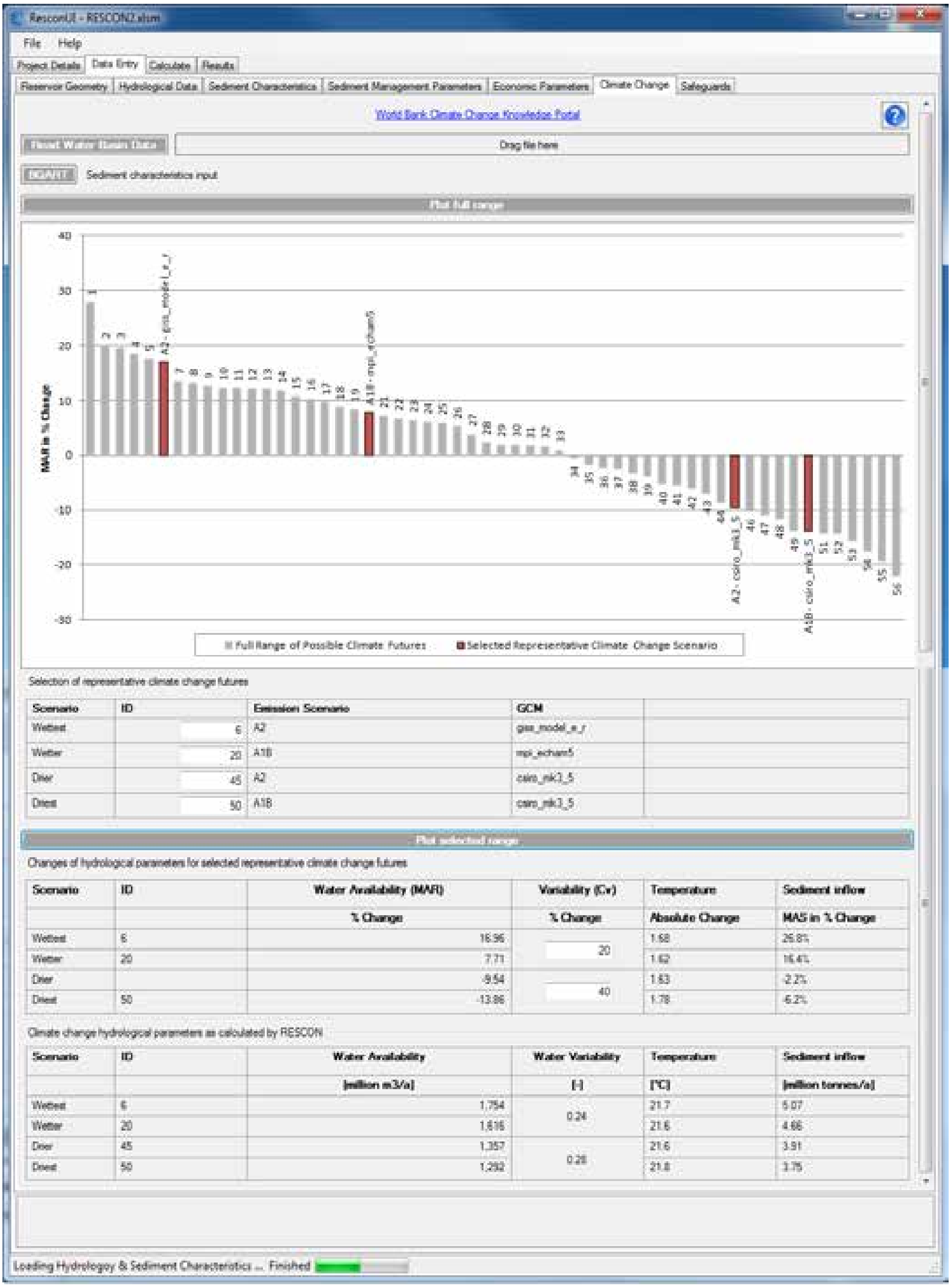
Parameter	Unit	Description	Value	Help
pcl	[%]	% clay of suspended sediment inflow	16	
psi	[%]	% silt of suspended sediment inflow	46	
pss	[%]	% sand of suspended sediment inflow	38	
ws_cl	[m/s]	Settling velocity of clay particles	0.0001	
ws_si	[m/s]	Settling velocity of silt particles	0.001	
ws_ss	[m/s]	Settling velocity of sand particles	0.01	

Water Characteristics			
MAR	[million m^3/a]	Mean annual reservoir water inflow	This parameter expresses the mean annual water inflow in the reservoir expressed in million m^3 per year and shall be determined by the available flow records. Allowable values: $MAR > 0$
Cv	[-]	Coefficient of variation of annual run-off volume	This parameter expresses the variability of annual flows and can be determined from statistical analysis of the annual runoff volumes. It can be calculated by dividing the mean annual water inflow with the standard deviation of incoming flows. It shall be determined by the available flow records. Allowable values: $Cv > 0$
Twater	[°C]	Representative water (reservoir and river) temperature	This parameter will be used for the assessment of feasibility of density current venting. It affects also the settling velocity of suspended sediment. Allowable values: $0 < T < 30$
Distribution		Distribution of annual inflows	Please select one among the following available options: • Gamma • Log-normal • Normal The distribution of the annual flows has to be derived from the annual streamflow statistics.
Sediment Characteristics			
rd	[tonnes/ m^3]	Specific weight of in-situ reservoir sediment	Typical values of deposits specific weight range between 0.9–1.5 depending on the grain size distribution. The higher the fractional content of sand in sediment load, the higher the representative specific weight of deposits
MAS	[million tonnes/a]	Mean annual total (suspended and bedload) sediment inflow mass	The amount of sediment carried on average annually by the river at the reservoir location. If the sediment yield is unknown the BQART equation is one method that may be used for a preliminary assessment. Allowable values: $MAS > 0$
Intra-annual variation of water & sediment inflow (for sediment routing)			Example: within 10% of a year (i.e. 36.5 days) 25% of mean annual runnoff and 75% of mean annual sediment inflow enters the reservoir
Exceed T	[%]	Percentage of time exceeded	This parameter is necessary for the specification of the intra-annual distribution of water and sediment inflow. This specific parameter reflects the partitioning of the year in wet and dry season.
Exceed MAR	[%]	Percentage of mean annual water inflow	The intra-annual distribution of water inflow is specified on basis of this input.

Exceed MAS	[%]	Percentage of mean annual sediment inflow	The intra-annual distribution of sediment inflow is specified on basis of this input.
pcl	[%]	% clay of suspended sediment inflow	This input is not compulsory. It will be used only if the trap efficiency is calculated with the Borland equation. This parameter can be determined by grain size analysis of samples of suspended load. Refer to Maddock Table if no data are available.
psi	[%]	% silt of suspended sediment inflow	This input is not compulsory. It will be used only if the trap efficiency is calculated with the Borland equation. This parameter can be determined by grain size analysis of samples of suspended load. Refer to Maddock Table if no data are available.
psa	[%]	% sand of suspended sediment inflow	This input is not compulsory. It will be used only if the trap efficiency is calculated with the Borland equation. This parameter can be determined by grain size analysis of samples of suspended load. Refer to Maddock Table if no data are available.
ws_cl	[m/s]	Settling velocity of clay particles	 Source: DVWK-Regel 125/1986, Schwebstoffmessungen
ws_si	[m/s]	Settling velocity of silt particles	
ws_sa	[m/s]	Settling velocity of sand particles	
TE_Method		Trap efficiency method	It is recommended to perform the analysis with Churchill method. Apply Brune if it is known that it fits better the studied reservoir. Apply Borland if the other two methods fail to deliver satisfactory results or if you want to perform a calibration of the model on basis of existing field measurements. The trap efficiency of reservoirs regularly sluiced, semi dry or desilting reservoirs as well of reservoirs serving for flood retention, i.e. reservoirs characterized by shallow water depths and/or relatively high flow velocities should be calculated with application of Churchill (1948) and Borland (1971) methods, which are more appropriate for short term predictions of a variable over time trap efficiency.

<table>
<tr><td></td><td></td><td></td><td>Brune (1952) curve provides a reasonable assessment of the average trap efficiency to be expected on the long term.
This method however is not appropriate for relatively short time intervals, whereby the flow conditions in the reservoir are altered significantly. Therefore this method should only be used for normally ponded reservoirs because it accounts only for the average retention time of the water in the reservoir, ignoring however the flow conditions in the reservoir (Versraeten et al. (2000)).</td></tr>
<tr><td>Brune Curve No</td><td>[-]</td><td></td><td>This parameter is used for assessment of reservoir trap efficiency with the Brune (1952) method.
Is the sediment in the reservoir:
(1) Highly flocculated and coarse sediment
(2) Average size and consistency
(3) colloidal, dispersed, fine-grained sediment</td></tr>
<tr><td>p_b</td><td>[%]</td><td>% bedload of total sediment inflow</td><td>
<table>
<tr><th>Concentration os suspended load [p.p.m.]</th><th>Type of bed material forming the channel of the stream</th><th>Texture of suspended material</th><th>Per cent bedload in terms of measured suspended load</th></tr>
<tr><td>low[1]</td><td>Sand</td><td>Similar to bed material</td><td>25%–150%</td></tr>
<tr><td></td><td>Gravel, rock or consolidated clay</td><td>Small amount of sand</td><td>5%–12%</td></tr>
<tr><td>medium[2]</td><td>Sand</td><td>Similar to bed material</td><td>10%–35%</td></tr>
<tr><td></td><td>Gravel, rock or consolidated clay</td><td>25% sand or less</td><td>5%–12%</td></tr>
<tr><td>high[3]</td><td>Sand</td><td>Similar to bed material</td><td>5%–15%</td></tr>
<tr><td></td><td>Gravel, rock or consolidated clay</td><td>25% sand or less</td><td>2%–8%</td></tr>
</table>
1 Low: suspended load concentration < 1000 p.p.m.
2 Medium: suspended load concentration 1000 - 7500 p.p.m.
3 High: suspended load concentration > 7500 p.p.m.
Partitioning between bedload and suspended load according to Lane & Borland (1951). [Retrieved from Turowski et al. (2010)]
</td></tr>
<tr><td>T_b</td><td>[%]</td><td>Duration of bedload transport</td><td>[% of annual time, e.g. 5% equals to 0.05 x 365 days = 18.25 days</td></tr>
</table>

7.1.4 Climate change analysis



Selection of representative climate change futures

Scenario	ID	Emission Scenario	GCM	
Wettest	6	A2	giss_model_e_r	
Wetter	20	A1B	mpi_echam5	
Drier	45	A2	csiro_mk3_5	
Driest	50	A1B	csiro_mk3_5	

Changes of hydrological parameters for selected representative climate change futures

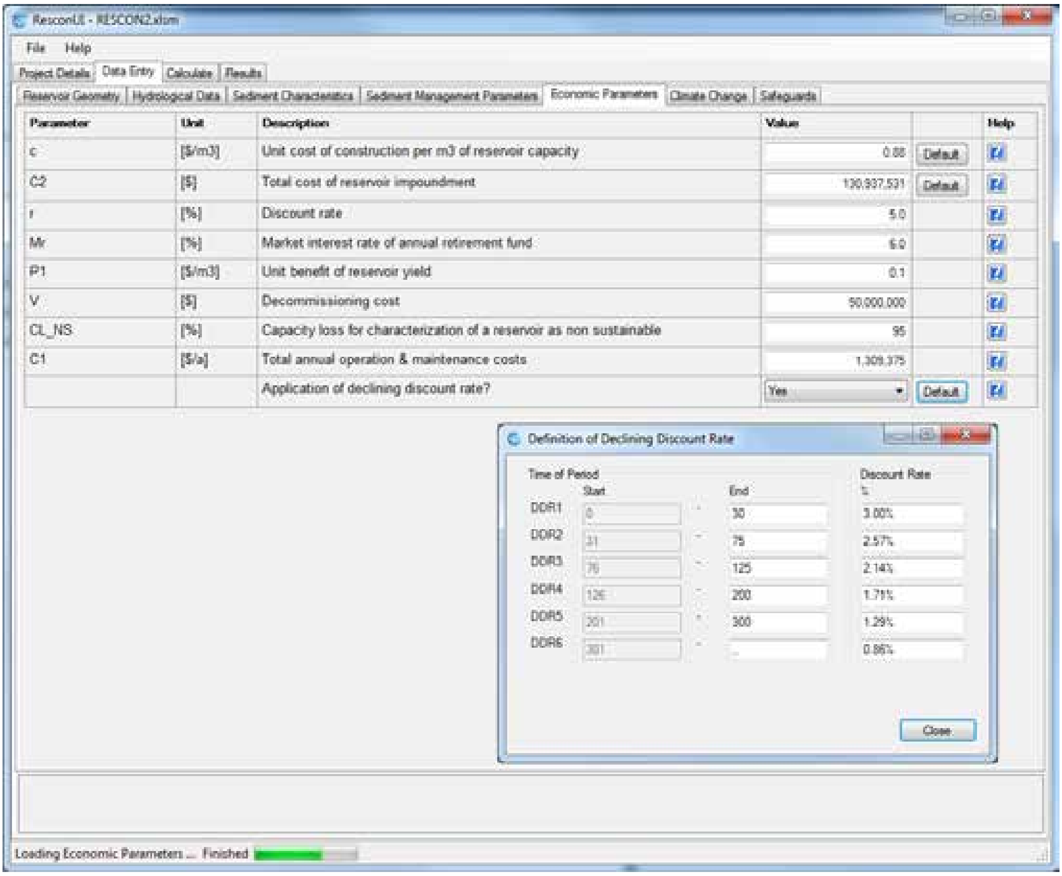
Scenario	ID	Water Availability (MAR)	Variability (Cv)	Temperature	Sediment inflow
		% Change	% Change	Absolute Change	MAS in % Change
Wettest	6	16.96	20	1.68	26.8%
Wetter	20	7.71		1.62	16.4%
Drier		-9.54	40	1.63	-2.2%
Driest	50	-13.86		1.78	-6.2%

Climate change hydrological parameters as calculated by RESCON

Scenario	ID	Water Availability	Water Variability	Temperature	Sediment inflow
		[million m3/a]	[-]	[°C]	[million tonnes/a]
Wettest	6	1,754	0.24	21.7	5.07
Wetter	20	1,616		21.6	4.66
Drier	45	1,357	0.28	21.6	3.91
Driest	50	1,292		21.8	3.75

Loading Hydrology & Sediment Characteristics ... Finished

7.1.5 Economic parameters



Parameter	Unit	Description	Value		Help
c	[$/m3]	Unit cost of construction per m3 of reservoir capacity	0.88	Default	
C2	[$]	Total cost of reservoir impoundment	130,937,531	Default	
r	[%]	Discount rate	5.0		
Mr	[%]	Market interest rate of annual retirement fund	6.0		
P1	[$/m3]	Unit benefit of reservoir yield	0.1		
V	[$]	Decommissioning cost	50,000,000		
CL_NS	[%]	Capacity loss for characterization of a reservoir as non sustainable	95		
C1	[$/a]	Total annual operation & maintenance costs	1,309,375		
		Application of declining discount rate?	Yes	Default	

Definition of Declining Discount Rate

	Time of Period Start		End	Discount Rate %
DDR1	0	-	30	3.00%
DDR2	31	-	75	2.57%
DDR3	76	-	125	2.14%
DDR4	126	-	200	1.71%
DDR5	201	-	300	1.29%
DDR6	301	-	-	0.86%

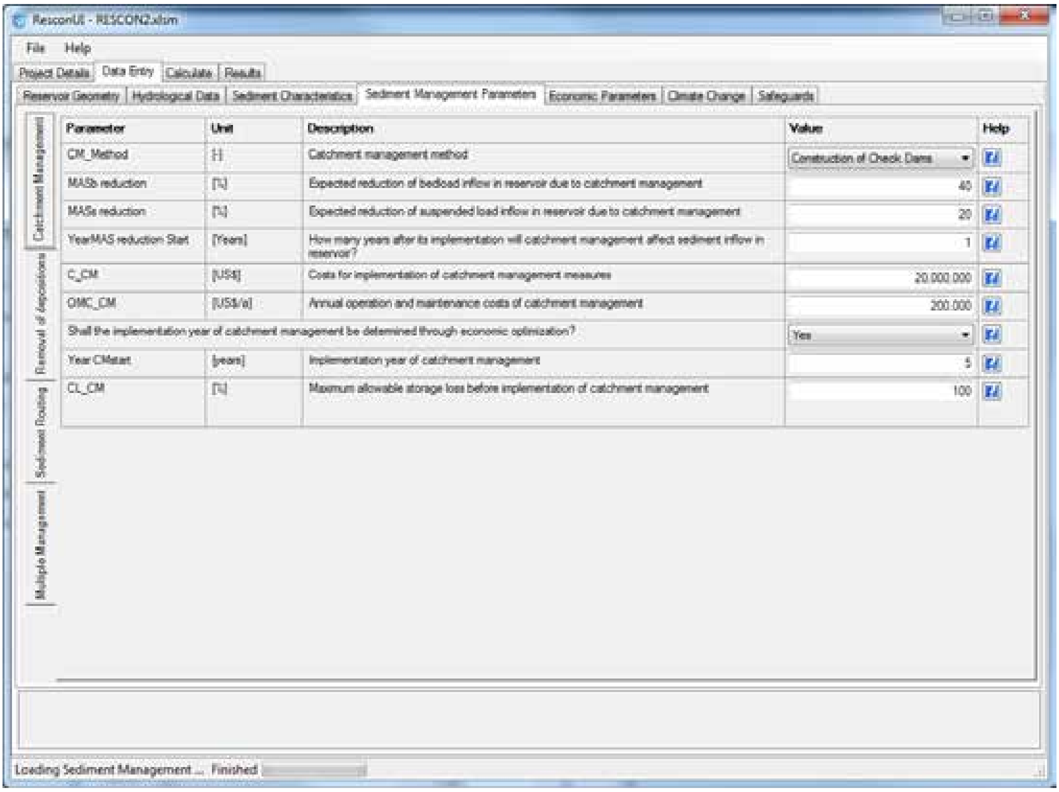
Loading Economic Parameters ... Finished

c	[$/m³]	Unit cost of construction per m³ of reservoir capacity	The default value given here is a crude estimate based on original reservoir storage capacity. The user is encouraged to replace this value with a project specific estimate.
C2	[$]	Total cost of reservoir impoundment	This cost is calculated as unit cost of construction times initial reservoir storage volume (C2 = So*c). If it is a greenfield project, this cost will be calculated in the above manner unless a different value is specified. If it is an existing reservoir, the total construction cost will be taken as 0.
r	[%]	Discount rate	This fixed value of discount rate will be used if the option of Declining Discount Rate is not selected. A default value of 6% is recommended as the base case. For the first sensitivity case a value of 3% shall be used in order to account for the renewable nature of the resource of reservoir storage.

Mr	[%]	Market interest rate of annual retirement fund	This could be different from discount rate "r". The annual retirement fund is provided only as additional information. The calculated annual retirement fund is not introduced in the economic appraisal as additional annual cost.
P1	[$/m^3]	Unit benefit of reservoir yield	Where possible use specific data for the project. If no data is available refer to User Manual for guidance.
V	[$]	Decommissioning cost	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.
CL_NS	[%]	Capacity loss for characterization of a reservoir as non sustainable	When the storage capacity loss exceeds the CL_NS % of the original gross storage capacity within the first 300 years of reservoir operation due to sedimentation, the sediment management solution is characterized as non-sustainable
C1	[$/a]	Total annual operation & maintenance costs	Regular annual Operation & Maintenance costs. The user is encouraged to input her/his own estimate. Should this be difficult at the pre-feasibility level, it can be calculated as follows: C1 = omc*C2. Where: omc: operation and maintenance cost coefficient omc C2: initial reservoir construction cost The parameter omc takes usually values between 1% and 3%.
Application of declining discount rate?			"In order to take into account the renewable nature of the natural resource of reservoir storage, the user is strongly recommended to apply a declining discount rate for assessment of the Net Present Value of the streamflow of annual costs and revenues. As default Declining Discount Rate is recommended the sequence included in the UK Treasury Supplementary Green Book (Lowe 2008) 0–30 years : 3.00% 31–75 years : 2.57% 76–125 years : 2.14% 126–200 years : 1.71% 201–300 years : 1.29% 301– ...... years : 0.86%"
DDR1	[%]	Definition of Declining Discount Rate	
DDR2	[%]		
DDR3	[%]		
DDR4	[%]		
DDR5	[%]		
DDR6	[%]		

7.1.6 Sediment management

7.1.6.1 Catchment management

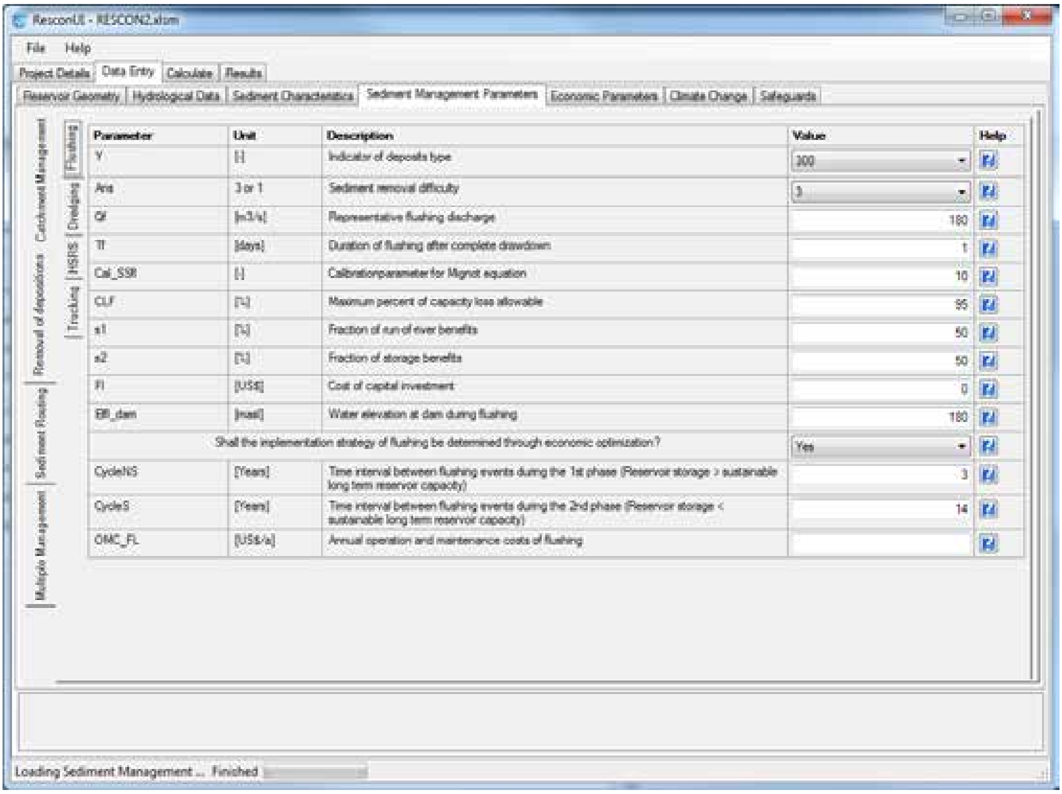


Parameter	Unit	Description	Value	Help
CM_Method	[-]	Catchment management method	Construction of Check Dams	
MASb reduction	[%]	Expected reduction of bedload inflow in reservoir due to catchment management	40	
MASs reduction	[%]	Expected reduction of suspended load inflow in reservoir due to catchment management	20	
YearMAS reduction Start	[Years]	How many years after its implementation will catchment management affect sediment inflow in reservoir?	1	
C_CM	[US$]	Costs for implementation of catchment management measures	20.000.000	
OMC_CM	[US$/a]	Annual operation and maintenance costs of catchment management	200.000	
Shall the implementation year of catchment management be determined through economic optimization?			Yes	
Year CMstart	[years]	Implementation year of catchment management	5	
CL_CM	[%]	Maximum allowable storage loss before implementation of catchment management	100	

		Catchment management method	*Please select one of the available options for catchment management*
MASb reduction	[%]	Expected reduction of bedload inflow in reservoir due to catchment management	Expected reduction of bedload inflow in reservoir due to implementation of catchment management measures. Usually this is achieved with construction of check structures upstream of the reservoir in mountainous tributaries with torrential character. If this parameter takes value of 0% it means that the bedload will not be reduced at all and reduction of 100% means that bedload will be retained in the check structures and will not enter the reservoir.
MASs reduction	[%]	Expected reduction of suspended load inflow in reservoir due to catchment management	Expected reduction of suspended load inflow in reservoir due to implementation of catchment management measures. Usually this is achieved with implementation of watershed management measures such as implementation of improved agricultural practices or reforestation. If this parameter takes value of 0% it means that the implemented catchment method will not have an effect on suspended load transport and therefore the suspended inflow entering the reservoir will not be reduced at all. Contrary, a reduction of 100% means that suspended load will not enter the reservoir, something that is not realistic.

Year MAS reduction Start	[Years]	How many years after its implementation will catchment management affect sediment inflow in reservoir?	Time lag between implementation of catchment management measures and realization of their effect on sediment inflows in reservoir, i.e. how many years will take the appearance of the effect of catchment management on sediment inflow in reservoir.
C_CM	[US$]	Costs for implementation of catchment management measures	Cost of capital investment required for application of catchment management. The cost entered will be incurred in the implementation year.
OMC_CM	[US$/a]	Annual operation and maintenance costs of catchment management	Annual costs for operation and maintenance of catchment management measures. The depend strongly on the selected catchment management technique.
Shall the implementation year of catchment management be determined through economic optimization?			If "Yes" the economic performance of the reservoir is calculated for different values of catchment management implementation year. The timing maximizing the economic performance under consideration of the user defined technical constraints is selected as the optimum scheduling of catchment management. If "No" the user specifies explicitly the implementation scheduling of this sediment management activity.
Year CM start	[years]	Implementation year of catchment management	First year of catchment management, i.e. year of completion of necessary structures or changes.
CL_CM	[%]	Maximum allowable storage loss before implementation of catchment management	For an existing reservoir, this number must be greater than the percentage of capacity lost already. Catchment Management will be implemented before this percent of the reservoir is filled completely.

7.1.6.2 *Flushing*



Parameter	Unit	Description	Value	Help
Y	[-]	Indicator of deposits type	300	
Ans	3 or 1	Sediment removal difficulty	3	
Qf	[m3/s]	Representative flushing discharge	180	
Tf	[days]	Duration of flushing after complete drawdown	1	
Cal_SSfl	[-]	Calibrationparameter for Mignot equation	10	
CLF	[%]	Maximum percent of capacity loss allowable	95	
s1	[%]	Fraction of run of river benefits	50	
s2	[%]	Fraction of storage benefits	50	
FI	[US$]	Cost of capital investment	0	
Elfl_dam	[masl]	Water elevation at dam during flushing	180	
		Shall the implementation strategy of flushing be determined through economic optimization?	Yes	
CycleNS	[Years]	Time interval between flushing events during the 1st phase (Reservoir storage > sustainable long term reservoir capacity)	3	
CycleS	[Years]	Time interval between flushing events during the 2nd phase (Reservoir storage < sustainable long term reservoir capacity)	14	
OMC_FL	[US$/a]	Annual operation and maintenance costs of flushing		

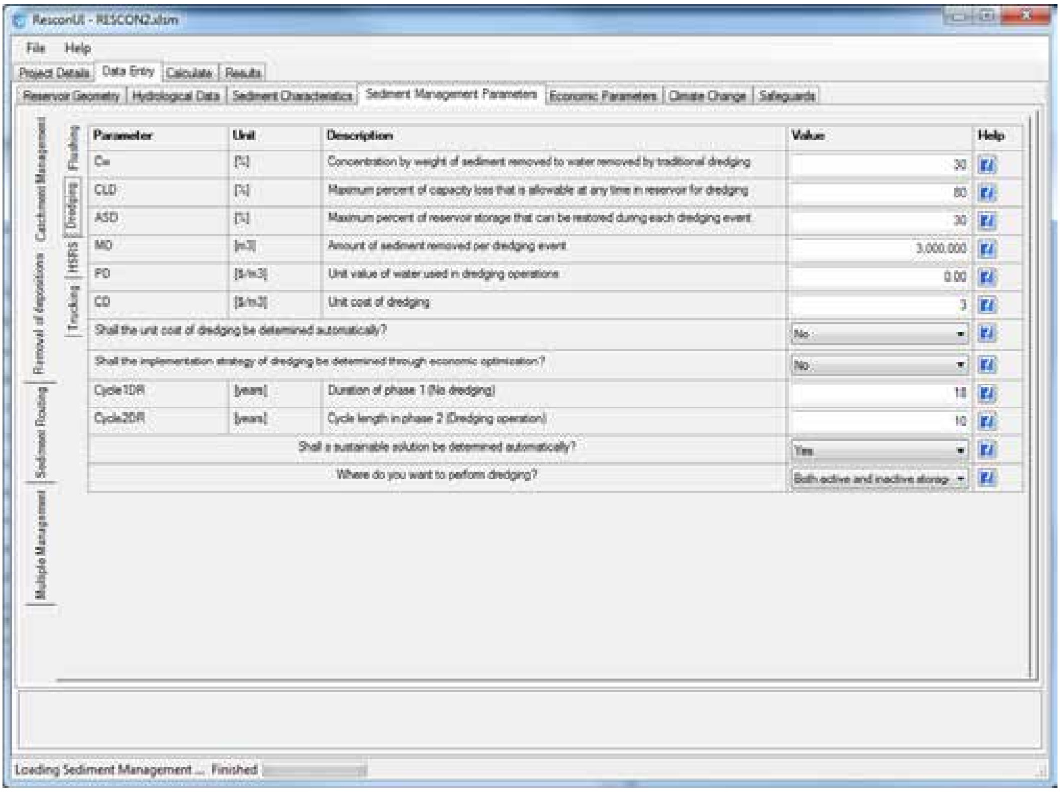
Y	[-]	Indicator of deposits type	Select from: 1600 for fine loess sediments; 650 for other sediments with median size finer than 0.1 mm; 300 for sediments with median size larger than 0.1 mm; 180 for flushing with Qf < 50 m^3/s with any grain size
Ans	3 or 1	Sediment removal difficulty	This parameter gives the model a guideline of how difficult it will be to remove sediments. - "3" if reservoir sediments are significantly larger than median grain size (d50) = 0.1 mm or if the reservoir has been impounded for more than 10 years without sediment removal. - "1" if otherwise.
Qf	[m^3/s]	Representative flushing discharge	This should be calculated with reference to the actual inflows and the flushing gate capacities.
Tf	[days]	Duration of flushing after complete drawdown	The duration of flushing operation determines together with other parameters the amount of deposits that can be removed from the reservoir.
Cal_SSfl	[-]	Calibration parameter for Mignot equation	The adjusted Migniot's equation often over-estimates side slopes. Therefore the calculated side slope of incised flushing channel is divided by this calibration parameter to obtain a more reasonable result. Suggested value is 10.

CLF	[%]	Maximum percent of capacity loss allowable	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.
s1	[%]	Fraction of run-of-river benefits	The fraction of Run-of-River benefits available in the year flushing occurs (s1 ranges from 0 to 100%). When flushing is carried out, the reservoir is completely emptied. This parameter expresses the water yield that can be utilized for beneficial uses in the year flushing is performed, assuming that the reservoir storage does not affect the available water yield. It is considered that the water yield supplied by the reservoir will be lower the year of flushing compared to the water yield supplied a year with no flushing operation. The reduction is associated with the duration of flushing operation, i.e. the number of days the intake is out of operation due to reservoir emptying, flushing and refilling. During the year in which flushing occurs, the water yield (Wt) is calculated as follows: $Wt = s1 \times W(0) + s2 \times (W(St+1) - W(0))$ 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(St+1) is water yield from storage capacity after flushing.
s2	[%]	Fraction of storage benefits	The fraction of storage benefits available in the year flushing occurs (s2 ranges from 0 to 100%). When flushing is carried out, the reservoir is completely emptied. This parameter expresses the water yield that can be utilized for beneficial uses in the year flushing is performed, under consideration of the effect of reservoir storage on the supplied water yield. It is considered that the water yield supplied by the reservoir will be lower the year of flushing compared to the water yield supplied a year with no flushing operation. The reduction is associated with the duration of flushing operation, i.e. the number of days the intake is out of operation due to reservoir emptying, flushing and refilling. During the year in which flushing occurs, the water yield (Wt) is calculated as follows: $Wt = s1 \times W(0) + s2 \times (W(St+1)-W(0))$ 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(St+1) is water yield from storage capacity after flushing.
FI	[US$]	Cost of capital investment	Cost of capital investment required for implementing flushing measures. The cost entered will be incurred when flushing is first practiced.
Elfl_dam	[masl]	Water elevation at dam during flushing	This is a function of gate capacity and reservoir inflow sequence. Lower elevation will result in a more successful flushing operation.

Shall the implementation strategy of flushing be determined through economic optimization?	If the option of economic optimization is selected, the implementation schedule of flushing operation will be determined through an optimization procedure of the reservoir economic performance.

CycleNS	[Years]	Time interval between flushing events during the 1st phase (Reservoir storage > sustainable long term reservoir capacity)	Frequency of flushing operations until the reservoir storage converges to the capacity that can be sustained in the long term by flushing.
CycleS	[Years]	Time interval between flushing events during the 2nd phase (long term reservoir capacity)	Frequency of flushing operations during sustainable phase.
OMC_FL	[US$/a]	Annual operation and maintenance costs of flushing	Costs associated with flushing performance. This entails operational costs, environmental compliance, compensation and maintenance of flushing infrastructure. This cost incurres only the years during which flushing is performed.

7.1.6.3 *Dredging*



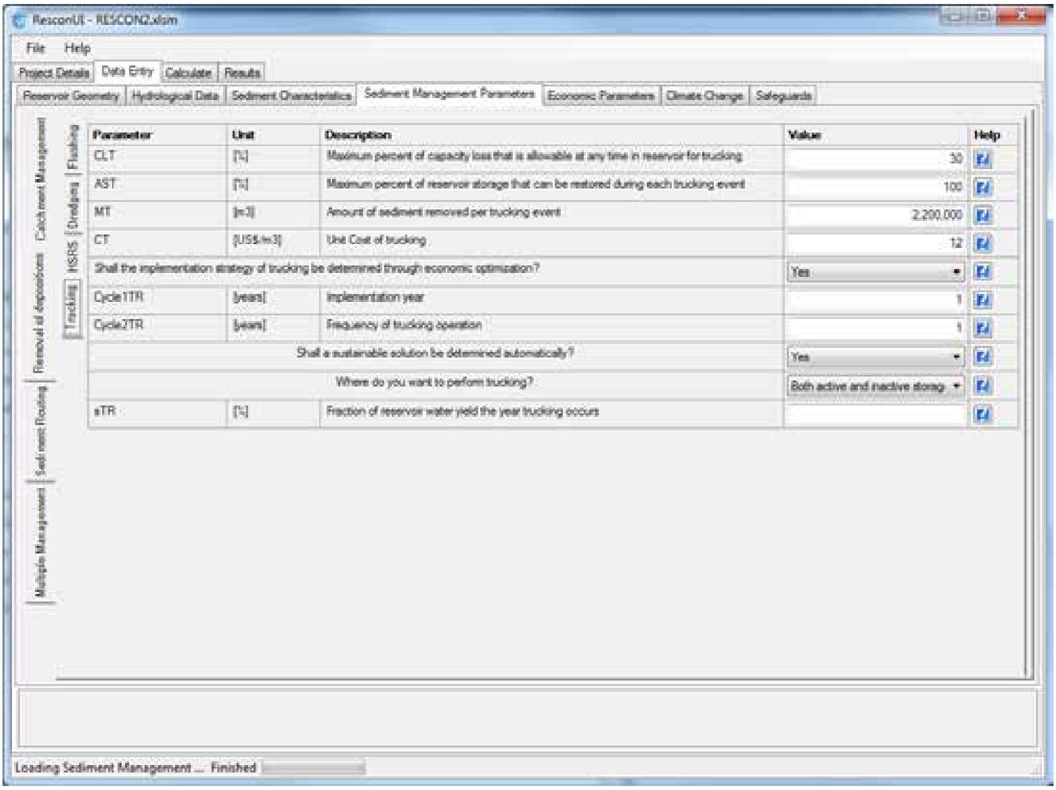
Parameter	Unit	Description	Value	Help
Cw	[%]	Concentration by weight of sediment removed to water removed by traditional dredging	30	
CLD	[%]	Maximum percent of capacity loss that is allowable at any time in reservoir for dredging	80	
ASD	[%]	Maximum percent of reservoir storage that can be restored during each dredging event	30	
MD	[m3]	Amount of sediment removed per dredging event	3,000,000	
PD	[$/m3]	Unit value of water used in dredging operations	0.00	
CD	[$/m3]	Unit cost of dredging	3	
Shall the unit cost of dredging be determined automatically?			No	
Shall the implementation strategy of dredging be determined through economic optimization?			No	
Cycle1DR	[years]	Duration of phase 1 (No dredging)	18	
Cycle2DR	[years]	Cycle length in phase 2 (Dredging operation)	10	
Shall a sustainable solution be determined automatically?			Yes	
Where do you want to perform dredging?			Both active and inactive storag	

Loading Sediment Management ... Finished

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.
CLD	[%]	Maximum percent of capacity loss that is allowable at any time in reservoir for dredging	This technical constrain is used only when RESCON searches for a sustainable reservoir solution. The latest allowable implementation year of dredging is determined by this parameter. Sediment will be removed by dredging before this percent of the reservoir is filled completely. Hence the long term sustainable reservoir capacity will be always higher than a minimum value Smin determined by the CLD parameter. $S_{min} = (1-CLD) \times S_o$ Where: So : pre-impoundment reservoir capacity If deposit removal takes place only in active storage then So refers to pre-impoundment active storage respectively. If deposit removal takes place in both active and inactive storage then So refers to pre-impoundment gross storage respectively. ____________________ Allowable values: $0\ \% < CLD <= 100\ \%$
ASD	[%]	Maximum allowable percent of accumulated sediment removed per dredging event	This technical constrain is used when RESCON searches for a sustainable reservoir solution. The maximum allowable frequency of dredging operations, i.e. the time interval between dredging events, is determined by this parameter. During the sustainable phase, dredging will be performed before the sedimentation occurring between two subsequent events exceeds the ASD% of reservoir storage. This limits the frequency of dredging events. Maximum Deposits Removed during one dredging event: ASD x So Where: So : pre-impoundment reservoir capacity If deposit removal takes place only in active storage then So refers to pre-impoundment active storage. If deposit removal takes place in both active and inactive storage then So refers to pre-impoundment gross storage. ____________________ Allowable values: $0\ \% < ASD <= 100\ \%$
MD	[m^3]	Maximum amount of sediment removed per dredging event	This parameter is used to specify explicitly the maximum amount of deposits that can be removed during each dredging event. This parameter is compulsory if the question "Shall a sustainable solution be determined automatically?" is answered with "No". The actual amount of removal will depend on the availability of deposits in the reservoir. - If the specified amount of removal MD is lower than the deposits occurring between the dredging events, this will lead presumably to a non-sustainable solution, i.e. the reservoir storage will continue reducing only at a slower pace than in the no action scenario. - If the specified amount of removal MD is higher than the deposits occurring between the dredging events, the reservoir storage will increase until the pre-impoundment storage capacity is reached.
PD	[$\$/m^3$]	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.

CD	[$/m^3]	Unit cost of dredging	The user is encouraged to input her/his own estimate. Should this be difficult at the pre-feasibility level, do not insert a value in this input box and answer the question: "Shall the unit cost of dredging be determined automatically?" with yes.
Shall the unit cost of dredging be determined automatically?			If "Yes" the unit cost of dredging will be determined with application of an empirical equation as a function of the volume of dredged material. It will vary over time depending on the deposit removal. If "No", the fixed user defined dredging unit cost will be used by the economic appraisal.
Shall the implementation strategy of dredging be determined through economic optimization?			If "Yes" the economic performance of the reservoir is calculated internally for different constellations of implementation year and frequency of dredging operation, which are subject to the CLD and ASD technical constraints. The values maximizing the economic performance under consideration of the user defined technical constraints are selected as optimum scheduling of dredging operation. If "No" the user specifies explicitly the implementation scheduling of reservoir dredging.
Cycle 1DR	[years]	Duration of Phase 1 (No dredging)	Implementation year of dredging operation. Before this year no sediment management is applied in the reservoir.
Cycle 2DR	[years]	Cycle length in Phase 2 (Dredging operation)	Frequency of dredging operations.
Shall a sustainable solution be determined automatically?			If the option of automatic determination of a sustainable solution is selected, RESCON 2 will calculate the amount of deposits that have to be removed via dredging out of the reservoir in order to maintain sustainably the reservoir storage. If the user wants to specify explicitly the amount of deposits to be dredged by every dredging operation, the option "No" should be selected.
Where do you want to perform dredging?			Herein the user can specify the volume of deposits to be dredged by every dredging operation. The time schedule of dredging implementation has to be specified by providing the duration of 1st phase (no dredging) and the frequency of dredging operation in the second phase. If the specified annual dredged volume is small the reservoir might be non-sustainable.

7.1.6.4 *Trucking*



Parameter	Unit	Description	Value	Help
CLT	[%]	Maximum percent of capacity loss that is allowable at any time in reservoir for trucking	30	
AST	[%]	Maximum percent of reservoir storage that can be restored during each trucking event	100	
MT	[m3]	Amount of sediment removed per trucking event	2,200,000	
CT	[US$/m3]	Unit Cost of trucking	12	
Shall the implementation strategy of trucking be determined through economic optimization?			Yes	
Cycle1TR	[years]	Implementation year	1	
Cycle2TR	[years]	Frequency of trucking operation	1	
		Shall a sustainable solution be determined automatically?	Yes	
		Where do you want to perform trucking?	Both active and inactive storag	
sTR	[%]	Fraction of reservoir water yield the year trucking occurs		

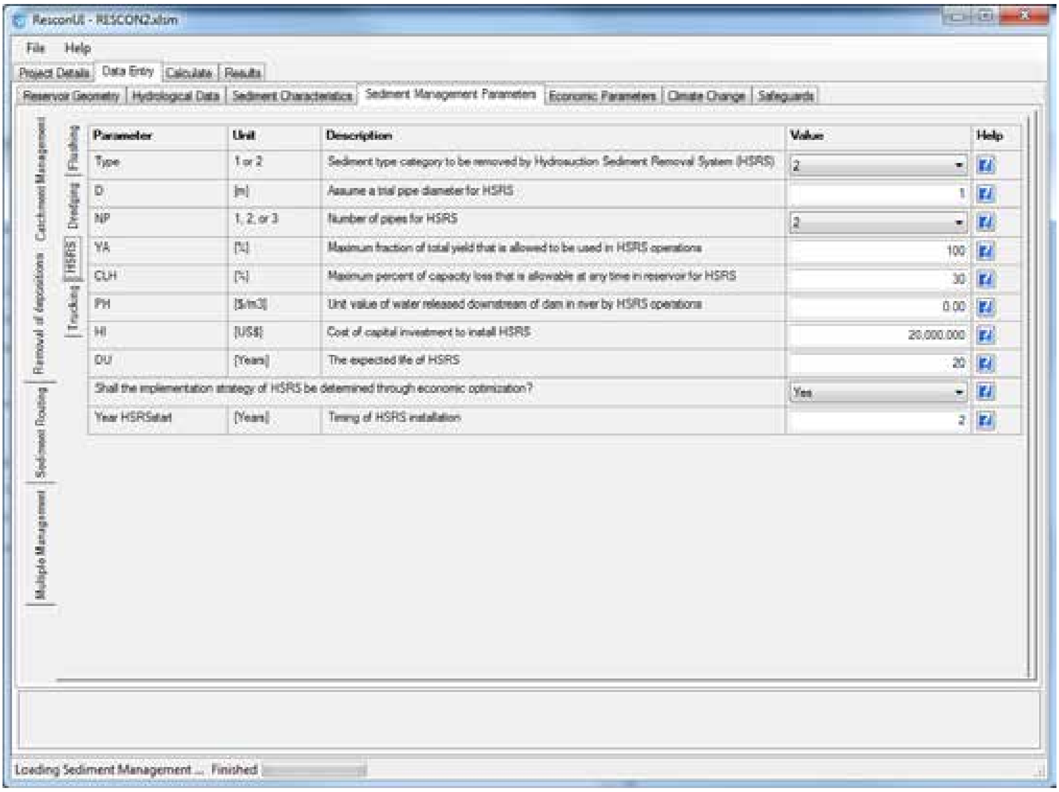
Loading Sediment Management ... Finished

CLT	[%]	Maximum percent of capacity loss that is allowable at any time in reservoir for trucking	This technical constrain is used only when RESCON searches for a sustainable reservoir solution. The latest allowable implementation year of trucking is determined by this parameter. Sediment will be removed by trucking before this percent of the reservoir is filled completely. Hence the long term sustainable reservoir capacity will be always higher than a minimum value Smin determined by the CLT parameter. Smin = (1-CLT) x So Where: So : pre-impoundment reservoir capacity. If deposit removal takes place only in active storage then, So refers to pre-impoundment active storage. If deposit removal takes place in both active and inactive storage then, So refers to pre-impoundment gross storage. Allowable values: 0 % < CLT <= 100 %

AST	[%]	Maximum percent of accumulated sediment removed per trucking event	This technical constrain is used when RESCON searches for a sustainable reservoir solution. The maximum allowable frequency of trucking performance, i.e. the time interval between trucking events, is determined by this parameter. During the sustainable phase, trucking is applied before the sedimentation occurring between trucking events exceeds the AST% of reservoir storage. This limits the frequency of trucking events. Maximum deposit removal by trucking = AST x So Where: So : pre-impoundment reservoir capacity If deposit removal takes place only in active storage then Se and So refer to existing and pre-impoundment active storage respectively. If deposit removal takes place in both active and inactive storage then Se and So refer to existing and pre-impoundment gross storage respectively. Allowable values: $0\ \% < AST <= 100\ \%$
MT	[m^3]	Maximum amount of sediment removed per trucking event	This parameter is used to specify the maximum amount of deposits that can be removed during each trucking event. It is compulsory if the question "Shall a sustainable solution be determined automatically?" is answered with "No". The actual amount of removal will depend on the availability of deposits in the reservoir. - If the specified amount of removal MT is lower than the deposits occurring between the trucking events, this will lead eventually to a non-sustainable solution, i.e. the reservoir storage will continue reducing at a slower pace than in the no action scenario. - If the specified amount of removal MT is higher than the deposits occurring between the trucking events, the reservoir storage capacity will increase until the pre-impoundment storage capacity is reached.
CT	[US$/ m^3]	Unit Cost of trucking	The user is encouraged to input her/his own estimate. Should this be difficult at the pre-feasibility level, the default value of 13.0 US$/$m^3$ is recommended.
Shall the implementation strategy of trucking be determined through economic optimization?			If "Yes" the economic performance of the reservoir is calculated for different constellations of implementation year (Cycle1TR) and frequency of trucking operation (Cycle2TR). The values maximizing the economic performance under consideration of the user defined technical constraints are selected as optimum scheduling of trucking operation. If "No" the user has to specify explicitly the implementation scheduling of trucking (Parameters Cycle1TR and Cycle2TR).
Cycle1TR	[years]	Duration of phase 1 (No trucking)	Implementation year of trucking operation. Before this year no sediment management is applied in the reservoir. This value must be higher than the time interval between trucking events in the sustainable phase. The latter is specified in the below input box. Allowable values: Cycle1TR >= 1
Cycle2TR	[years]	Cycle length in Phase 2 (Trucking operation)	Frequency of trucking operations. This value must be lower than the duration of non-sustainable phase, i.e. the time period until trucking is implemented for first time. The latter is specified in the above input box.

Shall a sustainable solution be determined automatically?			If the option of automatic determination of a sustainable solution, i.e. the answer "Yes" is selected, RESCON will calculate the amount of deposits that have to be removed via trucking out of the reservoir in order to maintain sustainably the reservoir storage. The sustainable solution will be subject to the technical constrain imposed by the parameters CLT and AST. If the user wants to specify explicitly the amount of deposits to be removed by every trucking operation, the option "No" should be selected. In that case the amount of deposits that will be removed during each trucking event has to be specified through parameter MT. This might lead to a non-sustainable solution, which will extend the lifetime of the reservoir.
Where do you want to perform trucking?			This parameter determines the reservoir storage pool where trucking will be performed. If the option "Active storage" is selected, deposit removal will be limited only in active storage. If the option "both active and inactive storage" is selected deposits will be removed from both storage pools depending on the availability. If the user has already specified the amount of deposits that can be removed during each event priority is given to the deposits located in active storage. If the specified amount MT is higher than the deposits in active storage then deposits for inactive storage pool are removed until the amount MT is exhausted.
sTR	[%]	Fraction of reservoir water yield the year trucking occurs	The fraction of reservoir benefits available in the year trucking occurs (sTR ranges from 0 to 100%). During the year trucking operation, the water yield (Wt) is calculated as follows: Wt = sTR x W(St) where: sTR is the fraction of benefits available in the year trucking occurs W(St) is the firm water yield for the storage capacity available this year.

7.1.6.5 HydroSuction Removal System (HSRS)

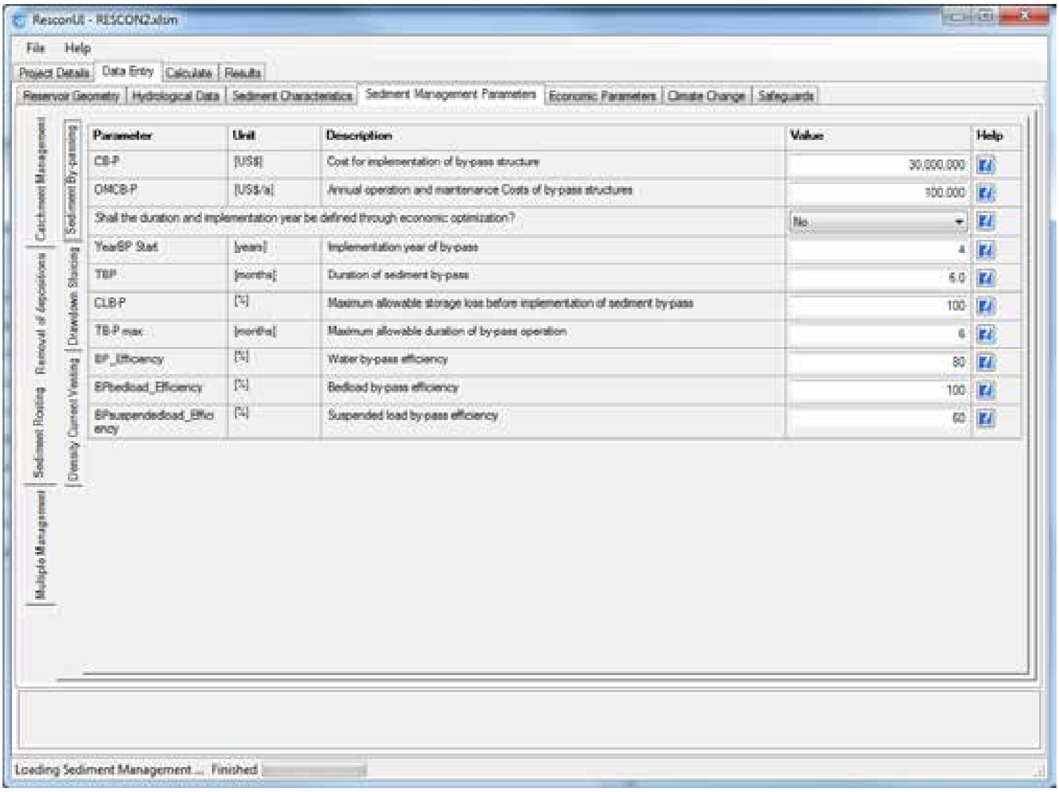


Parameter	Unit	Description	Value	Help
Type	1 or 2	Sediment type category to be removed by Hydrosuction Sediment Removal System (HSRS)	2	
D	[m]	Assume a trial pipe diameter for HSRS	1	
NP	1, 2, or 3	Number of pipes for HSRS	2	
YA	[%]	Maximum fraction of total yield that is allowed to be used in HSRS operations	100	
CLH	[%]	Maximum percent of capacity loss that is allowable at any time in reservoir for HSRS	30	
PH	[$/m3]	Unit value of water released downstream of dam in river by HSRS operations	0.00	
HI	[US$]	Cost of capital investment to install HSRS	20,000,000	
DU	[Years]	The expected life of HSRS	20	
Shall the implementation strategy of HSRS be determined through economic optimization?			Yes	
Year HSRSstart	[Years]	Timing of HSRS installation	2	

Type	1 or 2	Sediment type category to be removed by Hydrosuction Sediment Removal System (HSRS)	Enter the number corresponding to the sediment type category to be removed by hydrosuction dredging: - 1 for medium sand and smaller; - 2 for gravel.
D	[feet]	Assume a trial pipe diameter for HSRS	Should be between 0.3 and 1.2 m.
NP	1, 2, or 3	Number of pipes for HSRS	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.
YA	[%]	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 % fraction from 0 - 100%.
CLH	[%]	Maximum percent of capacity loss that is allowable at any time in reservoir for HSRS	For an existing reservoir, this parameter 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.

PH	[$/m^3]	Unit value of water released downstream of dam in river by HSRS operations	This could be zero, but may have value if downstream released water is used for providing some of required yield.
HI	[US$]	Cost of capital investment to install HHSRS	Cost of capital investment required for installation of Hydrosuction Sediment Removal System (HSRS). The cost entered will be incurred when HSRS is first practiced.
DU	[Years]	The expected life of HSRS	This value varies usually between 20 and 30 years
Shall the implementation strategy of HSRS be determined through economic optimization?			If "Yes" the economic performance of the reservoir is calculated for different values of HSRS installation year. The timing maximizing the economic performance under consideration of the user defined technical constraints is selected as the optimum scheduling of HSRS. If "No" the user has to specify explicitly the implementation scheduling of this sediment management activity.
Year HSRS start	[Years]	Timing of HSRS installation	Installation year of HSRS system, i.e. duration of time period during which no HSRS is applied.

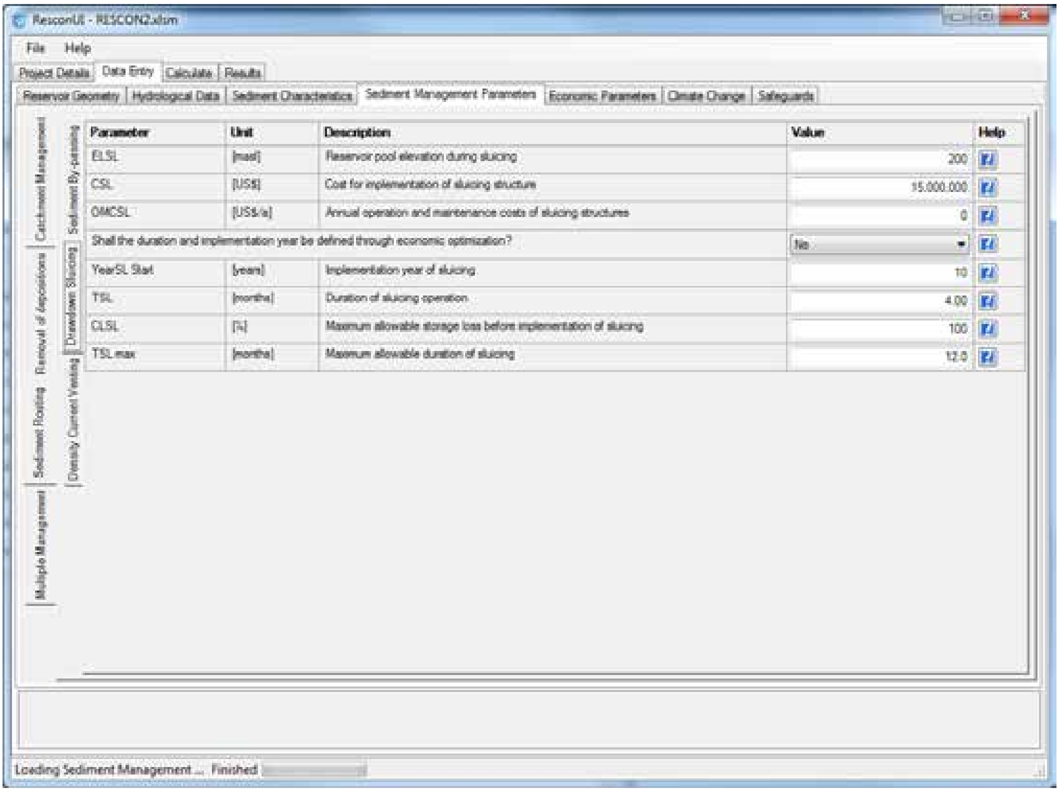
7.1.6.6 By-Pass



Parameter	Unit	Description	Value	Help
CB-P	[US$]	Cost for implementation of by-pass structure	30,000,000	
OMCB-P	[US$/a]	Annual operation and maintenance Costs of by-pass structures	100,000	
Shall the duration and implementation year be defined through economic optimization?			No	
YearBP Start	[years]	Implementation year of by-pass	4	
TBP	[months]	Duration of sediment by-pass	6.0	
CLB-P	[%]	Maximum allowable storage loss before implementation of sediment by-pass	100	
TB-P max	[months]	Maximum allowable duration of by-pass operation	6	
BP_Efficiency	[%]	Water by-pass efficiency	80	
BPbedload_Efficiency	[%]	Bedload by-pass efficiency	100	
BPsuspendedload_Efficiency	[%]	Suspended load by-pass efficiency	60	

CB-P	[US$]	Cost for implementation of by-pass structure	It is assumed that it is technically feasible to construct the necessary diversion structures for performance of sediment by-pass. The cost shall be specified by the user. It depends on the geological and topographical conditions, the discharge capacity of by-pass tunnel or open channel, the distance between diversion inlet and outlet and other parameters.
OMCB-P	[US$/a]	Annual operation and maintenance Costs of by-pass structures	The structures used for diversion of water and sediment inflow are highly susceptible to hydro abrasive erosion. This risk has to be considered by the assessment of annual maintenance costs.
Shall the duration and implementation year be defined through economic optimization?			"If the option of economic optimization is selected, the implementation year and the annual duration of sediment by-pass operation will be optimally determined. If not, the user has to specify the corresponding parameters Year BP Start and TBP. "
Year BP Start	[years]	Implementation year of by-pass	First year of by-pass operation. This parameter has to be specified by the user for assessment of economic performance of sediment by-pass, if the option of economic optimization is not chosen.
TBP	[months]	Duration of sediment by-pass	Duration of by-pass operation in months. It is assumed that sediment by-pass will be operated every year during the wet months. This parameter will be used for assessment of economic performance of sediment by-pass, if the option of economic optimization is not chosen.
CLB-P	[%]	Maximum allowable storage loss before implementation of sediment by-pass	Technical constrain for limitation of the latest possible implementation of the by-pass sediment management technique.
TB-P max	[months]	Maximum allowable duration of by-pass operation	User defined constrain of maximum allowable duration in months of annual by-pass operation. The user defined duration of by-pass operation or the duration determined by economic optimization cannot exceed this constrain.
BP_Efficiency	[%]	Water by-pass efficiency	Efficiency of by-pass, i.e. % of water inflow arriving at the by-pass tunnel inlet at the time period of by-pass which is diverted. The rest enters the reservoir during the time period of by-pass. It depends on the discharge capacity of by-pass structure and operation of diversion weir.
BP_ bedload_ Efficiency	[%]	Bedload by-pass efficiency	Efficiency of bedload by-pass, i.e. % of bedload arriving at the inlet of by-pass structure when the latter is in operation which is diverted. For instance 80% bedload by-pass efficiency means that 80% of the bedload arriving at the by-pass tunnel inlet when the latter is in operation is diverted and 20% enters the reservoir. 100% bedload can be diverted only if there is sufficient transport capacity to actually move the bed material.
BP_ suspended load_Efficiency	[%]	Suspended load by-pass efficiency	Efficiency of suspended load by-pass, i.e. % of suspended load arriving at the inlet of by-pass structure when the latter is in operation which is diverted. It is subject to the geometrical features of the diversion tunnel inlet and diversion weir.

7.1.6.7 *Sluicing*



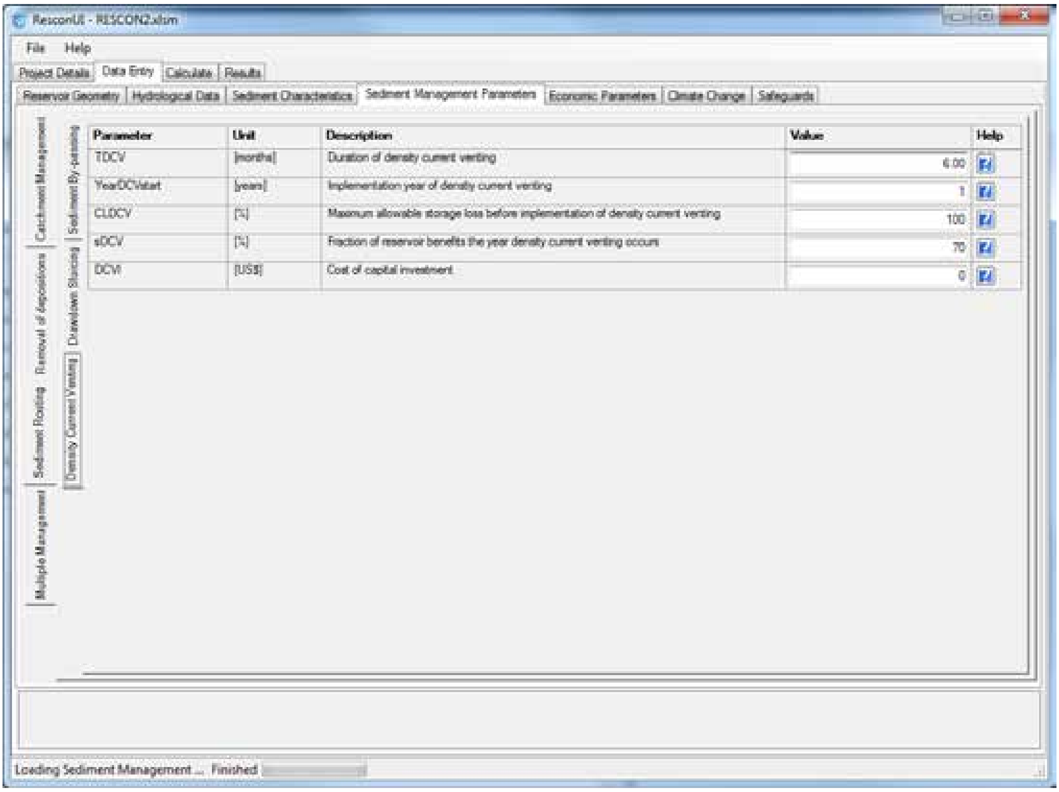
Parameter	Unit	Description	Value	Help
ELSL	[masl]	Reservoir pool elevation during sluicing	200	
CSL	[US$]	Cost for implementation of sluicing structure	15.000.000	
OMCSL	[US$/a]	Annual operation and maintenance costs of sluicing structures	0	
Shall the duration and implementation year be defined through economic optimization?			No	
YearSL Start	[years]	Implementation year of sluicing	10	
TSL	[months]	Duration of sluicing operation	4.00	
CLSL	[%]	Maximum allowable storage loss before implementation of sluicing	100	
TSL max	[months]	Maximum allowable duration of sluicing	12.0	

Loading Sediment Management ... Finished

ELSL	[masl]	Reservoir pool elevation during sluicing	This parameter determines the reservoir water level drawdown during seasonal sluicing operation.
CSL	[US$]	Cost for implementation of sluicing structure	This involves the costs for e.g. retrofitting of spillway or construction of new outlet to allow reservoir drawdown.
OMCSL	[US$/a]	Annual operation and maintenance costs of sluicing structures	The annual costs for sluicing are added to the normal O&M costs specified in the Economic parameters tab. If normal releases and sluicing releases use the same outlet, sluicing is not expected to increase essentially the normal O& M costs. If an additional outlet is required for implementation of sluicing this might affect significantly the annual O& M costs.
Shall the duration and implementation year be defined through economic optimization?			If the option of economic optimization is selected, the implementation year and the annual duration of seasonal sluicing operation will be determined through an optimization procedure of the reservoir economic performance.
YearSL Start	[years]	Implementation year of sluicing	This parameter will be used for assessment of economic performance of sediment by-pass, if the option of economic optimization is not chosen.

TSL	[months]	Duration of sluicing operation	This parameter determines the amount of sediment entering the reservoir during sluicing. It shows the duration of reservoir water level drawdown. It will be used for assessment of economic performance of sluicing, if the option of economic optimization is not selected.
CLSL	[%]	Maximum allowable storage loss before implementation of sluicing	If the user defines explicit the year of sluicing implementation, the constrain of maximum allowable storage loss before implementation of sluicing is not further considered.
TSL max	[months]	Maximum allowable duration of sluicing	User specified technical constrain regarding the maximum allowable duration of annual sluicing operation.

7.1.6.8 Density current venting

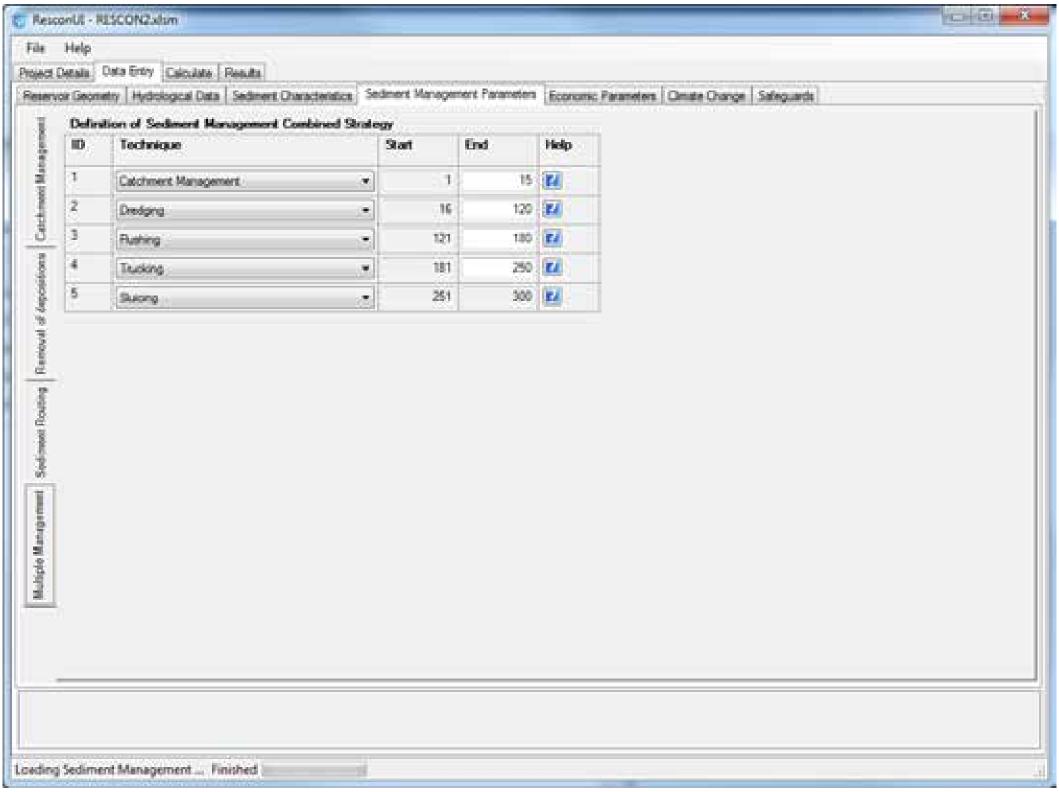


Parameter	Unit	Description	Value	Help
TDCV	[months]	Duration of density current venting	6.00	
YearDCVstart	[years]	Implementation year of density current venting	1	
CLDCV	[%]	Maximum allowable storage loss before implementation of density current venting	100	
sDCV	[%]	Fraction of reservoir benefits the year density current venting occurs	70	
DCVI	[US$]	Cost of capital investment	0	

Loading Sediment Management ... Finished

TDCV	[months]	Duration of density current venting	This parameter determines the concentration of sediment entering the reservoir during density current venting. It shows the duration of opening the low level outlet for venting of the density current which reaches the dam location. It will be used for assessment of economic performance of density current venting if the option of economic optimization is not selected.
Year DCV start	[years]	Implementation year of density current venting	Timing of installation of low level outlets for venting of density currents created in the reservoir. This parameter will be used for assessment of economic performance of density current venting.
CLDCV	[%]	Maximum allowable storage loss before implementation of density current venting	If the user specifies explicitly the year of density current venting implementation, the constrain of maximum allowable storage loss before implementation of density current venting is not further considered.
TDCV max	[months]	Maximum allowable duration of density current venting operation	The fraction of reservoir benefits available in the year density current venting occurs (sDCV ranges from 0 to 100%). When density current venting is carried out, part of the water inflow is discharged through the bottom outlet. This parameter expresses the water yield that can be utilized for beneficial uses in the year density current venting is performed. It is considered that the water yield supplied by the reservoir will be lower the year of density current venting compared to the water yield supplied a year with no such operation. The reduction is associated with the duration of density current venting operation, i.e. the number of days density currents appear in the reservoir and the bottom outlet is opened to release the turbid water. During the year in which density current venting occurs, the water yield (Wt) is calculated as follows: $Wt = sDCV \times W(St)$ where: sDCV is the fraction of benefits available in the year density current venting occurs W(St) is water yield from the available storage capacity.
DCVI	[US$]	Cost of capital investment	This involves the costs for construction of new low level outlet to allow venting of density currents.

7.1.6.9 Multiple management



Definition of Sediment Management Combined Strategy

ID	Technique	Start	End	Help
1	Catchment Management	1	15	
2	Dredging	16	120	
3	Flushing	121	180	
4	Trucking	181	250	
5	Sluicing	251	300	

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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 result 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.
Sum Ki = 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:

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

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

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):

$\gamma s := 80 \text{Ib/ft}^3$,

density of in-situ reservoir sediments (converted from metric on User Input)

$\gamma s := 62.4 \text{ Ib/ft}^3$,

assumed specific weight of water

$\rho s := \frac{\gamma s}{g}$ slugs/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 = 9.5 mm
d50 = 0.73 mm
d90 = 3.6 mm
d35 = 0.42 mm
d65 = 1.3 mm

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

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

Program calculates drag co-efficient 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:

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

let : Cdold := Cd

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

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

ω 100 = fps ω 90 = 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 Reynolds Number using fall velocity for each category of grain size distribution.

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

$$\mathrm{Re90} := \frac{\omega 90 \cdot \left(\dfrac{d90}{25.4 \cdot 12}\right)}{v} \quad \mathrm{Re90} =$$

$$\mathrm{Re65} := \frac{\omega 65 \cdot \left(\dfrac{d65}{25.4 \cdot 12}\right)}{v} \quad \mathrm{Re65} =$$

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

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

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

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

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

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

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

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

Cd100 = Cd90 = Cd65 = Cd50 = Cd35 =

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

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

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

$$\omega 100 := 8.42 \cdot \sqrt{\frac{\left(\frac{d100}{25.4 \cdot 12}\right)}{\mathrm{Cd100}}} \qquad \omega 90 := 8.42 \cdot \sqrt{\frac{\left(\frac{d90}{25.4 \cdot 12}\right)}{\mathrm{Cd90}}}$$

ω100 = fps ω90 = fps

$$\omega 65 := 8.42 \cdot \sqrt{\frac{\left(\frac{d65}{25.4 \cdot 12}\right)}{\mathrm{Cd65}}} \qquad \omega 50 := 8.42 \cdot \sqrt{\frac{\left(\frac{d50}{25.4 \cdot 12}\right)}{\mathrm{Cd50}}}$$

ω65 = fps ω50 = fps

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

ω35 = fps

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

Check tolerance on Cd:

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

Continue to iterate unit tol <1%

let: $\quad \mathrm{Cdold} := \mathrm{Cd}$

B) Calculate Reynold's Number using fall velocity for each category of gram size distribution

$$\mathrm{Re}100 := \frac{\omega 100 \cdot \left(\frac{d100}{25.4 \cdot 12}\right)}{v} \qquad \mathrm{Re}100 =$$

$$\mathrm{Re}90 := \frac{\omega 90 \cdot \left(\frac{d90}{25.4 \cdot 12}\right)}{v} \qquad \mathrm{Re}90 =$$

$$\mathrm{Re}65 := \frac{\omega 65 \cdot \left(\frac{d65}{25.4 \cdot 12}\right)}{v} \qquad \mathrm{Re}65 =$$

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

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

$$\mathrm{Cd}90 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot \mathrm{Re}90^{0.56}} + \left(\frac{\mathrm{Re}90}{\mathrm{Re}90 + 700 + 1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^{4} + 20 \cdot \beta^{20}\right)^{0.175}}\right]^{1.428}$$

$$\mathrm{Cd}65 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot \mathrm{Re}65^{0.56}} + \left(\frac{\mathrm{Re}65}{\mathrm{Re}65 + 700 + 1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^{4} + 20 \cdot \beta^{20}\right)^{0.175}}\right]^{1.428}$$

$$\mathrm{Cd}50 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot \mathrm{Re}50^{0.56}} + \left(\frac{\mathrm{Re}50}{\mathrm{Re}50 + 700 + 1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^{4} + 20 \cdot \beta^{20}\right)^{0.175}}\right]^{1.428}$$

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

Cd100 = Cd90 = Cd65 = Cd50 = Cd35 =

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

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

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

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

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

e) Continue Heration 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 gram size distribution

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

$$\mathrm{Re}90 := \frac{\omega 90 \cdot \left(\frac{d90}{25.4 \cdot 12}\right)}{v} \qquad \mathrm{Re}90 =$$

$$\mathrm{Re}65 := \frac{\omega 65 \cdot \left(\frac{d65}{25.4 \cdot 12}\right)}{v} \qquad \mathrm{Re}65 =$$

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

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

b) 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

$$\mathrm{Cd}100 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot \mathrm{Re}100^{0.56}} + \left(\frac{\mathrm{Re}100}{\mathrm{Re}100 + 700 + 1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^{4} + 20 \cdot \beta^{20}\right)^{0.175}}\right]^{1.428}$$

$$\mathrm{Cd}90 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot \mathrm{Re}90^{0.56}} + \left(\frac{\mathrm{Re}90}{\mathrm{Re}90 + 700 + 1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^{4} + 20 \cdot \beta^{20}\right)^{0.175}}\right]^{1.428}$$

$$\mathrm{Cd}65 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot \mathrm{Re}65^{0.56}} + \left(\frac{\mathrm{Re}65}{\mathrm{Re}65 + 700 + 1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^{4} + 20 \cdot \beta^{20}\right)^{0.175}}\right]^{1.428}$$

$$\mathrm{Cd}50 := 0.84 \cdot \left[\frac{33.78}{\left(1 + 4.5 \cdot \beta^{0.35}\right)^{0.7} \cdot \mathrm{Re}50^{0.56}} + \left(\frac{\mathrm{Re}50}{\mathrm{Re}50 + 700 + 1000 \cdot \beta}\right)^{0.28} \cdot \frac{1}{\left(\beta^{4} + 20 \cdot \beta^{20}\right)^{0.175}}\right]^{1.428}$$

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

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

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

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) Contribution 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 gram size distribution.

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

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

$$\mathrm{Re65} := \frac{\omega 65 \cdot \left(\frac{d65}{25.4 \cdot 12}\right)}{v} \qquad \mathrm{Re65} =$$

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

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

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

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

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

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

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

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

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

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

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

b) Use new Cd to re-calculate fall velocity

$$\omega 100 := 8.42\cdot\sqrt{\frac{\left(\frac{d100}{25.4\cdot 12}\right)}{Cd100}} \qquad \omega 90 := 8.42\cdot\sqrt{\frac{\left(\frac{d90}{25.4\cdot 12}\right)}{Cd90}}$$

$\omega 100 =$ fps $\qquad$ $\omega 90 =$ fps

$$\omega 65 := 8.42\cdot\sqrt{\frac{\left(\frac{d65}{25.4\cdot 12}\right)}{Cd65}} \qquad \omega 50 := 8.42\cdot\sqrt{\frac{\left(\frac{d50}{25.4\cdot 12}\right)}{Cd50}}$$

$\omega 65 =$ fps $\qquad$ $\omega 50 =$ fps

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

$\omega 35 =$ fps

e) Contribution Heration 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 gram size distribution.

$$Re100 := \frac{\omega 100\cdot\left(\frac{d100}{25.4\cdot 12}\right)}{v} \qquad Re100 =$$

$$Re90 := \frac{\omega 90 \cdot \left(\frac{d90}{25.4 \cdot 12}\right)}{v} \quad Re90 =$$

$$Re65 := \frac{\omega 65 \cdot \left(\frac{d65}{25.4 \cdot 12}\right)}{v} \quad Re65 =$$

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

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

c) Equation below calculate 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.

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

b) Use new Cd to re-calculate fall velocity

$$\omega 100 := 8.42 \cdot \sqrt{\frac{\left(\frac{d100}{25.4 \cdot 12}\right)}{Cd100}} \qquad \omega 90 := 8.42 \cdot \sqrt{\frac{\left(\frac{d90}{25.4 \cdot 12}\right)}{Cd90}}$$

ω100 = fps ω90 = fps

$$\omega 65 := 8.42 \cdot \sqrt{\frac{\left(\frac{d65}{25.4 \cdot 12}\right)}{Cd65}} \qquad \omega 50 := 8.42 \cdot \sqrt{\frac{\left(\frac{d50}{25.4 \cdot 12}\right)}{Cd50}}$$

ω65 = fps ω50 = fps

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

ω35 = fps

e) Contribution Heration 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%–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:

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

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

$K = 280$ for $\psi < 10$
$K = 6.3$ for $\psi \geq 10$

$m = -1.93$ for $\psi < 10$
$m = 0.354$ for $\psi \geq 10$

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

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

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.

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

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:

$$Re := \frac{V \cdot D}{v}; \; Re =$$

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

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

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

$$Qs := \left[\frac{Jm}{\left[\begin{array}{l}\dfrac{f\cdot\left[\dfrac{-\pi\cdot D^{2}}{2\cdot\alpha\cdot(1+2\cdot m)}\right]^{\frac{2}{(2\cdot m-1)}}}{2\cdot g\cdot D}+\dfrac{2\cdot f\cdot\alpha}{\pi\cdot f\cdot D^{3}}\cdot\left[\dfrac{-\pi\cdot D^{2}\,!}{2\cdot\alpha\cdot(1+2\cdot m)}\right]^{\frac{1+2\cdot m}{2\cdot m-1}}\\ \qquad cfs\end{array}\right]}\right]^{\frac{(1+2\cdot m)}{2\cdot m-1}}$$

$$Qs :=$$

Step 6 :

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

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

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).

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

Step 9:

Using Vm, Program will recalculate Jm and fm and compare with value of fm calculated in step 8. Repeat step 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:

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

Mixture Velocity : Vm = fps

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

Sediment Concentration through Hydrosuction Pipe;

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

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 : = Wbol + 2.SSres (ELf-ELmin) m

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

Wf : = 12.8 $Qf^{0.5}$ 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:

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

The Tsinghua 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 losses sediments

650 for other sediments with median size finger than 0.1 mm

300 for sediments with median size larger than 0.1 mm

180 for flushing with a low discharge (less than 50 m 3/s) with any grain size.

$\psi :=$ <== *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 is question is similar to the Chinese reservoir studied in Atkinson's report (especially with regards to sediment gradattions). The equation below should only be used if the reservoir in question is dissimilar to Chinese reservoir studied. If reservoirs are similar, insert 1 for adj below. If reservoirs are not similar, insert 3 for adj below.

Ams : = <== Determine value for Ans (1 or 3) in User input Sheet:

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

Sediment mass flushed annually Mf:

$Mf := 86400\, TfQs$ tonnes

Where Tf = nduration of flushing

Trapping Efficiency, TE, is the percent of inflowing sediment that is trapped the reservoir. The Brune curve method 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 sediments 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 : = choos 1, 2 or 3 for reservoir type for Brune Curve on User Input Sheet

Brune - ratio value is calculated below:

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

The result is used in a piecewise fir equation of the Brune Curve determine the trap efficiency (TE) for tases 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:

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

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

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

CRITERION : Must have SBR > 1.0

LTRC calculation – 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 approxi mating 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:

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

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

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

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

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

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

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

$$\mathrm{ht} := \mathrm{ELmax} - \mathrm{ELf} - \mathrm{hm} \quad \mathrm{m}$$

$$\mathrm{hf} := \mathrm{ELmax} - \mathrm{ELf} \quad \mathrm{m}$$

$$\mathrm{Af2} := \mathrm{Whf} + (\mathrm{hf} + \mathrm{ht})\ \mathrm{hm} \cdot \mathrm{SSs} + \mathrm{ht}^2 \cdot \mathrm{SSres} \quad \mathrm{m}^2$$

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

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

$$\mathrm{Af} := \mathrm{if}\ (\mathrm{Wtf} \le \mathrm{Wl}, \mathrm{Afl}, \mathrm{Af2} \quad \mathrm{m}^2$$

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:

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

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

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

Guideline : Use Caution if LTCR < 0.35.

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

$$\mathrm{DDR} := 1 - \frac{\mathrm{ELF} - \mathrm{EL\,min}}{\mathrm{ELmax} - \mathrm{EL\ min}}$$

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 that the representative bottom width of reservoir, Wbot:

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

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

TWR Calculation – 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:

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

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

$A := (Wres\ Wf)$

$W := \min(A)$ m

$$S := \frac{ELmax - ELf}{L}$$

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

A qualitative analysis must be made to determine whether the reservoir in question is similar to the Chinese reservoirs studied in Atkinson, 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 Resuluing adjusted Qs:

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

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

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

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

Guideline : SBRd preferably > 1.0:

ANNEX 3

Density Current Venting Calculations

The calculation implemented in RESCON 2 is based on the iterative procedure presented by Morris & Fan (1998). It involves the following Steps 1-4. These steps are repeated on annual basis until the storage capacity of the reservoir is eliminated.

Step 1: Calculation of the water depth at the plunge point.

The water depth at the location where the turbid water entering the reservoir plunges beneath the clear water, i.e. at the plunge point is given by the following equation

$$h = \left(\frac{Q}{F_p B} \right)^{\frac{2}{3}} \left(\frac{\Delta\rho}{\rho} g \right)^{-\frac{1}{3}}$$

Where:

Q: Average inflow flowrate (m^3/s)

B: Reservoir bottom width (m)

Δρ: density difference between clear impounded water and turbid water inflow $\Delta\rho = \rho' - \rho$

ρ´: density of turbid water, depending on sediment concentration and water temperature

ρ: density of clear water, depending on water temperature

Table A.1: Density of Water and Sediment Mixtures as a function of temperature and suspended solids

Temperature °C	*Pure water*	*Water + Sediment*		
		1g/L	*10 g/L*	*100 g/L*
0	0.999868	1.000491	1.006095	1.062137
4	1.000000	1.000623	1.006226	1.062264
10	0.999728	1.000351	1.005955	1.062002
20	0.998232	0.998855	1.004465	1.060562
30	0.995676	0.996300	1.001919	1.058103

Source: Morris & Fan (1998).

Fp: Densimetric Froude number at the plunge point. According to Moris & Fan (1998) the turbid water inflow plunges beneath clear water when the densimetric Froude number has a value of about 0.78. This is based on results of both flume tests and field measurements. RESCON 2 will use this value by default but at the same time it will provide the user with the possibility to perform the calculations with a different value. The software will provide guidelines to the user for helping him selecting an appropriate value through values reported in the reservoir.

Table A.2: Measured densimetric Froude number Fp at plunge point

Author	*Laboratory or field data*	*Fp*
Bu et al. (1980)	Liujiaxia reservoir, Tao River	0.78
Fan (1981)	Guanting Reservoir	0.5-0.78
Fan (1960)	Turbid water flume tests: 3-19 g/l	0.78
Cao et al. (1984)	Turbid water flume tests:	
	10-30 g/l	0.55-0.75
	100-360 g/l	0.4-0.2
Singh and Shan (1971)	Saline water	0.3-0.8
Farrel and Stephan (1986)	Cold water	0.67

Source: Morris & Fan (1998).

If the calculated water depth at the plunge point is larger than the maximum water depth of the reservoir, then turbid current venting is technically not feasible, because the density difference between turbid water inflow and impounded clear water is not sufficient to induce a turbid current that will plunge beneath the water surface.

Step 2: Calculation of the average longitudinal slope of the reservoir bottom.

This calculation is repeated annually using as input the bottom elevation of each compartment.

Step 3: Calculation of the amount of sediment load that the density current is able to transport along the reservoir.

This calculation is based on an iterative procedure as described by Morris & Fan (1986). The following calculations are performed within each iteration, until the calculated transport capacity of the current converges.

3a: Calculation of the velocity of the turbidity current based on the suspended solids concentration of the inflow.

The flow velocity of the density current is determined by the following equation, which is similar to the equation used for open channel flow.

$$V = \sqrt[3]{\frac{8}{f}\frac{\Delta\rho}{\rho}g\frac{Q}{B}S} \qquad \textbf{Equation 0.2}$$

Where:

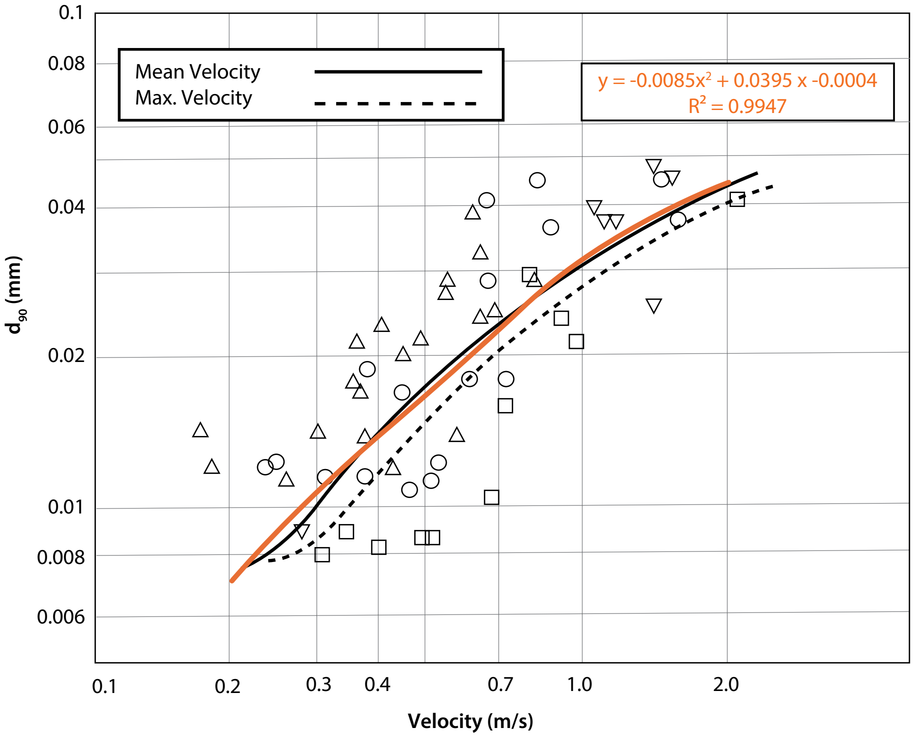
S: Average reservoir bottom longitudinal gradient

f: represent the total interfacial frictional effects including the channel bed plus the boundary with the overlying stationary fluid. Observations in Chinese reservoirs show that this value is typically in the vicinity of 0.025. This value is used by default by the model.

3b: Determination of the maximum grain size that can be transported by the density current.

The maximum grain size that can be transported by the turbid density current is roughly estimated by the relationship presented by Fan (1986), which is shown in the figure below.

Figure A.1: Relationship between turbidity current velocity and the grain size that can be maintained in suspension (after Fan (1986)



Source: Morris & Fan (1998)

The relationship between maximum grain size transported by the turbidity current for a given velocity is calculated by the polynomial of second order fitted to the figure of Fan (1986).

3c: Recalculation of the sediment concentration after removal of the fraction larger than the maximum grain that can be transported by the turbidity current and iteration of steps 2, 3 and 4.

After several iterations the computations converge to a sediment concentration. When the latter is equal to zero the turbidity current will fade away rapidly. If the result of the iterations is a positive concentration the turbidity current under the given hydraulic conditions can be sustained and when venting is applied in an appropriate manner a part of the sediment inflow can travel through the reservoir and exit.

Step 4: Calculation of annual deposits and allocation in inactive and active storage.

The result of the iterations 3a-3c is used for the calculation of the amount of sediment inflow that the current is not strong enough to keep in suspension and therefore will deposit with the boundaries of the reservoir before the current is vented through the low level outlet.

The total deposits are subject to limitations imposed by the available storage of each compartment and the maximum allowable deposits in the reservoir as calculated by the selected trap efficiency equation. Based on the predefined width of active and inactive storage as well as the minimum bed elevation the deposits are allocated in the corresponding storage pools.

ANNEX 4

Assessment of Mean Annual Sediment Inflow with BQART equation

Source: Syvitski, J., P.M. and J. D. Milliman (2007): “Geology, Geography and Humans Battle for Dominance over the Delivery of Fluvial Sediment to the Coastal Ocean”, The Journal of Geology, Vol. 115, No. 1, pp. 1-19.

The BQART model for prediction of sediment load is expressed as follows:

$$Q_s = \begin{cases} \omega \ \mathrm{B} \ \mathrm{Q}^{0.31} \ A^{0.5} \ R \ T, & \text{for } T \geq 2°\mathrm{C} \\ 2 \ \omega \ \mathrm{B} \ \mathrm{Q}^{0.31} A^{0.5} \ R \ T, & \text{for } T < 2°\mathrm{C} \end{cases}$$

Where:

Qs: is the long term mean annual total sediment load expressed in dimension of [M/T]

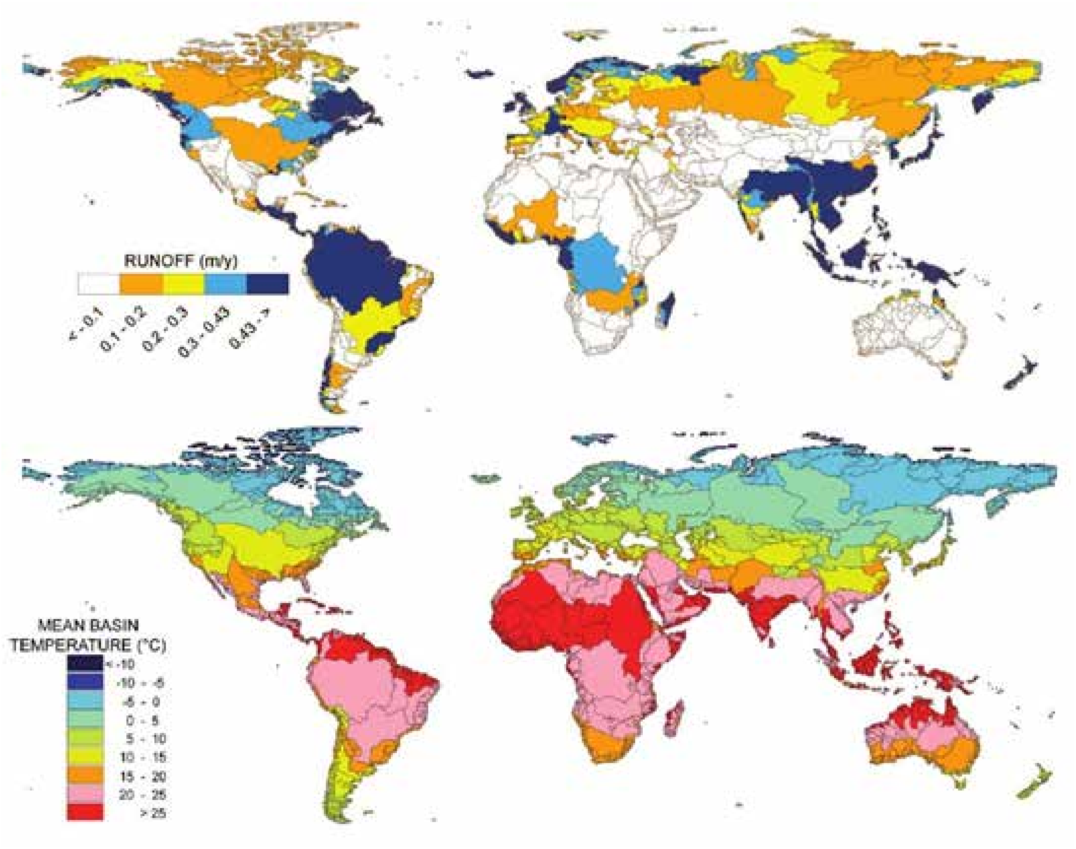
ω: constant for sediment load unit transformation (-)
It takes the value:

- 0.02 for units of sediment load Qs kg/s
- 0.0006 for units of sediment load Qs million tones/year

A: Basin area of the river (km^2)
R: Maximum relief of drainage basin (km)
Q: Mean annual water flow (km^3/year)
T: Basin-averaged temperature (°C)

If the mean annual water flow and the basin averaged temperature can be assessed by the following global maps published by Syvitski and Milliman (2007).

Figure A.2: Global map indicating the basin-averaged values of hydrological runoff and temperature



Source: Syvitski, and Milliman (2007)

B: Term accounting for influence of geological conditions (lithology, ice cover), and human activities (reservoir trapping, soil erosion) on sediment flux (-)
$B = I\ L\ (1 - T_E)\ E_h$

Where:

I: glacier erosion factor (-) defined as
$I = (1 + 0.09\ A_g)$

Where:

Ag: the area of the drainage basin covered by glacier as a percentage of the total drainage area of the basin.

L: average basin-wide lithology factor (-).
Its value depends on the lithology class prevailing at the river basin. It can take the following values:

Table A.3: Value of average basin-wide lithology factor L for different basin lithology classes

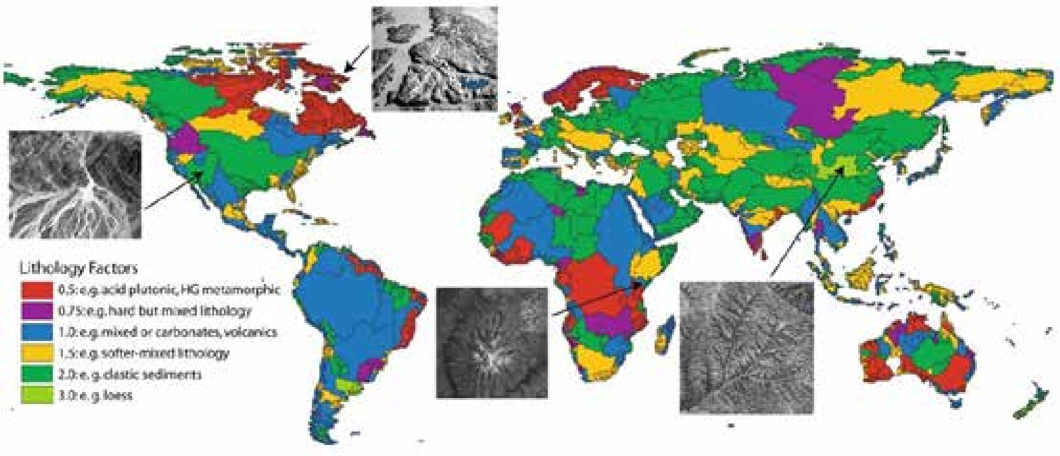
Basin lithology class	*Average basin-wide lithology factor L*
Principally hard, acid plutonic and/or high-grade metamorphic rocks	0.5
Mixed, mostly hard lithology, sometimes including shield material	0.75
Volcanic, mostly basaltic rocks (e.g., Tapti, India), or carbonate outcrops (e.g., Suwannee, United States), or mixture of hard and soft lithologies (Niger, Orinoco, Amazon)	1.0
Predominance of softer lithologies but having a significant area of harder lithologies	1.5
Fluvial systems draining a significant proportion of sedimentary rocks, unconsolidated sedimentary cover, or alluvial deposits	2.0
Abundance of exceptionally weak material, such as crushed rock (e.g., Waipaoa or Waiapu, New Zealand; Eel, United States) or loess deposits (e.g., Huanghe, China)	3.0

If the lithology of the river basin is not known, Syvitski and Milliman (2007) provide the global map shown below which classifies the world's drainage basins in terms of their basin-averaged lithology.

TE: Trap efficiency of lakes and man-made reservoirs in the catchment area. It takes values between 0 and 1 and depends on the spatial distribution of the sediment retaining lakes and reservoirs and their hydrologic size. If this parameter is not known an assessment can be obtained by the global map sown in the figure below

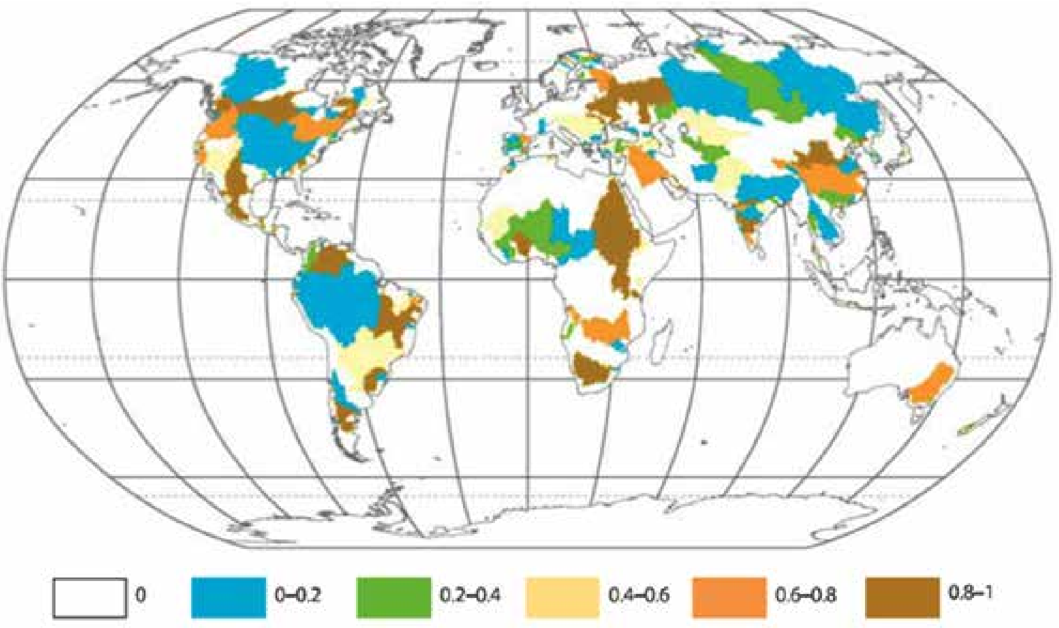
E_h: Human-influenced soil erosion factor

Figure A.3: Global map indicating the basin-averaged lithology



Source: Syvitski, and Milliman (2007)

Figure A.4: Global map indicating the basin-averaged trap efficiency



Source: World Water Development Report II (Figure Retrieved from http://wwdrii.sr.unh.edu/index.html).

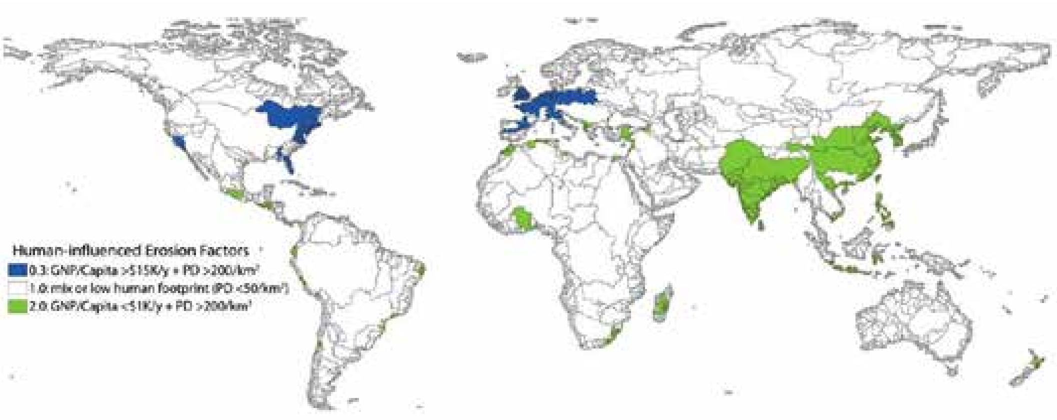
Accounts for the overarching anthropogenic influence on sediment yield. Its value depends on the population density and GNP per capita.

Table A.4: Value of human-influenced soil erosion factor Eh for depending on the population density and GNP per capita in the river basin

Population density (PD) and GNP per capita in the river basin	*Human-influenced soil erosion factor E_h*
High-density population PD > 200 km^2 per capita GNP >$15K/yr	0.3
Low human footprint PD < 50 km^2 or basins containing a mixture of the competing influences of soil erosion and conservation (e.g., Amazon, Lena and Orange)	1.0
High population density PD >200 km^2 low per capita GNP ≤$1K/yr	2.0

If the classification of the river basin in one of the three aforementioned classes is not known the human influenced soil erosion factor can be determined by the following global map presented by Syvitski and Milliman (2007).

Figure A.5: Global map showing the human-influenced erosion factors



Source: Syvitski and Milliman (2007).

ANNEX 5

Environmental Considerations

Source:
Alessandro Palmieri, Farhed Shah George W. Annandale, Ariel Dinar (2003): Reservoir Conservation, Volume I: The RESCON Approach Economic and engineering evaluation of alternative strategies for managing sedimentation in storage reservoirs.

Introduction

This annex provides an expanded discussion of the environmental considerations outlined in the main text. While the safeguards approach presented there is an important step, a more careful consideration of environmental costs is necessary to determine the true costs of alternative sediment management strat-egies.

The world's ecosystems are an asset that, if properly managed, yields a flow of vital services. Unfortunately, relative to other forms of capital, ecosystems are poorly understood, rarely monitored and many are undergoing rapid degradation and depletion. More often than not, the importance of ecosystem services is widely recognized and appreciated only upon their loss.

Worldwide, ecosystems are being protected or restored to control floods, filter water, enhance soil fertility, mitigate climatic extremes and provide for human enjoyment. These developments all involve putting a "price tag" on nature. Individuals and societies already assess the value of nature implicitly in their collective decision making, often considering ecosystem services as "free." Until recently, such an approach was generally acceptable, because generally speaking ecosystem capital was abundant and the impacts of economic activity were minimal. However, as ecosystem capital becomes increasingly scarce, it is critical to understand both how to value ecosystems and the limits of such valuations.

To establish sound policy, the "production functions" that describe how ecosystems generate ser- vices need to be characterized and the interactions among the functions quantified. To begin, the sources and consumers of ecosystem services must be catalogued. For any given location this would document service flows occurring locally, regionally and globally. The production functions would also reveal critical points and interdependencies in the supply of services and in the time frame over which services are amenable to repair. Yet these are currently poorly known and are likely to remain elusive. Eco-systems typically respond to perturbation in a non- linear fashion. Putting theory into practice will require locally based information.

There are three fundamental steps in decision making. The first step, identification of alternatives, is probably the most important and frequently the most underrated. In this decision making tree the RESCON Model provides the first step. The analysis of the model will provide a set of feasible alternatives for sediment management. The second step requires that all impacts be identified and measured for each alternative; everything from immediate needs for labor, capital and other inputs to long-term bio-physical and social impacts. Rarely does sufficient knowledge exist to make precise estimates, but it is important to try to quantify uncertainties and the risks of proceeding. This annex provides an overview of the impact parameters, the values of which should be considered in determining the environmental cost of each of the feasible alternatives generated by the RESCON Model. The third and final step, valuation, translates the consequences of maintaining the status quo and opting for each alternative into comparable units of impact on human wellbeing, now and in the future. The common measuring unit is typically monetary. There are drawbacks associated with most ways of inferring value and coupled with the functional lack of information on ecosystem services, valuation is especially difficult. Another key problem is the relative weight given to current issues versus future costs and benefits. In theory, any valuation process should allow for social and intergenerational equity.

This annex does not purport to solve the issues associated with the valuation of ecosystem services, nor does it try. Rather, valuation should be seen as a way of organizing information to help guide decision making, not a solution. As a result the annex provides a discussion of the factors that should be considered in the decision making process without proposing any weighting of factors or specific valuation process. These considerations in valuation can then be placed in a context within the conceptual decision making flow model described below. This suggested decision making process implicitly suggests that environmental costs be added to the costs of feasible sediment management strategies, in order to determine a true cost for sediment management.

It must be remembered that each application of this analysis will be unique, because the flow of ecosystem services is site-specific.

Description of the Decision making Process

Step 1: Run the RESCON Model. Output of the RESCON Model will provide feasible engineering alternatives for sediment management.
Go to Step 2

Step 2: Determine the environmental impacts (temporary and/or permanent loss of ecosystem services). This will require a site-specific analysis. This annex provides an overview of possible considerations.
Go to Step 3

Step 3: Determine if there is an applicable regulatory framework in which a decision will be made. In many developed countries there is a complex regulatory framework in which the project will be evaluated. In some countries there are no appropriate regulations. If a regulatory framework exists:
Go to Step 4
If no regulatory frame exists:
Go to Step 5

Decisions within Regulatory Framework

Step 4: The impact analyses will be evaluated within the framework and a decision will be made allowing the project to proceed with mitigation. Where impacts cannot be adequately mitigated the project will be prohibited from proceeding. This analysis should be conducted for each alternative, recognizing that the environmental impacts rather than the engineering feasibility or cost may be the primary determining factor.

- **4a** If various alternatives are acceptable then the cost of the mitigations should be determined and added to the cost of the sediment management alternatives to determine the economically preferred alternative.
- **4b** If no alternatives are permitted, the existing or proposed dam is not sustainable.

No Regulatory Framework Exists

Step 5: There is no regulatory framework that will determine the decision making.

The value of ecosystem services that will be permanently lost should be calculated and added to the value of interim loss of ecosystem services. The sum of these two factors will equal the environmental cost for each alternative and can be added to the sediment management cost to obtain total cost. Any ecosystem benefits that may exist should also be evaluated and added to the project benefits.

Step 6: If the total environmental cost is less than the economic benefit derived from the new project then the project should go ahead. If the total environmental cost is more than the economic benefit derived from the proposed project, then the project should not go ahead.

Step 5 Note. These are the most sensitive calculations. Weighting of factors, social and intergenerational equity and the difficulty in providing precise valuation of ecosystem services will be the most pronounced in Step 5, making this the most difficult calculation.

It must however be pointed out that, beyond scientific challenges, defensibility of any "calculation," and reaching stakeholder agreement on results, represents the real challenge.

Environmental Impacts to be Considered in a Valuation Procedure

The following is a brief discussion of the environmental impacts that should be considered when attempting to evaluate the environmental cost of any sediment management alternative. The list cannot be regarded as exhaustive, because the number of potential variables is enormous. It is also important to remember that all listed parameters may not apply to each dam, or even each sediment management alternative at a specific dam.

The environmental variables discussed here are in relation to sediment management only. They are not intended to provide a comprehensive evaluation of whether a new dam should be built, except to the extent that if sediment management cannot be cost effective because of the environmental cost, then implementation should be reconsidered.

In order to evaluate the benefits/costs of sediment management it is necessary to examine the overall impacts of dams and then evaluate how sediment management would yield positive or negative value to the system.

Geomorphology and Turbidity

Reservoirs act as a sediment trap, holding back sediments, especially gravel and cobbles. The river downstream of the dam, deprived of its sediment load, tends to erode the downstream channel and banks. This can result in the undermining of bridges and other riverbank structures. Within nine years of the impoundment of Hoover Dam Reservoir in the United States, the riverbed below the dam had been lowered by more than four meters. River deepening will also lower the groundwater table along the river, threatening native vegetation and requiring the irrigation of agricultural products where it had been previously unnecessary. The depletion of river gravel reduces habitat for many gravel spawning fish species and for invertebrates such as mollusks, insects and crustaceans.

The depletion of the sediment source caused by the impoundment of a reservoir can have effects many kilometers downstream. These effects include reduction of sediment sources to the river delta or estuary as it enters the sea, resulting in the gradual erosion of the delta. Deltas and estuaries are complex ecosystems that support many habitats (including salt marshes) and species and therefore they need to be protected.

However, the decommissioning of a dam or the implementation of a sediment management program which passes sediments downstream will not necessarily improve the geomorphology and ecosystems downstream; detailed studies by specialists will be required.

Hydrological Effects

Reservoirs change the flow pattern of rivers, by affecting their seasonal variations. The nature of the impacts depends on the size of the reservoir in comparison with the annual inflows, purpose and operation of the dam, among other things. River estuaries are particularly rich ecosystems, which depend on the volume and timing of nutrients and freshwater. It has been estimated that 80 percent of the world's fish catch comes from these environments. The alteration of flows reaching estuaries because of upstream consumptive water uses has been linked to the decline of sea fisheries in the Gulf of Mexico, the Black and Caspian Seas, California's San Francisco Bay, the eastern Mediterranean and others. Overall hydrological changes can alter all downstream riverine habitats. Detailed fisheries impact data are lacking for most dams, but where available the habitat alterations caused by dam building appear to have been severe. The reduction in freshwater flows to the mouth of the river can also result in saltwater intrusion, a problem in the Sacramento River Delta of California, United States.

Flood Patterns

The impounding of water by reservoirs attenuates flood peaks by reducing the peak flood discharge rate and delaying the timing of the flood peak. Riverine and floodplain ecosystems are closely adapted to a river's flooding cycle. The native plants and animals depend on its variation for reproduction, hatching, migration and other important lifecycle changes. Annual floods deposit nutrients on the land, flush out backwater channels and replenish wetlands. Floods are important in the maintenance of fish communities even in relatively simple the impoundment of a reservoir can have effects many kilometers downstream. These effects include reduction of sediment sources to the river delta or estuary systems. In the West Fork of the San Gabriel River system in southern California, United States, flooding removes riparian trees and opens the canopy in patches. This improves the habitat for an endemic sucker, which feeds on the epilithic diatoms that flourish under the open patches in the canopy. The canopy, however, keeps summer water temperatures down for a sympatric trout. The alterations in river hydrograph and the temperature of releases have significant effects on the fauna. Since the Waitaki River in New Zealand was dammed, the river has become excellent habitat for the exotic Chinook salmon, while the black stilt (bird) has become so endangered that fewer than 100 individuals remain, largely as a result of patterns of sandbar formation and stabilization. A similar pattern has been seen in the Colorado River of the southwestern United States where dam releases of cold clear water have produced an excellent non-native trophy trout fishery at the expense of the native big river fish of the Colorado River, all of which are now listed as endangered.

The floodplain itself is also affected. Studies on the floodplain of the Pongolo River in South Africa have shown a reduction in forest species after it was dammed. Forests along Kenya's Tana River appear to be slowly dying out because of the reduction in high floods due to a series of dams. The eucalyptus forests of the Murray floodplain in Australia depend on periodic flooding for germination, which has been curtailed by the water impoundment.

The Kainji Dam on the Niger River is reported to have adversely affected hundreds of thousands of people by reducing yam production and fisheries. Also, former wetlands that had been seasonally inundated no longer provided essential grazing for livestock at the end of the dry season or water for flood recession cultivation of rice and other crops.

Environmental considerations of flushing

Introduction

Sediment control in reservoirs is often associated with downstream sedimentation. In cases where downstream aquatic organisms depend on clean gravels for spawning, such deposition of fine sediments may significantly degrade downstream habitats for gravel spawners. The deleterious impacts of fine sediment deposition on spawning gravels and the resultant effects on hatching success, fry survival etc. have been most completely studied for salmonids. However, most of these studies provide only single factor analyses. Even when multiple factors such as dissolved oxygen, flow velocity through gravel, fine sediment size/quantity, etc. are studied, they are treated independently and predictive relationships are developed only for single factors. It is clear from the results of these studies however, that in-gravel incubation environments are complex systems, which are simultaneously affected by many factors. Fu-Chun Wu, 2000, attempted to integrate three quantitative relationships in order to predict embryo survival as a function of sediment deposition. His model integrates variations of substrate permeability with sediment deposition, apparent velocity with substrate permeability and embryo survival rate with apparent velocity. His analyses indicate that embryo survival is most sensitive to fine sediment-gravel size ratio. Wu then applies his model to analyze the timing of flushing flows. Wu's results were not tested experimentally nor field verified and they do not address factors known to be critical, such as dissolved oxygen, pH, temperature, interspecies variation and other temporal and spatial variables.

Flushing Flow Prescriptions

It is recommended that Wu's relationships between timing of the flushing flows and survival rates be used as a guideline for determining periodicity of flushing flows. Among Wu's assumptions is that seasonally high periods of runoff are frequently correlated with spawning times, so that spawning may be affected by sediment deposition as a result of the seasonally high runoff (releases of sediment from reservoirs may follow a similar pattern). Addition ally, it is suggested that one management option in a controlled stream is to allow sediment accumulation and then flush the sediments periodically. This concept can be extended to sediment management in reservoirs. Because almost any sediment management option that involves movement of reservoir sediments downstream will result in some deposition of fine sediments in downstream gravel, Wu's model can be used to determine the amount of flushing that will be necessary to achieve acceptable sediment releases. If this model is used, the stream impacts should be studied and the methodology adjusted to meet the specific conditions on the river in question. The next value to consider is the magnitude of the flushing flow; again data from individual rivers are best but general guidelines are available. Parker and Klingman (1982) suggest that fine sediments can be removed from the gravels when the flushing flows are sufficient to break up the armor layer. Such a method would be an alternative when there are sufficient gravels, but if sufficient gravels are not available, such a flushing flow could result in armoring of the stream with material too large for spawning and could scour any eggs/larvae currently in the substrate.

The above only provides initial guidelines that may require adjustment depending on the actual stream parameters and target species. In order to accurately determine the needs of a specific river, natural flows should be studied, but in the absence of actual stream data, the above guidelines can be applied, then modified as necessary based on collection of data documenting the results of the generalized flushing flow prescription.

General Applicability

The above recommendations are based on studies of salmonids. Salmonids are a widely distributed Boreal species. Their range has been significantly expanded due to introductions in both the northern and southern hemispheres. They frequently provide important commercial and/or recreational fisheries throughout their distribution. The recommended flow prescriptions should be generally applicable. Flushing flows are by definition, predetermined discharges for a specific duration designed to remove fine sediments from river gravels (Reiser et al, 1989). Therefore, the above generalizations should be of use as general guidelines whenever the purpose is to remove fines from potential spawning gravels (some tropical species are also gravel spawners, i.e., some cichlids), as long as the limitations of the guidelines are recognized and local measurements are collected to refine the initial generalizations.

One final consideration: periodic high discharges can also be used to enhance other riverine ecosystem functions, such as sand/gravel bar formation or overbank flooding. These should not be termed flushing flows and flow releases for these purposes may not follow the parameters of flushing flows described above.

Environmental Valuation

Some of the potential ecosystem costs are quantifiable, while others are not. Measurements of loss of productivity of floodplain agriculture, costs of fertilizer, reduction or increase in fisheries catch, etc. are readily quantifiable.

Biodiversity losses or losses of ecosystem integrity, on the other hand, are virtually impossible to quantify. The quantification of losses of subsistence activities such as artisanal fisheries is also difficult to quantify. Many economists simply account for the economic loss of the product while neglecting to account for the social impact that the loss of a particular way of life has on the affected community as a whole.

In order to go beyond the safeguards approach presented in Chapter 7, it is necessary to initially split valuations into two categories. First are cases that involve the permanent loss or reduction of an ecosystem service and second are situations where there is only an interim loss of ecosystem services. Valuation of cases that involve a permanent loss or reduction may be based on the cost of replacement of the lost services. Permanently lost services can sometimes be "replaced" by similar services. For example, at Morris Dam (San Gabriel River, California, USA), sluicing has been used to manage reservoir sedimentation but has caused the permanent destruction of downstream ecosystem services. As a result, the project was mitigated through the acquisition of similar habitat on another river. Because this was done in the United States, where there is a regulatory framework, the efficacy of the mitigation was evaluated within that framework and the project proponent had to demonstrate that the replacement habitat supplied the same ecosystem services as the one destroyed. Replacement which involves the purchase or donation of land is directly quantifiable. Restoration costs are also quantifiable, but they involve the cost of restoration along with the cost of the interim loss of services.

Valuations of interim service loss can use a direct valuation in cases such as a temporary reduction of fisheries catch by determining the percent of the service lost in year 1, translating that to quantity of fish lost (in weight) times a discount factor (3 percent commonly used in environmental calculations). This would then equal the discounted effective fisheries loss. The form of the recovery curve and the time to recovery must be determined. Then, for each year during the recovery period, the discounted effective fisheries loss could be calculated. The total interim loss is therefore the sum of the annual discounted effective fisheries losses. A very simple example is shown in the table below. In this example there is a 50 percent loss of fisheries catch due to sediment management, but the system recovers in a linear fashion in a period of four years. The baseline catch is assumed to be 100 tons.

The monetary value of 97.9 tons of fish represents an environmental cost of sediment management in this scenario. This scenario assumes natural recovery without restoration. This valuation procedure has been borrowed from habitat equivalency analysis, which is commonly used to value the cost of natural resource damages.

In the case of biodiversity loss or other non-quantifiable impacts, the valuation procedure would at the very least involve an enumeration of the impacts to be considered in the decision making process.

Table A.5: Example of using discounting techniques to quantify environmental losses

Year	*% Service Loss*	*Effective Fisheries Loss (in tons)*	*Discount Factor (3% discount rate)*	*Discounted Effective Fisheries Loss (tons)*
2001	*50*	*50*	*1*	*50*
2002	*33.3*	*33.3*	*0.97*	*32.3*
2003	*16.6*	*16.6*	*0.94*	*15.6*
2004	*0*	*0*	*0.91*	*0*
Total Discounted Effective Fisheries Loss				*97.9*

ANNEX 6

Water Pricing

Source:
Alessandro Palmieri, Farhed Shah George W. Annandale, Ariel Dinar (2003): Reservoir Conservation, Volume I: The RESCON Approach Economic and engineering evaluation of alternative strategies for managing sedimentation in storage reservoirs.

One of the inputs necessary for the RESCON analysis is the value of the water that is stored in the reservoir. While this parameter has great implications for optimal management of the reservoir, it is usually unavailable to the decision maker.

There exist several sources for calculation of the value of water in various uses, including Gibbons (1986), Young (1996 and 2003). However, quite extensive preparatory work is needed in order to estimate the value of water using the procedures suggested in these sources.

A range of water prices in various sectors and uses could also be used as a reference. Available sources include: Dinar and Subramanian (1997), Ahmad (2000), OECD (1998a), OECD (1998b), OECD (1999), Jones (2000) and Savedoff & Spiller (1999), Dinar (2000).

A compilation of observed prices from various countries and sectors is provided in the Table on next page. The prices are expressed in 1997 US$ values, so they should be easy to use and compare. It should be emphasized that the values in the Table do not necessarily represent the true worth of water but are based on water prices that have been observed in various countries. Therefore, appropriate care and caution should be exercised when making use of these numbers.

Table A.6: Ranges of water prices for various sectors and countries (1997 US$)

Country	*Agriculture*		*Domestic*		*Industry*	
	Fixed	*Variable*	*Fixed*	*Variable*	*Fixed*	*Variable*
	(per hectare per year or season)	*(per cubic meter)*	*(per household per year or month)*	*(per cubic meter)*	*(per plant per year or month)*	*(per cubic meter)*
Algeria	3.79–7.59	0.019–0.022		0.057–0.27		4.64
Australia	0.75–2.27	0.0195	9-162	0.23–0.54		7.82
Austria		0.36–0.98		0.85		
Belgium				2.06–2.47		
Botswana				0.28–1.48		
Brazil	3.5	0.0042–0.032		0.4		
Canada	6.62–36.65	0.0017–0.0019		0.34–1.36		0.17–1.52
Czech Republic				0.68		
Denmark		0.71		3.18		
Egypt				0.07–0.09		0.12–0.59
Finland				2.76		
France		0.11–0.39		0.36–2.58		0.36–2.16
Germany				1.69		1.022–3.704
Greece	92–210	0.021–0.082		1.14		
Hungary				0.82		
India	0.164–27.47		0.824	0.0095–0.082	5.49	0.136–0.290
Israel		0.16–0.26		0.36		0.26
Italy	20.98–78.16			0.14–0.82		
Japan	246			1.56		
Jordan		0.01–0.04		0.27–1.03		0.12–0.35
Lebanon			8.71			
Luxembourg				1.01		
Madagascar	6.25–11.25		0.075–0.25	0.392		
				0.325–1.25		
				0.9–1.75		
Mexico	33-60					0.08–0.35
Namibia	53.14	0.0038–0.028	1.54–4.28	0.22–0.45		
				0.33–1.38		
Netherlands				3.16		0.57–1.71
New Zealand	6.77–16.63		16–164	0.31–0.69		
Pakistan	1.49–5.80		0.25–1.63	0.06–0.10		0.38–0.97
Palestinian Authority (Gaza)				0.33		
Palestinian Authority (WB)				0.79–1.12		

Country	*Agriculture*		*Domestic*		*Industry*	
	Fixed	*Variable*	*Fixed*	*Variable*	*Fixed*	*Variable*
	(per hectare per year or season)	*(per cubic meter)*	*(per household per year or month)*	*(per cubic meter)*	*(per plant per year or month)*	*(per cubic meter)*
Poland						0.20–0.94
Portugal		0.0095–0.0193	4.46–1937	0.1526–0.5293	8.86–2,705	1.19
Saudi Arabia				0.04–1.07		
South Korea				0.27		
Spain	0.96–164.48	0.0001–0.028		0.0004–0.0046		0.0004–0.0046
Sudan	4.72–11.22		1.67–3.33	0.08–0.10	1.67–3.33	0.08–0.10
Switzerland		0.33–1.96		1.29		
Syria	50		3.21	0.11–0.53		0.71
Taiwan	23.30–213.64			0.25–0.42		
Tanzania		0.260–0.398		0.062–0.241		0.261–0.398
Tunisia		0.020–0.078		0.096–0.529		0.583
Turkey		12–80				
Uganda				0.38–0.59		0.72–1.35
United Kingdom			152–171	0.0095–0.0248		
United States		0.0124–0.0438				

Source: Dinar (2000)

The REServoir CONservation (RESCON) approach, initially published in 2003 by the World Bank, has proved a valuable tool for rapid assessment of reservoir sustainability and identification of technically feasible and economically optimal sediment management techniques. Since, understanding of reservoir sedimentation management strategies and the impact of climate change on the need for storage improved, prompting the World Bank to update the RESCON approach.

The revised RESCON 2 has been updated to the state of the art techniques in sediment management and has been set up on a user friendly graphical user interface. The model is now capable of performing rapid assessment of the technical feasibility and economic optimality of catchment management, deposits removal, sediment routing as well as a user specified sediment management strategy comprising up to five different sediment management techniques applied sequentially. The calculation of annual sedimentation is improved through incorporation of widely used methods for assessment of the reservoir trap efficiency, the allocation of sediment deposits among active and dead storage pools and the partitioning of sediment inflow to bedload and suspended load.

The economic appraisal has been complemented by the concept of a declining discount rate in order to account for the nature of reservoir storage as a renewable resource. In addition and upon request of the user, RESCON 2 is capable of reporting back the economic performance of a reservoir over its lifetime for a user specified implementation schedule.

The issue of climate change and its impact on reservoir sediment management is addressed through a climate stress test. The purpose of the analysis is the quantification of the vulnerability of the reservoir under climate change conditions. This allows the identification of the sediment management technique that increases the resilience and robustness of the infrastructure for the future climatic conditions.

The data input and the reading of the results of RESCON 2 analysis is performed through a Graphical User Interface which improves the user friendliness since it provides directly accessible help during model setup and presentation of the results in graphics. The results of the analysis are saved in spreadsheets which allow an uncomplicated post processing and incorporation in reports.

The present User Manual provides a detailed description of the theoretical background and a description of all parameters involved in the RESCON 2 analysis.

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