SEDIMENTATION OF SAND AND MUD IN RESERVOIRS IN RIVERS

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1 Introduction

Generally, reservoirs are built in rivers for water supply (irrigation), power generation, discharge regulation and flood control. The reservoir capacity can be divided in three portions: the dead storage volume (volume below the lowest outlet level, which cannot be removed), the active or live storage volume (volume between lowest outlet level and normal surface level) and the flood control storage volume (volume between normal level and maximum surface level).

Reservoir sedimentation is caused by the flow of water and sediment into the reservoir. Basically, all sediment (gravel, sand and mud) transported to a reservoir by a river is derived from erosion of the land surface. When the river flow enters a reservoir, its velocity and hence transport capacity are reduced and the sediment load is deposited in the reservoir (see **Figure 1.1**).
The amount of sediment deposited depends on the types of sediment in the river system, the shape of the reservoir, the detention storage time and the operating procedures. The principal sedimentation processes in reservoirs fall into three basic categories:

- deltaic deposition of primarily coarse (gravel and sand) materials (in entrance section of reservoir);
- deposition of fine sediments (silt and mud) from homogeneous flow;
- deposition of fine sediments (silt and mud) from stratified flow (turbidity current).

Often, more than 90% of the incoming sediment load is trapped and deposited in horizontal strata or thin bands across the bottom of the reservoir.
Worldwide around 40,000 large reservoirs suffer from sedimentation and it is estimated that between 0.5% and 1% of the total storage capacity is lost per year (**White, 2001**).

Reservoirs frequently develop density stratifications due to temperature, salinity and turbidity differences between different layers. These density stratifications are important for water and sediment circulation. Very important is the influence of the river inflow. The inflow of a current with a certain density into stagnant reservoir water of a slightly different density may proceed as a plume or jet like current. Driven by the density differences between the sediment-laden inflow and the clear water in the reservoir, the turbidity current plunges beneath the clear water and moves towards the dam as a submerged current. Sediments will settle out of the turbidity current and be deposited along the length of the reservoir as the current moves towards the dam. Under unfavourable conditions, such as inadequate bottom slope or insufficient flood duration, the turbidity current will dissipate before it reaches the dam.
The turbidity current can be supercritical ($(Fr_d=u_d/(\Delta\rho/\rho_d g h_d)^{0.5}>1$, with u_d= velocity of turbidity current, h_d= layer thickness of turbidity current, $\Delta\rho$= density difference, ρ_d= mixture density of lower turbidity layer) or subcritical ($Fr_d<1$), depending on the slope. The sediment in a turbidity current often is cohesive (flocculation, consolidation). Low-velocity turbidity currents are capable of carrying large amounts of fine sediment into the deeper parts of the reservoir.
Generally, three types of turbidity currents are distinguished: accelerating-erosive, decelerating-erosive and decelerating-depositive turbidity currents. In a depositing turbidity current the density difference will gradually diminish and finally disappear. The propagation of the turbidity current (generally along pre-existing channels) induces a reverse flow or circulation in the reservoir. The point where the river current and induced reverse flow meet is known as the plunge point (starting point of underflow). The head or nose of the turbidity current is a front to provide the potential energy to overcome inertia of reservoir water ahead of the current.
Finally, the removal of reservoir sediment by flushing is discussed.

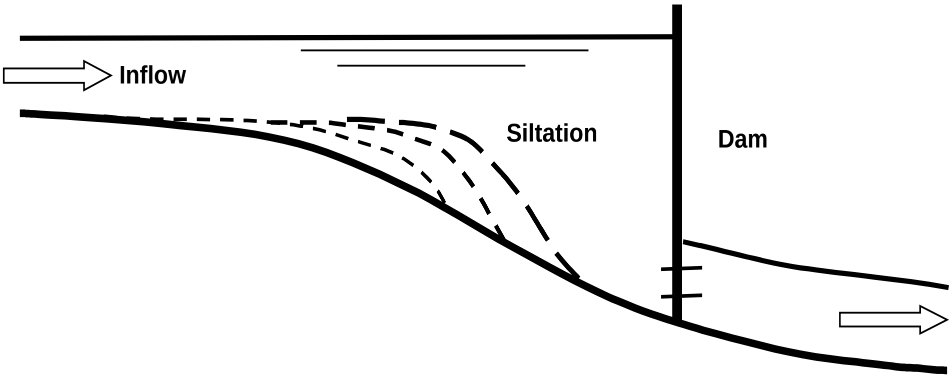

Figure 1.1 *Siltation in a reservoir*

Most reservoirs have a basically one-dimensional configuration with the length of the reservoir being much larger than the width and depth of the reservoir.

The behaviour of different reservoirs with respect to sedimentation can be expressed by plotting the ratio (V/V_s) of reservoir volume (V in m^3) and mean annual sediment inflow (V_s in m^3/year, including porosity) as function of the ratio (V/V_w) of reservoir volume (V in m^3) and mean annual water inflow rate (V_w in m^3/year).

V is defined as the storage volume below the horizontal line through the bed level at the upstream reservoir boundary (x=0 m, see Figure 2.3). Both ratios have the unit of time (years) and represent the time required for the reservoir to be filled up by the sediment input and the water input (assuming zero output from the reservoir).

Some values for well-known reservoirs are (**Di Silvio, 2001**) are:
High Aswan Reservoir in Egypt: V/V_s=1200 year and V/V_w=2 year,
Low Aswan Reservoir in Egypt: V/V_s= 60 year and V/V_w=0.07 year,
Tarbela Reservoir in Pakistan: V/V_s= 80 year and V/V_w=0.25 year,
Three Gorges Reservoir in China: V/V_s= 120 year and V/V_w=0.1 year,
Bhakra Reservoir in India: V/V_s= 300 year and V/V_w=0.6 year.

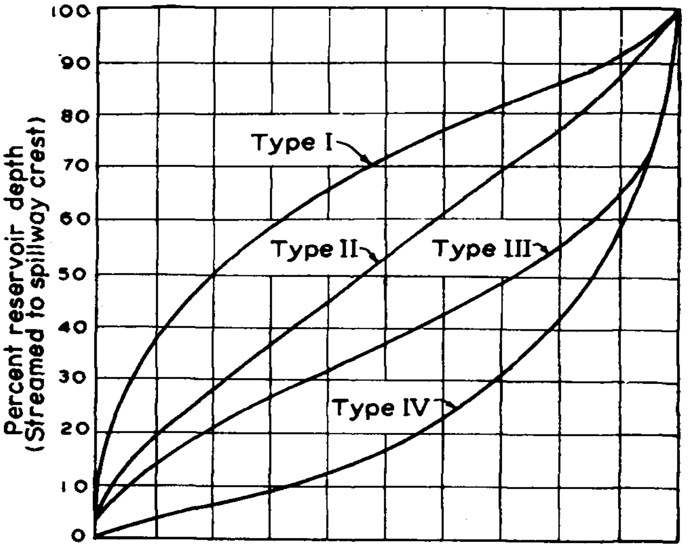

Figure 1.2 *Types of reservoir according to Borland and Miller (1960)*

Based on analysis of reservoir sedimentation data in the USA, **Borland and Miller (1960)** have distinguished four types of reservoirs. The data indicated that a definite relationship exists between the reservoir shape and the percentage of sediment deposited at various depths throughout the reservoir. The type of reservoir can be related to the reciprocal value (M) of the slope of the line obtained by plotting reservoir depth as ordinate and reservoir capacity as abscissa on log-log scale.

The four standard types are (see **Figure 1.2**):
- lake type I; M= 3.5-4.5; greater portion of the sediment is deposited in the upper part of the reservoir;
- flood plain-foot hill type II; M= 2.5-3.5;
- hill type III; M= 1.5-2.5;
- gorge type IV; M=1-1.5; greater portion of the sediment is deposited in the deeper part (dead storage zone) of the reservoir.

These types of standard curves were found to be valid for most reservoirs in India (**Murthy, 1977**).

The most important impacts due to reservoir sedimentation are:
- loss of storage volume;
- difficulties in flood protection (raising of bed);
- rising of ground-water table in backwater region;
- navigation (reduction of clearance under bridges in backwater region).

The loss of storage volume of the reservoir may cause severe problems as the primary function of most reservoirs is to store water for flood control, water supply, irrigation and power.

If the outlets are closed, the deposition of sediments in the reservoir will be maximum and the sediments will eventually accumulate against the outlets. To remove the sediments as much as possible, the outlets should be opened regularly when the water level is high to exert sufficient pressure on the sediments deposited in the outlet zone and to create a zone of concentrated erosion near the outlet (flushing zone, see **Figures 4.1** and **4.2**). To maintain the erosion process, the water level in the reservoir must be lowered. Flushing operations should be performed regurlarly to minimize the deposition of sediments near the outlets. It can also be tried to generate density or turbidity currents that carry the fine sediments to the deepest parts of the reservoir and through the outlets. Flushing operations are discussed in Section 4.

Appropriate measures for the release of sediment from the reservoir are required to deal with excessive sedimentation. Dams should be constructed with adequate bottom sluices for flushing of sediments. The hydraulic regime should be designed to route the inflowing sediment through or around the storage section of the reservoir to minimize deposition and to remobilize and flush out previously deposited sediments.

2 Sediment input and trapping efficiency

The basic sources of sediment supply into a river system are:
- sheet and gully erosion of land surface during heavy rainfall (surface runoff during floods): gullies are formed by concentrated surface runoff in soil;
- streambed erosion: erosion of the river bed and banks during flood events;
- mass movement: land slides, slumps, avalanches, creep, mud and debris flows along slopes;
- erosion around structures;
- dumping of sediment into river (related to mining activities).

The sediment load into a reservoir should be determined from sampling stations in the river just upstream of the reservoir and from the direct sediment input into the reservoir by mass movement due to mud slides and slumps (steep valley slopes). Long-term records should be used. Often, the suspended transport is different during the rising limb and the declining limb of the hydrograph. Sampling must be extensive during extreme flood events. If long-term records are missing, it is necessary to apply geomorphological methods based on map information, aerial photography, types of land use (surface cover) and estimated surface erosion values to quantify the total sediment yield in the catchment area.

Measures to reduce the sediment input into a reservoir are:

- replanting and reafforestation of eroded areas (soil conservation);
- crop rotation and regulation of grazing;
- terracing of relatively steep valley slopes;
- building of (removable) check dams, debris-retention basins and sand traps;
- bypassing of sediments (bypass channels);
- fire control.

Based on the mass balance for sediments, the sedimentation along a reservoir can be determined from the following equation:

$$\partial A_s/\partial t + (\rho_b(1-p))^{-1}\, \partial Q_s/\partial x = 0 \qquad (2.1)$$

with: $A_s = b\ a_s$ = sedimentation area of cross-section, b= width of cross-section, a_s= sedimentation thickness, t= time, p= porosity factor, ρ_b = dry bulk density of deposited sediment (kg/m^3), Q_s= sediment transport (in kg/s) at cross-section x, x= longitudinal coordinate.

The sediment transport at section x can be related to the upstream sediment transport by:

$$Q_s=(1-E)Q_{s,o} \qquad (2.2)$$

with: E= trapping efficiency at section x, $Q_{s,o}$= incoming sediment transport at x=0.

Based on Equations (2.1) and (2.2), the mass balance equation can be formulated as:

$$\partial A_s/\partial t - Q_{s,o}(\rho_b(1-p))^{-1}\, \partial E/\partial x = 0 \qquad (2.3)$$

Equation (2.3) can be solved numerically to determine the sedimentation along the length of the reservoir. The water level should be constant during each time step. The distribution of the sediment deposits along the cross-section can be assumed to be constant or proportional to the water depth of the cross-section. Erosion cannot be simulated using this approach.

Empirical methods for estimation of the trapping efficiency and hence the sedimentation rate in a reservoir have been presented by many researchers. Basically, the trapping efficiency depends on:

- water and sediment characteristics of the inflow;
- reservoir characteristics and operational procedures.

Churchill (1948) presented a trapping efficiency curve based on data from reservoirs in the USA.
The trapping efficiency (E_{res}) is defined as: $E_{res}=(Q_{s,o}-Q_{s,L})/Q_{s,o}$, with $Q_{s,o}$= incoming sediment transport (m^3/s or kg/s), $Q_{s.L}$= outgoing sediment transport leaving the reservoir or reservoir section (m^3/s or kg/s).

The sedimentation volume in the reservoir or reservoir section is defined as:

$$\Delta S= E_{res}\, Q_{s,o}\, \Delta t \qquad (2.4a)$$

with: E_{res}= trapping efficiency of reservoir (percentage of sediment trapped in reservoir or reservoir section), $Q_{s,o}$= incoming sediment transport (m^3/s or kg/s) and Δt= period considered (s). This may result in zero transport in a certain section of the reservoir if the trap efficiency is maximum (E_{res}=1), which may not be realistic for the transport of very fine sediments. As long as there is flow and turbulence, there will be a minimum transport of sediment. This latter transport can be defined as the equilibrium transport.

Taking the equilibrium transport into account, the sedimentation volume in the reservoir can be defined as:

$$\Delta S = E_{res}\,(Q_{s,o} - Q_{s,eq})\,\Delta t \qquad (2.4b)$$

with: E_{res}= trapping efficiency of reservoir (percentage of sediment trapped in reservoir or reservoir section), $Q_{s,o}$= incoming sediment transport (m^3/s or kg/s), $Q_{s,eq}$=equilibrium sediment transport at end of reservoir or reservoir section and Δt= period considered (s). The equilibrium transport can be estimated as: $Q_{s,eq}=(u/u_o)^3Q_{s,o}$, with u_o= mean flow velocity at upstream reservoir boundary (x=0 m), u =mean flow velocity at end of reservoir or reservoir section.

The curve of **Churchill** relates the percentage of incoming sediment and the sedimentation index (SI) of the reservoir. This latter parameter (sedimentation index, SI=V/(QU)) is the ratio of the reservoir capacity (V in cubic feet) and the product of daily-average inflow discharge (Q in cubic feet per second) and cross-section-averaged flow velocity in the reservoir (U=Q/A=QL/V with A= area of cross-section in square feet, L= length of reservoir in feet), V= storage volume (in cubic feet) defined as the volume below the horizontal line through the bed level at the upstream reservoir boundary (x=0 m, see **Figure 2.3**). Thus: trapping efficiency= Function of V/(Q U)= Function of $V^2/(Q^2\,L)$. The sedimentation index (SI) in the feet-system (in s^2/ft) is approximately 3 times smaller than that in the metre-system (in s^2/m). The trapping efficiency curve (with SI in s^2/m) of **Churchill** is shown in **Figure 2.1**. The trapping efficiency is independent of sediment properties (size, fall velocity). The curve of Churchill can be represented (with inaccuracy of about 5%) by:

$$E_{res}= [-20 + 0.95SI^{0.63}]/[7500+SI^{0.63}] \quad \text{for } SI> 6\ 10^4 \qquad (2.5a)$$

or (with inaccuracy of 10%) by:

$$E_{res}= -1.1+ 0.25\log(SI) \quad \text{with } E_{res}= 0 \text{ for } SI\leq 2.6\ 10^4 \text{ and } E_{res}= 1 \text{ for } SI\geq 2.5\ 10^8 \qquad (2.5b)$$

with: $SI= V^2/(Q^2L)$ in s^2/m. Eqs. (2.5a and 2.5b) are also shown in **Figure 2.1**.

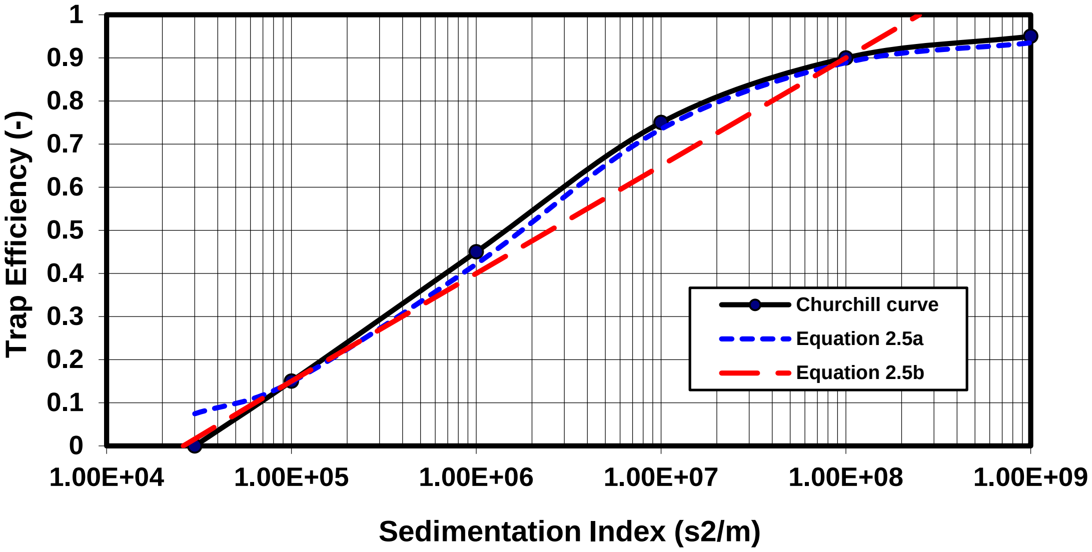

Figure 2.1 *Trap efficiency of reservoir sedimentation according to Churchill (1948)*

Brune (1953) also presented an empirical relationship based on data from reservoirs in the USA. His curve relates the trap efficiency and the ratio of reservoir capacity (V) and the mean annual water inflow (V_w), see **Figure 2.2**. Thus: trapping efficiency= Function of V/V_w. The ratio (V/V_w) is known as the capacity-inflow ratio.

The trapping efficiency is independent of sediment properties (size, fall velocity). The curve of Brune can be represented (with inaccuracy of about 10%) by:

$$E_{res}= [0.000085 + (V/V_w)^{1.1}]/[0.0085 + (V/V_w)^{1.1}] \quad \text{for } V/V_w>0.003 \tag{2.6}$$

Borland (1971) proposed:

$$E_{res}= 1 - \exp[-A_b(L/h)(w_s/u)] \tag{2.7}$$

with: L=length scale (m), w_s= settling velocity of sediment, h= mean flow depth of reservoir (or section of reservoir), u= mean flow velocity in reservoir, A_b=1.055=coefficient.

Siyam et al. (2001) found that the **Brune** curve can be very well represented by $E_{res}=e^{-\beta(Vw/V)}$, with: V_w= average annual inflow volume, V= storage volume of reservoir below line through bed level at upstream boundary (x=0 m, see **Figure 2.3**), β=empirical coefficient=0.0079. The β-coefficient is not a universal coefficient, but it depends on settling velocity of the sediments, reservoir shape, reservoir area and reservoir operation. Siyam et al. suggest to determine the annual sedimentation volume by summation of all monthly contributions to better include the reservoir operation procedures.

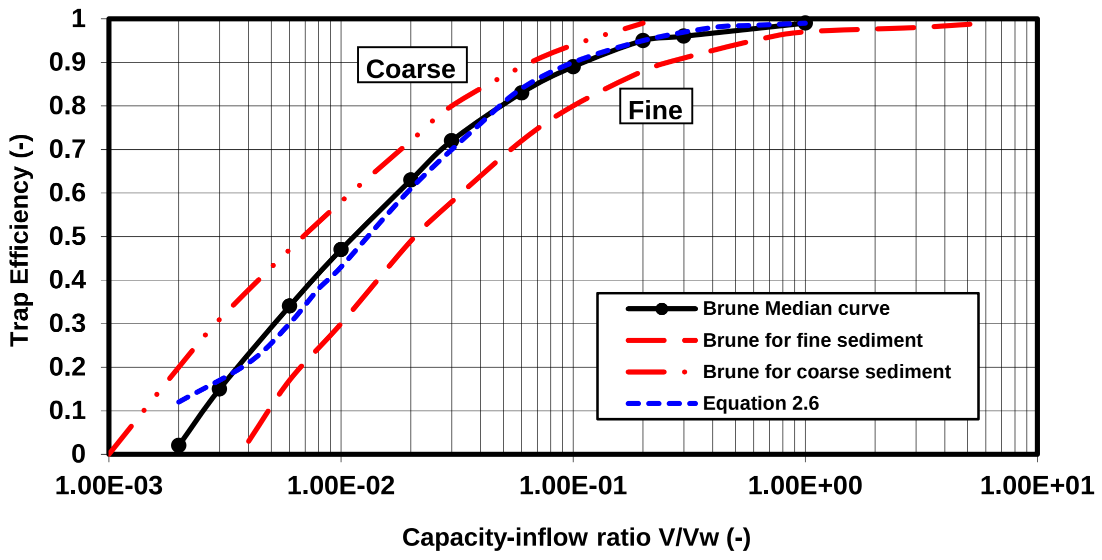

Figure 2.2 *Trap efficiency of reservoir sedimentation according to Brune (1953)*

The trap efficiency can also be estimated by using the deposition formulae of Eysink and Vermaas (1981) and that of Van Rijn.

The trap efficiency according to the formula of **Eysink and Vermaas (1981)** is:

$$E_{res}= 1 - \exp[-A_{ev}L/h] \tag{2.8a}$$

with: L= length of reservoir, h= mean flow depth of reservoir (or section of reservoir), (see **Figure 2.3**), $A_{ev}=\alpha_s(w_s/u_*)(1+2w_s/u_*)$= deposition parameter, α_s= 0.06= coefficient (in range of 0.04 to 0.08; assuming k_s/h= 0.003, C= 65 $m^{0.5}/s$), w_s= settling velocity of sediment, u_*= mean bed-shear velocity in reservoir.

The trap efficiency of **Van Rijn** is:

$$E_{res}= 1 - \exp[-A_{vr}L(h-h_o)/h^2] \tag{2.8b}$$

with: L= length of reservoir, h_o= flow depth at upstream reservoir boundary (x=0 m), h= mean flow depth of reservoir (or section of reservoir), (see Figure 2.3), $A_{vr}= \alpha_s(w_s/u_*)(1+2w_s/u_*)$= deposition parameter, α_s= 0.25= coefficient (in range of 0.2 to 0.3), w_s= settling velocity of sediment, u_*=mean bed-shear velocity in reservoir.

If necessary, the incoming sediment load can be divided into a series of representative sediment fractions and the sedimentation can be computed for each fraction. The total sedimentation can be obtained by summation over the fractions: $\Delta S = \Delta t \sum(E_{res,i}\, Q_{s,o,i})$.
Using one single fraction with w_s= 0.1 mm/s (sediment of about 10 μm), u_*= 1 mm/s, u= 50 mm/s, the following trap efficiency values according to Eysink-Vermaas and Borland are obtained:

Eysink-Vermaas (A=0.007; α_s=0.06)	**Borland (w_s/u=0.002)**
E_{res}=0.07 for L/h=10,	E_{res}=0.02 for L/h=10,
E_{res}=0.50 for L/h=100,	E_{res}=0.19 for L/h=100,
E_{res}=0.88 for L/h=300,	E_{res}=0.47 for L/h=300,
E_{res}=0.97 for L/h=500,	E_{res}=0.65 for L/h=500,
E_{res}=0.999 for L/h=1000,	E_{res}=0.88 for L/h=1000.

The trap efficiency of large-scale reservoirs (L/h>500) will be about 90% to 100%; thus nearly all sediments entering the reservoir will be trapped. The coarse fractions will be deposited in the upper part of the reservoir (backwater region), while the finer sediments will be deposited in the lower part (region with horizontal water surface). The proportion of sediment passing through the reservoir will depend primarily on the average flow velocity in the reservoir and the settling velocity of the sediment. In small-scale reservoirs the fine sediments may remain in suspension long enough to pass through the reservoir.

The length scale of the settling process is: $L_s = h\, u/w_s$ with: h= mean depth, u = mean velocity and w_s= settling velocity. A particle at the surface of the reservoir will settle after L_s (assuming no upward mixing).
Large-scale reservoirs should be divided into a series of compartments to estimate the sedimentation thickness along the reservoir. The trap efficiency formulae can be applied from compartment to compartment ($E_{res,i}$).

For example, if a reservoir is schematized into three compartments (see Figure 2.3) with L_1, b_1, h_1; L_2, b_2, h_2 and L_3, b_3, h_3, the sedimentation in each compartment and the total sedimentation can be expressed as (using Eq. 2.4a):

$$\Delta S_1 = E_1\, Q_{s,o}\, \Delta t$$
$$\Delta S_2 = E_2\, Q_{s,1} = E_2\, (1-E_1)\, Q_{s,o}\, \Delta t$$
$$\Delta S_3 = E_3\, Q_{s,2} = E_3\, (1-E_2)(1-E_1)\, Q_{s,o}\, \Delta t$$

The total sedimentation is: $\Delta S = \Delta S_1 + \Delta S_2 + \Delta S_3 = [E_1 + E_2(1-E_1) + E_3(1-E_2)(1-E_1)]\, Q_{s,o}\, \Delta t$.
A similar expression can be derived using Equation (2.4b).
This approach can be expanded to more compartments (if necessary).

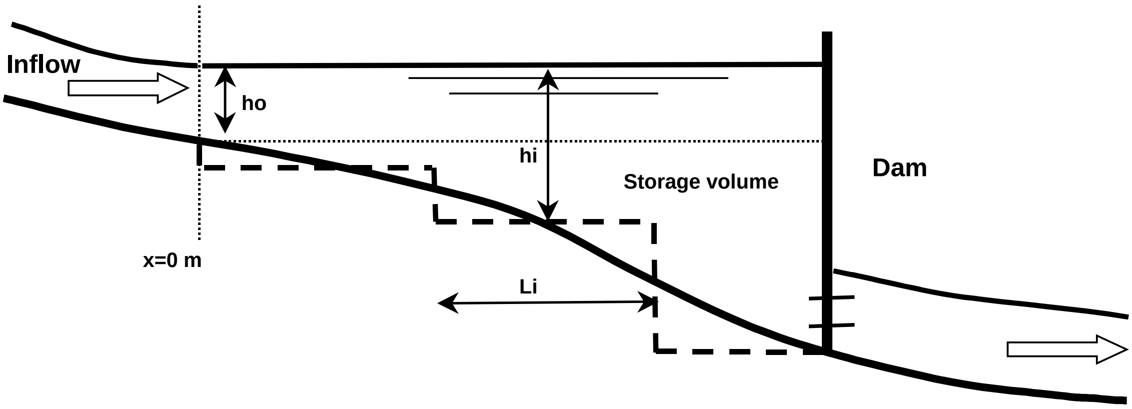

Figure 2.3 *Schematization of reservoir into compartments (storage volume is volume below line through bed level at x=0 m)*

Example Case

A reservoir has the following dimensions: L= 25000 m, depth below bed at x=0 m from 0 to 40 m (mean depth $h\text{-}h_o$=20 m), width from 100 to 500 m (mean width= 300 m), yielding a reservoir storage volume of $V=25000\text{x}20\text{x}300=1.5\ 10^8\ m^3$. The river just upstream of the reservoir (x=0 m) has a depth h_o= 5 m and width= 100 m.
The discharge is Q= 500 m^3/s. The settling velocity of the sediment is 0.1 mm/s. The Chézy-roughness in the reservoir is assumed to be C=65 $m^{0.5}/s$.
What are the trap efficiency values?

Trap efficiency according to Churchill: $V=1.5\ 10^8\ m^3$, $SI=V^2/(Q^2L)=3.6\ 10^6\ s^2/m$, yielding E=0.55
Trap efficiency according to Brune: $V=1.5\ 10^8\ m^3$, $V_w=365\text{x}24\text{x}3600\text{x}500=1.57\ 10^{10}\ m^3$, yielding E=0.45
Trap efficiency according to Borland: h_{mean}=20 m, $u_{mean}=500/(300\text{x}20)=0.0833$ m/s, yielding E=0.80
Trap efficiency according to Eysink-Vermaas: $u_*=(g^{0.5}\ u_{mean}/C)=0.004$ m/s, A=0.0016, yielding E=0.87
Trap efficiency according to Van Rijn: $u_*=0.004$ m/s, A=0.0066, $(h\text{-}h_o)/h=20/25$ yielding E=0.99

The settling length of a particle at the surface is roughly: $L_s=h\ u/w_s \cong 17000$ m (assuming no upward mixing).

Sedimentation model and example computation

An EXCEL programme (**SED-RES**) is available to compute the sedimentation in a reservoir for given sediment transport and sediment characteristics at the upstream reservoir boundary (x=0 m).

Three sediment fractions are considered:
- clay with settling velocity $w_{s,clay}$=0.0001 m/s (input value),
- silt with settling velocity $w_{s,silt}$=0.001 m/s (input value),
- sand with settling velocity $w_{s,sand}$=0.01 m/s (input value).

The reservoir is schematized into five sections (or compartments) A, B, C, D and E, each with length L, width W and depth $d_o=h\text{-}h_o$=depth below line through bed level at x=0 m, h=flow depth, h_o=flow depth at x=0 m.
The total storage volume is : $V=\sum(L_iW_i\ (h_i\text{-}h_o))$.

The upstream transport rates are defined as:
- $Q_{s,clay}=c_{clay}\ Q_o$,
- $Q_{s,silt}=c_{silt}\ Q_o$,
- $Q_{s,sand}=c_{sand}\ Q_o$,

with: Q_o= flow discharge (input value in m^3/s), c= depth-mean concentration (input values in kg/m^3).

The sedimentation (ΔS_i) in each Section i is computed as:
- $\Delta S_{i,clay}=E_{i,clay}\,(Q_{s,i,in,clay}\text{-}Q_{s,i,eq,clay})\ \Delta t$,
- $\Delta S_{i,silt}=E_{i,silt}\,(Q_{s,i,in,silt}\text{-}Q_{s,i,eq,silt})\ \Delta t$,
- $\Delta S_{i,sand}=E_{i,sand}\,(Q_{s,i,in,sand}\text{-}Q_{s,i,eq,sand})\ \Delta t$,

with: $Q_{s,i,in}$=sediment transport at upstream boundary of Section i, $Q_{s,i,eq}=(u_i/u_o)^3Q_{s,o}$=equilibrium transport in Section i, E_i=trap efficiency in Section i according to the methods of **Van Rijn** (Eq. 2.8b) , **Eysink-Vermaas** (Eq. 2.8a) and **Borland** (Eq. 2.7).
These methods have been implemented, because the type of sediment is explicitly represented by the settling velocity. The equilibrium transport rates can be included or excluded by a correction factor (1or 0).

The total sedimentation mass in Section i is: $\Delta S_{i,tot}=\Delta S_{i,clay}+\Delta S_{i,silt}+\Delta S_{i,sand}$.

The total sedimentation volume in Section i is: $\Delta S_{i,tot,\ volume}=\Delta S_{i,tot}/\rho_{i,bulk}$.

The bulk density (ton/m^3) in Section i is represented by:
- constant input value (in range of 0.4 to 1.5 ton/m^3); or by
- formula; $\rho_{i,bulk}= (\Delta S_{i,clay}/\Delta S_{i,tot})(0.415+0.43x0.255\gamma) + (\Delta S_{i,silt}/\Delta S_{i,tot})(1.12+0.43x0.09\gamma) + (\Delta S_{i,sand}/\Delta S_{i,tot})(1.55)$, with: $\gamma=[\{(T/(T-1))\ln(T)\}-1]$=consolidation factor (T in years) and 'always submerged values' from **Table 3.1**.

The deposition layer thickness in Section i is: $\Delta h_i=\Delta S_{i,tot, volume}/(L_i W_i)$.

The new flow depth in Section i at time t+Δt is: $h_{i,t+\Delta t}=h_{i,t}-\Delta h_{i,t}$; the maximum sedimentation thickness can be somewhat larger than the maximum storage thickness due to sedimentation in last time period just before the maximum sedimentation volume is reached; time periods should be smaller than about 6 months to minimize this effect.

The sediment transport rates at the upstream boundary of Section i+1 at time t are:
- $Q_{s,i+1,clay} =Q_{s,i,clay} -E_{i,clay} (Q_{s,i,clay}-Q_{s,i,clay,eq})$,
- $Q_{s,i+1,silt} =Q_{s,i,silt} -E_{i,silt} (Q_{s,i,silt}-Q_{s,i,silt,eq})$,
- $Q_{s,i+1,sand} =Q_{s,i,sand} -E_{i,sand} (Q_{s,i,sand}-Q_{s,i,sand,eq})$.

The **SED-RES** model has been applied to the sedimentation of the **Kindaruma reservoir** in Kenya in Africa (**HR Wallingford, 1983**). This reservoir in the Tana River was opened in 1968. In 1974 a new reservoir was opened just upstream of the Kindaruma reservoir, thereby reducing the sediment input of the Kindaruma reservoir after 1974 to almost zero. Measured sedimentation values are available for the period of 1968 to 1974 based on bottom sounding surveys. The Tana River is the largest river in Kenya and has an annual mean discharge of about 100 m^3/s in the period 1968 to 1974. The width of the river just upstream of the reservoir is about 70 m. The mean flow depth is assumed to be about h_o=3 m. The reservoir is schematized into 5 sections (see **Table 2.1**). Measured sedimentation values are also given in **Table 2.1**. The initial storage volume is about 12.2 10^6 m^3 in 1968. As measured sediment concentrations upstream of the reservoir are not available, the clay, silt and sand concentrations have been estimated to give an overall sedimentation volume of the right order of magnitude (about 6.5 10^6 m^3 in six years), resulting in c_{clay}=0.175 kg/m^3, c_{silt}=0.1 kg/m^3 and c_{sand}=0.025 kg/m^3. The clay fraction is assumed to be about twice as large as the silt concentration. The input concentrations have been kept constant in all computations. The Chézy-coefficient used to compute the bed-shear velocity ($u_*=u\ g^{0.5}/C$) in each Section of the reservoir is assumed to be 70 m$^{0.5}$/s.

Section	**Length L (m)**	**Width W (m)**	**Initial depth d=h-h$_o$ (m)**	**Initial storage volume V (m^3)**	**Measured sedimentation volume after 6 years (m^3)**	**Measured layer thickness after 6 years (m)**
A	1050	170	8.2	1.46 10^6	1.2 10^6	6.8
B	950	300	8.5	2.42 10^6	1.9 10^6	6.8
C	550	415	4.5	1.03 10^6	0.5 10^6	2.2
D	1350	245	10	3.3.1 10^6	1.4 10^6	4.2
E	1000	340	11.7	3.98 10^6	1.5 10^6	4.4
Total	4900			12.2 10^6	6.5 10^6	

Table 2.1 *Characteristics of Kindaruma reservoir in Kenya, Africa*

The sedimentation results based on the three trap efficiency methods used (A_{vr}=0.25, A_{ev}=0.06, A_b=1.055; bulk density according to formula) are given in **Table 2.2**. These results show that the three methods used give similar sedimentation volumes in the range of 5.4 to 6.6 10^6 m^3 in 6 years. The overall trap efficiency values (defined as total sedimentation volume/total sediment influx) are respectively 100%, 98% and 86% for the methods of Van Rijn, Eysink-Vermaas and Borland. According to the method of Van Rijn, the storage volumes of Section A, B and C are completely filled up with sediments. According to both other methods, only Section A is filled up with sediments. Including the equilibrium transport rates in each section, the sedimentation results are marginally smaller (<1%; not shown). The influence of the bulk density on the sedimentation results is shown in **Table 2.3**. A constant bulk density of 0.8 ±0.2 t/m^3 results in a variation of about 25% in the sedimentation volumes. A variable bulk density based on the percentages clay, silt and sand (including consolidation factor) results in a slightly smaller sedimentation volume (5%; see **Table 2.3**) than based on a constant bulk density of 0.8 t/m^3.

Section	**Sed. volume (m^3)**				**Sed. layer thickness (m)**			
	Van Rijn A_{vr}=0.25	**Eysink-Vermaas** A_{ev}=0.06	**Borland** A_b=1.055	**Measured after 6 yrs**	**Van Rijn** A_{vr}=0.25	**Eysink-Vermaas** A_{ev}=0.06	**Borland** A_b=1.055	**Measured after 6 yrs**
A	1.49 10^6	1.48 10^6	1.61 10^6	1.2 10^6	8.36	8.31	9.01	6.8
B	2.49 10^6	2.16 10^6	1.60 10^6	1.9 10^6	8.73	7.59	5.60	6.8
C	1.10 10^6	0.91 10^6	0.77 10^6	0.5 10^6	4.80	3.98	3.35	2.2
D	1.22 10^6	0.89 10^6	0.83 10^6	1.4 10^6	3.67	2.69	2.51	4.2
E	0.28 10^6	0.58 10^6	0.60 10^6	1.5 10^6	0.82	1.71	1.77	4.4
Total	6.58 10^6	6.02 10^6	5.40 10^6	6.5 10^6				

Table 2.2 *Computed and measured sedimentation volume and layer thickness for Kindaruma reservoir in Kenya, Africa (Chézy coefficient= 70 m$^{0.5}$/s, bulk density according to formula)*

Section	**Sed. volume (m^3)**				**Sed. layer thickness (m)**			
	ρ_b=0.8 (t/m^3)	**ρ_b=0.6 (t/m^3)**	**ρ_b=1.0 (t/m^3)**	**ρ_b= variable (t/m^3)**	**ρ_b=0.8 (t/m^3)**	**ρ_b=0.6 (t/m^3)**	**ρ_b=1.0 (t/m^3)**	**ρ_b= variable (t/m^3)**
A	1.56 10^6	1.59 10^6	1.54 10^6	1.49 10^6	8.76	8.91	8.65	8.36
B	2.60 10^6	2.68 10^6	2.55 10^6	2.49 10^6	9.12	9.39	8.95	8.73
C	1.20 10^6	1.15 10^6	0.87 10^6	1.10 10^6	5.26	5.04	3.83	4.80
D	1.35 10^6	3.18 10^6	0.50 10^6	1.21 10^6	4.07	9.63	1.52	3.66
E	0.24 10^6	0.61 10^6	0.11 10^6	0.28 10^6	0.71	1.80	0.32	0.82
Total	6.95 10^6	9.21 10^6	5.57 10^6	6.57 10^6				

Table 2.3 *Influence of bulk density on computed sedimentation volume and layer thickness for Kindaruma reservoir in Kenya, Africa (Method of Van Rijn; Chézy coefficient= 70 m$^{0.5}$/s, A_{vr}=0.25)*

The sensitivity of the results for different values of the A_{vr}-coefficient (Van Rijn method) was studied by using a value of A_{vr}=0.4 and A_{vr}=0.1 (and constant bulk density of 0.8 t/m^3). Using these values, rather small variations of the total sedimentation volume are obtained (within 5%). A value of A_{vr}=0.1 results in less sedimentation in all Sections. A value of A_{vr}=0.4 results in more sedimentation in all Sections except in Section E.

A Chézy-coefficient of 100 m$^{0.5}$/s (smaller u_* and hence less turbulence production) results in slightly more sedimentation (1%), whereas a Chézy-coefficient of 50 m$^{0.5}$/s (larger u_* and hence more turbulence production) yields slightly less sedimentation (2%).

A reduction of the settling velocities (factor 2) results in slightly less sedimentation (about 5%).

A 20%-reduction of the upstream sediment discharge results in a 20%-reduction of the sedimentation volume. Similarly, a 20%-increase of the upstream sediment discharge results in a 20%-increase of the sedimentation volume.

3 Bulk density of deposited sediment

The bulk density (unit weight of dry sediment material in kg/m^3) of the deposits will vary with the proportions of sand (>0.05 mm), silt (0.01 to 0.05 mm) and clay materials (<0.01 mm), the type of reservoir operation (exposed or submerged sediment deposits) and the consolidation period. The variation range is about 300 to 1600 kg/m^3. The lower densities generally occur in the vicinity of the dam under submerged conditions, while the higher densities generally occur in the upstream part of the reservoir and exposed regions after drawdown of the reservoir. Based on data from reservoirs in the USA, **Lara and Pemberton (1963)** derived an expression for the initial (at t=0) bulk density:

$$\rho_{bulk} = p_{clay}\,\rho_{clay} + p_{silt}\,\rho_{silt} + p_{sand}\,\rho_{sand} \tag{3.1}$$

with: p= percentages of clay, silt and sand in sediment deposits, the values of ρ_{clay}, ρ_{silt}, and ρ_{sand} are given in **Table 3.1**.

Murthy (1977) presents many data of bulk density values from reservoirs (mostly submerged sediments in reservoirs with moderate drawdown) in India. Based on a total of 380 samples (taken by a corer sampler):

$$\rho_{clay,\,initial} = 480\ kg/m^3,\ \rho_{silt,\,initial} = 1040\ kg/m^3,\ \rho_{sand,initial} = 1470\ kg/m^3.$$

The bulk density increases with time due to compaction. **Lane and Koelzer (1943)** proposed an expression, which gives the bulk density of the first year's deposition after T years of compaction due to later deposits (on top of the first year's deposit):

$$\rho_{bulk} = \rho_{initial} + K\log(T) \tag{3.2}$$

with: $\rho_{initial}$= initial bulk density (see **Table 3.1**), K= coefficient (see **Table 3.1**), T= time (years).

Miller (1953) developed an expression representing the average density of the total deposited sediment package in the reservoir from one to T years:

$$\rho_{bulk} = \rho_{initial} + 0.43K\,[\{(T/(T-1))\ln(T)\}-1] \tag{3.3}$$

The value according to Eq. (3.3) is always smaller than that according to Eq. (3.2).

Reservoir type	**Initial (t=0)**			**Compacted after time t**		
	ρ_{clay} **(kg/m^3)**	ρ_{silt} **(kg/m^3)**	ρ_{sand} **(kg/m^3)**	$\rho_{clay,initial}$; K **(kg/m^3)**	$\rho_{silt,initial}$; K **(kg/m^3)**	$\rho_{sand,initial}$; K **(kg/m^3)**
Always submerged	415	1120	1550	480 K=255	1040 K=90	1550 K=0
Normally moderate to considerable drawdown	560	1140	1550	735 K=170	1185 K=45	1550 K=0
Normally empty	640	1170	1550	960 K=100	1265 K=15	1550 K=0
River bed sediment	960	1170	1550	1250 K=0	1310 K=0	1550 K=0

Table 3.1 *Characteristic values of bulk density (initial and after compaction)*

Example Case
A bed sample from a reservoir (always submerged) contains 20% sand, 40% silt and 40% clay.
What are the bulk density values?

The initial bulk density (see Table 3.1)= 0.2x(1550) + 0.4x(1120) + 0.4x(415)= 310+450+165= 925 kg/m^3.

The bulk density of this sample after 100 years =0.2x(1550) + 0.4x(1040+90x2) + 0.4x(480+255x2) =310+490+395= 1195 kg/m^3 (see Table 3.1; log100=2).

The average bulk density of all deposits (same composition) after 100 years=0.2x(1550) + 0.4x(1040+0.43x90x3.65) + 0.4x(480+0.43x255x3.65)= 310+473+352=1135 kg/m^3
(based on Eq. 3.3 and coefficients of Table 3.1).

4 Sediment removal

Adequate reservoir management is required to reduce the sedimentation by means of various operational procedures. Sediment removal management is often in conflict with short-term water-use management. Most effective is to reduce the inflow of sediment into the reservoir (by preventing soil erosion and landslides, etc). A review of sediment removal methods from reservoirs is presented by **White (2001)**, **Brandt (2000)** and **Atkinson (1996)**. **Fan and Morris (1992)** have reviewed the experiences on the control of sedimentation in silt-laden rivers and reservoirs in China.
The following methods can be operated to remove sediments from reservoirs:

- **sluicing of sediment**; routing of sediment through the reservoir during flood events (with high concentrations); water levels in the reservoir should be kept low (drawdown of water levels by opening of multiple and multi-level bottom sluices in dam); during rising water level of flood event, the outflow of sediment from the reservoir is always smaller than the inflow of sediment into the reservoir; during falling water level, the outflow of sediment is larger than the inflow of sediment due to erosion of bed material from the reservoir; only a small amount of runoff can be stored in the reservoir during the falling limb of the flood event (relatively clear water); large multi-level outlet works are required over the width of the dam; V/V_w should be relatively small (<0.2);
  favourable conditions are:
  - narrow and short reservoir configuration;
  - drawdown level below half dam height;
  - river flow larger than two times mean annual flow discharge (flow hydrograph should be predictable);
  - many large low-level outlets;
  - sediment inflow should be mainly suspended sediments;
  - experienced operators for correct timing of procedures;
- **venting of sediment**; routing of sediment through the reservoir in the form of a density current (movement of fluid-sediment mixture by gravity under another mixture of lower density) near the bed without drawdown of the water level in the reservoir; V/V_w should be larger than 0.2; the ratio of sediment outflow and sediment inflow (venting efficiency) should be as large as possible; values upto 0.5 have been observed in China (**Fan and Morris, 1992**);
  favourable conditions are:
  - narrow reservoir and steep bed slopes; presence of one main channel;
  - large sediment inflow and large transport capacity;
  - long duration of flood events (larger than travel time of density current through reservoir);
  - many low-level outlets; correct timing of opening and closing procedures;
- **emptying and flushing of sediment** (V/V_w<0.2); removal of previously deposited sediments; two types of operational methods are applied (see **Figures 4.1** and **4.2**):
  - under pressure: sudden release of water and sediment through low-level outlets with high water level in reservoir (no drawdown); only a relatively small flushing cone will be obtained (Figure 4.1);
  - free flow: erosion of sediment from bed in an almost empty reservoir (low water level in reservoir) by the inflowing water (Figure 4.2); when the original bottom gradient is approximately re-established, the operation should be stopped as the transport capacity will be greatly reduced and almost clear water will be flushed out; generally only sediment is removed from the old river channel (flushing channel) and the banks on both sides of the main channel are not eroded; additional measures are often required for flushing of banks; bed erosion from the upper part of the reservoir is generally small; flushing is efficient if

both retrogressive erosion of fine sediments moving upstream the channel and progressive erosion of coarse materials moving downstream can be established;
favourable conditions are (see also ***Sloff, 1991****)*:
- river inflow discharge should be larger than three times the mean annual inflow discharge;
- narrow reservoir with steep bed slopes;
- many low-level outlets (water levels should as low as possible);
- regular operation (each year) to prevent consolidation of bed materials and negative downstream effects;
- start at beginning of flood events;

- **dredging of sediment** for small-scale reservoirs in situations with frequent shortage of water (V/V_w>0.2 and V/V_s<100); sediment disposal usually is performed by siphoning through pipelines over the dam.

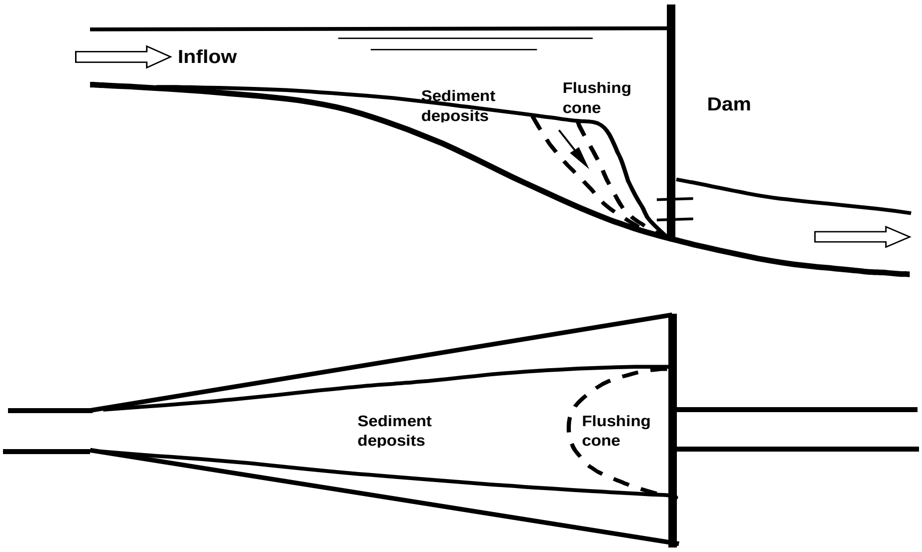

Figure 4.1 *Flushing without drawdown of water surface*

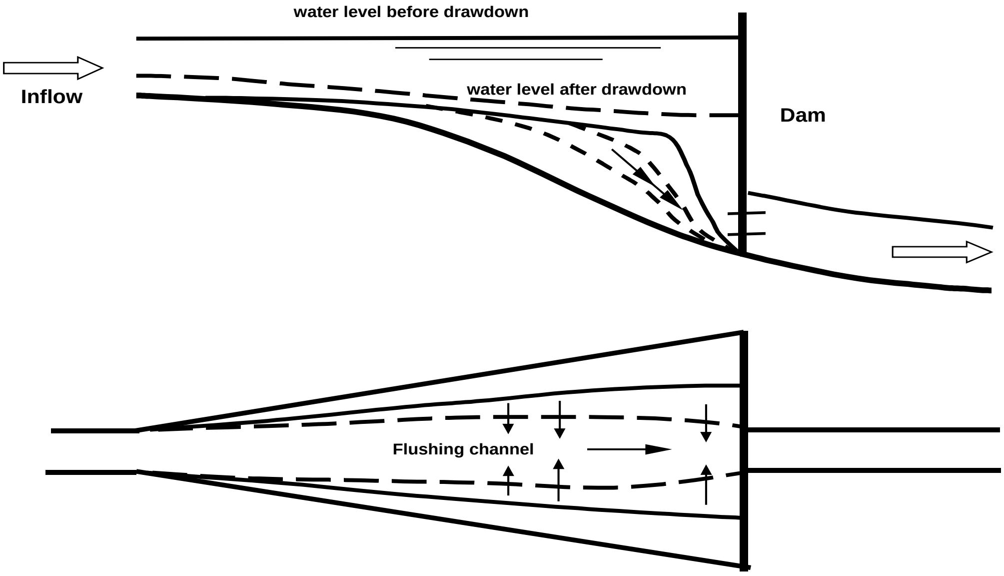

Figure 4.2 *Flushing with drawdown of water surface*

All hydraulic methods to remove sediments from a reservoir require that water is released from the reservoir to transport sediments and all methods (except venting) also require a substantial or full drawdown of the reservoir. Therefore, flushing is not efficient for reservoir operation because the reservoir has to be emptied and it requires large volumes of water passing through the dam. Furthermore, the reservoir should be rather narrow with relatively steep bed slopes and steep valley side slopes. It is also more easy to keep sediments in suspension (sluicing) than to remove them after settlement and consolidation (flushing). An overview of sites with successful flushing operations has been given by **Atkinson (1996)**.

Empirical flushing rates (fine sediments) based on data from Chinese reservoirs can be estimated by:

$$L= \alpha\, Q^{1.6} S^{1.2} B^{-0.6} \qquad (4.1)$$

with: L= total sediment transport (in tons/s), S= bed slope (m/m), Q= water discharge in range between 1 and 5000 (m^3/s), B= width of flushing channel (m), α= erodibility coefficient =1600 for loess sediments, α=650 for fine sediments of 0.01 to 0.1 mm, α=300 for sediments of 0.1 to 0.3 mm, α =100 (estimated by present author) for sediments>0.3 mm; α=180 for weakly consolidated mud (**Brandt, 2000**).

During flushing, the channel cuts itself into the sediment deposits and is thus self formed. The effective width B can be estimated by **(Atkinson, 1996)**:

$$B= 13Q^{0.5} \quad (4.2a)$$

The side slopes ($\tan\gamma$ in %) of the channel can be estimated from (**Atkinson, 1996**):

$$\tan\gamma = 6.4\, (\rho_d)^{4.7} \qquad (4.2b)$$

with: ρ_d= dry density of bed sediment (in t/m^3).

According to **Atkinson (1996)**, successful flushing requires that the flushed sediment mass is equal or larger than the sediment deposited in the period since the previous flushing event ($Q_{s,flush} T_{flush} \geq T_{sed}\ E\ Q_{so,sed}$; with $Q_{s,flush}$= mean sediment flushing rate in kg/s, $Q_{so,sed}$= mean sediment inflow rate in kg/s during sedimentation period, T_{sed}= sedimentation period between two successive flushing event in s, T_{flush}= flushing period in s, E= trap efficiency).

5 References

Atkinson, E., 1996. *The feasibility of flushing sediment from reservoirs. Report OD137, HR Wallingford, Wallingford, UK.*

Borland, W.M., 1971. *Reservoir sedimentation, Chapter 29 in River Mechanics, Water Resources Publications, Fort Collins, USA*

Borland, W.M. and Miller, C.R., 1960. *Distribution of sediment in large reservoirs. Paper No. 3019, ASCE, Transactions, Vol. 125, p. 166-180*

Brandt, S.A., 2000. *A review of reservoir desiltation, p. 321-342. International Journal of Sediment Research, Vol. 15, No. 3*

Brune, G.M., 1953. *Trap efficiency of reservoirs, p. 407-418. Trans. American Geophysical Union, Vol. 34., No. 3, Washington, D.C., USA*

Churchill, M.A., 1948. *Discussion of analysis and use of reservoir sedimentation data, p.139-140. Proc. of Federal Interagency Sedimentation Conference, Denver, Colorado, United States Bureau of Reclamation*

Di Silvio, G., 2001. *Basic classification of reservoirs according to relevant sedimentation processes, p. 285-293. 29th IAHR, Beijing, China*

Eysink, W. and Vermaas, H., 1981. *Simple methods for determination of sedimentation in dredged channels and harbour basins (in Dutch). Report S151, Delft Hydraulics, Delft, The Netherlands*

Fan, J. and Morris, G.L., 1992. *Reservoir sedimentation,I: Delta and density current deposits, p. 354-369. Journal of Hydraulic Engineering, Vol. 118, No 3*

Fan, J. and Morris, G.L., 1992. *Reservoir sedimentation,II: Reservoir desiltation and long-term storage capacity, p. 370-384. Journal of Hydraulic Engineering, Vol. 118, No 3*

HR Wallingford, 1983. *Sedimentation in reservoirs; Tana river basin, Kenya. Report No. OD 46, Wallingford, UK*

Lane, E.W. and Koelzer, V.A., 1943. *Density of sediments deposited in reservoirs. Report No. 9***,** *St. Paul U.S. Engineer, District Sub-Office, Univ. of Iowa, USA*

Lara, J.M. and Pemberton, E.L., 1963. *Initial unit-weight of deposited sediments, Paper No. 28, Proc. Federal Inter-Agency Sedimentation Conference, U.S.D.A., USA*

Miller, C.R., 1953. *Determination of the unit weight of sediment for use in sediment volume computations. U.S. Bureau of Reclamation, USA*

Murthy, B.N., 1977. *Life of Reservoir, Technical Report No. 19. Central Board of Irrigation and Power, New Delhi, India*

Siyam, A.M., Yeoh, J.S. and Loveless, J.H., 2001. *Sustainable reservoir sedimentation control, p. 77-82. 29th IAHR, Beijing, China*

Sloff, C.J., 1991. *Reservoir sedimentation in reservoirs; literature review. Report No. 91-2, Civil Engineering Department, Delft University of Technology, Delft, The Netherlands*

White, R., 2001. *Evacuation of sediments from reservoirs. Thomas Telford, London*