Bathymetric survey by depth-sonar and lake sediment coring by Beeker sampler to identify sediment budgets and siltation rates of small reservoirs

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Scope

The construction of small dams is a common practice for dealing with erratic and unevenly distributed rainfalls in semi-arid environments. Dams have the function to store rainfall and runoff water from the catchment and serve as water storage for domestic use, irrigation, and stock watering. At the same time, they are potential sinks for upstream sediments. Soil particles accumulating in the reservoirs can lead to changes in their morphology, which will decrease water storage capacity and water use potential. Small reservoirs in particular are affected by these storage losses as the maximum water depth is often only a few meters and an accumulated sediment layer of a few decimeters at the bottom of the reservoir causes a comparatively large reduction in water volume. Therefore, it would be useful to monitor changes in reservoir morphology, to measure the thickness of the layer of accumulated soil particles and to calculate siltation rates by bathymetric survey or lake sediment retrieval.

Target group

Hydrologists, water engineers, water resources planners, soil scientists

Requirements for application

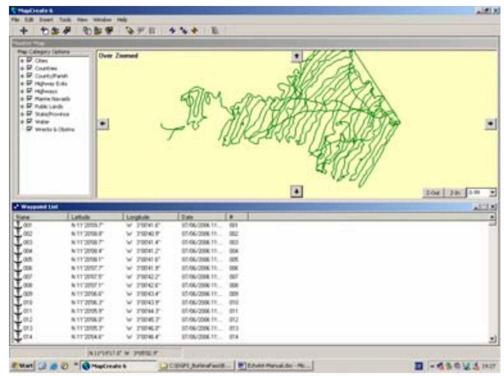
- Bathymetric survey: Boot; Echolot or sonar equipment for depth measurements (here: Sonar and mapping GPS unit, LMS-480M from Lowrance with software package); the echolot/ sonar can also be replaced by a simple stadia rod); hand-hold GPS (e.g. Garmin, e-Trex).
- Sediment sampling: Beeker sampler (e.g. from Eijkelkamp) and ordinary sampling utilities (e.g. plastic bags, bucket, fieldbook).
- Soil laboratory facilities: Bulk density determination; soil texture analysis.
- Computer facilities and software to produce digital elevation models and 3-D maps (e.g. Golden Surfer Software).
- Others: Topographical maps and technical reports of the dam’s construction

Description and application of the tool

Estimates of siltation rates in small reservoirs can be obtained from several methods, indirectly by measurements of suspended sediment fluxes, sediment traps or runoff/sediment yield estimations and more directly by bathymetric surveys or sediment coring of deposited bottom sediments. The latter methods are described here.

The bathymetric approach is based on a simple comparison of reservoirs morphology at two different time periods, first at the time of the construction of the dam and second at the time of the survey, which should be at least 10 years later to detect significant changes. The initial topographical map of the reservoir (resolution at least 1:1000) and the corresponding geo-technical report are required to get information about area-volume curves, potential water storage capacity, water surface and catchment area, spillway, overflow and runoff data as well as construction details of the dam, such as the degree of surface soil disturbed or sediments removed. Additionally, a clear elevation point should be selected (e.g. at the spillway), which serve later as a fixed point for comparative analysis.

Depth-sonar survey with GPS unit



Processing of water-depth and GPS data

Dano Dam, Dry Season, May 2006

Dano Dam, Rainy Season, Sept 2006

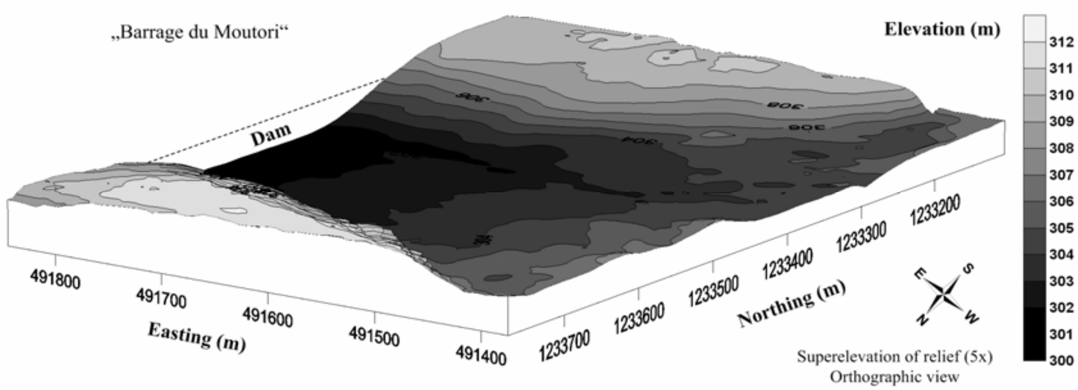


Figure 1 Bathymetric survey with depth-sonar in southwestern Burkina Faso

At the time of the actual survey, the current water level is recorded and its difference to the fixed point determined. The sonar depth-sounder and mapping GPS unit is attached to an inflatable boat and the water depth is taken point by point in a sampling grid fine enough to yield a map of resolution similar to the baseline information to which it will be compared. . The sampling design depends on the size of the reservoir as well as on the number and density of the elevation points in the initial topographical map (Figure 1).

The collected water-depth points and the corresponding GPS-coordinates can be processed by a geographical information system (e.g. ArcView, ArcGIS) or a grid-based graphic software (e.g. Surfer). For the interpolation of the survey points, known interpolation routines (such as linear triangulation, kriging and inverse distance to a power) can be used, but sampling points should be limited to the bottom surface of the reservoir as bank area points might generate large variations in the digital elevation model. The same procedure is repeated with the initial topographical map and a second digital elevation model derived based on the original elevation points and/or contour lines. Then, by overlaying the two elevation models, differences in elevation can be calculated and the volume contained between the modeled surfaces estimated. The resulting volume is an estimate of the quantity of sediment that has accumulated.

The second approach, the description of soil horizons and the coring of sediments, offers a feasible option to crosscheck single point data and to validate the depth/volume calculation described above. If the reservoir or at least a large part of it dries up seasonally, soil profiles can be easily dug and the thickness of the accumulated soil layer can be measured. Several soil profiles need to be selected both along the longitudinal and transverse cross sections of the reservoir to account for the varying deposition patterns of the accumulated sediment. The thickness of the upper sediment layer can be estimated roughly with a tape measure based on soil color and soil texture changes. Additionally, soil samples taken in a few centimeter depth intervals are required to determine soil bulk density and soil texture in a laboratory.

If the water level is too high and the reservoir does not dry out by the end of the dry season, the retrieval of sediment cores from a boat is proposed (Figure 2). Undisturbed sediment cores of max. 1 m length can be taken by a Beeker sampler until a max. water depth of 5 m (if needed the depth can be increased by adding extension rods). The sediment core sampler consists of a frame in which a transparent tube of 1 m is inserted. A piston on a rod is twisted into the transparent tube and fixed at the cutting head of the sampler. The inflatable membrane at the inside of the cutting head is connected by an extension hose with a pressure pump.

To assure an accurate vertical penetration of the core sampler and a successful withdrawal of the sediment, the boat should be stabilized with several iron rods pushed into the ground. Then, the sediment sampler is lowered until the solid bottom sediment (“the nautic depth”) is reached. While pushing and/or hammering the cutting head into the sediment, the cord of the piston is fixed to the stable boat so that the piston will remain at the same height while the sampler and its tube are pushed downwards. Once the required depth is reached, the inner membrane of the sediment head is inflated by two to three bars pressure closing the core opening to stop the sediment from dropping from the sampler. The sampler is pulled slowly up into the boat and the sediment thickness in the transparent tube is recorded. After deflating the inner membrane, the sediment can be removed centimeter by centimeter from the transparent tube.

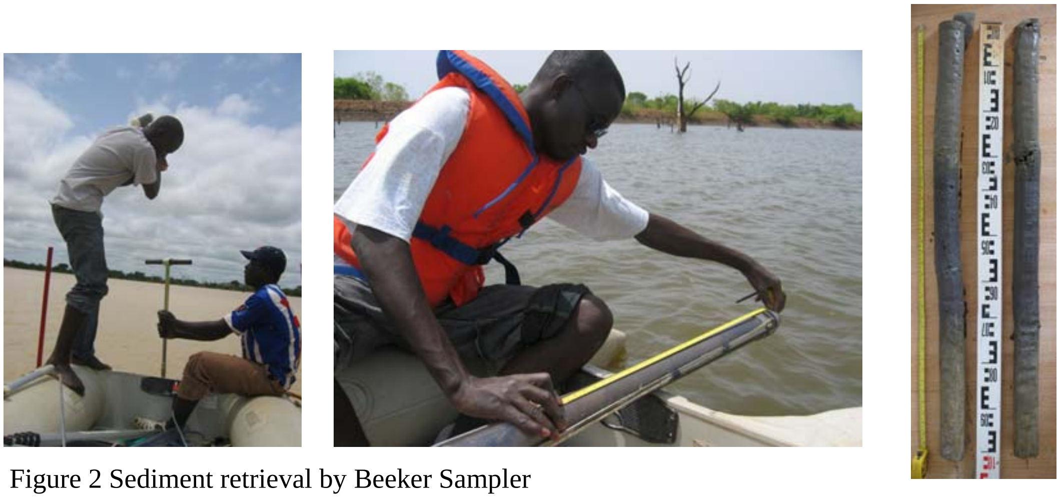


Figure 2 Sediment retrieval by Beeker Sampler

Stratification techniques allow the identification of changes in soil texture, soil structure or chemical composition and the reconstruction of the maximum sediment depth in the reservoir. A chronology of specific events, e.g. extreme floods or historical events, can be derived when a representative number of samples from different reservoirs are available and a specific sediment depth allows a clear correlation of single layers (for details see Appleby, 2001; Foster, 2006; Foster, 2007; Morris and Fan, 1997). In this study, a chronological analysis was not possible due to a limited sampling number and high variations in stratification. However, by knowing the sediment thickness, the sediment yield from the surrounding catchment can be estimated. Therefore, the dry bulk density of the samples (also known as unit weight of the deposits) is determined using the initial unit weight, the consolidation rate of the deposits and the operational mode of the reservoir (Table 1 and Table 2). The initial unit weight is calculated by the empirical equation developed by Lara and Pemberton (1963):

$$W_0 = W_c*P_c+W_{si}*P_{si}+W_{sa}*P_{sa}$$

Where W_0: initial unit weight; P_c, P_{si} and P_{sa}: ratios of clay, silt and sand in the sample; W_c, W_s and W_{sa}: initial weights for clay, silt and sand.

Table 1 Initial sample weight in relation to grain size and operation conditions (Lara and Pemberton, 1963)

Operation condition	Initial density (kg/ m³)		
	Clay	Silt	Sand
Continuously submerged	416	1121	1554
Periodic drawdown	561	1137	1554
Normly empty reservoir	641	1153	1554
Riverbed sediment	961	1169	1554

Table 2 Compaction factor k in relation to grain size and operation conditions (Lara and Pemberton, 1963)

Operation condition	Compaction factor k		
	Clay	Silt	Sand
Continuously submerged	256	91	0
Periodic drawdown	135	29	0
Normally empty reservoir	0	0	0

Taking the time as temporal variable into account, Miller (1953) suggested following equation to determine the average unit weight of a deposited sample:

$$W_t = W_0 + 0.4343 * k * \left[\frac{t}{t-1} \ln(t) - 1 \right]$$

Where W_t: average unit weight in t years, W_0: initial unit weight and k is the compaction factor.

Based on these equations, the volume of sampled sediments in the reservoir could be converted into mass to estimate the sediment yield from the catchment.

Therefore, following sediment yield equation can be used (Verstraeten and Poesen, 2002):

$$SY = 100 \frac{SV * dBD}{TE}$$

Where SY: sediment yield ($t\ y^{-1}$), SV: measured sediment deposition rate in volumetric units ($m^3\ y^{-1}$), dBD: dry bulk density of the sediment deposit ($t\ m^{-3}$) and TE: sediment trap efficiency of the reservoir (%). The area specific sediment yield (SSY) is calculated by dividing SY by the catchment area.

In sediment yield analysis, there is generally a wide range of uncertainties and potential errors (due to measurements, estimations and parameter predictions) involved. Therefore, an accuracy assessment can serve as a useful tool to determine the range of error, to identify sources of uncertainties and to evaluate the accuracy and reliability of the approach (see also Evans and Church, 2000; Verstraeten and Poesen, 2002).

Lessons learned and recommendations

The bathymetric survey provides a useful tool to get an overview of sediment storage in reservoirs. The fieldwork requires a comparatively small commitment of time and does not involve permanent monitoring and/or maintenance of sediment yield/runoff devices. However, the technical equipment is relatively costly (such as a depth-sonar and a Beeker sampler) and some expertise is needed for data processing and the construction of a digital elevation model. The sonar equipment was found very helpful, especially for the sampling of larger dams and the integrated GPS-unit as well as the digital screen facilitated both field work and data processing. A limitation of the described sonar device is that depth-measurements can be taken only in 10cm depth intervals and shallow depths below 0.5 m can not be considered. Therefore, the water depth was crosschecked with a simple stadia rod, which is still a very good and low-cost tool. However, when using the stadia rod alone, an accompanying hand-hold GPS is needed for geo-referencing.

For sediment sampling, the description of soil profiles provides a fast and easy way to estimate the sediment thickness at the bottom of the dam. Uncertainties due measurement errors are comparatively low and a quick first calculation of sediment storage for the entire area can be made. Sediment core retrieval from the bottom of the lake can also provide useful evidence about sediment accumulation, but in contrary to soil profile descriptions, this method is costly and both sampling knowledge and laboratory experience are needed to interpret the results.

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