A REVIEW OF METHODS FOR ESTIMATING THE STORAGE CAPACITY OF MINOR RESERVOIRS IN ARID AND SEMI-ARID REGIONS

Abstract

The tank system is quite old and designed to store and distributes water to fulfil the population's diverse requirements. However, the dramatic increase in the world's population has forced people to seek more secure and reliable groundwater resources, such as dug and deep bore wells. In addition, excessive siltation, poor maintenance, and unauthorized encroachment exacerbated the degradation. Hence over the past few decades, a drastic declination in the functionality of tanks has been noticed. Besides many, the storage capacity is considered the prime factor in dictating the functionality of a tank. In light of the current water shortage, it is high time to restore the deteriorating tank system. For rehabilitation, data on the storage capacity of tanks is essential. However, due to their number and negligence, there is a lack of data availability. Therefore, the first challenge is to gather information concerning tank capacities. Traditionally, the capacity is estimated in the field using survey instruments. Later by applying mathematical formulas, the capacity was assessed with minimum field measurements. The estimation has been made easier with almost no fieldwork, thanks to modern technologies like DGPS, Total Station, SONAR, Remote Sensing, and LIDAR. A brief description of various methods for estimating storage capacity is provided in this paper.

Keywords: storage capacity, surface area, echo sounder, sonar, Lidar

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I. INTRODUCTION

In different parts of the world, the minor reservoir has been used for centuries to store and distribute water during times of surplus and scarcity [1],[2]. The reservoirs satisfy the diverse needs of the communities, including the demands for agriculture, drinking water, and livestock, particularly in arid and semi-arid regions worldwide. Their role is significant during dry periods because it helps the rural population and farmers remain economically viable and reduces social inequality for 15% of the global population [3]. There are approximately 2.9 million small reservoirs in semi-arid regions, with a total water surface area of 17,000 km^2, and a seasonal storage capacity of 37,000 km^3. Their distribution and density across space are highly variable (0 to 420 reservoirs per 100 km^2). Despite their relatively low storage capacity, minor reservoirs have considerable socioeconomic value due to their high density [4].

However, their utility has dwindled in recent decades. [5],[6]. Several factors determine the functionality of a tank; among the most significant is its storage capacity. There is a considerable reduction in their capacity [7]. The primary cause of the decline in tank dead and live storage is catchment erosion and siltation [8]. As a result, tanks cannot store even the scarce resources currently available.

Furthermore, considering the present water crisis, it is time to restore the system. Any such reclamation activities will necessitate critical data on the spatial distribution, original capacity, current capacity, and siltation level. In addition, periodic measurements are required to assess variations in their capacity. Unfortunately, such data are scarce because of their number and negligence. Thus, the primary task is to create a database. Generally, conventional in situ techniques such as survey instruments, echo sounders, sediment inflow-outflow quantification, etc., are in practice for estimating the capacity. However, these methods necessitate extensive fieldwork and skilled labour, both expensive and tedious.

Besides, due to their large number, periodic measurement and evaluation are time-consuming [9], [10]. Indirect methods, such as estimating the capacity from the contours derived using topographic sheets, the surface water spread area using satellite images, Lidar, etc., have recently gained popularity due to minimal field work. Thus, the current paper comprehensively reviews various direct and indirect methods for measuring small reservoirs' storage capacity.

II. DIRECT METHODS

In the direct method, by measuring three parameters: length, width, and depth, the tank's storage capacity is estimated. Survey instruments such as a dumpy level, levelling staff, tacheometer, and so on are commonly used for measurements. However, in recent times, advanced instruments such as an echo sounder, DGPS (Differential Global Positioning System), and Total Station have been used for measuring and collecting data. Subsequently, capacity is calculated either manually or using conventional software such as surfer and geographic information systems [11], [12], [13]. On the contrary, the other method measures the volume of sediment flowing in and out of a reservoir. The silt retained within will then be calculated. We can estimate the reservoir's current storage capacity by subtracting the volume of silt from its original volume [14], [15]. The above methods are applicable only when the tank is at its full capacity level (FTL) or water flows to and from the tank. In contrast, excavation pits and trenches are dug in a grid pattern during dry periods to estimate the depth of silt inside the tank bed instead of measuring the bathymetry. Theisen polygon method will calculate the volume of silt inside the tank. We can determine the tank's current capacity by dividing its measured volume by design volume [14]. Thus, the above methods estimate storage capacity for small reservoirs depending on time, instrument availability, and expertise. The direct methods used in the capacity estimation are detailed below.

1. **Survey instruments:** Survey instruments like tacheometer, levelling staff, tape, plummet, and dummy level is used to generate the tank's bathymetric profile. Previously, the water column was measured using a rowboat plummet at predefined grid locations. Later, a tachometric survey with the stadia rod was used for better horizontal and vertical control [12]. In recent years, the global positioning system (GPS), which provides precise coordinates of the measuring stations, has been used in conjunction with the measurements [13]. Then, the contours were prepared either manually or with the aid of software like a surfer using depth data. Lineu et al. [16] conducted a field survey to determine the storage capacity of small reservoirs in the Brazilian Savannah region. He divided the tank area into evenly spaced grids and measured the reservoir depth with a plummet from a boat and GPS coordinates. The data was then extrapolated using the Kriging interpolation method, and a 3D model was generated using surfer software to estimate the reservoir volume. The geographic information system (GIS) software has enabled it to automate volume estimates by transforming point data into a triangulated irregular network [17].

2. **Geometrical method:** The above methods need extensive field measurement, while the mathematical model enables volume computation with minimum fieldwork.

   - **Based on Mathematical formula :** The standard units used for measurement are the width, throwback, and maximum impounded water depth of a reservoir. Then, by using a mathematical formula, capacity is calculated [12]. The width is the maximum width of the reservoir. The depth is the vertical distance from the river's lowest point to the top of the spillway crest, and the throwback is the horizontal distance from the dam to the tank's inlet. In general, the storage capacity of a minor reservoir can be estimated as follows:

     $$\mathrm{C} = \mathrm{K1 \; x \; K2 \; x \; D \; x \; W \; x \; T} \qquad (1)$$

     D is the vertical distance between the bottom of the reservoir and the top of the spillway in metres, and W is the water surface width at the top of the spillway in metres. C is the volume of the reservoir in cubic metres, K1 and K2 are constants that depend on the cross-section of the valley, and T is the distance from the dam to where the river enters (m).

   - **Based on Geometrical Formula:** If a tank has a well-defined geometrical shape, its capacity can be computed based on simple geometrical formulas [18, [19]. Volume = length x width x depth for "square" and "rectangular" tanks, and volume = length x width x depth for circularly shaped tanks.

$$volume = 3.14 \times radius^2 \times depth \quad (2)$$

The length, radius and width were measured inside the reservoir while its depth was at the appropriate water level. In general, the height of the sluice from the tank bottom is taken as depth. The estimation for a triangle tank depends on whether one of the triangle's corners is square or 90 degrees. In the case of a right angle, the formula is:

$$\text{Area} = \frac{1}{2} \text{x length x width} \quad (3)$$

And if the sides are unequal, then the formula is:

$$Area = \sqrt{}(S \times (S - A)) \times (S - B) \times (S - C) \quad (4)$$

Where S = 1/2 (A+B+C) and A, B and C are the lengths of the sides. Multiplying the measured depth by the tank area yields an estimate of the tank volume. In addition to taking readings in the field, depth was extrapolated from topographic sheets: (i) using the cross sections, (ii) the spot levels, and (iii) the contours.

3. **Echo sounder:** If the area and depth of the reservoir are too large, then the hydrographic survey is conducted using echo sounders [20]. It uses acoustic waves and measures the water column's depth based on travel time. The computerized data collection software and GPS (global positioning systems) equip the sounding. Using the digital acoustic bathymetric sounders and global positioning systems, the Kansas Biological Survey department [21] generated maps on the bottom profile of the reservoirs in the Kansas Biological reserve for comprehensively assessing and monitoring the reservoirs. Multiple beam ecosystems, airborne laser systems, and airborne electromagnetic systems now achieve a higher acquisition rate than single beam echo sounders [22].

4. **Pit Method:** Instead of measuring the water column, the amount of silt inside the tank was calculated, especially during the dry seasons. At first, the thickness of the sediments in the tank floor was measured by excavating pits or trenches in a grid pattern. The area of influence of each pit was calculated using the Thiessen polygon interpolation method. Then the quantity of silt in each polygon will be calculated by multiplying it by the sediment thickness. Finally, the total volume of sediment trapped within the tank was determined [23]. Later, the capacity loss will be calculated by comparing it to the original volume.

5. **Inflow-out flow method:** In the inflow-outflow method, the sediment load will be measured at both points where the river enters and leaves the tank. The data is collected daily or during its peak discharge period. Then using mathematical models like HEC-6, GSTARS, FLUVIAL, TABS, etc. [14], [24], the variation in the sediment load supplied in and out of the tank was estimated, and therefrom the amount of sediment deposited within the reservoir was computed. By correlating with the original storage, the loss was calculated.

6. **Differential global positioning system:** As a recent advancement, the differential global positioning system (DGPS) is used to measure the tank profile's elevation. The measurements are made on a series of cross sections along the reservoir's horizontal and longitudinal axis. The survey provides data as point information comprising its geographical location and elevation concerning the mean sea level. Later, using conventional GIS software, the triangulated irregular network (TIN) was generated and there from the volume of the tanks was estimated [25].

7. **SONAR:** The advanced hydrographic instrument SONAR (Sound Navigation and Ranging) accurately estimates the storage capacity. The survey-grade hydrographic sonar is coupled with survey-grade RTK-GPS (Real time kinematic global positioning system). It records the bathymetry, geographic position and timestamp for each location. Hydrographic software was later used to estimate the elevation of the water column, bathymetry, and total storage capacity. [26],[27].

II. INDIRECT METHODS

In the case of small tanks, owing to their number and size, the estimation using the above direct methods will be time-consuming and uneconomical. Hence indirect methods are preferred in computing their storage capacities.

1. **Elevation-based computation:** This method uses topographic sheets to map the contours of the tank bed. Then a planimeter cross along the longitudinal section of the tank axis is prepared. Using the area between the contours and the height difference between them, we could determine the tank's volume between the contours. Likewise, the tank volume can be calculated for each contour level. While estimating the full tank's capacity, the highest and lowest contour values and the area between them will be used (Sawunyama et al., 2006). Later, an elevation-area table will be prepared for different water levels. The data from the site's water level indicator can be used in conjunction with the above table to provide reliable capacity estimates whenever necessary. However, the method requires large-scale topographic maps to generate high-resolution contours. The elevation-based computation described above can be further classified as follows.

   - **Mid-Area method:** As stated earlier, contours were used for calculating the capacity. The areas between the successive contours are computed from the cross-section. To calculate capacity, we need to measure the contour interval (the distance between two contours) and apply it to the given formula.

     $$C = \sum_{i=1}^{n}\left(\frac{A_i + A_{(i+1)\times dh}}{2}\right) \qquad (5)$$

     Where C= Reservoir capacity,
     A_i =Surface area at contour interval i,
     A_{A+I} =Surface area at the next contour level above contour level 1 and
     dh = contour interval. This method is suitable for small contour intervals.

- **Prismoidal method:** In this method, the shape of the tank is assumed as a pyramid. Considering the water surface as its base, the capacity enclosed by two successive contours is calculated using the prismoidal formula.

$$V = \mathrm{L\,x\,1/(A1\ +\ A2)} \qquad (6)$$

- **Trapezoidal method:** However, for capacity estimates, the trapezoidal formula is widely used (Goel and Jain, 1996). In this method, the tank is assumed as a trapezium, and the formula for calculation is

$$V = \frac{H}{3}(A_1 + A_2\sqrt{(A_1\ \times\ A_2\,)}) \qquad (7)$$

Where V = Volume, A1 = Elevation Contour Area, A2 = Elevation Contour Area, and dh = Difference Between Elevations 1 and 2.

2. **Surface Area based computation:** The above methods are applicable for medium and large reservoirs. However, due to the large number and varied sizes of small tanks, estimating their total capacity is challenging. The volume of water stored in a tank is proportional to its surface area. We can calculate the volume of water in a tank based on the proportion for any given water spread area. Since the surface area can be precisely mapped from satellite images, the estimation can be done without field measurements. The added advantage of this method is that estimates can also be done even for date-back periods using the respective satellite images.

Further, the above-derived relationship can be extended even for the nearby tanks, provided they should be within the same hydrogeographical condition. Initially, the surface area and capacity were measured in the field for a few tanks, and an empirical equation was derived through linear regression analysis. We can derive the storage of each tank by substituting the water spread area in the equation.

The power relationship provides the general equation for computing capacity from the area [28], [29].

$$\text{Storage Capacity C} = \mathrm{a \times A^{b}} \qquad (8)$$

Where C = the reservoir capacity (m3)
A = the surface area (m2)
a and b = calibration constants based on reservoir characteristics.

At the same time, Mitchell [30] carried out a linear regression analysis between the log area/log capacity of 12 reservoirs in the Zimbabwe region. He derived a power relationship as follows $\mathrm{C = 2.646 \times A^{1.5}C}$. Similarly, Meigh developed a power relationship $\mathrm{C = 7.381 \times A^{1.251}}$ (R^2 = 93.1%) for estimating the reservoir capacity in Botswana. While Liebe [32] assessed and monitored the reservoirs in the Upper East Region of Ghana, by mapping the surface area using satellite images and calculating their capacity periodically using the power relationship equation $\mathrm{C = 0.00857 \times A^{1.4367}}$

Similarly, Rodrigues [16] estimated the storage capacities of small reservoirs in the Brazilian Savannah region using Landsat ETM satellite data. Further, he correlated the results with the field measurements, observed a deviation in the results, and attributed the same to the resolution of the satellite image. Sawunyama [12] carried out a remote sensing based storage capacity estimation in 12 small reservoirs of Mzingwane catchment, Zimbabwe. Thus, from the above studies, it is evident that the storage capacity can be easily estimated by mapping the surface area. The difference in the constant value is attributed to the variation in reservoir profile, climatic conditions and the spatial resolution of satellite data used.

IV. FUTURE POTENTIAL

However, subtle field measurements are essential in the above methods, whether by preparing 3D or surface area-based models. While the recent advancement in remote sensing technology, namely the LIDAR (Light Detection and Ranging), provides data on the water surface and the bottom profile more precisely. Airborne sensors transmit laser light of both NIR (1040 - 1060 nm) and Blue- green region (approximately centred at 532 nm) are used. Due to its longer wavelength, the NIR region gets reflected from the water surface. The green region transmits through the water body and, after interacting with the bottom, gets reflected. The reservoir's bottom profile is generated based on its travel time.

Further, based on the difference in travel time between NIR and the Green band, the thickness of the water column is determined. Because LIDAR is an active system, data can be collected at night rather than relying on passive solar illumination. The aforementioned technology, however, is expensive and unaffordable for many developing and underdeveloped countries. Nowadays, waterbody mapping can be done on a large scale using the increasing availability of high-resolution earth observation (EO) datasets in conjunction with machine learning (ML) classification models [33].

A sonar device mounted on ROV can enhance the precision and safety of measurements by minimizing the need for on-site personnel. Technologies like UAVs help acquire high-resolution images of tanks during the dry period, which can be used to generate a terrain model and an EAC curve for these tanks. Consequently, various methods have pros and cons, and it is up to the applicants to choose the most appropriate method for the circumstances.

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