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Depth-Area-Storage Capacity Relationships of Village Tanks

K.A.U.S. Imbulana

Abstract: Village Tanks in Sri Lanka have the potential to enhance climate resilience particularly through water management. The depth-area-capacity curves are very important for their improved management. However, many of these small reservoirs do not have such curves and it is difficult to develop them due to the reservoirs being numerous. Attempts to fit an equation to these curves have been carried out for a long time. This work analysed the data from approximately 150 Village Tanks, tested the validity of the equations currently used in Sri Lanka, and attempted to improve the presentation of depth-area-capacity relationships through modification to existing equations. The results show that a frequently used older equation is still valid with slight modifications. When the absolute values of the variables used in that equation are replaced by relative values, a linear relationship with a high correlation coefficient and small variation of the gradients of the linear plots was obtained. It was also found that a substantially accurate depth-area-capacity relationship could be derived with 4 to 5 measurements of depth and water surface area. The use of relative variables has several advantages including the ability to readily indicate the status of water availability in the Tank.

Keywords: Village Tank, Tank-cascade, Depth-area-capacity curve, Relative variables

1. Introduction

It is generally believed that the origin of the small reservoirs in the Dry Zone of Sri Lanka, also termed "Tanks", were among the earliest irrigation works of the country. These reservoirs were built using the labour of villagers almost in every village and they were the first irrigation works of the country [1]. It is further theorized that early settlers of the island constructed small communal tanks to store rainwater for domestic purposes and for irrigating a farm downstream of the Tank [2].

The important role played by these small reservoirs or Village Tanks to enhance the climate resilience of small-scale farmers and village communities in the Dry Zone of Sri Lanka is getting increased recognition. The Climate Resilient Integrated Water Management Project (CRIWMP) is an intervention to improve the climate resilience of Village Tank-based smallholder farmers in the Dry Zone through improved water management. It is implemented by the Ministry of Irrigation, Sri Lanka, with funds from Green Climate Fund (GCF) and with the technical Support of the United Nations Development Programme (UNDP). The project used Tank-cascades (a cluster of hydrologically connected Tanks and diversions), located in Malwathu Oya, Yan Oya, and Mi Oya river basins, as the spatial units for irrigation system upgrading and water management. Figure 1 shows the location of the Tank-cascades used for the analysis conducted in this paper.

2. Rationale and Objective of the Paper

While a substantial amount of investment has been made in the rehabilitation and restoration of Village Tanks since the 1980s, water management in these systems needs further improvement. In the case of Tank-cascades, where the reservoirs and diversions are hydrologically inter-connected, improved water management will contribute to both drought and flood management.

The CRIWMP has developed depth-area-capacity curves for the Tanks, established water level gauges in the Tanks, established flow measuring gauges at the head end of irrigation canals, and formulated an operation and maintenance plan for each Tank, so that the improved knowledge of water storage can be used to plan and scientifically manage the cultivation season. During the training and capacity building carried out by the project,

Eng. K.A.U.S. Imbulana, *MIE(SL), MASCE, B.Sc. Eng. (Moratuwa), M.Sc. Irrig. Eng. (Utah State), Consultant, United Nations Development Programme (UNDP).*

the farmers were educated to read the water depth gauges installed in the reservoirs and relate such readings to the storage. Awareness was made of the approximate water requirement of main crops including paddy, and training was provided to help decisions on the extent to be cultivated each season. They were also encouraged to carry out land preparation using rainfall and made aware of the water savings that could be made by such practices. Depth-area-capacity curves developed by the project was a frequently used tool in training and awareness creation regarding water management.

The CRIWMP experience highlights that depth-area-capacity curves are essential for better water management. Recent surveys carried out by the Department of Agrarian Development and the UNDP show that there are approximately 21,000 Village Tanks including the abandoned Tanks in Dry and Intermediate Zones, but only about 51% are functioning. Even the functioning Tanks have rehabilitation needs. If low-cost rehabilitation is planned for these reservoirs, many of them would not have the necessary depth and volume relationships for improved water management.

Given the current advances in computational capacity due to the increased availability of computers and technologies such as GPS and satellite images for measurements, it will be useful to explore the possibilities of simplifying the process for the development of depth-area-capacity curves.

Therefore, the objective of this paper is to analyse depth-area-capacity curves obtained from topographical surveys conducted by the CRIWMP and identify relationships that could be used to simplify the process of developing those curves.

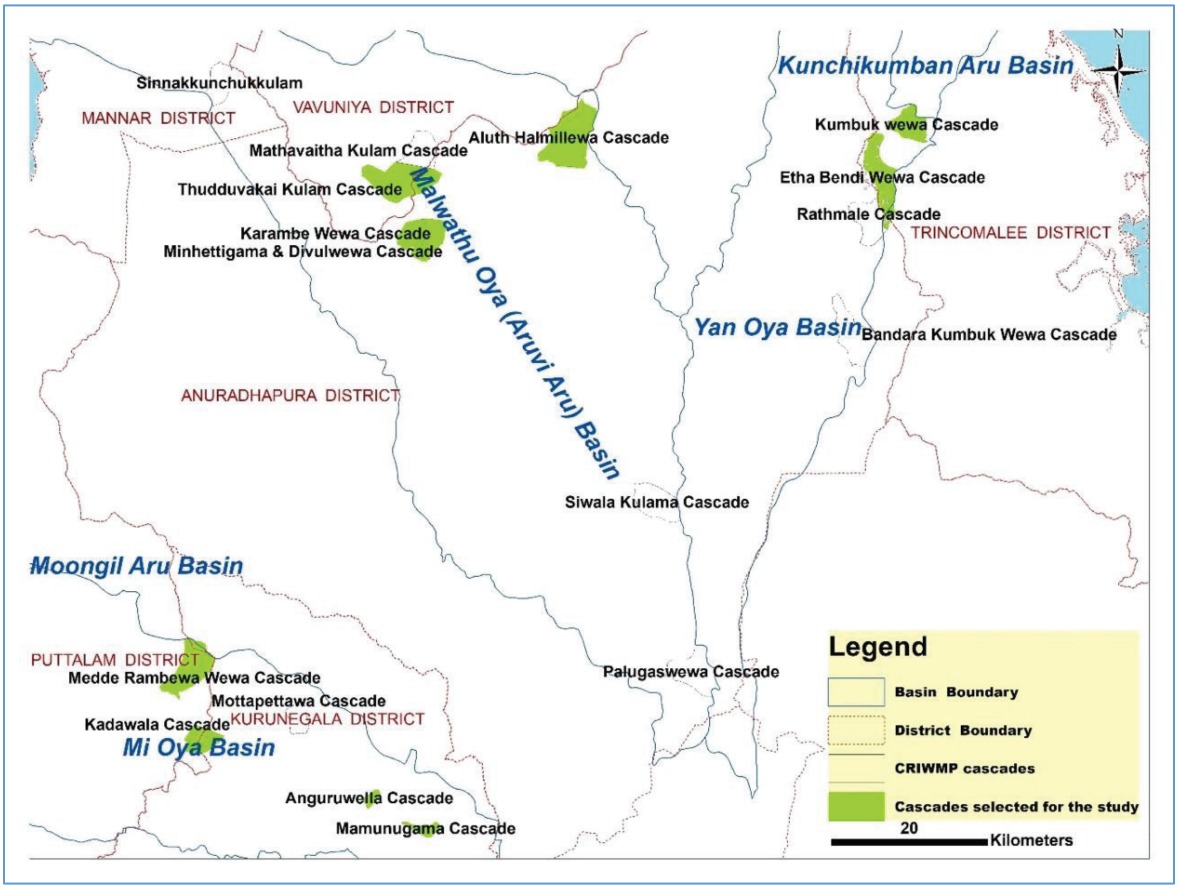

Figure 1 - Tank-Cascades Selected for CRIWMP and this Study

3. Literature Survey

3.1 Depth-Area-Capacity Curves and Their Importance

Similar studies and experiences in other countries corroborate the experiences gained during CRIWMP implementation. A study in selected watersheds in Brazil and Ghana noted that depth-area-capacity curves are one of the most important physical characteristics of a reservoir [3]. The information obtained from the curves is useful for, *inter-alia*, flood routing, reservoir operation, and reservoir classification.

However, a majority of small reservoirs do not have such curves in many parts of the world. A major constraint to developing them is the large number of small reservoirs and the resources required. In India, the reported number of Tanks is estimated to vary anywhere between 200,000 and 350,000 [4]. In Tamil Nādu, India, the number is approximately 40,000 tanks [5]. A study conducted in Brazilian Semi-arid Region indicates that the density of small reservoirs was about one per 5 km^2 [6]. Out of the 21,000 Tanks (both functioning and abandoned) in Sri Lanka's Dry and Intermediate Zones, more than 55% are located in North Western Province (NWP) and North Central Province (NCP). Accordingly, the Tank densities work out to one Tank per 1.02 km^2 in the NWP and one Tank per 2.16 km^2 in the NCP. Apart from this high number of Tanks, the relationship between depth, area, and storage are site-specific [3]. Therefore, while accurate surveys are required to derive depth-area-capacity curves, they also need substantial time, human, and financial resources.

3.2 Relationship Among Depth, Water Surface Area and Reservoir Capacity

The depth-area-capacity relationships in small reservoirs were studied in the Preto river basin in Brazil and the Upper East Region of Ghana [3]. The researchers theorized that the volume of reservoirs can be expressed as either a function of the surface area or the depth of water. Satellite imagery could be used to estimate the surface area and the depth has to be assessed using water level measurements. In either case, it was noted that volume could be expressed as a power function in the form:

$$V = \theta \times (H \; or \; A)^{\sigma} \qquad \ldots(1)$$

where V is the volume of the reservoir, θ and σ are constants, H is the depth of water, and A is the water surface area.

The researchers selected 147 small reservoirs with surface area ranging from 1 and 50 ha from the Preto river basin in Brazil, and another set of 154 reservoirs having a surface area ranging from 1 to 35 ha were selected from the Upper East Region of Ghana. The data were analyzed to obtain a linear relationship between logarithms of depth (H) and volume. The correlation was expressed as R^2 greater than 0.97 for Brazil and it was greater than 0.95 for Ghana.

In the case of the H and V relationship, the constant parameter θ varied from 18.12 to 36,855.30 in Brazil and from 377.88 to 26,413.39 in Ghana. The parameter σ varied from 1.58 to 3.75 in Brazil and 1.83 to 4.08 in Ghana. Similar variations were observed in the A and V relationship. Accordingly, it was concluded that relationships are region-specific and depend on several factors like topography, valley shape and geology of the area. Therefore, although the analysis yielded a linear relationship with acceptable correlation, high variability in the constant parameters of the equations indicate they cannot be extrapolated.

A study was conducted in the semi-arid region of Brazil to develop a method to estimate the geometry and volumes of unmonitored reservoirs based on remote sensing data [6]. The researchers expressed the reservoir volume as a function of the flooded area with a complex power equation.

In this study, the geometric characterization of reservoirs was based on the water depth–area–capacity curves from a database published by the Brazilian National Department of Works Against the Droughts. A subset of 312 reservoirs from the database having a complete dataset and an equation to describe the volume of a reservoir as a function of the flooded area, and two geometric coefficients were derived. The researchers obtained the terrain characteristics and shape of the reservoir surface at maximum water extent by remote sensing data and tested the transferability of the equations with geometric coefficients to reservoirs with similar terrain and shape characteristics. It was found that the volume of a reservoir could be predicted with a mean-absolute-percentage error varying from 24% to 39%.

One of the earliest references to the storage volume of Village Tanks in Sri Lanka was made in 1933 [7]). Emphasizing that reliable information of the storage volume of a Tank is required before starting investigations leading to its development, the following formula was suggested as a first approximation of the storage volume:

$$V = 0.4 \times A \times D \qquad \ldots(2)$$

where, V is the capacity in acre-feet at depth D (feet) and A is the water spread area (acres) at that depth. It was described as an empirical formula that was in frequent use at that time.

Equation (2) is again mentioned in a manual on village irrigation works. It was noted that calculation of the capacity of a Tank using standard survey and drafting techniques is not a difficult task. However, difficulties arise due to access problems and when the Tank is full or partly full at the time of investigations [8].

Considering the difficulties that could be associated with surveying, it would be desirable to have a simple equation of volume expressed as a power function of the independent variable, depth. However, the length, width and shape of the basin could influence the Tank capacity, and therefore, obtaining a simple relationship could be challenging [7], [8]. This observation was similar to those made by the study in the semiarid region of Brazil [6]

3.3 Concept of Relative Water Depth and its Relevance to Assessing Tank Performance

Relative water height, defined as the current tank water height/tank water height at the Full Supply Level (FSL), had been used in a study to develop a function to estimate Tank seepage [9]. In the case of a cascade, expressing the storage, water surface area, and water depth on relative terms has an advantage over absolute values of the same parameters. The relative values readily indicate whether the Tank is full or empty and such information is useful for modelling water balance and water management. Furthermore, being unitless quantities, the relationships derived from analysing them could be used for any unit system.

An analysis of storage data of 573 Village Tanks identified five storage states and five transitions between those states [10]. The five storage states include dry (state 1), below sluice sill level (state 2), partially full (state 3), at spill level (state 4) and spilling (state 5). The main transition categories include improving, neutral and depleting. The ability of the Tank to recover either from dryness or failure in providing sluice water issues is defined as storage resilience, and the ability of the tank to provide water issues through the sluice or providing for social and environmental needs is termed storage reliability. The storage state was used to assess the performance in terms of resilience and reliability.

This methodology could be used to assess the performance of an individual Village Tank with reference to an expected performance level, or the reliability of providing the expected services by the Village Tank. The use of relative depth of water simplifies the description of the storage state and the tank's performance.

4. Methodology Employed in the Current Analysis

The project's database consisted of depth-area-capacity relationships of approximately 200 village tanks, derived during the design stage. Several of those relationships were corrected to accommodate the changes of sluice sill level after upgrading.

The analysis was carried out in two stages:

1. An investigation of the relationship between the capacity at FSL, water surface area, and the depth of water as described by Equation (2); and
2. An analysis of individual depth-area-capacity curves to obtain a relationship among the parameters at different water levels

In both cases, the depth of water was measured relative to the lowest sluice sill level. Accordingly, the storage discussed here is the "live" storage. The first stage of analysis was relatively simple. Considering the changes to sluice sill level during rehabilitation can affect the depth measurements, the data from the cascades where rehabilitation was completed were analyzed separately from the cascades where only the design stage information was available.

The first step in stage 2 analysis was a preliminary examination of the depth-area-capacity curves, which showed that there is a distinct relationship between their relative depth (as defined by Jayatilake et al., 2001), relative area and relative capacity, which are defined as follows:

Relative depth = current depth (d)/full supply depth (D)

Both d and D were measured relative to the lowest sluice sill level.

Relative area = current water-spread area (a)/water-spread area at FSL (A)

Relative storage = current storage (s)/capacity at FSL (C)

Preliminary investigations of the data included plotting relative area and relative storage separately against relative depth and deriving equations to define the relationships for each case. Although polynomial equations and power equations could be fitted to the data, it was noted that the parameters describing the relationship among variables were specific to the particular reservoir. As such, an attempt was made to derive a relationship similar to that described by Kennedy (1933), while replacing absolute variables (depth, area and storage) with relative variables. The proposed equation is as follows:

$$\frac{s}{C} = m \times \left(\frac{a}{A}\right) \times \left(\frac{d}{D}\right) \qquad \ldots(3)$$

where, d/D = relative depth, m = gradient of the graph, a/A = relative area, and s/C = relative storage.

Village Tanks were selected from 10 Tank-cascades from Yan Oya, Malawathu Oya, and Mi Oya river basins, as shown by Figure 1.

5. Results

5.1 Stage 1 Analysis - Relationship Among *C*, *A*, and *D*

Post-rehabilitation data from 62 Tanks in Thudduvakaikulam, Mamunugama, Anguruwella, and Medde Rambewa cascades (Figure 1) were analyzed first. The basic characteristics of the selected Tanks are given in Table 1. The results of the analysis are illustrated in Figure 2.

Table 1 - Basic Characteristics of the Selected Tanks at FSL (Post-Rehabilitation Data)

	Depth (D), m	Water surface area (A), ha	Storage capacity (C), m^3
Maximum	3.54	55.74	784,493
Minimum	0.76	0.20	1,067
Average	1.93	11.33	114,215

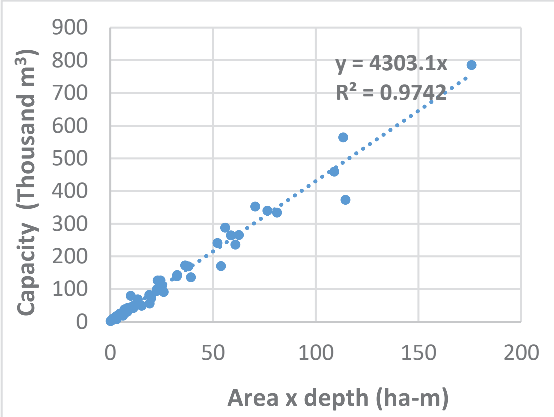

Figure 2 - Capacity against Area x depth at FSL (post-rehabilitation)

The derived equation is as follows:

$$C = 4303 \times A \times D \qquad \ldots(4)$$

where C is in m^3, A in ha and D in m.

Expressed in imperial units, the equation would read as:

$$C = 0.4303 \times A \times D \qquad \ldots(5)$$

where C is in Acre feet, A in acres and D is in feet.

A correlation coefficient exceeding 0.98 was obtained.

Pre-rehabilitation (design stage) data from 100 Tanks in Aluth Halmillewa, Kadawala, Kumbukwewa, Etha Bendi Wewa, Divul Wewa-Minihettigama, and Karambawewa cascades (see Figure 1) were used for this analysis. The basic characteristics of the selected Tanks are given in Table 2.

Table 2 - Basic Characteristics of the Selected Tanks at FSL (Design Stage Data)

	Depth (D), m	Water surface area (A), ha	Storage capacity (C), m^3
Maximum	3.77	98.54	1,558,638
Minimum	0.93	0.50	1,844
Average	1.96	12.74	137,216

The largest Tank used for this analysis, Etha Bendi Wewa, is not a Village Tank by definition. The relationships obtained from data analysis are demonstrated in Figure 3.

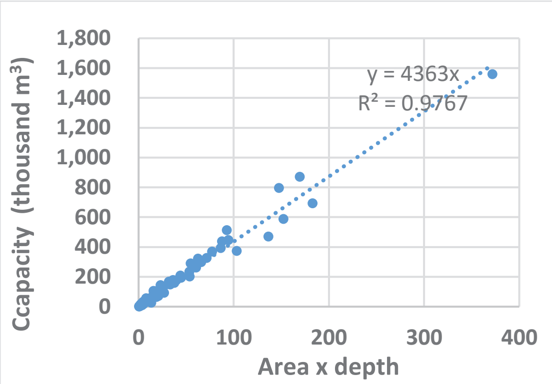

Figure 3 - Capacity against Area x Depth at FSL (Pre-Rehabilitation)

The relationship between C, A, and D is expressed as:

$$C = 4363 \times A \times D \quad \ldots(6)$$

where C is in m^3, A in ha and D in meters.

And, in imperial units:

$$C = 0.4363 \times A \times D \quad \ldots(7)$$

where C is in Acre feet, A is in acres and D is in feet.

The correlation and the scatter are very much similar to the previous case where data were obtained after rehabilitation. It can be seen that a slight change in the sluice sill level after rehabilitation has not made a notable difference to the relationship among the parameters.

A visual observation tends to suggest that the scatter of the observations increases at higher capacities. However, the relative error, in both pre-rehabilitation and post-rehabilitation cases, shows a higher deviation at lower storage capacities, as shown by Figure 4.

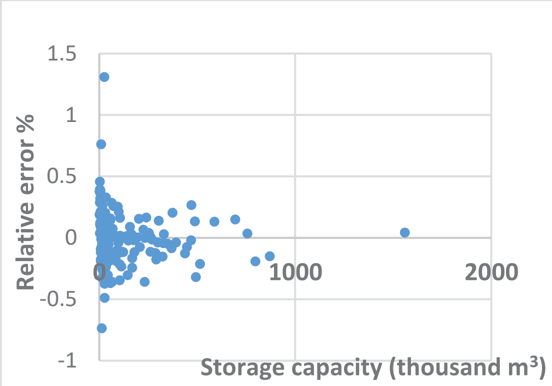

Figure 4 - Relative Error of Calculated Storage Capacities

5.2 Stage II Analysis: Relative Depth, Relative Area and Relative Storage

This analysis was carried out to develop a methodology to derive a depth-area-capacity relationship with the minimum human and financial resources spent on topographical surveys. For this analysis, 30 Tanks were randomly selected from Thuduvakaikulam, Etha Bendi Wewa, Kumbuk Wewa, Aluth Halmillewa and Medde Rambewa Wewa cascades where the data were continuous and acceptable.

It was noted that some surveys conducted to develop depth-area-capacity curves did not measure water surface area below the sluice sill level. This could have been due to the presence of water during initial surveys. However, while the information below the sluice sill level does not affect relative depth or relative storage, it affected the relative area, because the water surface area at the sluice sill level is not zero unless the Tank is silted up to the sluice level. Therefore, the Tanks with inadequate information below the sluice sill level were not considered for this analysis.

A regression analysis was carried out using relative storage as the dependent variable and the product of relative area and relative depth as the independent variable. The intercept was forced to zero.

A sample graph of the relationship obtained for Thuduvakaikulam Tank is as shown in Figure 5.

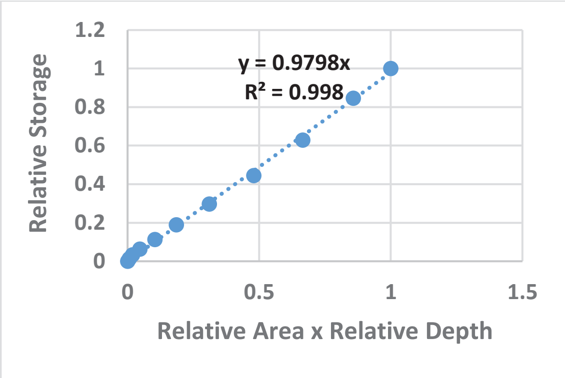

Figure 5 - Graph of Relative Storage against Relative Area x Relative Depth Thuduvakaikulam Tank Vavuniya

5.3 Summary of Results: Stage II Analysis

A summary of the results of the gradient of relative storage against the product of relative area and relative depth is as follows:

Average of m (Equation (3)) = 1.0137

Standard Deviation of m = 0.023

Range of m = 0.955 to 1.050

The correlation coefficient between the variables relative storage and the product of relative area and relative depth was 0.99 or higher for the selected 30 Tanks. Figure 6 shows that about 70% of the gradients for this relationship were between 1.00 and 1.04, and more than 80% were between 0.98 and 1.04. The differences among values of the gradients could not be explained with the characteristics such as storage capacity and water surface area. They may be due to the differences in terrain and shape characteristics [6] which were not analyzed for this study.

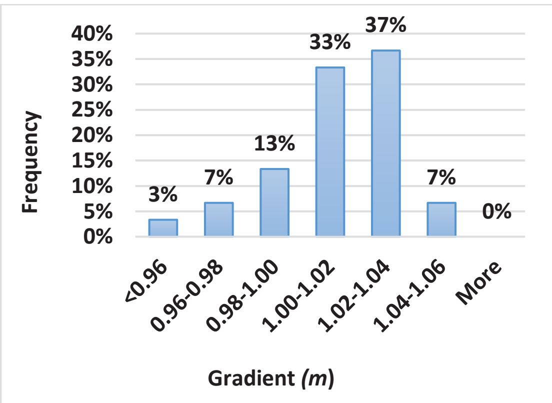

Figure 6 - Frequency Distribution of the Gradient of Relative Storage against Relative Area x Relative Depth Graphs

This analysis showed that the relationship of relative depth, relative area, and relative storage obtained using a sample of Tanks can be extrapolated for other Tanks when there is a high degree of accuracy is not needed. However, still, some measurements of the variables such as depth of water and water surface area are needed to build the depth-area-capacity curves.

While the storage at any water depth is a function of depth and water spread area, the relationship between area and depth varied among the Tanks. Therefore, the relationship between relative area and relative depth was investigated to determine the minimum number of such measurements. It was found that a reasonably good relationship between two variables could be obtained by four measurements of water surface area, preferably at D, $2/3D$, $1/3D$ and zero depth. This would introduce some errors below $1/3$ D which would not affect much when the capacity at FSL is calculated.

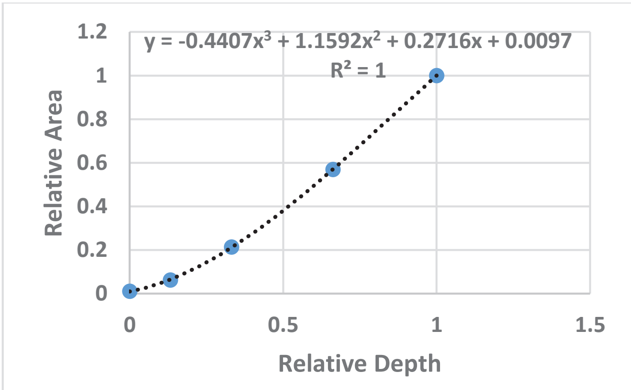

Figure 7 - Relative Area against Relative Depth with Five Measurements

However, even such errors could be minimized by introducing one more measurement of the area between zero depth and the depth at $1/3\,D$. Figure 7 shows the relationship between relative area and relative depth in Etha Bendi Wewa Tank in Trincomalee District, as sample output. Five measurements of depth and water surface area are used for this analysis.

Figure 8 compares the storage curve developed with the polynomial relationship obtained from those five measured points for the same Tank with the other measured depth and area values. This comparison showed that the relative error is less than one per cent for depths larger than $1/3$ D, for this particular Tank. Extending the analysis to the other 29 Tanks showed that relative error for similar depths were less than 5% when the gradient (m), as shown by Figure 5, remained between 0.98 and 1.04.

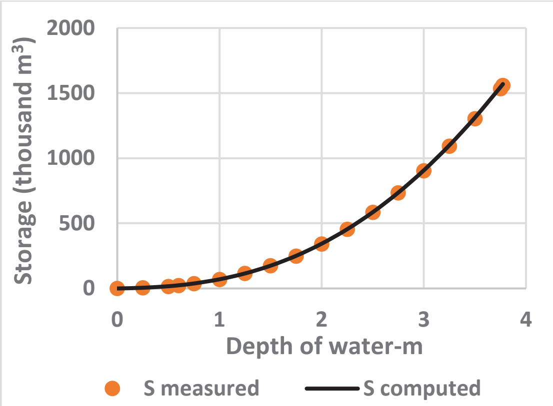

Figure 8 - A Comparison of Computed Storage and Measured Storage against the Depth of Water - Etha Bendi Wewa

6. Discussion

To develop a depth-area-capacity relationship for a reservoir using this method, the following steps can be recommended:

a. Establish a water level gauge in the reservoir, preferably reading zero at the lowest sluice sill level;
b. Periodically take water surface area measurements, preferably at FSL, 2/3 *D*, 1/3 *D*, in between zero and 1/3 *D* and at zero water levels; and
c. Use this relationship to develop a depth-area-capacity curve.

Other observations made during the analysis included the following:

a. Even though the relationships were developed for live storage, the storage below the sluice sill level (dead storage) affects the relationship. Therefore, obtaining the data to calculate the dead storage is important.
b. The relationships applied better to the Tanks located in the middle and lower river basin rather than those at the upper reaches.

7. Conclusions

The above analysis shows that Equation (2) can be used for a rapid assessment of the storage capacity of Village Tanks at FSL. The current analysis gives a slightly higher value for the storage capacity at FSL, compared to the results obtained by Equation (2). Studying Village Tanks in a few more river basins could be useful before deciding whether Equation 2 can be replaced by Equation (4) or Equation (6).

When the absolute variables used in Equation (2) are replaced by relative variables, a linear relationship with a high correlation coefficient was obtained. As the gradients of these linear plots are within a narrow range, the relationship can be extrapolated for other Tanks when there is a high degree of accuracy is not needed.

With the advent of modern technology such as remote sensing, Geographic Information Systems (GIS), and Global Positioning Systems (GPS) [11], the data required to develop depth-area-capacity curves, especially water surface area, can be obtained within a short period. In case such modern equipment is not available, and when there is a need to improve water management, such curves could be developed using the relationship between relative depth and relative area, and normal survey methods.

The results showed that the relationships between storage, surface water area and depth of water were consistent among the different Tanks when they are located in the middle or lower reaches of the river basin. The reasons for inconsistent relationships obtained for the Tanks located in the upper reaches are not clear and need to be investigated further.

The Tanks are built on narrow and shallow inland valleys [12] and a Tank can be described as an alteration to the natural landform which contains both the Tank bed and the irrigated command. Therefore, the location of the sluice has a relationship to the natural landform. However, if the location of the sluice is changed due to non-agricultural requirements, then the relationships described above may not be applicable. An example is the location of the sluice at a high elevation from the Tank bed to preserve water for wild animals and prevent irrigation expansion in wildlife conservation areas. Extensive alterations of the Tank bed, such as excavations for the earth, can also have similar effects.

Expressing depth-area-capacity relationships in relative terms has several advantages compared to expressing the same in absolute terms. Being dimensionless variables, the relationships are not affected by the units used for measurement or surveys. Relative depth or relative storage indicates the status of water availability in the Tank and facilitates water management.

While the rehabilitation of Village Tanks is expensive, the establishment of a simple water depth gauge in a Tank and engaging the farmer organization for water management and maintaining water level records can be achieved within a small budget. The use of the concepts such as storage resilience and storage reliability can be facilitated with such a measure, and those concepts, which can be derived in one or two years, will provide a baseline for prioritizing Tanks and cascades for rehabilitation, upgrading, or modernization.

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