
H.A.H. Jayasena, Rohana Chandrajith* and K.R. Gangadhara

Department of Geology, University of Peradeniya, Peradeniya, Sri Lanka.

(*)Corresponding Author email: rohanac@pdn.ac.lk

ABSTRACT

Since 3rd century BC tank cascade systems in the lowlands within the dry and intermediate zones of Sri Lanka have evolved in order to efficiently manage the surface water resources. The spatial distribution of tanks as exemplified by the topographic maps seems to follow a regular pattern. This study was conducted with data collected from 4633 tanks, to understand the distribution pattern of tanks in cascades in the Deduru Oya river basin. This river basin recorded the highest tank density (one tank in terms of numbers per 1.2 km²) in Sri Lanka. We devised a tank sequence number and assigned to each tank along the axes of the watersheds. Based on rainfall regime of 100mm intervals over individual cascades, the sequence number variations were plotted considering rainfall regime and cascade characteristics. The results indicate that the number of tanks against the tank sequence number is following a log linear relationship in which the gradient varies from -0.210 (1200-1300 mm rainfall regime) to -0.653 (1800-1900 mm regime). The gradient of graphs defined in this study as the “Degree of Cascading” varies from 1.6 to 4.5 towards the wet regions in the Deduru Oya basin. System attributes such as more tanks in wetter areas and increasing tank size in a downstream direction reflect the integration of the cascade system with the local morphologic and geographic setting. The study indicates that the tank cascade systems in Sri Lanka have evolved from simple ponds to systematic pattern of tanks for efficient water distribution.

INTRODUCTION

The dry zone minor irrigation clusters of Sri Lanka were widely considered as one of the unique water conveying and management systems among the ancient civilizations of the world. This is now known as ‘Tank Cascade Systems’ (TCS) and has been known to impact the irrigation systems in Sri Lanka since 3rd century BC. The island of Sri Lanka is characterized by two contrasting climatic zones known as the “wet zone” and the “dry zone”. An intermediate zone is also recognized between these zones (Fig. 1). Limited water availability and high ambient temperatures are characteristic of the dry zone where the monsoon rains are confined to two or three months of the year with a bimodal annual distribution.

Intermittent water flows are common in the dry zone lowland areas which cover nearly two thirds of the island. Since water is a scarce resource in the dry zone of Sri Lanka, drainage from the highlands towards the dry lowlands has been harnessed by tanks to irrigate extensive paddy fields by ancient communities. The tanks and related water conveying structures were particularly developed in the dry and intermediate climate zones of Sri Lanka where average annual rainfall varies from 900 to 1800 mm. More than 12,000 operational tanks and reservoirs have been identified within these zones, and a similar number still remains abandoned.
A TCS is defined as a connected series of tanks organized within minor or meso-catchments of the dry zone landscape (Fig. 2). The tanks in these meso-catchments served to store, convey and utilize water from ephemeral rivulets (Madduma Bandara, 1985). Panabokke (1999) identified meso-catchments within the cascade system as a small unit in the topo-sequence with an average area of 21 sq km and ranging from 13 to 26 sq km. The dry and intermediate lowlands of Sri Lanka are characterized by a rolling topography surrounding the central mountainous highlands. Surface streams from central mountain regions slowly meander through the dry zone lowlands to the Indian Ocean. The lowland plain, where TCSs were mainly constructed, has an average relief of 100 meters above msl. The geology and the geological structure of the dry zone are also factors that govern the tank distribution (Jayasena et al., 1986, Jayasena, 1993). Most tanks were constructed in this Precambrian terrain, and in many cases, rock exposures have been used as their embankments (Cooray, 1984). However, the tank beds are located on alluvial deposits and on weathered overburden of varying thickness (Jayasena et al., 1986).

The small tanks in Sri Lanka have been subjected to a number of studies during the last two centuries because of its remarkable socio-technical significance associated with the natural environment. For instance, the distribution and irrigation potential of tanks have been discussed by Nicholas (1954, 1960) and Dharmasena (1985, 1989). In addition, the archeological and historical significance (Nicholas and Paranavithana, 1951; de Silva, 1977; Gunawardana, 1971), the morphological and geological controls (Cooray, 1984; Tennekoon, 2000), the endowment within the socio-technical systems (Jayasena and Selker, 2004; Gangadara and Jayasena, 2005; Jayasena and Gangadara, 2006) of tanks have been extensively discussed. Several attempts have been made to describe the evolution of the TCSs in Sri Lanka; however, more recent investigations have shed some light on the outcome of the planning and designing of the tanks. The modeling of TCS (Jayatilake et al., 2003) and return flow through paddy fields (Matsuno et al., 2003; Li and Gowing, 2005) express that the seepage and percolation losses from a tank in a cascade system are considerably higher than the design seepage and percolation rates for small tanks. Mahatantila et al. (2007) showed the presence of an active ‘constructed wetland’, locally known as ‘Thaulla’ (Fig. 2) which plays a major role in decontaminating the water flow into the tanks. It appears that some aspects of the TCS design were developed to improve return flow and to control non-point pollution of the water supply.

Although extensively studied, tanks and associated diversion canals in Sri Lanka unearthed scanty information about their planning and design. Therefore, the main objective of this paper is to characterize the spatial distribution of tanks along the meso-catchments with respect to the climatic variations and basin characteristics in an area. Water storage tanks in the Kurunegala District, which are mainly drained by the Deduru Oya, were selected for this study. The Deduru Oya basin is known as an area of high climatic variability that invariably resulted in the highest density of small tanks (one tank per 1.2 km²) in Sri Lanka (Panabokke et al., 2002).

**METHODOLOGY**

The Deduru Oya basin is the fourth largest river basin in Sri Lanka which extends over an area of approximately 2600 km², with the main stream having a total length of 115 km. The river originates from the headwater regions in the mountains of central Sri Lanka and flows over the Precambrian terrain. Most part of the basin falls within the intermediate climatic zone (Fig. 1). The Deduru Oya flows through the three physiographic regions, namely, the highlands, uplands and lowlands, identified on the basis of three major breaks-in-slope (Vitanage, 1972).

Information such as rainfall, cascade names and individual boundaries, number of tanks and their sequence numbers of 4633 small tanks in 25 cascades in the Deduru Oya basin and surrounding regions in the Kurunegala District was collected from topographic maps, aerial photographs and digital base maps. From the above, 11 cascades covering approximately 100 sq. km area in the Wariyapola topographic sheet were selected for detailed desktop and field studies.
The watershed boundaries (meso-catchments) were delineated, and tank sequences were enumerated based upon the drainage network of the watershed moving from source to the outlet. The sequences of tanks were classified based on the number of tanks upstream where the first sequence number indicates a tank at the headwater with none above it. Sequentially higher orders are always located towards the tail end of the cascade as water from each tank passes into the next (Fig. 2). The average annual rainfall collected by the Meteorology Department (from 1300-1900 mm/year) was used to delineate seven rainfall regimes with 100 mm/year increments. Smaller or larger check-dams (locally known as is-wetiya or wetiya, respectively) which are confined to the headwater regions of the basin were disregarded in the calculations. Both features are small earthen dams with relatively smaller height with a saddle in the center, which were identified on aerial photographs and confirmed during the field investigations.

At present, these check dams serve as temporary detention structures to retain water during the rainy season. All tanks which are represented by a sequence number within each rainfall regime were recorded for each local watershed.

**RESULTS AND DISCUSSION**

The sporadic rainfall received in the study area shows a bimodal distribution in which most rains in the region are received between October and December with small peak in March and April. The annual rainfall over the system of tanks within the study area decreases towards northwest. The tank sizes are increasing and the total number of tanks within a given sequence decreases towards the mouth of the individual drainage basin, which shows a quasi-parallelism with the rainfall pattern. The tank sequence data were categorized based on individual rainfall regimes and on some selected individual cascade systems (Fig. 1).
Figure 2: (a) Schematic diagram showing progression of check dam based water ponds to TCS and associated man-made features; (b) The nomenclature of tanks used for the analysis.

The plots of the sequence numbers vs. number of tanks in the cascade system, classified based on individual cascades and rainfall regimes are shown in figures 3 and 4, respectively. These plots show a clear log linear relationship. The regression ($R^2$) of graphs for individual cascades is given in Table 1. The gradients and the regression ($R^2$) of graphs obtained from tank sequence vs. rainfall regimes are given in Table 2. The regression ($R^2$) was found to be $< -0.975$ for data based on individual cascades after eliminating the extreme end sequence tank for larger cascades while the gradient of $<-0.970$ was obtained for data based on rainfall regimes (at $p=95%)$. These linear relationships are very well established in many sub catchments in the Deduru Oya basin, when the largest tank at the end of the cascade system is not considered. The respective gradients obtained for tank distribution within different rainfall regimes vary from $-0.210$ (1200-1300 mm) to $-0.653$ (1800-1900 mm).

Based on the above plots, the gradient (slope) of the plot and its relevance to the geometry of the tank network could be described using the term “Degree of Cascading” (DOC) introduced by us and given below.

$$\text{DOC} = 10^{-|\text{Slope}|} \quad \quad \quad (1)$$

The DOC can be defined as branching of sequential tank distribution in a drainage network, which is theoretically equal to 1, if tanks were built only along a single linear basin, or approaches to infinity, if the basin has infinite branches with only headwater first sequence tanks. The DOC represents both the geomorphologic slope and the rainfall regime; because high rainfalls with higher slope regimes represent a large number of first sequences number tanks while low rainfall with lower slope regimes represents few sequentially arranged large tanks with a higher sequence number along the basin.

For the Deduru Oya basin, the DOC varies from 1.6 in the lower rainfall regime (1200-1300 mm) with relatively flat areas to 4.5 in the higher rainfall regime (1800-1900 mm) with gentle sloping areas. Therefore, the tank density within the TCS increases with increasing DOC.

However, in practical applications, steep mountainous regions with high rainfall cannot be used to construct cascade tanks due to rapid flows or landslides. The material used to construct such structures could not withstand impoundment of water into a tank and rather would prefer to divert the flow through artificial canals. On the other hand, in the extreme low rainfall regions with relatively flat terrains it may be necessary to inundate large areas to trap a meager flow. Therefore, as practiced by the ancient hydraulic experts, only runoff diversions could be possible in steep mountainous areas, whereas only very few large tanks could be constructed in the dry flat areas.
Table 1: Sequence distribution and respective gradients for some selected cascade systems in the Deduru Oya river basin (the number of tanks in the higher sequence number shown in parenthesis were eliminated for calculation of $r^{n-1}$).

<table>
<thead>
<tr>
<th>Name of the Cascade</th>
<th>Sequence number (n)</th>
<th>Regression ($R^2$)</th>
<th>Gradient ($r$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baladora</td>
<td>26 5 2 1 (1)</td>
<td>-0.938 -0.980</td>
<td></td>
</tr>
<tr>
<td>Bayawa</td>
<td>10 2 1 (1)</td>
<td>-0.903 -0.975</td>
<td></td>
</tr>
<tr>
<td>Bogoda</td>
<td>11 2 1 (1)</td>
<td>-0.900 -0.972</td>
<td></td>
</tr>
<tr>
<td>Nelliya</td>
<td>14 4 1 (1)</td>
<td>-0.946 -1.000</td>
<td></td>
</tr>
<tr>
<td>Thambarama</td>
<td>9 2 1 (1)</td>
<td>-0.908 -0.978</td>
<td></td>
</tr>
<tr>
<td>Pannithawa</td>
<td>8 3 1</td>
<td>-0.999</td>
<td></td>
</tr>
<tr>
<td>Karagaswewa</td>
<td>7 3 1</td>
<td>-0.997</td>
<td></td>
</tr>
<tr>
<td>Malagane</td>
<td>8 3 1</td>
<td>-0.999</td>
<td></td>
</tr>
<tr>
<td>Hiththrapola</td>
<td>12 3 1</td>
<td>-0.998</td>
<td></td>
</tr>
<tr>
<td>Dorabawaththa</td>
<td>4 2 1</td>
<td>-1.000</td>
<td></td>
</tr>
<tr>
<td>Kadawelagedara</td>
<td>20 5 1</td>
<td>-0.999</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Gradient and regression for tank sequence number vs. rainfall regimes in the tank cascade systems.

<table>
<thead>
<tr>
<th>Rainfall regime (mm)</th>
<th>Regression ($R^2$)</th>
<th>Gradient ($r$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200-1300</td>
<td>-0.970</td>
<td>-0.210</td>
</tr>
<tr>
<td>1300-1400</td>
<td>-0.993</td>
<td>-0.374</td>
</tr>
<tr>
<td>1400-1500</td>
<td>-0.998</td>
<td>-0.448</td>
</tr>
<tr>
<td>1500-1600</td>
<td>-0.996</td>
<td>-0.481</td>
</tr>
<tr>
<td>1600-1700</td>
<td>-0.977</td>
<td>-0.432</td>
</tr>
<tr>
<td>1700-1800</td>
<td>-0.997</td>
<td>-0.509</td>
</tr>
<tr>
<td>1800-1900</td>
<td>-0.998</td>
<td>-0.653</td>
</tr>
</tbody>
</table>

CONCLUSIONS

The number of tanks vs. tank sequence number in the cascade system follows a log linear relationship with strong negative gradient indicating the density of headwater tanks sequentially decreasing towards the tail-end of the watershed. The degree of cascading (DOC) varies from 1 to infinity and that depends on the rainfall regime and geomorphologic slope. The DOC in the Deduru Oya basin varies from 1.6 to 4.5. In the study area, the number of tanks is high in gently sloping terrains which are characterized by higher annual rainfall. On the other hand, the number of tanks is low but the sizes of tanks become large towards flat regions with low rainfall. The ancient cascade systems in Sri Lanka were developed through a systematic tank distribution network, considering the rainfall and the morphology of the terrain. This practice seems unique to Sri Lanka and due appreciation for the ancient hydraulic engineers should be placed in future studies. These ancient practices and the DOC could be a guideline for modern irrigation constructions and developments.

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