Implications of storage state behaviour of village tanks in adaptation to climate change, Sri Lanka

K. T. N. Perera, T. M. N. Wijayaratna, H. M. Jayatillake,
Tilak Priyadarshana and J. M. A. Manatunge

ABSTRACT

Following Decision 1/CP.21 of the Conference of the Parties, Sri Lanka has identified Nationally Determined Contributions for adaptation to climate change. Restoration and rehabilitation of all abandoned tanks is one such contribution in the irrigation sector. The country has around 13,600 working village tanks of ancient origin. These restored tanks provide irrigation and other water needs at different degrees while a large number of tanks remain abandoned. However, regional storage behaviour of the restored tanks is not adequately understood due to the non-existence of a methodology for storage data collection and assessment. The study presents a statistical approach to assess regional storage behaviour of the tanks with data collected using five storage states method. The storage data of 573 working village tanks in southern Sri Lanka covering three years were analyzed, and revealed a high temporal variation of storage behaviour and low resilience to recover from either dryness or failure for providing irrigation water issues. However, higher time-reliability of water-existence below sluice sill level indicates their potential for providing social and environmental needs. Such assessments facilitate identifying real-time management measures and reviewing policy on restoration of similar reservoirs as an adaptation option for climate change in any region.

Key words | climate change adaptation, reliability, resilience, storage states, transition probability, village tanks

K. T. N. Perera (corresponding author)
Irrigation Department,
Research Support & Process Improvement Branch,
230, P.O. Box 1138, Bauddhaloka Mawatha,
Colombo 7,
Sri Lanka
E-mail: *138037k@uom.lk*

T. M. N. Wijayaratna
J. M. A. Manatunge
Department of Civil Engineering,
University of Moratuwa,
Katubedda,
Sri Lanka

H. M. Jayatillake
Ministry of Mahaweli, Irrigation, Agriculture and Rural Development,
ADB – Transaction Technical Assistance, Integrated Water Productivity Improvement Project,
Colombo 5,
Sri Lanka

Tilak Priyadarshana
Department of Limnology and Water Technology, Faculty of Fisheries and Marine Sciences & Technology,
University of Ruhuna,
Wellamadama, Matara (81000),
Sri Lanka

HIGHLIGHTS

- Use of five state assessment methods to monitor the storage behaviour of small scale reservoirs where storage measurements are not available.
- Use of statistical approach to analyse storage behavoiur on a regional basis.
- Analysis of storage behaviour using storage state and storage state transitions.
- Comparison of seasonal storage behavior of reservoirs using state transition probabilities.
- Assessment of resilience and reliability of reservoirs using storage state behaviour.

INTRODUCTION

Increasing water storage capacity is identified as one of the key adaptation strategies to mitigate the effects of climate change on water resources (UNCCS 2019). Traditional surface storage systems such as small scale reservoirs play a vital role in providing water needs and exist in many countries in the Asian Region such as Sri Lanka, India, Japan, Burma, Thailand and Cambodia (Begum 1987). In India, about 208,000 such reservoirs exist, and they account

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for 60% of the tank irrigation in the country (Nagarajan 2013).

In Sri Lanka, around 13,600 small scale reservoirs termed village tanks exist in working condition with periodic rehabilitation (DoAD 2012). The village tanks in Sri Lanka fall under the category of the minor irrigation works which are defined as those having command areas up to 80 ha (GoSL 2000). Around 25% of Sri Lanka's paddy production comes from minor irrigation systems, and the livelihood of people relying on these systems highly depends on the water availability of these tanks (Bronzoni 2015).

The country has a history of over 2500 years in building reservoirs of varying scale for storing water to manage the effects of the seasonality of rainfall. A large number of village tanks of ancient origin are spread over the agro-ecological regions in the dry and intermediate climatic zones of the low-country. The climate of the dry zone is tropical alternating wet and dry, while both zones have a bi-modal rainfall pattern. The village tanks provide water mainly for supplementary irrigation, in addition to providing other water needs of the communities at different degrees. These tanks are also considered as a sustainable measure for watershed management in coping with the effects of climate change (Bebermeier *et al.* 2017).

However, they have been experiencing water scarcities affecting their agricultural performance. The command areas of most of them are more than the tanks can support, and the cropping performance realized has been far below the optimum (Dharmasena 2000; Somasiri 2000; MIWR&DM 2018). The situation has further been aggravated by varied catchment yields that depend on factors such as catchment shape and size, surface cover, soils, land use, rainfall intensity-duration relationship, drainage density and the rainfall season (Somasiri 2000). In this background, frequent water shortages and seasonal crop failures have been reported making the people depending on them more vulnerable in terms of both food security and their livelihoods (MIWR&DM 2018).

The effects of climate change have become an added stressor on these systems, and higher temperatures, reduced rainfall and higher evaporation with an increased frequency of extreme events affect the spatial and temporal freshwater availability in the country (Eriyagama *et al.* 2010). The projections on climate change indicate that the effects will further be increased and water and agricultural sectors will be more vulnerable (Collins *et al.* 2013; Hijioka *et al.* 2014; IPCC 2014, 2018). Adaptation measures such as increased water harvesting and storage, improving irrigation efficiency and implementation of climate criteria for agricultural programmes have been proposed to mitigate the effects of climate change in the sectors (UNCCS 2019). However, the importance of the selection of optimum adaptation options, including them into policies and implementing them with suitable approaches have been emphasised (Dewulf *et al.* 2015) to face the vagaries of both prevailing and the projected impacts of climate change.

Sri Lanka has identified Nationally Determinant Contributions (NDCs) following the decision of the Conference of Parties (COP) 21 of the United Nations Framework Convention on Climate Change (UNFCCC). Restoration and rehabilitation of all abandoned tanks and irrigation canals of ancient origin are one of the irrigation sector NDCs identified for adaptation to climate change (MoMD&E 2016a, 2016b). The larger tanks of ancient origin that had been abandoned for a long period had been restored or renovated by the early 20th century, and the restoration of village tanks continued up to the 1980s, thus leaving only the remaining smaller village tanks to be restored.

However, the storage behaviour of restored village tanks has not been adequately understood either spatially or temporally due to the absence of data on storage behaviour. Although a water balance modelling approach has been adopted for a tank series to determine the water availability (Jayatilaka *et al.* 2003), such an approach will not facilitate generalization of the results for a region. The performance evaluation of water resource systems in terms of reliability, resilience and vulnerability can generally be carried out if measured data are available (Asefa *et al.* 2014).

However, the village tanks in Sri Lanka do not have a storage data monitoring or recording method, and the storage data collection method generally used for larger reservoirs is not practical in village tanks due to the large number and their vast distribution. Hence, the storage behaviour of village tanks on a regional basis has not been assessed. Therefore, it is essential to assess and adequately understand the spatial and temporal storage behaviour of the working village tanks to rationalize the restoration of abandoned tanks as an adaptation option to address the uncertainties and challenges associated with the effects of climate change.

This article presents the regional and temporal storage behaviour of working village tanks during three years with observed storage data of 580 such tanks in southern Sri Lanka. It also discusses the implications of regional storage behaviour of the tanks in terms of storage reliability and resilience for providing irrigation water through sluice issues and the existence of water in the tanks for other needs.

MATERIALS AND METHODS

Geographical and agro-ecological scope

The geographic scope of the study area covers the Hambantota Administrative District. The District has 642 working village tanks out of 13,578 in Sri Lanka, and it is the fifth highest-ranking district (DoAD 2012). The abandoned tank density in the district is high (Witharana 2007), and high tank densities are also prominent in some other areas of the country. The country consists of 46 categories of agro-ecological regions delineated based on rainfall characteristics, terrain and the dominant soil group. The 75% expectancy-value of annual rainfall and the 75% probability monthly rainfall distribution derived from the long-term rainfall characteristics of a particular region are the two rainfall attributes considered in delineating the agro-ecological regions. (Punyawardena *et al.* 2003).

The district located in the southeastern part of the country has an area of 2,623 km^2 and consists of four such agro-ecological regions. The major part of the district falls under the Dry zone in the Low-country (DL), and a significant portion of the remaining area falls under the Intermediate zone in the Low-country (IL) while a relatively smaller part falls under the Wet zone in the Low-country (WL) (Figure 1). The dry zone in the district consists of DL5 and DL1b agro-ecological regions where the 75% expectancy-value of annual rainfall ranges from 650–750 to 900–1,100 mm respectively. The intermediate zone in the district consists of IL1b agro-ecological region where

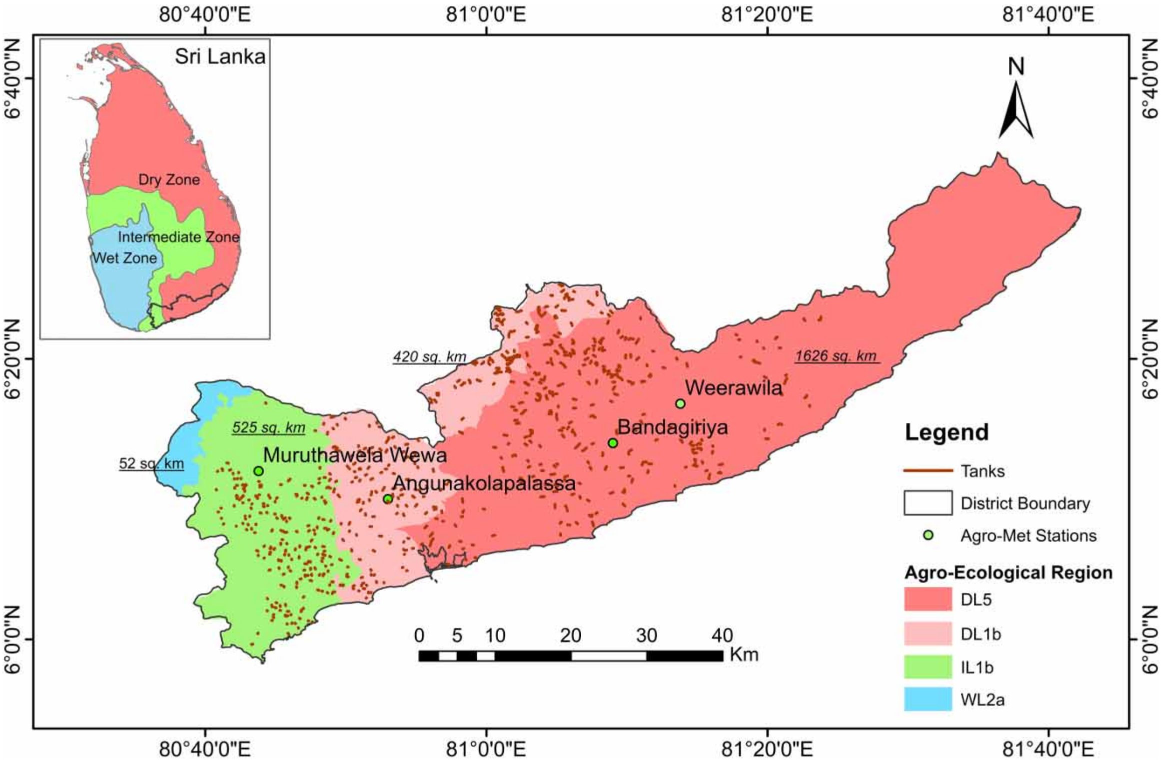

Figure 1 | Map of Hambantota District showing agro-ecological regions and village tanks.

the 75% expectancy-value of annual rainfall ranges from 1,100 to 1,400 mm, and the wet zone in the district consists of WL2a agro-ecological region where the 75% expectancy-value of annual rainfall ranges from 2,400 to 2,800 mm.

Accordingly, Hambantota District consists of the main categories of agro-ecological regions which are found in the other parts of the country where the tank densities are high. Hence, the storage behaviour of the tanks in the district would be an indicator of the performance of tanks in similar categories of agro-ecological regions in the country.

The country receives three types of rainfall, namely, monsoonal, convectional and depressional, and the monsoonal rains are the prominent type. There are two monsoons, namely, the northeast and southwest depending on the wind direction. The central highlands govern the rainfall driven by the monsoonal winds, and it causes a spatial variation of rainfall in the regions based on their location relative to the highlands. It also creates a bi-modal rainfall pattern which is prominent in most parts of the country within a water year starting from October to September of the following year (AMS 2012). The bi-modal nature of rainfall makes two main cropping seasons possible, namely, the *Maha* and *Yala*. *Maha*, the wet cropping season, runs from October to March with the *Yala*, the dry cropping season, lasting from April to September (Ponrajah 1984). Village tanks in the district are mainly used for agricultural purposes during the two cropping seasons, and their storages vary with the climatic factors and water uses.

Tank storage assessment

Storing water when there is a runoff during the rainy season and releasing water when irrigation of farmlands is required are the two main functions of village tanks. A working village tank generally consists of a 1.2–6.0 m high earth embankment built across shallow valleys, an overflow section, sluice outlets and the associated command area. The tank storages vary with inflows mainly generated from the rainfall, water issues for irrigation and evaporation from the tank.

These tanks do not have water level gauges, and hence the five storage states method has been developed to fill the gap of nonexistence of storage monitoring methods for village tanks (Perera *et al.* 2016). The method consists of five storage states, namely, *dry* (state 1), *below sluice sill level* (state 2), *partially full* (state 3), *at spill level* (state 4) and *spilling* (state 5). The *spilling* represents the hydrological endowment of the tank, and *partially full* and *at spill level* represent the ability to issue water through the irrigation sluice outlet. The state *below sluice sill level* indicates the availability of storage only to meet social and environmental needs, and the *dry* state means ceasing of all functions associated with the storage of the tank. The tank storage states are categorical variables in ascending order, and hence they are ordinal variables. Each of these states is a representation of the storage performance of the tank for a specific period.

Every storage state has five transitions depending on inflows and outflows of the tank, and the storage states transition diagram (Perera *et al.* 2016) illustrates 25 possible storage transitions associated with the five storage states. Improving, neutral and depleting are the three main transition categories, and neutral implies that the storage state remains the same in two adjacent months. The improving and depleting transitions are further divided into two subcategories: rapid and gradual. If the current state (state i) transits over two or more states at the end of the specific time interval, it is considered a rapid transition, while if the transited state (state j) is immediately above or below the state i, it is regarded as a gradual transition. The probabilities of all these transitions can be evaluated considering the total number of transitions associated with a particular state i. The summation of all transition probabilities starting from a specific state i is equal to 1.

Non-parametric statistical tests are required to be performed on the data sets to assess the association between nominal or ordinal variables (IBM Knowledge Center 2017) such as the storage state data and agro-ecological regions.

Data collection and analysis

Since recorded storage data of the village tanks do not exist, the five storage state assessment method was adopted in this study, and data collection was commenced in October 2014. Storage state and cropping data of the tanks were collected through the existing institutional setup of the District Office of the Department of Agrarian Development with the assistance of the field officers in Hambantota District.

Monthly storage states of 580 tanks in the district were collected for three water years from October 2014 to September 2017 with periodic field verifications. The tank sample included 90% out of the 642 working tanks in the district. The data set consisted of seven tanks in WL2a, 317 tanks in IL1b, 143 tanks in DL5 and 113 tanks in DL1b agro-ecological regions. The 573 tanks located in IL1b, DL5 and DL1b agro-ecological regions where the tank densities are high were analysed to understand the storage state behaviour.

Monthly tank storage states and state transitions were analysed to identify monthly and seasonal variations in different agro-ecological regions. The storage state data, storage transition data and agro-ecological regions are nominal (categorical) variables. Hence, the non-parametric Chi-square test was performed to examine the association and its strength between storage states behaviour and the agro-ecological regions. SPSS software which has this facility was used for the purpose. The transition probabilities during the two cropping seasons were analysed using linear and quadratic regression models to investigate the storage transition behaviour of the tanks in the regions.

Monthly rainfall and evaporation data of the three agro-ecological regions were obtained from the Meteorological Department of Sri Lanka, and the climatic conditions prevailing during the period of observation were compared with the average climatic conditions of the past ten water years to verify whether the duration is representative. Further, the cropping regimes prevailing in the six cropping seasons under the tanks were also examined with the collected data on command areas and the cropped areas.

Storage reliability and resilience for providing irrigation water through sluice issues and the existence of water in the tanks for other needs were assessed, and the implications of storage behaviour of the tanks and their adaptive capacity for climate change were discussed based on the analyses.

RESULTS

Storage state behaviour of the tanks is governed by the rainfall and evaporation characteristics prevailing in the region and status of cropping which relates to the water issues from the tanks. Hence, the analyses of climatic conditions and cropping performance are also incorporated in the results which explore the background when analysing the spatial and temporal storage behaviour of the tanks.

Rainfall and evaporation characteristics

Since the intermediate climatic zone of the country is mainly located in the eastern slopes of the central highlands, it receives rain from both monsoons. The lowlands, which have a minimum influence from the highlands, receive low rainfall mainly from the northeast monsoon. Similarly, agro-ecological regions in the intermediate climatic zone receive higher rainfall than those in the dry zone. As such, there are some variations in evaporation among the regions (Figure 2).

Two main climatic drivers, namely rainfall and evaporation, affect the storage state of the tanks. Hence, rainfall data of Badagiriya, Angunakolapalassa and Murutawelawewa stations and evaporation data of Weerawila, Angunakolapalassa and Monaragala stations (Figure 1) were used to characterize the statistical parameters of DL5, DL1b and IL1b regions, respectively. The three extreme rainfall values in the plot (Figure 2) are outliers which belong to the wet *Maha* seasons of 2006/07, 2012/13 and 2010/11, and are outside the period of observation. Therefore, the climate during the period of observation is representative of the average decadal climatic behaviour of the regions. However, the comparison of rainfall during the three water years with the average rainfall of the previous ten years revealed that 2016/17 is a near-average year while 2014/15 and 2015/16 are above- and below-average years, respectively.

Both seasonal rainfall and evaporation distributions are not symmetrical, and hence median value is the suitable central tendency measurement. When the median of rainfall is higher than the median of evaporation, there could be a rainfall excess; on the other hand, when the median of evaporation is higher than the median of rainfall a rainfall deficit exists. Accordingly, in all three agro-ecological regions, a rainfall deficit exists in the dry *Yala* season in contrast to the wet *Maha* season (Figure 2).

As such, agro-ecological region IL1b has the highest rainfall excess and the lowest deficit in *Maha* and *Yala* seasons respectively, and agro-ecological region DL5 has the lowest rainfall excess and the highest deficit in the two

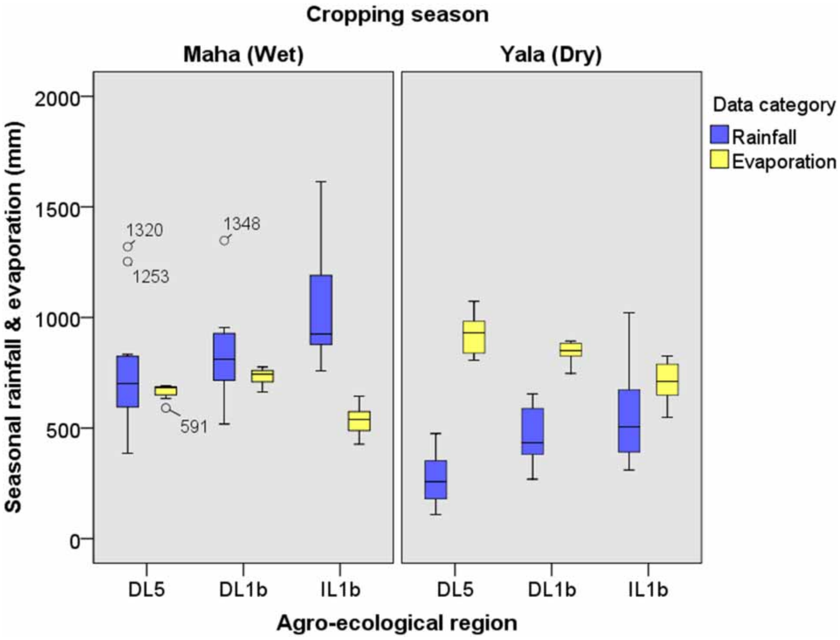

Figure 2 | Distribution of rainfall and evaporation for wet *Maha* and dry *Yala* cropping seasons in three agro-ecological regions for the period of 2004–2017.

respective seasons. Therefore, the potential of water availability of the three agro-ecological regions of DL5, DL1b and IL1b varies in ascending order.

Region-wise comparison of storage behaviour

The agro-ecological regions in the study area have different tank densities, and the IL1b region has the highest with 60 tanks per 100 km^2 while the other two regions DL1b and DL5 have 27 and 9 tanks per 100 km^2 respectively. Tables 1 and 2 provide the monthly observations of storage states and transitions of 573 tanks during the three years in the three agro-ecological regions.

The Chi-Square test of independence was performed on storage state data and storage state transitions data of agro-ecological regions to determine whether there is a significant difference between the expected frequency and the observed frequency of the given values. The cross-tabulations of agro-ecological regions vs. monthly tank storage states of the region and agro-ecological region vs types of storage state transitions are given in Tables 1 and 2 respectively.

The strength of association between the variables can be evaluated using the contingency coefficient, which ranges between 0 and 1. The zero indicates that there is no association between the two variables, and values close to 1

Table 1 | Cross-tabulation of agro-ecological regions vs monthly tank storage states of the region

		Monthly tank storage states					
		Dry	**Below sill level**	**Partially-full**	**At spill level**	**Spilling**	**Total**
Count and % within agro-ecological region	DL5	753	1,924	1,451	517	503	5,148
		14.6%	37.4%	28.2%	10.0%	9.8%	100%
	DL1b	271	1,902	1,222	367	306	4,068
		6.7%	46.8%	30.0%	9.0%	7.5%	100%
	IL1b	1,406	5,010	2,470	1,168	1,358	11,412
		12.3%	43.9%	21.6%	10.2%	11.9%	100%
Total		2,430	8,836	5,143	2,052	2,167	20,628
		11.8%	42.8%	24.9%	9.9%	10.5%	100%

Table 2 | Cross-tabulation of agro-ecological region vs types of storage state transitions

			Five types of monthly storage state transitions					
			Rapid depletion	**Gradual depletion**	**Neutral**	**Gradual improvement**	**Rapid improvement**	**Total**
Count and % within agro-ecological region	DL5	Count	195	701	3,332	562	215	5,005
		%	3.9%	14.0%	66.6%	11.2%	4.3%	100%
	DL1b	Count	168	566	2,547	486	188	3,955
		%	4.2%	14.3%	64.4%	12.3%	4.8%	100%
	IL1b	Count	639	1,546	7,271	934	705	11,095
		%	5.8%	13.9%	65.5%	8.4%	6.4%	100%
Total		Count	1,002	2,813	13,150	1,982	1,108	2,0055
		%	5.0%	14.0%	65.6%	9.9%	5.5%	100%

indicate a high degree of association between them. The results revealed that there is an association at the 95% confidence level between the storage state behaviour of the tanks and the agro-ecological regions.

However, the contingency coefficient value for the association between the agro-ecological regions and tank storage states is 0.131, while the contingency value for the association between the agro-ecological regions and the types of storage transition is 0.077. They imply that the association between agro-ecological regions and storage behaviour in terms of the tank storage states is low and that in terms of the storage state transitions is small. Hence, the storage behaviour of the tanks in the three agro-ecological regions could be considered as similar, and the temporal variations of storage states of tanks in the district were analyzed by taking the storage data of the tanks in the three regions as a single dataset.

Monthly behaviour of storage-states

The number of storage states observed is 20,628 during the 36 months for 573 tanks in the district, and the 100% stacked column plot (Figure 3) shows the monthly contribution of the tanks for each storage state.

The percentage of tanks in different storage states has a high monthly variation while tanks in all five storage states exist during any given month indicating the complexity of the tank storage behaviour in the study area. The reasons for the high variation of storage states of the tanks are the low depths and small storage capacities that make them highly sensitive to inflows, and outflows which include both water issues and evaporation losses.

The tanks also show the uncertainty of storage state behaviour due to the high variation of storage states year on year and among the cropping seasons. Low storage states

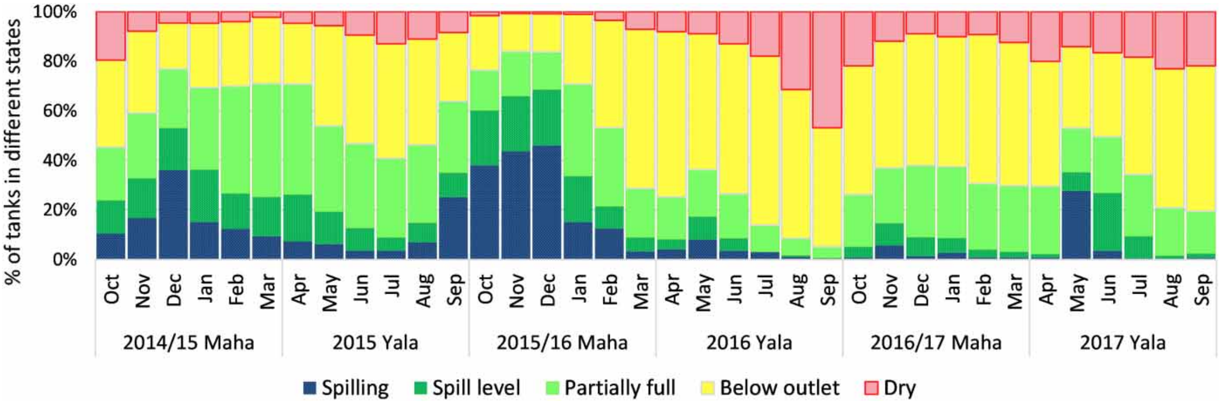

Figure 3 | Monthly variations of storage states of tanks in Hambantota District (October 2014–September 2017).

have been observed in *Maha* 2016/17 although the *Maha* season is usually wet.

The distribution of monthly percentage of tanks in each storage state is further analysed and shown in the form of a box plot in Figure 4.

The Kolmogorov–Smirnov test and the Shapiro–Wilk Test are two well-known tests of normality, and the Shapiro–Wilk test is performed with the 36 data as the test is more appropriate for small sample sizes. The results of the test reveal that the distribution of the *partially full* state is symmetrical and follows the normal distribution with a mean of 25%. The distributions of the other four states are skewed, and hence the suitable central tendency measurement is the median. The state *below sluice sill level* is the most prominent storage state of the tanks, and the state has the widest range with the highest median value of 45%.

Dry and *spilling* are the two outermost storage states of the tanks and the outliers shown in the distributions indicate the higher occurrence of outermost states. The dry state which severely affects the beneficiaries of the tanks has a median of 9%. The median of the existence of water in the tanks is around 91%, implying the higher potential for providing social and environmental benefits.

Monthly behaviour of storage state transitions

The number of monthly storage transitions occurring during the three years in the 573 tanks is 20,055, and they are divided into five transition categories. The 100% stacked column plot (Figure 5) shows the percentage of monthly storage state transitions over the study period.

All five transition categories were observed during the period with the neutral transition being prominent. The occurrence of transitions is synchronized with inflows and outflows, and the improvement transitions are mainly associated with the rainfall pattern. The rainfall in the water year 2014/15 is above average while it is below average in 2015/16. The rainfall is near average in 2016/17. There is a higher occurrence of improvement transitions in the water year 2014/15 and a lower occurrence in 2015/16, indicating the relative behaviour of improvement transitions with the rainfall pattern. A bi-modal improvement pattern exists in 2016/17, a year with near-average rainfall.

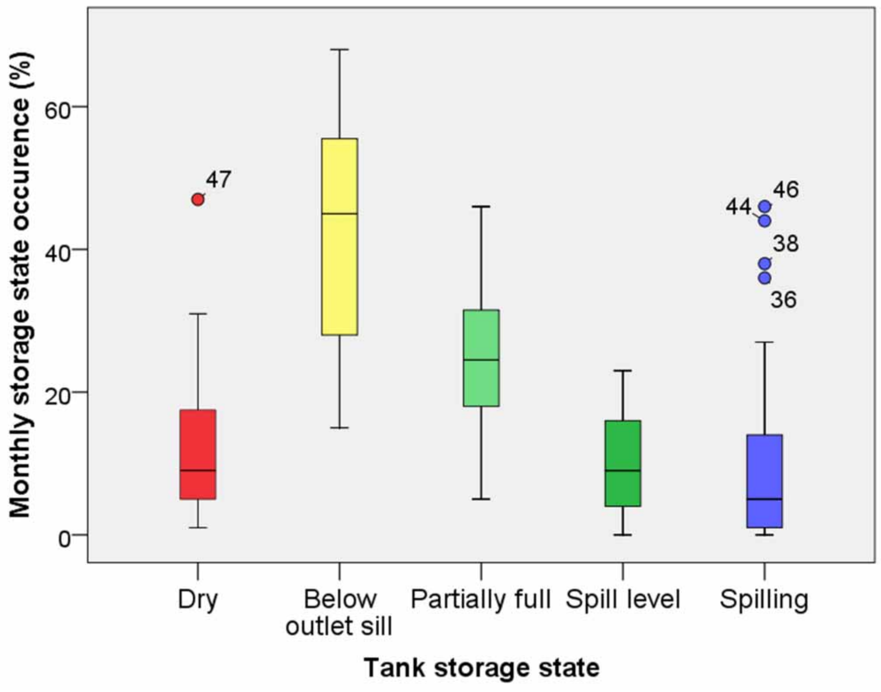

Figure 4 | Distribution of monthly tank storage states occurrences.

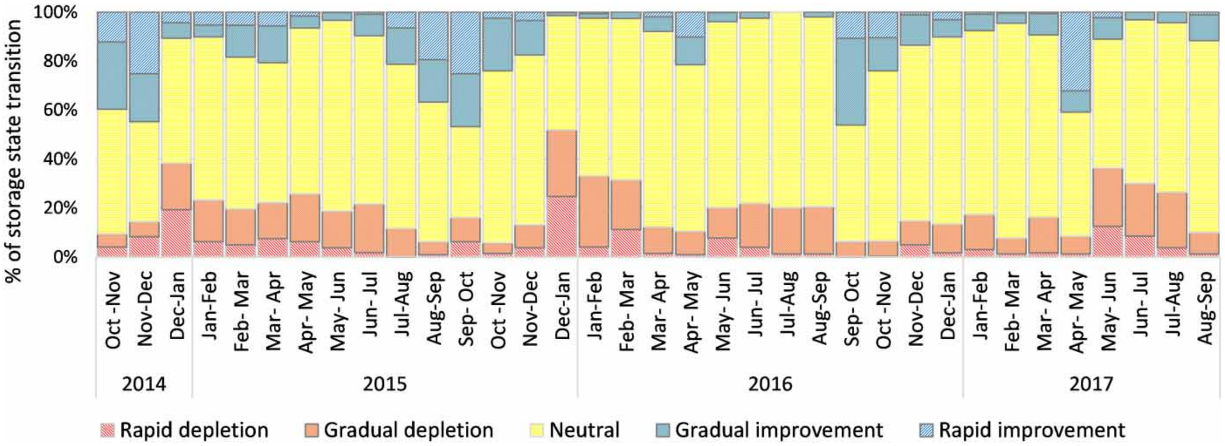

Figure 5 | Monthly tank storage state transitions in Hambantota District (October 2014–September 2017).

The box plot of five storage states transition types (Figure 6) shows that the percentage of tanks in the neutral state is the most prominent transition type over the period with a median of 68%. It implies that the likelihood of a tank being in the same state during the following month is higher, irrespective of its current state. The range of depletion and improvement transition distributions are low, and the outliers associated with rapid depletion and improvement transitions indicate the low adaptive capacity of the tanks to meet the climatic events prevailed.

The probabilities of monthly transitions occurring in the tanks during the three water years are given in the transition probability matrix of five storage states (Table 3).

The neutral transition probabilities of the tanks in each state range from 0.43 to 0.77, and the states *dry* and *storage below sluice sill level* show higher neutral transition probabilities. The higher neutral transition probabilities of the states *dry* and *storage below sluice sill level* imply low ability to improve storage state of the tanks when they go dry or fail to provide sluice issues. Further, the occurrence of gradual

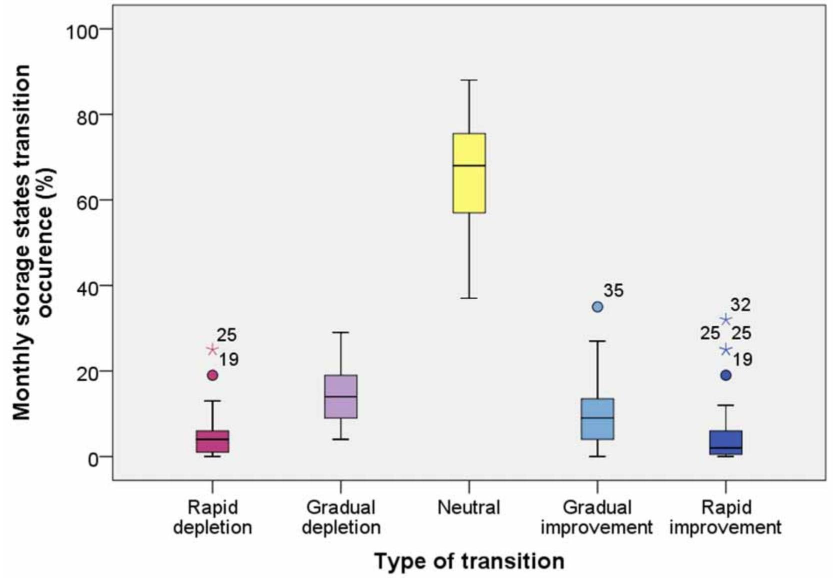

Figure 6 | Distribution of percentage of monthly storage transition occurrences.

Table 3 | Transition probability matrix of tank storage states

		Tank storage state in *j*th month					
		1	2	3	4	5	Total
Count and % of tank storage state in *i*th month	1	1575 68.3%	483 21.0%	107 4.6%	52 2.3%	88 3.8%	2305 100.0%
	2	628 7.4%	6520 76.7%	813 9.6%	236 2.8%	303 3.6%	8500 100.0%
	3	88 1.7%	1176 23.3%	3064 60.7%	395 7.8%	322 6.4%	5045 100.0%
	4	12 0.6%	246 12.0%	605 29.6%	888 43.5%	291 14.3%	2042 100.0%
	5	15 0.7%	210 9.7%	431 19.9%	404 18.7%	1103 51.0%	2163 100.0%
	Total	2318 11.6%	8635 43.1%	5020 25.0%	1975 9.8%	2107 10.5%	20055 100.0%

🟥 Rapid depletion ▨ Gradual depletion 🟨 Neutral ▨ Gradual improvement 🟦 Rapid improvement

transitions of the storage states in the tanks is higher than the rapid transitions.

Seasonal behaviour of storage state transitions

The scatter plots between Yala and Maha seasons (Figure 7(a) and 7(b)) show the linear and quadratic regressions for the three distinct clusters of improving, depleting and neutral transition probabilities. The neutral transition probability of the *dry* state in *Yala* season (0.82) is higher than that in *Maha* season (0.57), and it differs from the neutral transition probabilities of the other four states. Hence, linear and quadratic regressions of neutral transition probabilities are carried out only for the other four states (Figure 7(b)). The respective regression equations are given in Table 4.

The gradient of the linear regression equations allows the comparison of general storage transition behaviours between two cropping seasons for management purposes. The coefficient of regression is relatively higher in the quadratic regressions, and it is appropriate for the calculation of transition probability of a specific event. All three transition probabilities between *Yala* and *Maha* seasons show a strong positive correlation, and the improving transition probability of *Yala* season is around 40% of the improving transition probability of *Maha* season. The depletion and neutral transition probabilities in both cropping seasons show similar behaviour.

The storage resilience and reliability of village tanks

Storage states of village tanks vary among the five states, and the two states of *dry* and *storage below sluice sill level* are considered as failure states, taking into account the expected performance. As such, storage resilience of village tanks is defined as the ability of the tank to recover from either dryness or failure for providing sluice issues. Storage reliability is assessed on a temporal basis, and it is considered for the

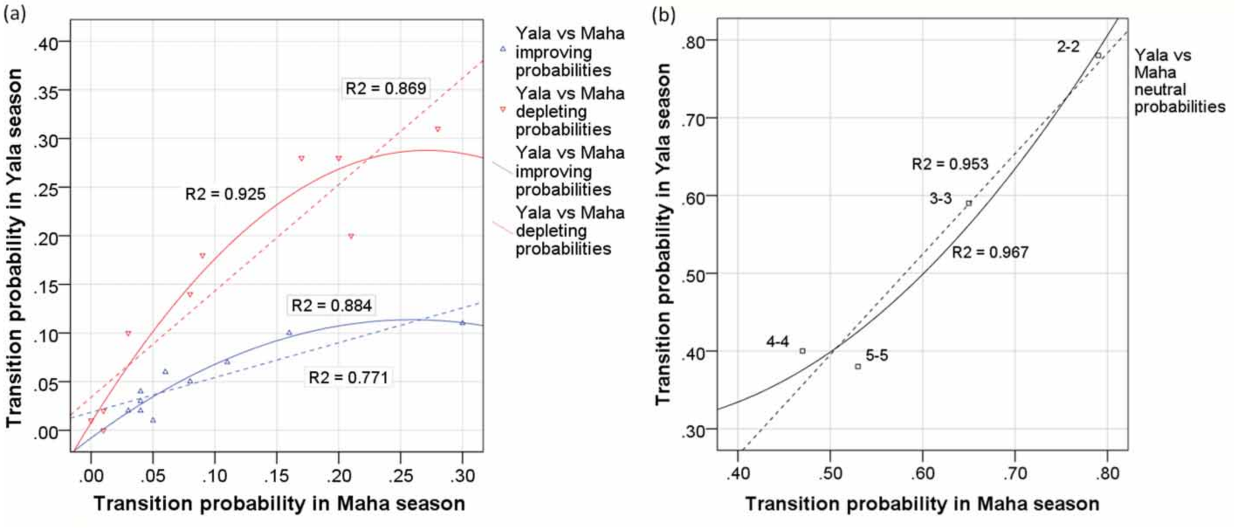

Figure 7 | Correlation of storage state transition behaviour between two cropping seasons: (a) Improving and depleting transitions; (b) Neutral transitions.

Table 4 | Linear and quadratic regression equations for storage state transitions

Transition type	**Linear regression**		**Quadratic regression**	
	equation	**R^2**	**Equation**	**R^2**
Depletion	$P_y = 1.09\ P_m + 0.03$	0.869	$P_y = -3.92\ P_m^2 + 6.1\ P_m - 1.61$	0.925
Improving	$P_y = 0.36\ P_m + 0.02$	0.771	$P_y = -1.81\ P_m^2 + 0.94\ P_m - 7.97\text{E-}3$	0.884
Neutral	$P_y = 1.29\ P_m - 0.25$	0.953	$P_y = 1.79\ P_m^2 - 0.96\ P_m + 0.43$	0.967

P_y – Storage state transition probability during *Yala* season.
P_m – Storage state transition probability during *Maha* season.

states with the ability to providing sluice issues or the existence of water in the tank. The time reliability of providing water as sluice issues is 45% during the observed period while the time reliability of the existence of water in the tanks is around 88%, implying higher potential for providing social and environmental benefits.

The transition probability diagrams for the performance on irrigation sluice issues and water-existent states for the period of observation and the two cropping seasons are shown along with the relevant key-diagrams of transition matrices (Figure 8(a) and 8(b)). The storage resilience of the tanks is evaluated from the transition probabilities, and the resilience for the possibility of sluice issues (0.15) is lower than the resilience for water-existent states (0.32). It implies that there is a high risk of water scarcity for the crops grown under the tank in case the storage state transit to a state of sluice issues is not possible. However, the probability of water existence in the tanks (0.96) is higher than the probability of drying up (0.04) during the period of observation. It indicates that the reliability of water availability in the tanks is high for social and environmental needs.

Seasonal cropping indices of the tank systems

The seasonal cropping index is defined as the ratio of the area cropped to the command area of the tank during a season, and it varies from zero to 1. Cropping indices of

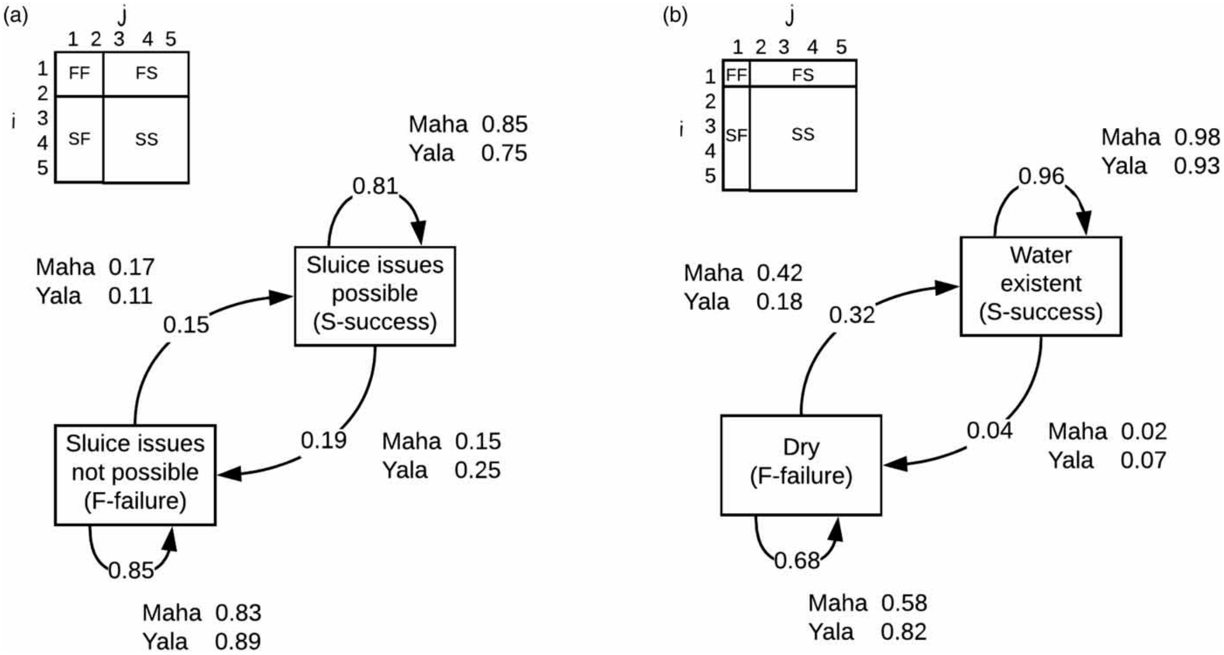

Figure 8 | Transition probability diagrams of: (a) possibility of irrigation sluice issues; (b) water-existence in tanks.

zero and 1 imply no cropping and cropping of the full command, respectively. A cropping index between zero and 1 means partial cropping. The crop grown under the tanks is mostly paddy rice during the wet *Maha* season while other field crops such as green gram, maize, peanuts, cowpea, millet, sesame along with rice are grown in the dry *Yala* season depending on the water availability. The command areas under the tanks in the district are small, and around 80% of them are below 16 ha.

Histograms of seasonal cropping indices (Figure 9) show the variability of the cropping performance of 573 tanks in the three agro-ecological regions under the prevailing storage behaviour. They have either unipolar or bipolar distributions which imply that partial cropping in any given season is minimal. The unipolar distribution is prominent in the wet *Maha* season with the full command area being cropped and little or no cropping in the dry *Yala* season. Bipolar distribution of cropping index is also identified in some *Yala* and *Maha* seasons, implying the uncertainty of cropping under these systems.

DISCUSSION AND CONCLUSIONS

The tanks in the three agro-ecological regions have near similar behaviours of storage states and storage transitions as there is only a low association between the agro-ecological regions and the occurrence of storage states. Hence, the impacts of the projected climate change on the tanks in the three agro-ecological regions would not be significantly different among regions, though the regions have different tank densities.

The behaviours of both storage states and storage transitions of the tanks in the study area have high temporal variations. The state *below sluice sill level* is the prominent state over the period, and the higher occurrence of neutral transitions associated with it means low water-existence in the tanks during most months of the year. There are significant differences in storage states and state transitions among the six cropping seasons, and the improvement of storage states during the wet *Maha* season is significantly greater than that during the dry *Yala* season. However, depletion and neutral transitions of the storage states are similar during both cropping seasons.

These storage behaviours indicate the low resilience of the tanks to recover from either dryness or failure for providing irrigation water through sluice issues. Accordingly, if the storage state transits to a state where sluice issues are not possible during the crop growing period, the risk of crop damage is high. Further, the variation of cropping indices over the seasons also validates the uncertainty of the water availability for irrigation. However, the low occurrence of *dry* state in the tanks signifies the social and environmental benefits associated with them.

The methodology presented in this study can ensure understanding of the near real-time storage behaviour of village tanks in a given region. The understanding of the storage behaviour allows the managers to be aware of and

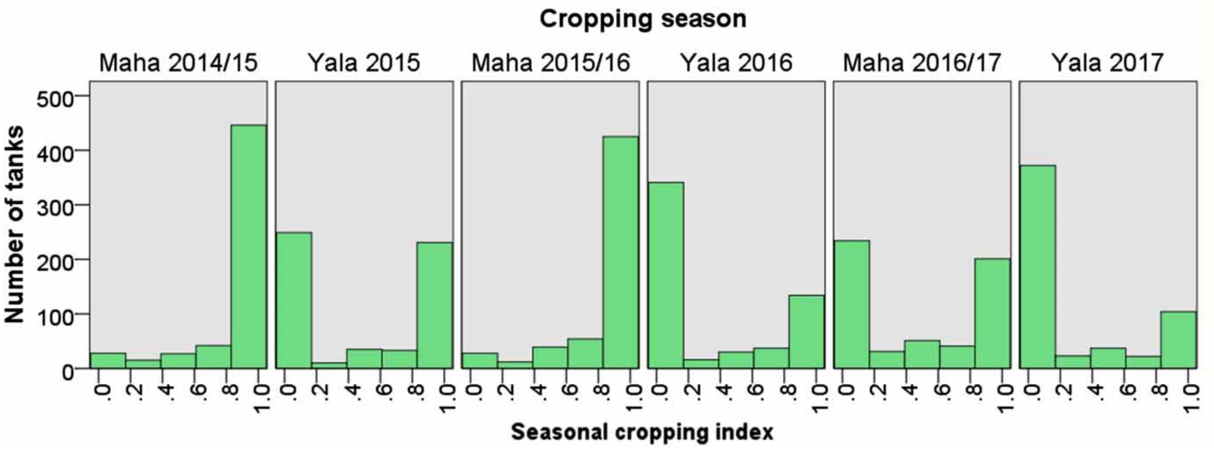

Figure 9 | Histograms of seasonal cropping indices in the area.

prepared for the times of water shortages to intervene with appropriate remedial measures. Further, the identification of storage behaviour for a longer period will also facilitate the planning of cropping patterns, improving water management and identification of modernization needs of the tank systems.

In addition to the managerial insights, the storage behaviour revealed by the study indicates that there could be limitations in adaptive capacity of the tanks for the projections of climate change. The smaller size and shallow depths of the tanks prevent storing more water during high-intensity rainfalls and the existence of water due to high evaporation caused by increased temperatures. Further, the occurrence of high-intensity rainfalls increases the possibility of tank breaching, and the limitations in increasing the spillway discharge capacities will aggravate the situation making these tank systems more vulnerable. Accordingly, there is potential for further reduction of storage reliability and resilience while increasing the vulnerability of the tank systems with the projections of climate change.

The extension of such evaluations to other areas will increase the data availability for the management and policy formulation. Storage state observations at short time intervals, such as weekly or at times of state changes for longer durations with beneficiary participation, will expand the scope of the analysis further. The developed methodology of the statistical approach can be applied to assess the spatial and temporal storage behaviour of regionally distributed small scale reservoirs where the scale type storage measurements are neither possible nor necessary.

Such evaluations are crucial for an adequate understanding of the real potential of small scale reservoirs in adaptation to climate change, and reviewing and updating the existing policies on the restoration of these reservoirs to make it a better option for adaptation in any region of the world.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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