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Analyzing the Dependence of Major Tanks in the Headwaters of the Aruvi Aru Catchment on Precipitation. Applying Drought Indices to Meteorological and Hydrological Data

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Abstract: This study aims to analyze the dependence of reservoirs (locally called tanks or wewas) in the headwaters of the Aruvi Aru catchment on precipitation and thus to evaluate their efficiency. The Aruvi Aru is located in the Dry Zone of Sri Lanka, and numerous human made reservoirs characterize the study area. The methodology is based on the application and correlation of climatic and hydrological drought indices. The Standardized Precipitation Index (SPI) is applied to precipitation data at different time scales and the Standardized Water-Level Index (SWLI) is applied to water-level data of five major tanks in the catchment. The results show that near normal present-day average precipitation is appropriate to fill the investigated tanks. The precipitation of the previous 6–12 months has the highest impact on water-level changes. A moderate to strong positive correlation between SWLI and SPI point to other factors besides precipitation affecting the water level of the tanks. These are: (i) catchment size together with the buffering capacity of the upstream catchment and (ii) management practices. As the overall conclusion of our study shows, the tanks functioned efficiently within their system boundaries.

Keywords: Sri Lanka; water harvesting; Standardized Precipitation Index (SPI); Standardized Water-Level Index (SWLI); wewa

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1. Introduction

For more than 2000 years, agriculture in the Dry Zone of Sri Lanka has been based on a sophisticated water management system [1,2]. This system consists of thousands of human made reservoirs that collect and store surface water, so called tanks or wewas, which are constructed cascade-wise in shallow valleys. The reservoirs are connected with each other by channels and spillways and increase in size downstream. Depending on the size of the water surface area of the reservoir and the irrigated area, the irrigation works in Sri Lanka are classified as major, medium, minor, and micro tanks [3]. Major tanks are in general located in the downstream part of the cascade and are defined by a water surface of > 200 ha and a command area (irrigated area) of > 600 ha [3,4]. The administration of the major tanks is the responsibility of governmental institutions. In contrast, small tanks are situated in the upstream parts of the cascades and are managed by local village communities [4].

The hinterland of the ancient capital Anuradhapura was the center for the spread of this water harvesting system throughout the Dry Zone of Sri Lanka from the 3rd century BCE onwards [5] (Figure 1). An initial expansion phase of the water harvesting system resulted in a distribution of tank cascade systems across the Dry Zone by the 2nd century CE. During the following centuries, the system experienced further expansion and refinement [5]. An essential measure to increase local water availability was the construction of a supra-regional channel network in the 5th century CE. This channel network enabled the routing of water from the catchment of the Mahaweli River via the catchment of the Kala Oya River to the catchment of the Aruvi Aru River in the vicinity of Anuradhapura [5,6] (Figure 1).

When evaluating this engineering feat of supra-regional water transfer, the question arises as to the reason for such costly and laborious activities. Was the exploitation of external water sources necessary because the tanks in the immediate hinterland of Anuradhapura did not function efficiently? Or was the exploitation of external water sources necessary to increase local water availability in drought periods? In this paper, we attempt to answer these questions by assessing the dependence of major tanks on precipitation. We apply meteorological and hydrological drought indices to modern meteorological data resulting in an evaluation of how efficiently and reliably the tanks are filled by local precipitation. Due to the lack of runoff or discharge data, the water-level data of major tanks serves as a proxy for water availability.

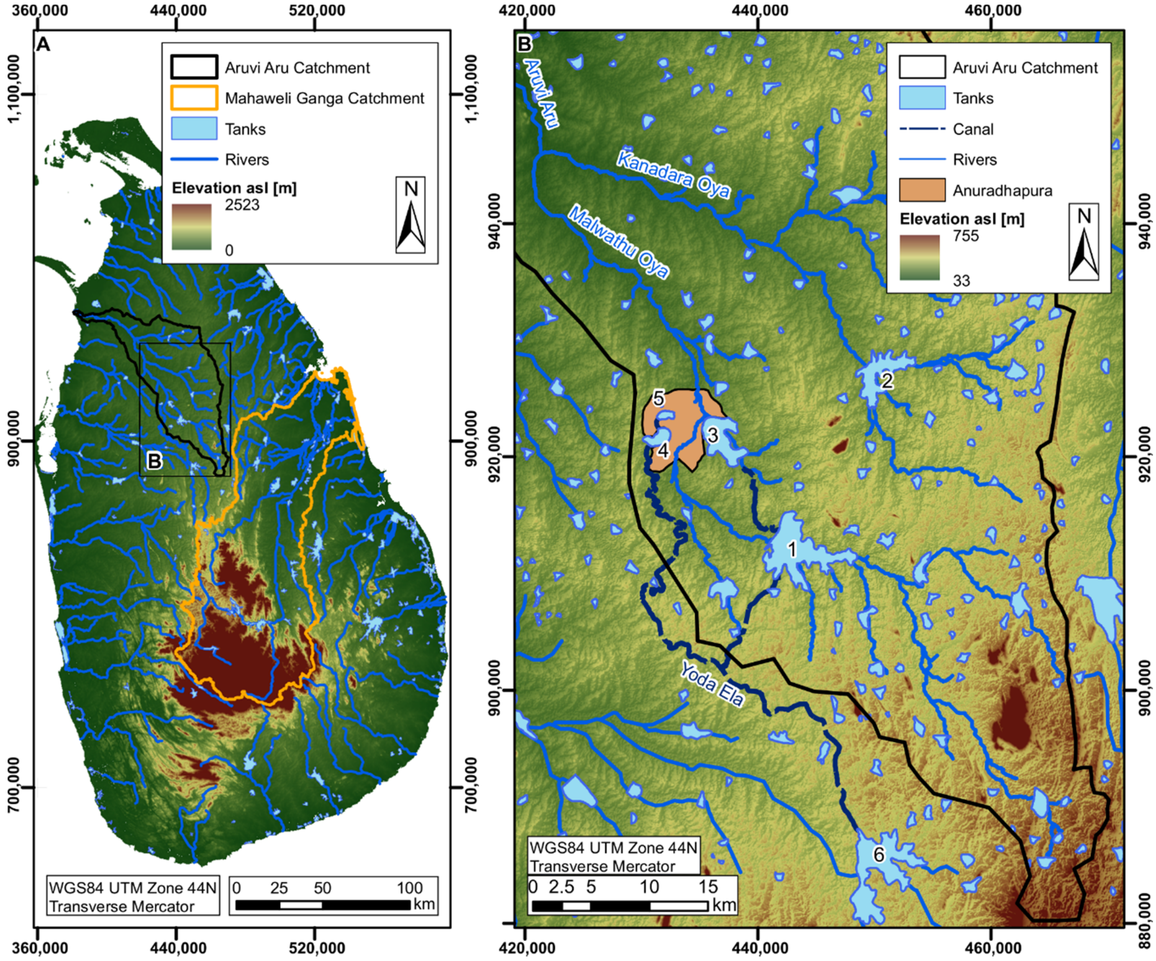


Figure 1. (**A**) Digital elevation model (DEM) of Sri Lanka, river network, location of the Aruvi Aru and Mahaweli Ganga catchments and study area; (**B**) DEM of the study area: the headwaters of the Aruvi Aru catchment and the tanks of interest within: (1) Nachchaduwa wewa, (2) Mahakanadarawa wewa, (3) Nuwara wewa, (4) Tissa wewa, (5) Basawakkulama wewa. Kala wewa (6), situated in the Kala Oya catchment, receives water via a channel from the Mahaweli Ganga and water from Kala wewa is diverted through the channel of Yoda Ela to different tanks within the Aruvi Aru catchment. Data source: DEM (Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global 30 m × 30 m, 2015); catchment, tanks, rivers, channel, Anuradhapura [7].

2. Study Area

The Aruvi Aru River and its tributaries drain a catchment area of about 3170 km^2 in north-western central Sri Lanka. The local relief is a slightly rolling plain corresponding to the expanded peneplain. This plain is intersected by shallow valleys and sporadic inselbergs. Altitudes vary between 33 and 755 m a.s.l. Bedrock consists of Precambrian crystalline basement rocks, mainly of granitic gneisses and quartzites [7,8]. Local soils are dominated by reddish brown earths and low humic gley [9], whereby reddish brown earths are the most frequent soil type [10]. Paddy cultivation is the main crop in the north central part of Sri Lanka, and in the areas of plateau-like divides this alternates with chena agriculture (shifting cultivation) [11]. The main cultivation period for rice is locally called Maha and lasts from October to March. The Aruvi Aru catchment is situated in the Dry Zone of Sri Lanka north of the Central Highlands. According to the Köppen-Geiger climate classification, the study area is categorized as an As-climate [12], with an average annual temperature of 28.4 °C and mean annual precipitation of 1341 mm (Figure 2). The major and minor rainy seasons (March to mid-May and October to November) alternate with the two Inter Monsoon seasons [13] (Figure 2). High evapotranspiration rates result in water stress especially during the period from May to September [14]. The central highland creates an orographic barrier for the South-West Monsoon [15]. Hence, the temporal precipitation pattern is predominantly disconnected from monsoonal periods. Dry spells and droughts are a common phenomenon in the study area [16]. Their occurrence is frequently associated with low or absent rainfall during the Maha season (October to March). In general, these droughts occur for six to nine months [17], and thus represent typical droughts in the humid tropics where drought duration is normally six months [18]. Multi-year droughts also occur in Sri Lanka, but are rare [19].

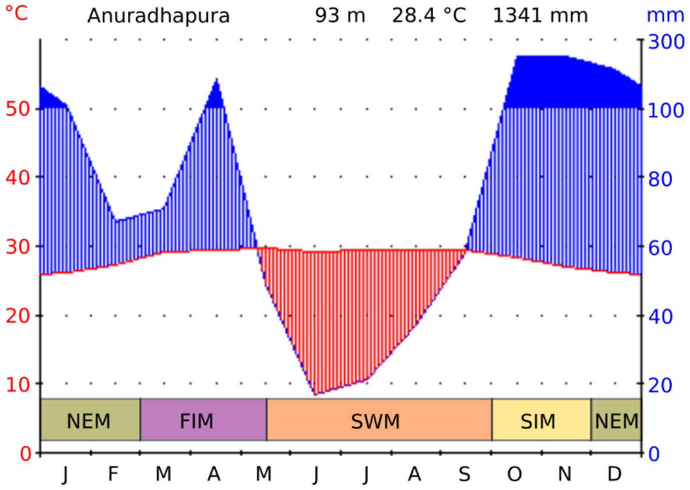


Figure 2. Climate graph for Anuradhapura meteorological station (8.35° N; 80.38° E), including the four climate seasons in Sri Lanka: the North-East Monsoon (NEM), the First Inter Monsoon (FIM), the South-West Monsoon (SWM) and the Second Inter Monsoon (SIM). Database: daily climate data from 01/1994–08/2014 from Department of Meteorology Sri Lanka; graphic generated by Klima 0.9 [20].

Seven major tanks together with numerous medium and minor tanks characterize the water harvesting and management system of the Aruvi Aru drainage basin. The upper catchment area is predominantly drained by two tributaries, the Malwathu Oya River and Kanadara Oya River, which after their confluence create the Aruvi Aru River. Four of the major tanks are situated in the sub-catchment of the Malwathu Oya, while Mahakanadarawa Wewa is located in the Kanadara Oya sub-catchment (Figure 1). The Aruvi Aru catchment receives additional water from the Mahaweli Ganga River via the Yoda Ela channel [21]. From the Kala Wewa, located in the Kala Oya drainage basin, water is routed through the Yoda Ela channel and through a system of smaller connecting channels to the Nachchaduwa Wewa (Figure 1B-1)), Tissa Wewa (Figure 1B-4), Nuwara Wewa (Figure 1B-3) and Basawakkulama Wewa (Figure 1B-5)), all located in the Aruvi Aru catchment. Despite being a medium-sized tank, Basawakkulama Wewa is also under governmental control and thus water levels are controlled regularly. Table 1 gives an overview of the basic characteristics of the tanks investigated in this study.

The management of major tanks is the responsibility of central and regional Irrigation Departments, while medium and minor reservoirs are maintained participatorily by village farmer organisations under the guidance of the Agrarian Service Department [5]. Farmer Organisations meet before each cultivation season in so-called Kanna meetings to debate when to open the wewa sluices to issue water in order to start the cultivation period, and to make decisions on the rice variety and area under cultivation, depending on water availability [5].

Table 1. Basic information for the five tanks of interest (MCM = million cubic meter, fsl. = full support level).

	Nachcha-Duwa Wewa	**Mahakana-Darawa Wewa**	**Nuwara Wewa**	**Tissa Wewa**	**Basawak-Kulama Wewa**
Area at fsl. [ha] *:	1780	1457	1198	212	107
Vol at fsl. [MCM] *:	55.7	44.59	44.47	4.32	2.07
Dead storage Volume [MCM] *:	0.12	4.67	1.23	0.32	0.01
Catchment Area [ha] *:	62,300	32,634	8418	518	932
Command area [ha] *:	2822	2428	917	365	186
Mahaweli inflow *:	yes	no	yes	yes	yes
No. of major tanks upstream **:	2	0	0	0	0
No. of medium tanks upstream **:	8	7	0	0	0
No. of minor tanks upstream **:	248	211	28	1	1
No. of micro tanks upstream **:	26	27	2	0	0
Ca. Vol of Tanks upstream [MCM] ***:	37.83	24.00	2.50	0.02	0.03

Source: * Irrigation Department Sri Lanka; ** ESRI Arc GIS Basemap, *** Calculated after [22].

3. Materials and Methods

The dependence of the major tanks' water levels on runoff controlled by precipitation was assessed by correlating climatic and hydrologic drought indices (as by [23]). Our methodological approach focuses on three main work steps:

1. Calculation of the climatic drought index (standardized precipitation index—SPI [24]) to identify droughts and humid periods;
2. Calculation of a hydrological drought index from data on the water level of tanks (standardized water-level index—SWLI), to characterize phases of high and low water-level conditions;
3. Testing the degree of relation between both indices by applying correlation approaches.

All statistical analyses were computed using R version 3.5.1 [25].

3.1. Data Basis

Calculation of the standardized precipitation index (SPI) is based on daily precipitation data for the climate station in Anuradhapura (8°18.7′ N 80°24.8′ E) from January 1994 to September 2016

(22 years and 9 months) (Sri Lankan Department of Meteorology; [26–28]). The SPI calculation requires monthly precipitation data as inputs and a gapless time series [24]. The daily precipitation records of the Anuradhapura weather station include one missing value and 194 days with <1 mm of rainfall. For calculation of the SPI the 194 days with precipitation < 1 mm were set to 0 mm precipitation. Additionally, the one day (18 September 1995) with no precipitation measurement was manually set to 0 mm. After this data pre-processing, the daily precipitation values were summed up to monthly values. Accordingly, monthly precipitation data from January 1994 to September 2016 (273 months) were available for SPI calculation.

Daily data on the water levels of the five major tanks in the Aruvi Aru catchment were provided by the Sri Lankan Irrigation Department, covering the time span 1 January 1990–20 September 2017. Table 2 shows the available water-level data and the missing values. These data served as a base for calculation of the standardized water-level index, as discharge or volume data are not measured and, thus, not available.

Table 2. Days of record and missing days for the water levels of the five tanks of interest in the period between 1 January 1990 and 20 September 2017 (10,125 days at all) provided by Irrigation Department, Sri Lanka.

Tank:	Days with Water-Level Data	Days with No Water-Level Data	NA [%]
Nachchaduwa Wewa	9752	373	3.7
Mahakanadarawa Wewa	9492	633	6.3
Nuwara Wewa	9974	151	1.5
Tissa Wewa	9964	161	1.6
Basawakkulama Wewa	9913	212	2.1

3.2. Standardized Precipitation Index (SPI)

The SPI [24] was applied to different temporal scales (3, 6, 9, 12 and 24 months). The consideration of multiple time scales allows analysis of the response of different water balance components to precipitation anomalies, e.g., soil moisture reacts in a relatively short time, while effects on groundwater and reservoir storage have longer time scales [29].

The SPI is based on standardized precipitation data, defined as "... the difference of precipitation from the mean for a specified time period divided by the standard deviation where the mean and standard deviation are determined from past records" ([24], p. 179). This procedure involves the fitting of a long-term precipitation record to a probability distribution. As precipitation is not normally distributed, the probability distribution was transformed to a normal distribution, where the mean SPI was zero [24,30].

The SPI values were computed using R package SPEI 1.7 [31] applying default settings. SPI values were classified as in Table 3 [24]. Accordingly a drought is defined as a period characterized by continuously negative SPI values, which in some cases reach values of ≤1. A drought starts when the SPI falls below zero and ends with the first positive SPI value [24].

Table 3. Classification of drought and water-level intensities (modified after [24], p. 2; [29], p. 5).

SPI Values	Category	SWLI Values	Category
≥2.00	Extreme humid	≥2.00	Extreme high water level
1.50–1.99	Severe humid	1.50–1.99	Severe high water level
1.00–1.49	Moderate humid	1.00–1.49	Moderate high water level
0.99–−0.99	Near normal	0.99–−0.99	Near normal water level
−1.00–−1.49	Moderate drought	−1.00–−1.49	Moderate low water level
−1.50–−1.99	Severe drought	−1.50–−1.99	Severe low water level
≤−2.00	Extreme drought	≤−2.00	Extreme low water level

3.3. Standardized Water-Level Index (SWLI)

The SWLI uses the same methodology and mathematics as the SPI calculation using monthly water-level data as inputs. To create a complete time series out of the water-level data, missing values were interpolated with the R package impute TS 2.7 [32], applying a seasonally decomposed linear missing value imputation approach. The resulting interpolated daily water-level data are summed up to monthly water-level data. The input data for the SWLI calculation are based on monthly water-level sums from January 1990 to September 2017 (333 months) for five major tanks in the headwaters of the Aruvi Aru catchment and were calculated using R package SPEI 1.7 with default settings for the time scale of one month [31].

SWLI values were classified following the approach for SPI values [24] (Table 3). SWLI values ≤ 1 refer to classes with low water levels and SWLI values ≥ 1 refer to high water levels. Values between 1 and -1 are near normal water-level conditions regarding the mean water level.

3.4. Comparison of Standadized Precipitation Index (SPI) and Standadized Water-Level Index (SWLI) Data

As SPI and SWLI are both normally distributed, the Pearson correlation coefficient was chosen to assess the degree of association between the climatic and hydrological drought index. For the climatic drought index (SPI) time scales from 1 to 24 months were included in the analysis to determine the SPI time scale which shows the best correlation with the SWLI. To assess the precipitation period, which has the highest influence on water levels, correlations between the SPI and SWLI were calculated under consideration of different SPI time scales:

(a) Correlation of the SPI data as an independent variable at time scales (1–24 months) with SWLI data as a dependent variable at the time scale of 1 month.

(b) For the assessment of seasonal correlation patterns a moving window correlation approach was applied to each tank, correlating the best fitting SPI time scale (determined by applying the correlation approach (a)) with the SWLI. As the methodological approach is precipitation driven, the chosen moving window is season based and splits the year into arid (May–September) and humid (October–April) seasons. The aim of this subdivision is to assess the impact of rainfall seasonality on water-level changes (SWLI). The seasonal moving window correlation was applied to both indices for 44 seasons throughout the whole observation period.

4. Results

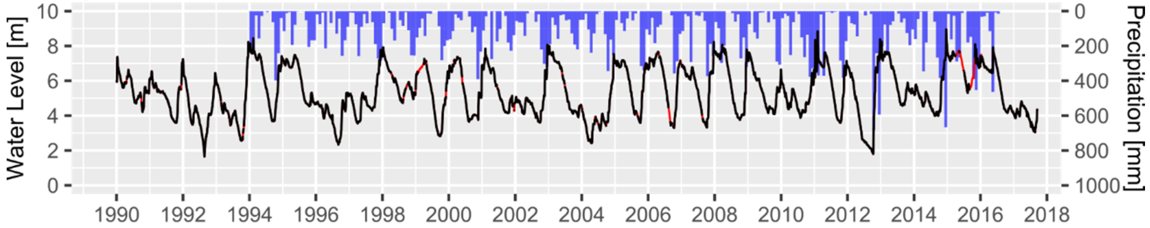
4.1. Water-Level Data for Major Tanks

The water levels of the major tanks show strong seasonal patterns (Figure 3). In all five major tanks water levels recurrently show a major peak at the turn of the year and usually remain at a relatively high water level until the end of the small rainy season (March–April). Frequently, this short rainy season coincides with a minor water-level peak. Repeatedly, maximum water levels expected around December/January each year fail to appear (Table 4). Furthermore, it can be observed that after the minor rainy season in March-April the water levels of the wewas continuously decrease until the onset of the major rainy season in September each year.

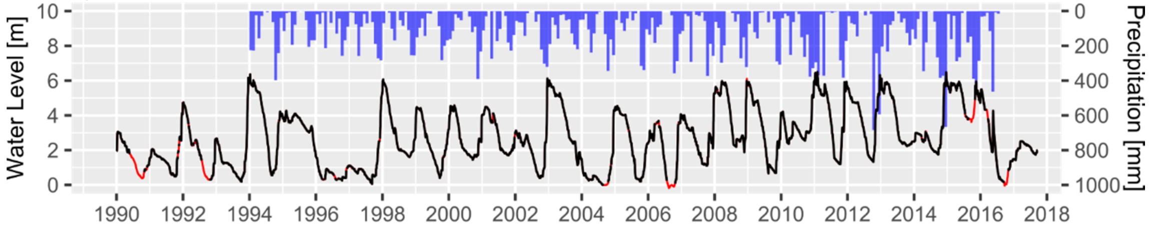
Table 4. Missing and weakly developed annual maximum water levels at the turn of the years for the five major tanks in the Aruvi Aru drainage basin (missing peaks = without brackets, weakly developed peaks = in brackets).

Tank:	Turn of the Year							
Nachchaduwa Wewa		95/96	96/97	01/02	03/04	(09/10)	13/14	16/17
Mahakanadarawa Wewa			96/97	(01/02)	03/04	(09/10)	13/14	(16/17)
Nuwara Wewa	92/93	95/96	96/97	01/02	03/04	(09/10)	13/14	16/17
Tissa Wewa				01/02	03/04		(13/14)	16/17
Basawakkulama Wewa	(92/93)	95/96	96/97	01/02	03/04		13/14	16/17

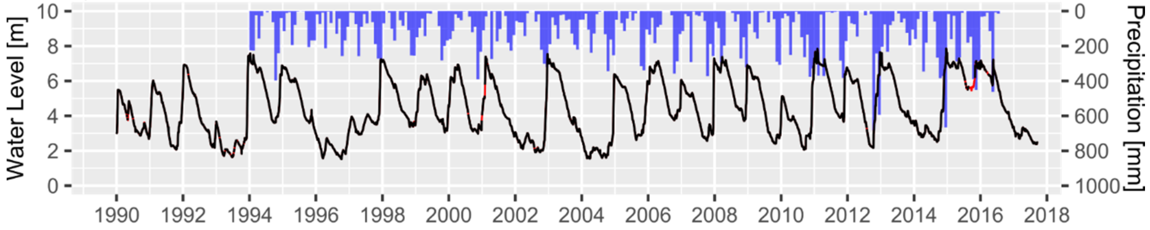
a) Nachchaduwa Wewa



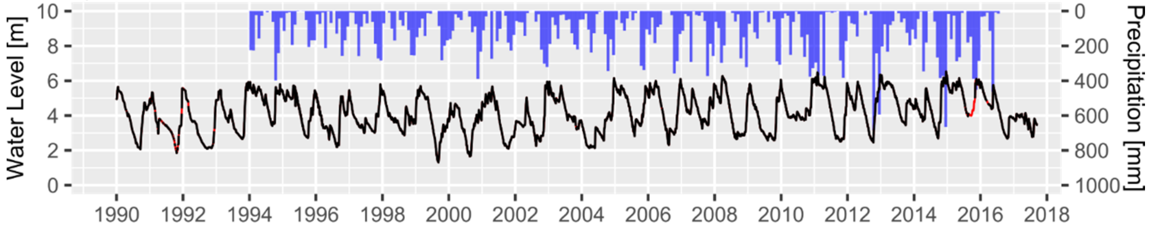
b) Mahakanadarawa Wewa



c) Nuwara Wewa



d) Tissa Wewa



e) Basawakkulama Wewa

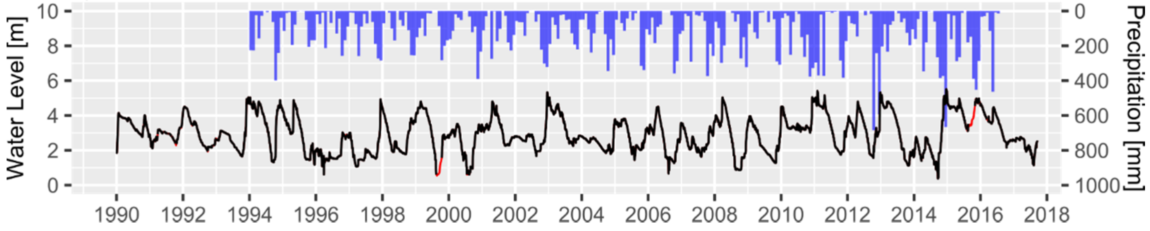


Figure 3. Daily water level of the five investigated major tanks: (**a**) Nachchaduwa Wewa, (**b**) Mahakanadarawa Wewa, (**c**) Nuwara Wewa, (**d**) Tissa Wewa, (**e**) Basawakkulama Wewa and monthly precipitation for Anuradhapura meteorological station (black line = original values, red line = interpolated values, blue bars = monthly precipitation values).

4.2. *Standardized Precipitation Index (SPI)*

The SPI for the Anuradhapura weather station was calculated for 3-, 6-, 9-, 12- and 24-month time scales for the period 1994–2016 (Figure 4). The SPI for the 3-month time scale (SPI-3) shows seasonal alternations between positive and negative values. Correspondingly, the data for SPI-3 show a predominance of near normal conditions ranging between values of 0.99 and −0.99 and mainly reflect the seasonal precipitation pattern.

Comparing the results of the SPI on different time scales reveals that, as the SPI time scale increases, the frequency of alternating periods of positive and negative SPI values decreases, while their duration increases (Table 5):

- For SPI-3 (3-month time scale) 78 alternating periods of positive and negative SPI values are observed, with a mean duration of 3.5 months for periods with negative SPI values and 3.4 months for periods with positive SPI values; 46 of the observed 78 periods belong to the category near normal conditions.
- For SPI-6 (6-month time scale) 51 alternating periods of positive and negative SPI values are observed, with a mean duration of 6.3 months for periods with negative SPI values and 4.3 months for periods with positive SPI values; 35 of the observed 51 periods belong to the category near normal conditions.
- For SPI-9 (9-month time scale) 31 alternating periods of positive and negative SPI values are observed, with a mean duration of 10.9 months for periods with negative SPI values and 6.3 months for periods with positive SPI values; 20 of the observed 31 periods belong to the category near normal conditions.
- For SPI-12 (12-month time scale) 19 alternating periods of positive and negative SPI values are observed, with a mean duration of 18.8 months for periods with negative SPI values and 9.3 months for periods with positive SPI values; 11 of the observed 19 periods belong to the category near normal conditions.
- For SPI-24 (24-month time scale) ten alternating periods of positive and negative SPI values are observed, with a mean duration of 33 months for periods with negative SPI values and 17 months for periods with positive SPI values; eight of the observed ten periods belong to the category near normal conditions.

From 2010 onwards, the SPI shows a trend towards more humid conditions with positive SPI for all calculated time scales (Figure 4). Extreme and in part severe droughts as well as humid phases are observed in all SPI time scales and are presented in Table 5.

Table 5. Number of droughts, near normal and humid phases for selected SPI time scales.

				SPI		
SPI Values	**Category**	**3-Month**	**6-Month**	**9-Month**	**12-Month**	**24-Month**
≥2.00	Extreme humid	4	3	3	3	1
1.50–1.99	Severe humid	2	0	0	0	0
1.00–1.49	Moderate humid	5	1	0	0	0
0.99–−0.99	Near normal	46	35	20	11	8
−1.00–−1.49	Moderate drought	12	9	6	4	0
−1.50–−1.99	Severe drought	6	1	2	1	1
≤−2.00	Extreme drought	3	2	0	0	0

Typical droughts in the tropics are represented by SPIs < -1 and last 6 months [18,33]. In consequence, the data of the SPI-6 (6-month time scale) are examined in more detail. The SPI-6 time series allows nine moderate droughts to be identified between 1994 and 2016. The moderate drought from December 1994 to July 1996 (20 months) lasted longest. In 2005 a severe drought occurred, lasting for 10 months (January–October 2005). Two extreme droughts with SPI-6 < -2.0 occurred from September 2008 to March 2010 (19 months) and from March to December 2000 (10 months). From 2010 on, three longer extreme humid events (starting in August 2010, October 2012 and May 2014) occurred with durations of 14, 11 and 29 months.

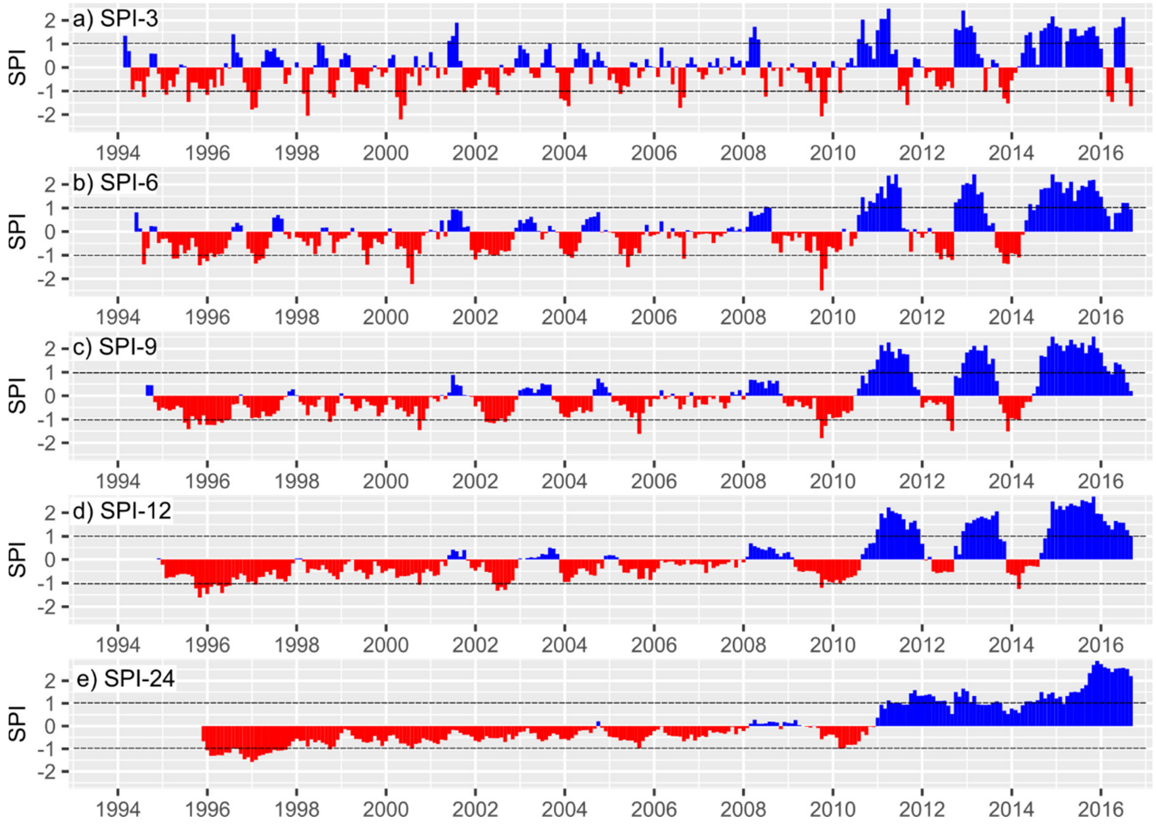


Figure 4. Standardized Precipitation Index (SPI) calculated for the time scales of (**a**) 3, (**b**) 6, (**c**) 9, (**d**) 12 and (**e**) 24 months for the period of 1994 to 2016 for Anuradhapura weather station. SPI classification according to [24] (Table 3). Blue bars mark SPI values > 0, red bars mark SPI values < 0. SPI values between 0.99 and −0.99 (area between the dashed lines) are classified as near normal conditions.

4.3. Standardized Water-Level Index (SWLI)

SWLI values for five major tanks in the headwaters of Aruvi Aru catchment were calculated on a 1-month time scale for the observation period January 1990–September 2017 (333 months) (Figure 5). Although the magnitude of low and high water-level periods differs from tank to tank, temporal patterns show similarities:

(a) Between 1990 and 1994, periods characterized by low water levels predominate; the only exception is the water level of Basawakkulama tank.
(b) Between late 1995 and 1997 extreme low water levels occurred at Nachchaduwa, Mahakanadarawa and Nuwara Wewa. The water level of Basawakkulama Wewa was also extremely low during this period, although from September to October 1996 near normal water levels could be observed.
(c) The most extreme low water-level period was observed in 2004, affecting all major tanks included in the investigation except Basawakkulama Wewa.
(d) At the turn of the year 2016-17 another low water-level period could be observed at all tanks.

In the following, we describe the main characteristics of water-level changes based on the data of the SWLI for each tank for the observation period 1990–2017 (for a numerical overview of each tank, also see Table 6).

For *Nachchaduwa Wewa*, between 1990 and 2017 a total of 46 alternating periods of positive and negative SWLI values can be observed, composed of 23 periods with negative SWLI values and 23 periods with positive SWLI values. 27 water-level periods belong to the class ‘near normal water level’. There were three short, moderate low water-level periods in 1999 (duration: 5 months), in 2000 (duration: 3 months) and in 2008 (duration: 2 months). One severe low water-level period occurred at the turn of the year 2001–2002 (13 months). Five periods of extreme low water levels occurred: 1992-93 (23 months), 1995 to 1997 (20 months), 2003–2004 (12 months), 2012 (8 months) and 2016–2017 (12 months). The average duration of low water-level periods is 10.9 months (std = 6.8, n = 9). Six periods of moderate high water levels occurred in 1990 (8 months), 1993–1994 (9 months), 2002-03 (12 months), 2005–2006 (13 months), 2007–2008 (11 months) and 2011 (8 months). Three periods of severe high water levels occurred: 1994–1995 (13 months), 1997–1998 (17 months) and 2012–2013 (13 months). There was only one extreme high water level from 2014 to 2016 (25 months). The mean duration of high water-level periods is 12.9 months (std = 4.8, n = 10).

For *Mahakanadarawa Wewa*, between 1990 and 2017 a total of 38 alternating periods of positive and negative SWLI values can be observed, composed of 19 periods with negative SWLI values and 19 periods with positive SWLI values. 24 of the 38 alternating water-level periods belong to the class 'near normal water level'. One moderate low water-level period occurred in 2005–2006 (7 months), while three severe low water-level periods occurred: 1990–1991 (22 months), 1992–1993 (21 months) and 2016–2017 (15 months). Three extreme low water-level periods appeared in 1995 to 1997 (23 months), 2003–2004 (13 months) and 2006 (6 months). The mean duration of low water-level periods is 15.3 months (std = 6.5, n = 7). There are five moderate high water-level periods: 1993–1994 (8 months), 1997–1998 (7 months), 2002–2003 (11 months), 2007 to 2009 (25 months) and 2010 to 2013 (43 months). One severe high water-level period occurred in 1994–1995 (14 months) and one extreme high water-level period dates to 2014 to 2016 (22 months). The mean duration of high water-level period is 18.6 months (std = 11.8, n = 7).

The SWLI between 1990 and 2017 shows 33 alternating periods of positive and negative SWLI values for *Nuwara Wewa*, composed of 17 periods with negative SWLIs and 16 periods with positive SWLIs. 16 of the 33 water-level periods belong to the class 'near normal water level'. Three moderate low water-level periods can be observed: 1990–1991 (3 months), 1991 (8 months) and 2009–2010 (16 months). Two severe low water-level periods occurred in 2013–2014 (10 months) and 2016/17 (10 months). Extreme low water-level periods occurred four times: 1992–1993 (14 months), 1995 to 1997 (19 months), 2001–2002 (13 months) and 2003-04 (13 months). The mean duration of low water-level periods is 11.8 months (std = 4.4, n = 9). Moderate high water levels occurred seven times: 1993 to 1995 (24 months), 1997–1998 (17 months), 2002–2003 (11 months), 2005 to 2007 (19 months), 2008–2009 (19 months), 2010 to 2012 (19 months) and 2012–2013 (13 months). There are no severe high water-level periods at Nuwara Wewa; one extreme high water-level period occurred from 2014 to 2016 (26 months). The mean duration of high water-level periods is 18.5 months (std = 4.7, n = 8).

For *Tissa Wewa,* between 1990 and 2017 the SWLI shows a total of 62 alternating periods of positive and negative SWLI values composed of 31 periods with negative SWLIs and 31 periods with positive SWLIs. 35 water-level periods belong to the class 'near normal'. Eight moderate low water-level periods can be observed: 1990 (6 months), 1990–1991 (8 months), 1996-97 (7 months), 1998-99 (3 months), 2008 (6 months), 2009 (7 months), 2011 (5 months) and 2017 (1 month). Two severe low water-level periods occurred in 1991 (4 months) and 1996 (8 months). Extreme low water-level periods appeared six times: 1992–1993 (11 months), 1999–2000 (9 months), 2000 (6 months), 2001–2002 (9 months), 2003–2004 (10 months) and 2016–2017 (10 months). The mean duration of low water-level periods is 6.9 months (std = 2.6, n = 16). Moderate high water-level periods occurred seven times: 1998 (2 months), 2002–2003 (12 months), 2004-05 (7 months), 2005–2006 (10 months), 2007–2008 (15 months), 2012 (5 months) and 2012–2013 (13 months). Four severe high water-level periods occurred from 1993 to 1995 (22 months), in 1996 (3 months), in 2010–2011 (13 months) and between 2014 and 2016 (24 months). An extreme high water-level period cannot be observed. The mean duration of high water-level period is 11.5 months (std = 6.8, n = 11).

Between 1990 and 2017 the SWLI for *Basawakkulama Wewa* shows 59 alternating periods of positive and negative SWLI values composed of 30 periods with negative SWLIs and 29 periods with positive SWLIs. 32 of these 59 water-level periods belong to the class 'near normal'. Seven moderate low water-level periods can be observed: 1990–1991 (6 months), 1992–1993 (9 months), 1998 (6 months), 2004 (3 months), 2006–2007 (15 months), 2009 (9 months), and 2016-17 (11 months). One severe low water-level period occurred in 2008 (6 months). Five extreme low water-level periods can be observed, occurring in 1995–1996 (13 months), 1996–1997 (12 months), 1999 (4 months), 2000 (5 months) and 2013-14 (14 months). The mean duration of low water-level phases is 8.7 months (std = 3.9, n = 13). Moderate high water-level phases occurred ten times: 1990 (10 months), 1991–1992 (17 months), 1995 (4 months), 1997–1998 (3 months), 1998–1999 (10 months), 2001 (8 months), 2002–2003 (11 months), 2008 (6 months), 2012 (5 months) and 2012-13 (10 months). There are also three severe high water-level periods occurring in 1993–1994 (10 months), 1994–1995 (6 months) and 2010–2011 (17 months). One extreme high water-level period occurred from 2014 to 2016 (24 months). The mean duration of high water-level phases is 10.1 months (std = 5.6, n = 14).

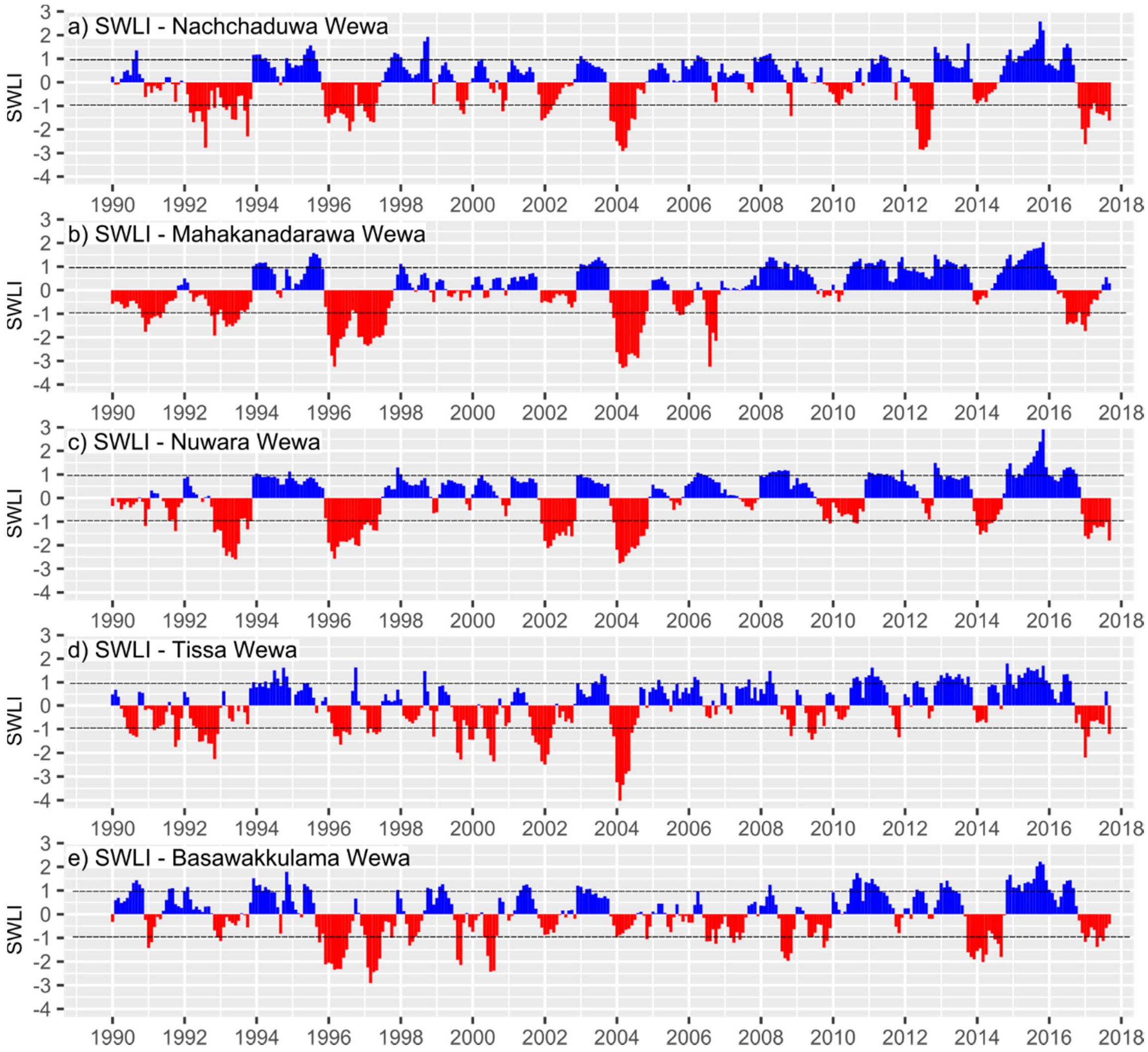


Figure 5. Results of Standardized Water-level Index (SWLI) for the five major tanks (**a**) Nachchaduwa Wewa, (**b**) Mahakanadarawa Wewa, (**c**) Nuwara Wewa, (**d**) Tissa Wewa, (**e**) Basawakkulama Wewa in the headwaters of Aruvi Aru catchment. Blue bars mark SWLI values > 0, red bars mark SWLI values < 0. SWLI values between 0.99 and −0.99 (area between the dashed lines) are classified as near normal conditions.

Table 6. Number of high, near normal and low water-level periods for SWLI for each major tank in the headwaters of Aruvi Aru catchment.

SWLI Values	Category of Water Level	Number of Periods for: Nachcha-Duwa Wewa	Mahakana-Darawa Wewa	Nuwara Wewa	Tissa Wewa	Basawa-Kulama Wewa
≥2.00	Extreme high	1	1	1	0	1
1.50–1.99	Severe high	3	1	0	4	3
1.00–1.49	Moderate high	6	5	7	7	10
0.99––0.99	Near normal	27	24	16	35	32
−1.00––1.49	Moderate low	3	1	3	8	7
−1.50––1.99	Severe low	1	3	2	2	1
≤−2.00	Extreme low	5	3	4	6	5

4.4. Relation between SPI and SWLI

Figure 6 displays the Pearson R correlation coefficients between the SWLI values and the SPI values on time scales of 2–24 months. All correlation coefficients shown are positive ($p < 0.001$; see supplementary data, Figure S1 for sample size for the correlations). The SPI time scale of 1 month was not included in the figure as the correlation was not significant ($p > 0.001$). The same holds true for the SPI 2-month time scale for Nuwara Wewa. The SPI values for short time scales generally show a weak correlation between precipitation and water levels ($r \leq 0.3$ for the SPI-2 month time scale). With increasing SPI time scales, the correlation coefficients rapidly increase and show highest values for time scales of 6 months (Tissa and Basawakkulama Wewa) to 12 months (Nuwara Wewa). Correlations between SPI and SWLI for each tank differ in quality between r = 0.612 (Nuwara Wewa, SPI time scale 12) and r = 0.529 (Nachchaduwa Wewa, SPI time scale 7) and thus reflect moderate to strong correlations between the SWLI and SPI (correlation classes according to [34]). The best correlation is found for the SPI time scale of 11 months (r = 0.533) for Mahakanadarawa Wewa, and of 6 months for Tissa (r = 0.538) and Basawakkulama Wewa (r = 0.598).

For three tanks, the correlations between SWLI and SPI show a second slightly weaker peak at SPI time scales of 11 months for Nachchaduwa (r = 0.523), 10 months for Tissa (r = 0.513) and 11 months for Basawakkulama (r = 0.564).

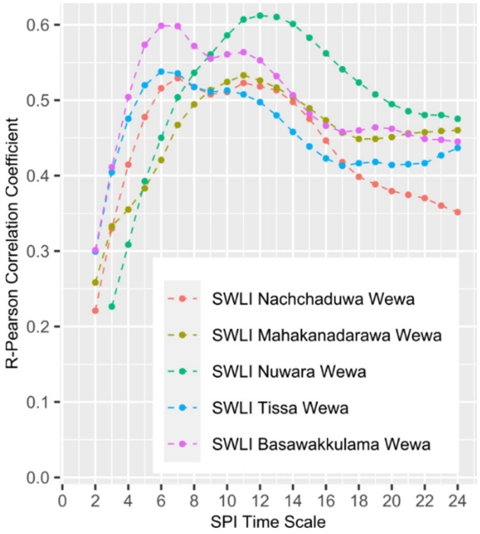


Figure 6. Pearson R correlation values for the SPI time scales 2–24 months and SWLI for each tank (points = calculated Pearson R correlation values).

The values of the SPI time scale with the highest correlation coefficient to the SWLI values is shown in Figure 7. For each tank, both indices run parallel in part. Especially, the periods from the end of 2002 until the end of 2004 and from 2014 on both indices show strong parallels for all tanks.

Other years are characterized by contrary behaviour of the SPI and SWLI, e.g., in 1995 water levels are in the positive range, while SPI values are ≤0.

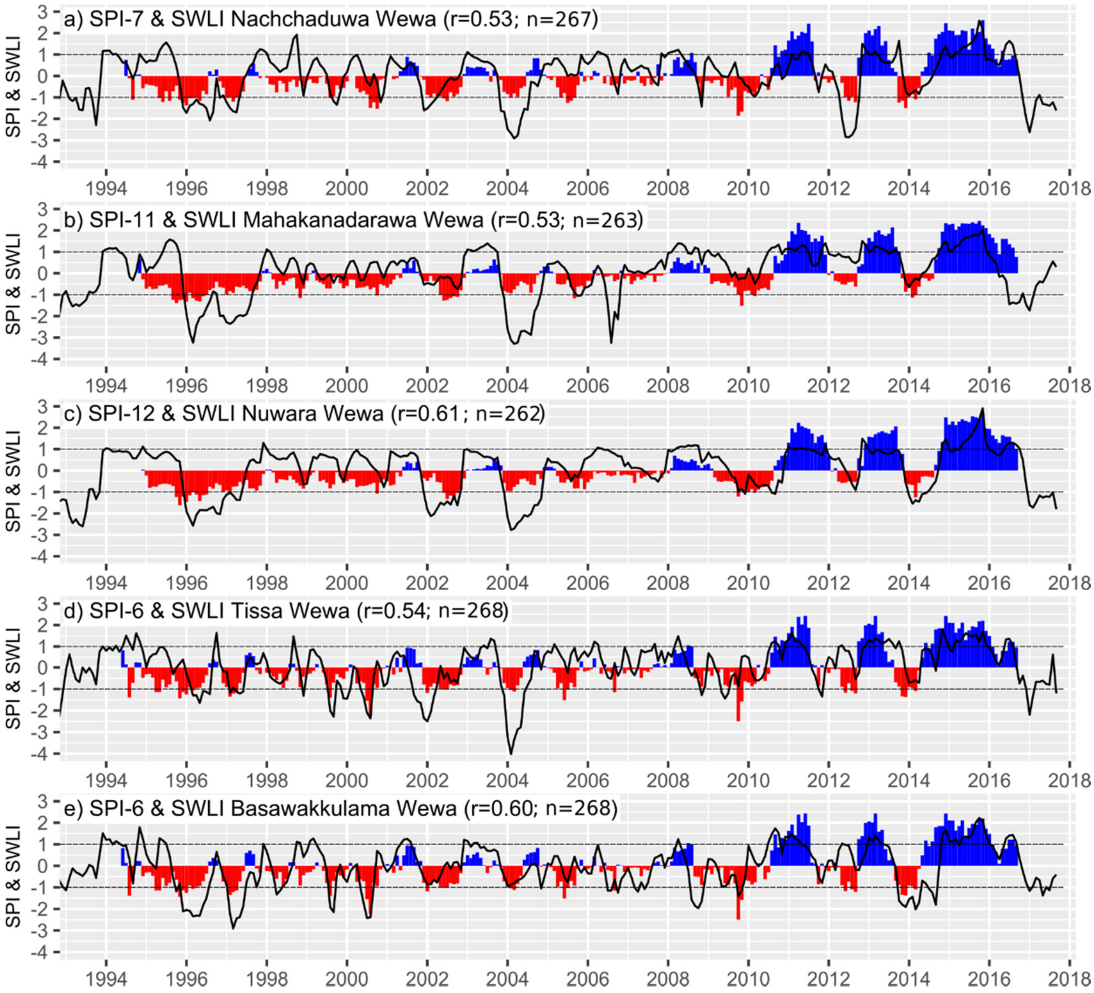


Figure 7. SPI (blue and red bars) and SWLI (black line). The SPI time scale displayed shows the best correlation expressed by the correlation coefficient (r) between SPI time scales and SWLI for each tank: (**a**) Nachchaduwa Wewa, (**b**) Mahakanadarawa Wewa, (**c**) Nuwara Wewa, (**d**) Tissa Wewa, (**e**) Basawakkulama Wewa (n = sample size). Dashed lines mark the classification 'near normal' for both indices [24].

The relationship between SWLI and SPI is characterized by randomly occurring time lags lasting up to several months. Two cases are manifested: (i) SPI ascends first and SWLI follows (2010 Nuwara Wewa, 2014 Basawakkulama Wewa), (ii) SPI descends first and SWLI follows (2013-14 Nachchaduwa Wewa, end of 2009 Mahakanadarawa Wewa and Nuwara Wewa, 2013 Tissa Wewa). In particular most low water-level periods of SWLI in all tanks are in line with low SPI values. Furthermore, the well-developed humid periods after 2010 are also visible in SWLI values.

The moving window correlation for the dry (May to September) and humid (October to April) climatic periods show 61 seasons with significant strong to very strong correlations between the SPI values and SWLI (for SPI time scale with highest correlation to SWLI for each tank, see Figure 7). Of these 61 seasons, 39 seasons correspond to the humid phase (October–April); 34 show a positive correlation between SPI and SWLI, while five seasons show a negative correlation. For the dry season (May to September) 22 seasons show a strong to very strong correlation (six of these correlate negatively). The correlation between both indices is higher during the humid than the arid seasons (see Figures S2–S6, supplementary data).

5. Discussion

5.1. Methodological Approach and Input Data for SPI and SWLI

This study evaluates the dependence of water-level changes in major tanks in the Dry Zone of Sri Lanka on precipitation for the observation period January 1994–August 2016, applying climatic and hydrologic drought indices. Although a time series of at least 30 years is recommended for the calculation of the standardized precipitation index [35], it can be applied for a data series of just 20 years [29].

Climatic droughts are analysed by applying the Standardized Precipitation Index (SPI) [24]. Due to its robustness [36], simplicity, temporal flexibility [37] and spatial consistency, this index has been used to study different types of drought worldwide [29,38]. Scripts and software for its calculation are available [29,31]. In addition to the standardized precipitation index, the standardized precipitation and evapotranspiration index (SPEI) exists [39]. SPEI takes both precipitation and evapotranspiration into account for drought index calculation. Several studies show that reservoirs are subject to strong evaporation processes [40,41]. Nevertheless, the SPI was chosen here because while evapotranspiration explains the variability of terrestrial water storage in mid-latitudes, in the tropics precipitation dominates reservoirs' water levels [42].

Precipitation data input to the SPI calculation is derived from the meteorological station in Anuradhapura, as this station is located inside the Aruvi Aru drainage basin and has high spatial proximity to the investigated major tanks. Additional weather stations are located c. 45 km north and 25 km south of Anuradhapura, both outside of the Aruvi Aru catchment and therefore not utilized.

The results of the calculated time scales for the standardized precipitation index (SPI) show typical trends. At longer time scales, alternating phases of positive and negative SPI become less frequent, in line with a prolongation of their duration [23,24,36]. From approximately 2011 onwards all SPI time scales show a clear trend towards extreme humid conditions.

Ekanayake & Perera (2014) applied the SPI to monitor droughts based on precipitation data from Anuradhapura climate station at a 3-month time scale [43]. Identified droughts and humid phases are in good accordance with the results presented in this study. The same holds true for the findings of Fernando (2010) [33], who calculated the SPI on a 6-month time scale based on areal precipitation. The Emergency Events Database EM-DAT (2019) [44] contains several floods, storms and droughts for the North Central Province and Anuradhapura District. Some of these events are also visible in the SPI data of this study, e.g., the distinct storm and flood events of 2010, 2011 and 2012 fit quite well and correspond to the severe and extreme humid periods reflected in the results of this study from approx. 2011 onwards. In summary, the SPI results are regarded as robust and are generally in line with the results of other studies.

Utilizing hydrological data as an input to create a hydrological drought index by applying SPI calculation was suggested by McKee et al. (1993) [24] and has been applied repeatedly [23,36,45,46]. In the framework of this study, water-level data measured at the gauges of the major dams were the only available data to assess the response of water storage in the tanks to precipitation. Other studies use reservoir volumes for standardized index calculations [23,36,47,48], which allows direct conclusions concerning the amount of available water. In this study a conversion of water level to volume data is not appropriate due to the topography of the shallow, wide-open valleys, and respective calculation approaches have only been developed for small village tanks [22]. Independent from the data availability we are convinced, that under these preconditions the direct measured water level data are suitable and provide a robust data set. Therefore, changes in water-level data are regarded as a direct proxy for the reaction of tanks to precipitation.

The time series of water-level data for the Standardized Water-level Index (SWLI) comprises 27 years rather than the recommended 30 years of input data [35]. The following incidences point nevertheless to the robustness of the SWLI calculation. In general, the curves of the standardized water-level index and the water-level data are parallel, especially during low water-level phases.

The missing and weakly developed water-level peaks at the turn of the years (92/93, 95/96, 96/97, 01/02, 03/04, 09/10, 13/14 and 16/17) are also apparent in the SWLI data. In summary, the parallels shown above point to a set of factors that trigger changes in the water levels of the investigated major tanks, as discussed in the following.

5.2. Dependence of Water Level on Precipitation

The SPI with a time scale of 6–12 months shows the highest correlation with the SWLI. These results indicate that the precipitation of the last 6–12 months has the greatest influence on water-level changes in the major tanks in the Aruvi Aru catchment.

Similar studies correlating SPI and standardized tank data are rare. In the Spanish Pyrenees the response of tank storage to different SPI time scales was studied with comparable results (best fitting SPI time scale = 8 months, r = 0.59) [36]. In addition, the development of the correlation coefficients between the SPI at different time scales and water storage shows a comparable pattern. Furthermore, the results of this study are also in accordance with other studies [24,29,37,49] and support the use of the presented methodological approach to assess interdependencies between climatic conditions and the hydrological response of reservoirs. In contrast, the results disagree with the findings concerning hydrological responses of tank storage in central Spain with different SPI and SPEI time scales [23] where results (best fitting SPEI timescale = 33 months, r = 0.87) differ considerably from the data presented in this paper. These differences are probably linked to the hyper-annual characteristics of the reservoir system studied.

The lag time of 6–12 months between precipitation and the arrival of the resulting runoff in the tanks raises the question of whether base flow components predominantly contribute to the recharging of the tanks. The Dry Zone of Sri Lanka is characterized by a shallow regolith aquifer, which is understood to benefit from seepage from the tanks [50,51]. Based on isotopic analysis in the Kala Oya catchment, it is concluded that such seepage contributes to groundwater recharge in downstream areas [52], to which the major tanks in our study area belong. Therefore, it seems rather to be the other way around: tanks contribute to groundwater recharge but are not fed significantly by groundwater. As there is no isotopic analysis of tank water in the Aruvi Aru catchment available, the identification of runoff components contributing to tank recharge remains a task for future research.

The moderate to strong positive correlation between SWLI and SPI points—beside precipitation—to other factors affecting the water levels of the tanks. As well as precipitation and its transformation into runoff, management of tanks needs to be regarded as a major factor. Water is taken from the tanks for paddy irrigation and other agricultural irrigation purposes. Approximately 7% of the total net inflow in Sri Lanka (precipitation) is used for paddy cultivation [53]. Water for drinking water treatment is withdrawn from Nuwara Wewa and Tissa Wewa for public water supply. Projects for extracting drinking water from Nachchaduwa and Mahakanadarawa Wewa are ongoing [54]. Although agricultural production in the Dry Zone of Sri Lanka is predominantly based on irrigation and thus the tank cascade systems, there is a substantial lack of data on water inflow and outflow to and from the reservoirs. There is also a lack of further reliable information on the system and amount of water channelled from Mahaweli Ganga to the tanks close to Anuradhapura. According to administrative documents from the archive of the Department of Irrigation of Sri Lanka (Anuradhapura), four tanks (Nachchaduwa Wewa, Nuwara Wewa, Tissa Wewa and Basawakkulama Wewa) receive water from Mahaweli Ganga. Other sources give contradictory information about which tanks participate in the supra-regional water distribution from the Mahaweli catchment [55–58]. At the local level, farmers frequently complain that they are not sufficiently involved in decision-making processes regarding management practises by the Irrigation Department. This lack of participation often leads to the implementation of measures that take insufficient account of the generally complex local structures [5]. Reservoir characteristics (such as capacity), type of supplied demand (such as irrigation) and management methods can lead to great variabilities in the way the water stored responds to SPI on different time scales [36]. Due to the lack of management data, a more detailed discussion or quantitative depiction of the influence of precipitation and tank management on water-level changes in tanks is not feasible.

Besides precipitation and management, the buffer capacity of the upstream catchment is relevant for interpretation of the correlation between SPI and SWLI. The two smallest tanks under investigation, Tissa and Basawakkulama Wewa, are both situated close to the western catchment divide and facilitate only small catchment areas. The highest correlation between standardized water-level data and SPI is found for the SPI time scale of 6 months here. In contrast, the SWLI for the large tanks Nuwara Wewa and Mahakanadarawa Wewa has the highest correlation with SPI at a 12- or 11-month time scale. Consequently, the water levels of small tanks with small catchment areas react more quickly to precipitation variations than large tanks with large catchments. The same relation holds true for the factors catchment size and upstream storage capacity (Table 1): the larger a catchment and the larger the upstream storage capacity, the longer the time lag between precipitation and changes in the water level. So catchment size and storage capacity upstream can be seen to have a buffering effect on the water levels of major tanks. Interestingly, Nachchaduwa Wewa as the biggest tank does not follow this trend. Its SWLI has the highest correlation with SPI at a 7-month time scale. However, at Nachchaduwa Wewa the correlation graph shows a second correlation peak between SWLI and SPI at a time scale of 11 months, which fits better into the described pattern.

The moving window correlation (at the seasonal temporal scale) between SWLI and SPI results in strong to very strong correlations during the humid season between October and April, when the majority of rain falls in the Anuradhapura region. The tanks are recharged in this period and stay more or less full until the end of this season. During the dry season between May and September the water levels decrease in all tanks. In summary, this correlation sustains the conclusion that the seasonal variability of the water level is a function of precipitation and its conversion to runoff and the annual pattern of reservoir management (water withdrawal and supply of water originating from the Mahaweli Ganga catchment). The short time lags of a few months between SPI and SWLI are probably a result mainly of reservoir management and water diversion inside the cascade systems. A similar connection between seasonal variability of reservoir storage and precipitation and its transformation to runoff, as well as the annual pattern of reservoir management, was found in the Spanish Pyrenees [36].

In summary, during the arid season in the Anuradhapura region the contribution of precipitation and its transformation to runoff with regard to the water supplied for irrigation is very low. The water levels of tanks during this season depend more on the stored level reached at the end of the humid season. The water stored during the humid season in the Anuradhapura region depends predominantly on the weather conditions at the beginning of the filling period (October to April) [36,59].

6. Conclusions

For more than 2000 years tank-cascade systems in Sri Lanka have stored and provided water for paddy cultivation and for domestic purposes. After the implementation of tanks in the hinterland of Anuradhapura (the early ancient capital) channels were constructed to route water from the Mahaweli River, whose headwater area is located in the Wet Zone, to the tanks close to Anuradhapura (in the Dry Zone). This expansion raises the question of how efficiently the tanks in the hinterland of Anuradhapura have functioned. Therefore, the dependence of the water levels of major tanks on precipitation was investigated by applying standardized indices to meteorological and hydrological data.

The results show that in general near normal precipitation, especially during the major rainy season, causes near normal water levels. Based on this observation it can be concluded that present day climatic conditions are sufficient to fill the major tanks in Sri Lanka's Dry Zone. Moderate to strong correlations between hydrological and climatic drought indices point to other factors having an effect on the water levels in the tanks. These are, first, tank management practices (water withdrawal for irrigation and drinking water) and, second, injection of water through a system of channels routing water across catchment boundaries from the Mahaweli River. Third, the size of the upstream catchment and its buffering capacity (number and size of tanks) has been identified as an important impact factor influencing the time needed until precipitation and resulting runoff arrive in the major tanks. Our results show that the precipitation of the last 6–12 months has the highest influence on water levels in the major tanks. Based on our finding that present-day average precipitation is sufficient to fill the investigated tanks, it can be concluded that the tanks have functioned efficiently within their system boundaries. With the growth of the ancient capital of Anuradhapura, demand for water probably increased, so that additional water sources from the Mahaweli River served as (i) general add-ons and (ii) additive during droughts, which occurred frequently in the investigated period.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/12/10/2941/s1, Figure S1: Sample Size N for the Pearson R correlation between different SPI timescales and SWLI values for all tanks. Figure S2: Moving window (arid window = May to September; humid window = October to April) correlation matrix between SPI-7 month time scale for Anuradhapura meteorological station and SWLI for Nachchaduwa Wewa with r & *p* values as well as significance level (NA = not significant correlation), for arid periods: n = 5; for humid periods: n = 7. Figure S3: Moving window (arid window = May to September; humid window = October to April) correlation matrix between SPI-11 month time scale for Anuradhapura meteorological station and SWLI for Mahakanadarawa Wewa with r & *p* values as well as significance (NA = not significant correlation), for arid periods: n = 5; for humid periods: n = 7. **Figure S4**: Moving window (arid window = May to September; humid window = October to April) correlation matrix between SPI-12 month time scale for Anuradhapura meteorological station and SWLI for Nuwara Wewa with r & *p* values as well as significance level (NA = not significant correlation), for arid periods: n = 5; for humid periods: n = 7. **Figure S5**: Moving window (arid window = May to September; humid window = October to April) correlation matrix between SPI-6 month time scale for Anuradhapura meteorological station and SWLI for Tissa Wewa with r & *p* values as well as significance level (NA = not significant correlation), for arid periods: n = 5; for humid periods: n = 7. Figure S6: Moving window (arid window = May to September; humid window = October to April) correlation matrix between SPI-6 month time scale for Anuradhapura meteorological station and SWLI for Basawakkulama Wewa with r & *p* values as well as significance level (NA = not significant correlation), for arid periods: n = 5; for humid periods: n = 7.

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