Assessment of the Proposed Malwathoya Dam for Flood and Drought Mitigation in the Lower Malwathoya River Basin, Sri Lanka

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Abstract

The aim of this study is to analyse the effectiveness of the proposed Malwathoya dam for flood and drought mitigation in the lower part of the Malwathoya River basin, Sri Lanka. In this study, the assessment is conducted by using existing indices and the distributed hydrologic BTOP model. The standardized indices highlight historical trends of floods and droughts in terms of magnitude and frequency from 1950 to 2015. Satellite-based indices identify affected agricultural area at different growth stages as well as standing water in paddies and storages. For the dam operation simulation, the 30-arcsec (about 1-km) grid model BTOP model was constructed from the global data sets with local ground-based precipitation and included reservoirs and small and medium water storage tanks with total capacity of 540 MCM located upstream of the Thekkam diversion weir. The BTOP model river discharges with short- and long-term precipitation were calibrated with observed river discharge data at the Thekkam and demonstrated a satisfactory statistical performance. Then, the calibrated BTOP model was used to simulate multi-purpose dam operation for the historical hazard events to store flood water during floods and to release irrigation water during droughts. From the BTOP model results, the proposed dam allowed us to establish an optimum operation for the flood and drought risk reduction and indicated a decrease in water related hazards. As a result, this study demonstrates a combined flood and drought risk assessment from the water resources infrastructure point of view and allows us to reduce farmers' vulnerability in the northern region of Sri Lanka. The BTOP model, which was developed with local and global data, provides information for short- and long-term water resources planning such as inflow to proposed dam, impact of existing storages, dam operation rule for flood control and dry season cultivation planning. Using the integrated hazard assessment approach, this study evaluated the flood peak reduction of several return periods at the Thekkam diversion as well as enhancement of dry season cultivation and serves as a starting point for the future studies for the basin.

Key words: *Flood hazard, drought hazard, BTOP model, dam operation, remote sensing.*

Introduction

The floods and droughts are the frequent hazards that are causing major social, economic and environmental impacts in Sri Lanka. The major/medium reservoirs as well as thousands of small tanks linked as cascaded systems are the special feature of Sri Lanka dry climatic zone and contribute to flood and drought mitigation by storing rain water in the wet seasons and distributing to meet domestic and irrigation demands during the dry season (OCHA, 2014; Bandara, 2009). Insufficient and inefficient water storages, improper operation and maintenance, poor water management practice, siltation and low safety level of small tanks are challenging factors for flood and drought mitigation incorporated to high intensity moon soon rainfall and pro-long dry-spell in the country. Hence, research investigations of flood and drought cycles and development activities of water resources sector are essential for disaster management to achieve the Wonder of Asia concept of Sri Lanka in 2020.

In Sri Lanka, the Malwathoya River basin, which is located in the northern part of Sri Lanka and completely fallen in the dry zone of country, is the second largest river basin with a catchment area of 3,246 km^2 (**Figure-1**). High density of small cascaded water storage tanks with a surface area between 1.5 to 3.0 km^2 is the unique characteristic of the Malwathoya River basin. Currently, there are more

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than 1240 small tanks, 146 medium tanks and 6 major reservoirs with storage facility of 570 MCM to irrigate an area of 654 km^2**.** The lower part of the Malwathoya river basin has been experienced frequent floods and droughts, which occurred during the civer war. After the end of long civil war in 2009, the necessety of hazard management was realized and the basin was selected for the flood and drought mitigation programme including proposed dam construction of the next five year investment plan (Central Bank Report, 2014). Therefore, the main objective of the study is to assess the effectiveness of the proposed dam and to develop dam operation rule for flood and drought mitigation in the lower part of the river basin by using indices and hydrological model.

Data

In the basin, the river discharge data have a poor quality due to the long civil war period from 1980 to 2009 and frequent damages of the Thekkam diversion weir (**Figure-1**). For the study basin, the global data set such as digital elevation model (dem), soil, and land cover are utilized for the BTOP model. The potential evaporattranspiration (PET) and leaf area index (LAI) are also estimated from global data sets on 1-km grid for the BTOP model setup of the study area. These long-term fortnightly PET and LAI are estimated by the Shuttle worth-Wallace model using climate forcing data CRU TS3.1 and a fortnightly Normalized Difference Vegetation Index (NDVI). For the local data, daily rainfall data is obtained from six gauaging stations and daily river dischargs at the Thekkam diversion from 1990 to 2014. In addition, daily inflow of the Pavatkulam reservoir is obtained for year 2012. The precipitation data is utilized for the BTOP model input and the observed discharges for the BTOP model calibration.

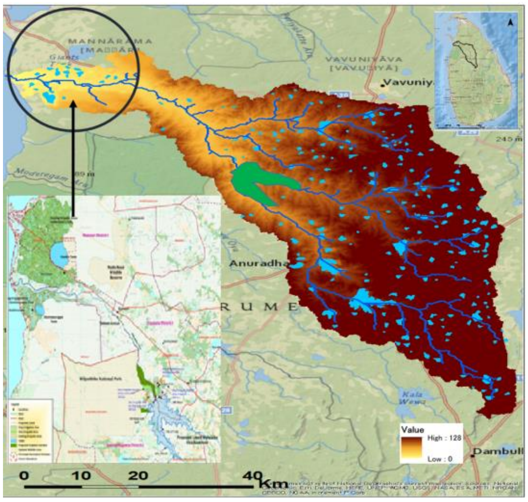

Figure-1. The Malwathoya River Basin, Sri Lanka, selected for this study.

Methodology

The main steps of the proposed methodology are illustrated in **Figure-2**. In Step 1, ground and sattelite data collection have been conducted for the Malwathoya River basin. In Step 2, historical floods and droughts are qunatified using standartidized indicies of Standardized Precipitaion Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) and satellite-based indices of Normalized Vegetaion Index (NDVI) and Land Surface Water Index (LSWI). In Step 3, a distributed hydrologic model, BTOP, is developed with current basin features of small and medium tanks to simulate past flood and drought events. In Step 4, the calibrated BTOP model is utilized to simulate the proposed dam operation and to determine the flood and drought mitigation in the lower part of the basin.

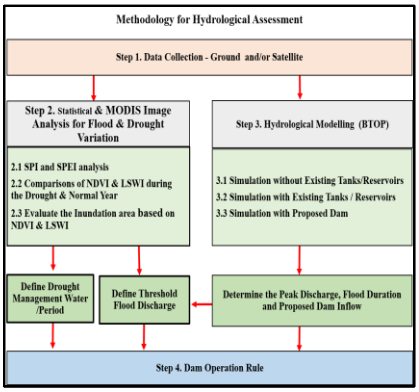

Figure-2. Steps of the adopted methodology.

Standartized indicies (SPI and SPEI)

The standardized indices are obtained by fitting the long-term monthly climatic record to a cummulative probability distribution, which is then transformed into a normal distribution. The SPI is transformed by the gamma distribution and the possitive SPI indicates greater than median precipitation and negative values indicates less than median precipitation (McKee et al., 1993). SPEI is calculated as a difference between precipitation and potential evapotranspiration and is transformed by several available distributions except gamma (Vicente-Serrano et al., 2010). The range of SPI and SPEI values indicate moderate drought from -1.0 to -1.49, severe drought from -1.50 to -1.99, and extreme drought below -2.0 (McKee et al.,1993).

Satellite-based indices (NDVI and LSWI)

The satellite-based indices such as NDVI and LSWI have been effectively used to characterize historical droughts and floods (Chandraseker et al., 2008). The NDVI is determined as $\mathrm{NDVI} = \frac{\mathrm{NIR-IR}}{\mathrm{NIR+IR}}$, where NIR and IR are represented the percentage reflected radiation in the near infrared portion and the red portion of the spectrum, respectively. The LSWI is calculated as $\mathrm{LSWI} = \frac{\mathrm{NIR-SWIR}}{\mathrm{NIR+SWIR}}$, where SWIR is the short wave infrared portion of the spectrum. For both indices, the range is from -1.0 to 1.0 and the flood events are indicated by low NDVI and high LSWI. The drought can be characterized by comparison of higher three month time series value of NDVI and LSWI.

Distributed hydrological model BTOP

BTOP model conducts rainfall-runoff simulations based on **(Figure-3)** vegetation, root, unsaturated and subsurface zones (Gusyev et al., 2015). From each BTOP grid, the river flow contribution is calculated as the sum of simulated Horitonian overland flow (q_{ofh}), saturation excess runoff flux (q_{oh}) and subsurface discharge (q_b) multiplied by an area of the BTOP grid. In this study, two dam operation types ("32" and "31") were developed in the BTOP model to simulate irrigation diversion requirement (IDR). Type "32" dam operation is designed to simulate daily release from small tanks to meet IDR, which is based on daily effective rainfall, monthly crop coefficient, irrigation efficiency and the irrigated area supplied by the associated infrastructure. Type "31" dam operation is multi-purpose dam operation with a flood control and IDR release for the dry season irrigable area, which is estimated from the reservoir water storage at the beginning of growing season. For the study basin, the thousands of small existing water storages were grouped into irrigation clusters and simulated with the dam operation type "32" and for the existing reservoirs and the proposed dam are implemented with the operation type "31".

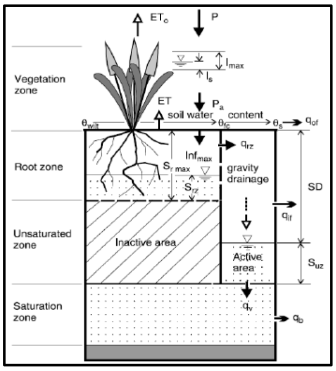

Figure-3. BTOP grid cell hydrological processes (Gusyev et al., 2015).

Result and Discussion

Standartized indicies (SPI and SPEI)

Figure-4 shows 3-month SPI and SPEI at the Lower Malawthoya basin from 1950 to 2014 and both standardized indices demonstrate a similar pattern of historical floods and droughts. There were no droughts with extreme severity between 1950 and 1984, but there was an extremely wet season in 1957, which is considered as 100-year flood. After year 1985, frequency and magnitude of droughts are increasing during dry seasons as well as having frequent floods during wet seasons. The recent droughts in year 2010, 2012 and 2014 and floods also indicated in year 2011, 2012 and 2014 are indicated as severe. These results highlight the necessity of water storage in headwaters of the Malwathoya basin to mitigate future floods and droughts in the lower part of the basin.

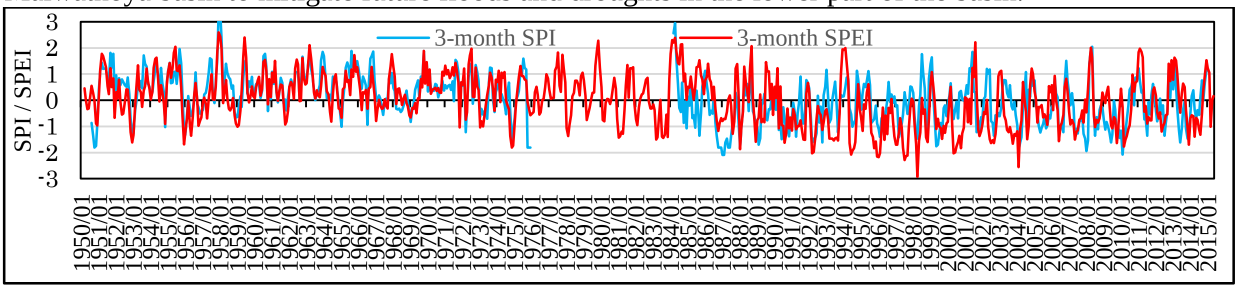

Figure-4. 3-month SPI and SPEI at the Lower Malwathoya basin, Sri Lanka

Satellite-based indices (NDVI and LSWI)

Figure-5 shows NDVI and LSWI values for a normal year, and flood and drought years in the Giants Tank and Mannar paddy field areas. In December 2012 and 2014, NDVI values are low and LSWI values are high compared with December 2013 due to flooding, that time rice stages were initial and development stages. NDVI and LSWI values are lowered from June to August in 2014 compared to 2013 due to drought that occurred during time mid- and late stages of rice. Diversion discharge to lower basin paddy field and overflow discharge at Thekkam are an indicator for flood and drought occurrences. **Figure-6** shows NDVI and LSWI reference to discharge at Thekkam, month of June to August in 2014, river discharge is almost zero and NDVI and LSWI decrease, this was indication for drought occurrence. In December 2014, NDVI low and LSWI high due to flood. Therefore, the remote sensing analysis provide information of flood threshold level, water scarcity months, stage of crop failure due to floods and droughts in the paddy field area of the lower Malwathoya basin.

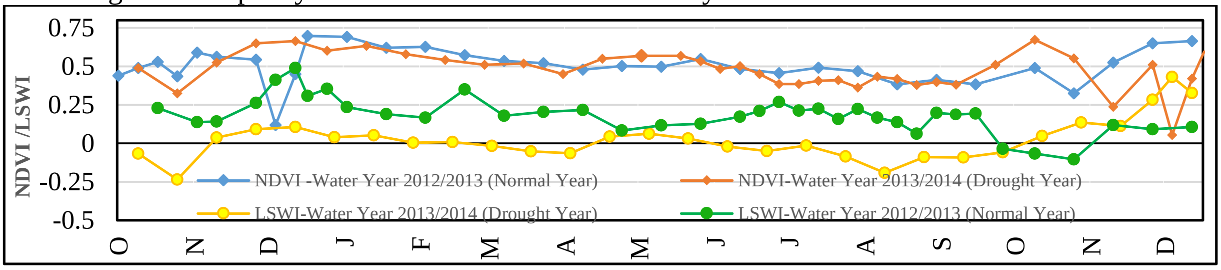

Figure-5. NDVI and LSWI values for normal, flood and drought years in the paddy field area in the lower part of the Malwathoya basin.

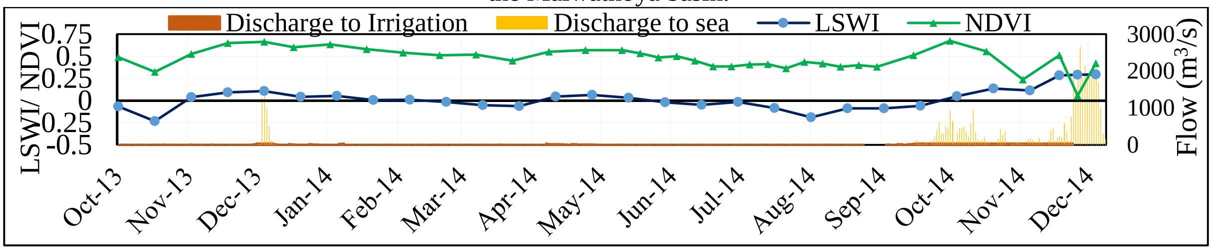

Figure-6. NDVI and LSWI of lower Malwathoya basin reference to discharge at the Thekkam diversion.

Short- and long-term BTOP model simulation

In the study basin, the importance of existing water storage reservoirs is demonstrated in **Figure-8**. **Figure-7** shows low flows occurring from January to October 2012 due to long dry period and high river discharges due to runoff starting from mid of October, 2012 for the short-term simulation. The simulated BTOP discharge without existing storages is over estimated from October to December. This is due to the water storage capacities of storages that are refilled and consumed for the paddy irrigation. The simulated BTOP discharges with existing storages and irrigation diversion releases have a better fit the observed discharges. For the flood season, high flood peak was not reduced by existing storages due to full storage. **Figure-8** shows inflow and volume of the proposed dam from 1990 to 2014 by the long-term BTOP simulation with type "32" dam operation. The proposed dam has sufficient inflows during wet season and is refilled on annual basin to release irrigation water during dry season.

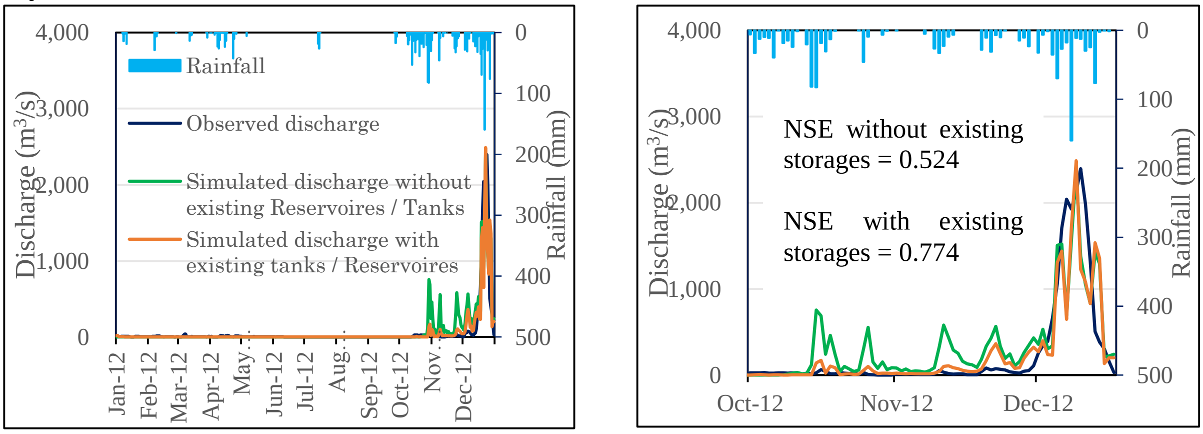

Figure-7. Simulated and observed river discharges at the Thekkam diversion in year 2012 (left) and from October to December 2012 (right).

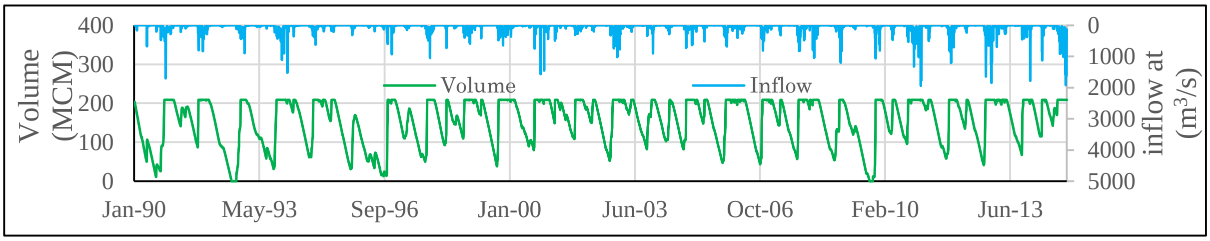

Figure-8. Variation of simulated inflow at dam site and proposed dam volume from 1990 to 2014

Dam Operation for flood control at Thekkam

Thekkam diversion is the reference point for the flood control in the lower part of the Malwathoya basin as shown **Figure-9.** For the proposed dam, flood operation rule is based on the long-term simulated inflow discharges and estimated flood peaks of the different return period at Thekkam. The correlation between discharge at the Thekkam diversion and dam site is shown in **Figure-10** using initial dam volume at the beginning of the wet season. Then**,** the operation rule of the proposed dam is applied for the 2012 flood event and the flood peak is reduced by 820 m^3/s at the Thekkam weir, see **Figure-11**. For the 2014 flood event, the first flood peak is reduced by 812 m^3/s as shown in **Figure-12**, but the second flood peak of about 2100 m^3/s is uneffected by the proposed dam flood operation rule. This is due that the initial volume of proposed dam is 40 MCM before the first flood peak and is fully occupied by the flood inflows leaving no flood storage for the second flood peak. As the result of this analysis, the proposed dam is more effective for capturing the flood peak inflow of up to the 5-year return flood and flood occures between 10- to 25-year return periods with small reduction of the flood peak and no flood water storage is available for the two consective flood peak inflows.

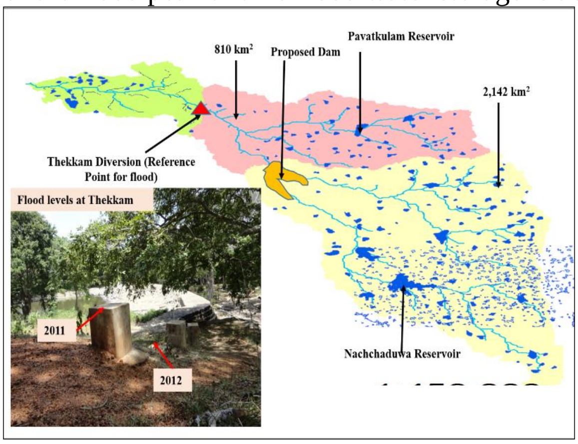

Figure-9. Catchment of inflow contribution at Thekkam diversion and flood levels in 2011 and 2012

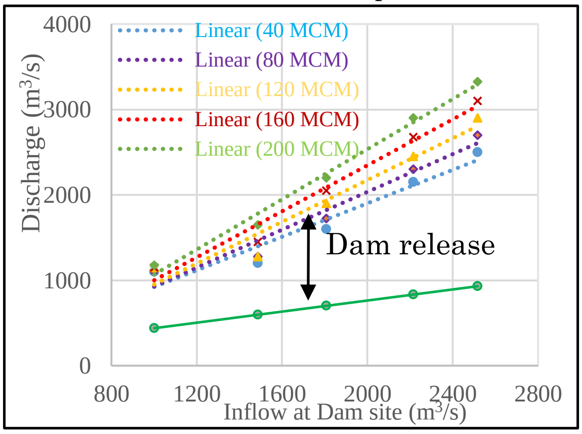

Figure-10. Correlation of inflow of dam and discharge at Thekkam by Dam operation

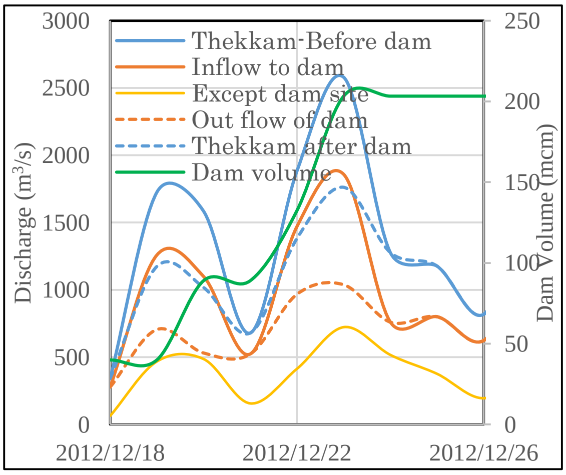

Figure-11. Hydrograph of Thekkam and dam site before/after dam in 2012 December

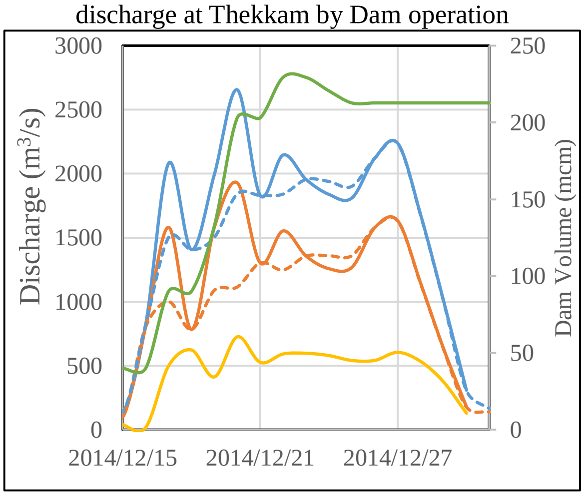

Figure-12. Hydrograph of Thekkam and dam site before/after dam in 2014 December

Dam Operation for Drought Management

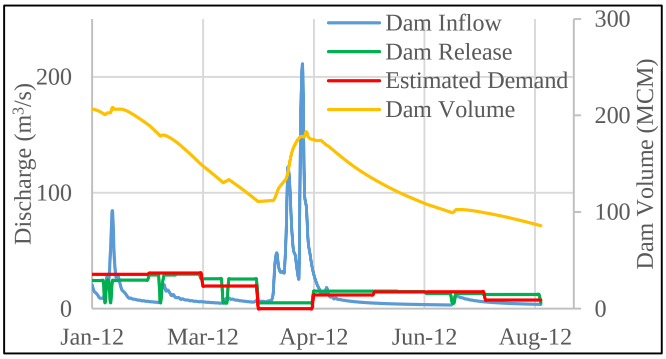

Figure-13. BTOP simulation with the proposed dam for the flood inflow reduction and irrigation water release from January to August in year 2012.

Figure-13 shows the BTOP simulation with type "31" dam operation of the proposed dam for 2012 wet and dry cultivation seasons. For the wet season, the peak inflows were captured by the dam's flood control capacity and the rice cultivation was successfully completed from January to March by fully utilizing the agricultural area of 170 km^2 in lower part of the basin. In the dry season, the water volume was carried over in the simulated and was used by type "31" dam operation to determine the irrigable area at the lower part of the basin. This allowed for the dry season cultivation of 73km^2 from May to August. In 2012, historical dry season cultivation was 33km^2 and had 22km^2 of drought affected paddy areas. Therefore, net benefit of the proposed dam would be 62km^2 of irrigated area during the dry season.

Recommendations

1. In the future studies, all existing storages should be implemented in the model on the stand-alone basis to improve the accuracy of the simulated discharge of each individual storage. These results should also provide useful information of drought management and water allocation.
2. Flood inundation should be simulated in the lower basin area with and without the proposed dam.
3. The flood operation of existing Nachchaduwa and Pavatkulam reservoirs should be integrated with the proposed dam flood control operation to enhance the operation rule at the Thekkam weir.
4. The Malwathoya basin has highly dense with water bodies, therefore satellite image based land surface indices analysis useful for the future drought monitoring and assessments.

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