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APPLICATION OF A PROCESS-BASED, DISTRIBUTED, HYDROLOGICAL AND MATERIAL TRANSPORT MODEL TO ASSESS WATER RESOURCES AND POLLUTE TRANSPORT IN MALWATHU OYA BASIN, SRI LANKA

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Abstract: The Water and Energy transfer Processes Model – WEP Model is a distributed, physically based hydrologic model that has been coupled with a material transport component. The model uses meteorological, geographical, hydrological data and, data relevant to anthropogenic activities and water quality simulation processes, as inputs. The model is capable of providing time series values of water and heat balance as well as water quality/material transport results for each grid, as outputs. It has been successfully applied to river basins in Japan, China, Korea and elsewhere to study the water resources management options and pollution caused by dissolved and particulate pollutants including the dispersal of excess Nitrogen and Phosphorous introduced by industrial effluents and chemical fertilizers. The present study incorporates a detailed modelling approach to the Nachchaduwa sub-catchment (598.74 km^2) of the Malwathu Oya river basin, to study the water resources management options under the effect of varying rainfall patterns and impending climate change impacts. The model can be extended to study the fate and behaviour of the elements (Nitrogen and Phosphorous) which are added to the waterways as a result of the extensive use of agrochemicals in paddy lands in the upstream catchment area. This paper reviews the current state of the catchment as well as the suitability of applying the proposed model to Sri Lanka to assess this basin, which is seasonally stressed due mainly to over exploitation and water pollution. Apart from the water resources management, a quantitative analysis on the fate of excess amounts of agrochemicals used can also be concluded by studying the dispersal and accumulation behaviour of these elements after they have been added to the crop fields and waterways. The findings of the research study will be useful in identifying possible better water management scenarios and managing the fertilizer/agrochemical usage of this catchment in a more pragmatic manner. This study will set the baseline for commencing and continuing quantitative studies regarding studying the behaviour of the pollutants including their conveyance and spatial and temporal accumulation patterns after they have been added to the waterways, in the North Central Province of Sri Lanka.

Keywords: Pollute transport; Process-based hydrological and material transport model; Water resources management.

1. Introduction

Even though several studies have been undertaken to study water quality parameters in few locations of the water bodies of the North Central Province of Sri Lanka, none have attempted to conduct a quantitative analysis of the particulate matter pollution in those waters. Most of the researches that have been done related to this topic are qualitative in nature. This study will set the baseline for commencing and continuing quantitative studies regarding this subject matter. Further, no studies have been done to study the behaviour of the pollutants including their conveyance and spatial and temporal accumulation patterns after they have been added to the waterways, in the North Central Province of Sri Lanka.

Based on the findings of this study, water resources management alternatives and measures to address issues related to degrading water quality in the basin, due mainly to over exploitation and excessive use of agro-chemicals, can be recommended.

By conducting a distributed hydrological model analysis on the Nachchaduwa watershed, a better insight into the behaviour of the water quality can be identified. The over usage of agrochemicals and fertilizers could be regulated by developing a guideline to the proper usage of fertilizers in required quantities. Particulate matter pollution density maps for the waters in that region could also be developed.

Even though the excessive usage of agrochemicals in the North Central Province has been suspected as one of the reasons for causing the Chronic Kidney Disease of unknown aetiology (CKDu), been quantitatively proven. Particulate matter pollution density maps can be overlapped with the CKDu affected patient density maps to find out whether the two aspects have a correlation between them. The CKDu has caused lot of social issues in Sri Lanka. Hence, the long term water resources development and optimal use of agrochemicals will benefit the society comprehensively by addressing water stress related issues as well as health problems related to CKDu.

This paper reviews the current state of the catchment as well as the suitability of applying the proposed WEP model to Sri Lanka to assess this basin, which is seasonally stressed due mainly to over exploitation and water pollution.

2. Methodology

The research gap has been identified by conducting a comprehensive literature survey. Then the data needed for the hydrological component and the material transport component of the WEP model have been collected. The data have been checked by several data checking procedures. The study area has been investigated by conducting field visits. Water quality samples have been collected throughout the stream and they have been tested for the water quality components.

At present, the remaining data are being collected and are being analysed. In addition, the input files are being prepared for the model trial runs for hydrologic calibration and validation. Furthermore, the model results pertaining to pollutant transport have to be obtained by conducting additional model runs in the future.

3. Overview and Present Status of the Basin

3.1 Malwathu Oya Basin

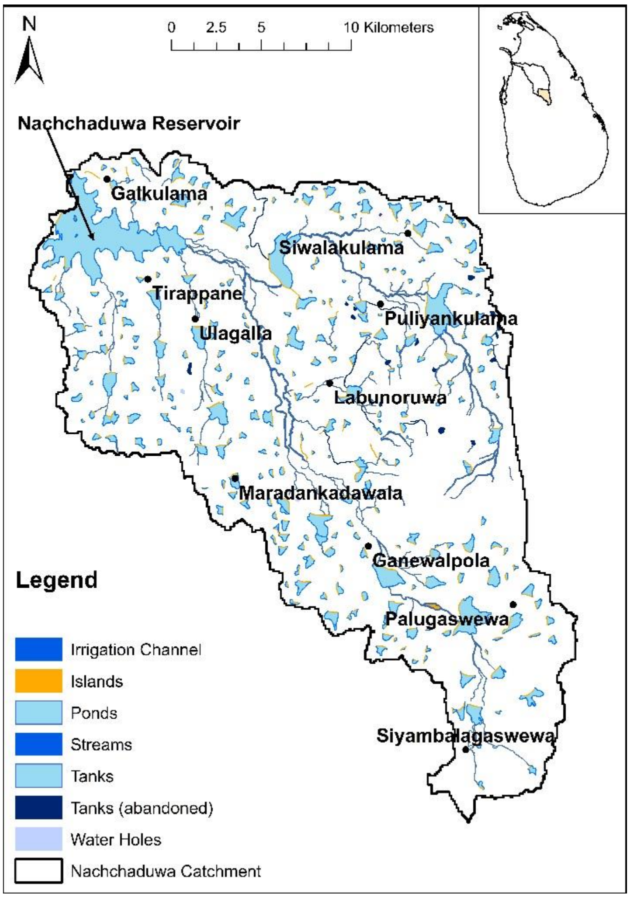

Fig. 01. Nachchaduwa Catchment

Malwathu Oya has the second largest catchment area (3284 km^2) amongst the river basins in Sri Lanka. Majority of the upper catchment area which accounts to about 70% of the total basin area lies in the Anuradhapura district while lower catchment areas are in the Vavuniya and Mannar Districts in the Northern Province. Though upper catchment of Malwathu Oya is intercepted by major reservoirs (1) Nachchaduwa (Fig. 01.), (2) Mahakanadarawa, (3) Pavatkulam, (4) Nuwara wewa, and (5) Tissa wewa, the lower catchment is not regulated at all. However, Tekkam anicut is located about 36 km up stream of sea coast and augments reservoirs located in the adjacent coastal basins viz: Giants tank and Akitamuruppu tank in the right bank and left bank, respectively. However, Malwathu Oya basin too is augmented by adjacent Kala Oya basin from Kala wewa reservoir via Yoda Ela to feed Nachchaduwa, Tissa wewa and Basawakkulama. The basin is peculiar as it possesses phenomenal number of tanks from small size village tanks to comparatively fair sized tanks (Anon., n.d.) [1].

Malwathu Oya is the only perennial stream passing through Anuradhapura, which provides water for various purposes. Moreover, the stream serves as a site for waste disposal in the urban area and water becomes polluted easily. A study has been conducted to assess the impacts of urban land use on pollution in upper Malwathu Oya stream to develop a comprehensive management plan to prevent further pollution. The study included measuring quality of water from nine sampling points representing different land uses along the three drainage canals; while two samples from the main stream at the inlet and outlet to the city were collected for analysis. Total dissolved solids, pH, electrical conductivity, dissolved oxygen level, PO_4^{3-} and NO_3^- of the collected water samples have been measured. According to the results, the sample collected at the outlet has shown higher values for all the water quality parameters, confirming the impact of urban land use on water pollution. Discharge levels of all drainage canals were lower and consisted of higher concentration of nutrients and other elements. Among them, the canal flowing across the city centre has shown the highest concentration of PO_4^{3-}, NO_3^- and K^+. Therefore, that study has concluded that there is a higher impact of urban land use on pollution of Malwathu Oya and a comprehensive plan is needed for preventing further pollution with the participation of other responsible parties (Madushanka, et al., 2014) [2].

In Malwathu Oya river basin, around 180 cascade systems in 15 sub watersheds have already been identified. A cascade is a connected series of small irrigation tanks organized within a meso catchment of the dry zone landscape, storing, conveying and utilizing water from an ephemeral rivulet. Malwathu Oya main cascade is a branched type large cascade of 25.88km^2 with overall length of 7.1 km (Gunarathna & Kumari, 2014) [3].

A study has been conducted to evaluate availability and quality of groundwater in Malwathu Oya main cascade. Twenty agro-wells were selected and water quality parameters such as pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS) and concentration of Sodium (Na^+), Potassium (K^+), Calcium (Ca^{2+}) and Magnesium (Mg^{2+}) were analyzed. Sodium percentage (Na %), Sodium Adsorption Ratio (SAR) and Residual Sodium Carbonate (RSC) were calculated using measured parameters (Nirmanee, et al., n.d.) [4].

In another study, eleven small tanks in Malwathu Oya main cascade were identified and water samples were collected monthly from February to June 2011. Three samples were collected from inlet, outlet and stored water of each tank and analysed for quality parameters such as temperature, dissolved oxygen, pH, electrical conductivity, total dissolved solids, turbidity, sodium, potassium, phosphorus, ammonium nitrogen, nitrate nitrogen and alkalinity. Water spread area was estimated using a global positioning system receiver. Tank cascade system and water quality parameters were mapped using Geographic Information System tool. Results has revealed that the water quality parameters varied spatially and there was temporal water quality deterioration. Water quality status were better in wet flow compared to dry flow, though, water quality is still good for irrigation even in dry flow in upper and middle parts of the cascade. Water resources at the bottom of the cascade showed slight to moderate salinity conditions during dry flow (Perera, et al., n.d.) [5].

3.2 Study Area - Nachchaduwa Catchment

Nachchaduwa catchment (Fig. 01.) was selected as the study area for this research since it is the uppermost sub catchment in the Malwathu Oya catchment.

Several previous studies have assessed the water quality parameters of few reservoirs, including the Nachchaduwa reservoir. Those parameters include, pH, salinity, electrical conductivity, SAR (Sodium Absorption Ratio) (Silva, 2004) [6].

Most of the water in an irrigation tank is brought in during the rainy season. However, only a small portion of the tank water is obtained by direct precipitation. The bulk of it comes from the catchment area. As this water flows into the tank, it brings dissolved material by contact with soil, rock and other inorganic and organic substances. Irrigation water may benefit crops by supplying certain plant nutrients. On the other hand, a saline water or a high sodium water may be harmful. Irrigation water quality is an important parameter which may determine the sustenance of an irrigated agricultural system. The pH, electrical conductivity, sodium, potassium, calcium, magnesium, chloride, sulphate, bicarbonate and silicon content of the Nachchaduwa reservoir have been measured (Amarasiri, 1972) [7].

Nachchaduwa reservoir is owned by the Department of Irrigation and it is fed by the Malwathu Oya and the feeder canal from Kala wewa. It has an irrigable area of 2833 ha and a catchment area of 598.74 km^2. The reservoir has three spillways, namely; the ungated ogee spillway, gated spillway and the left bank high level spill. It has sluices in its left bank (for irrigation releases) and in the right bank (for releasing water to Nuwarawewa). The irrigation system of the reservoir consists of two canals which are the high level main canal and the low level main canal.

3.3 Selection of the WEP Model for the Analysis

Distributed physically-based hydrological models can take account of spatial variations of all variables and parameters involved in the basic mathematical equations of the water flows for a watershed. In addition, the used parameters are physically measurable. Therefore, they give a detailed and potentially more correct description of the hydrological processes in the watershed than empirical and conceptual hydrological models. With more available data, especially with the development of GIS and remote sensing technology, the study and application of this type of models have been promoted and become more prevalent. Today, there exist several popular models of this type, like SHE, IHDM and MIKE SHE etc. (Jia, et al., 2001) [8].

The WEP model has been developed by adding more detailed energy balance analysis in hydrological modeling. The model is based on Jia and Tamai (1998) [9] and it is improved by adding simulation of multi-layered aquifers, direct computation of groundwater outflow to rivers and simulation of infiltration trenches. Although the WEP model simulates most of the hydrological processes by the similar methods as the distributed physically-based models mentioned above, its main differences from those models are as follows.

1) The energy transfer processes are also simulated in detail in addition to hydrological processes. Because of its detailed consideration of heat flux partitions on land surface, the model not only enhances the computations of interception and evapotranspiration but also is easy to be coupled with atmospheric models.

2) The sub grid heterogeneity of land use is considered by using the mosaic method, which is believed to be more reasonable than the usual dominant land use method, especially in urbanized area with complex land covers.

3) The generalized Green-Ampt model is developed to simulate infiltration and infiltration excess during heavy rains to save computation time.

4) The infiltration trenches are simulated in the model, which makes it possible to evaluate their effect on hydrological cycle.

Thus, the WEP model is developed to simulate spatially variable water and energy processes in watersheds with complex land covers. In the model, state variables include depression storage on land surfaces and canopies, soil moisture content, land surface temperature, groundwater tables and water stages in rivers, etc. The sub grid heterogeneity of land use is also taken into consideration by using the mosaic method. For hydrological processes, evapotranspiration is computed by the Penman–Monteith equation, infiltration excess during heavy rains is simulated by a generalized Green–Ampt model, whereas saturation excess during the remaining periods is obtained by doing balance analysis in unsaturated soil layers. A two-dimensional simulation of multilayered aquifers, i.e. quasi-3D simulation is performed for groundwater flow. River flow routing is conducted for every tributary and a main river by using the kinematic wave method. Overland flow is simplified as lateral inflow to rivers because the concentration time is estimated to be shorter than the simulation time interval in this study. For energy processes, short-wave radiation is based on observation or deduced from sunshine duration, long-wave radiation is calculated according to temperatures, latent and sensible fluxes are computed by the aerodynamic method and surface temperature is solved by the force–restore method. In addition, anthropogenic components, e.g. water supply, groundwater lift, sewerage drainage and energy consumption, etc. are also taken into account (Jia, et al., 2001) [10].

The model was applied to the Ebi River watershed (27 km^2) with a grid size of 50 m and a time step of 1 h. The model was verified through comparisons of simulated river discharges, groundwater levels and land surface temperatures with the observed values (Jia, et al., 2001) [10]. The model has also been successfully applied to the Haihe River Basin, China (Cunwen, et al., 2011) [11]. This has also been used to simulate both hydrological processes and accompanied pollutant transfer processes in the Yellow River Basin, China (Jia, et al., 2007) [12] as well as the Yata River Basin, Japan (Rajapakse, et al., 2010) [13].

The process-based WEP hydrologic model can be further improved by coupling a soil erosion-transport model to introduce particle-bound pollutant component. The WEP model, initially developed for the extensive analysis of water and energy budgets at catchment scale, was later enhanced by incorporating material transport component (nitrogen and phosphorus; N and P), targeting integrated river basin management and decision support. The model involved a discharge-based process to simulate both N and P, and was validated using data in Yata River Basin, Japan, considering land use, plant acreage, fertilizer loading, plant nutrient uptake and crop harvest in respective administrative units. Although the model could adequately reproduce the dissolved N (DN) component as per the measured river N concentrations at selected observation points, particulate N and P (PN, PP), and dissolved P (DP) components were not satisfactorily simulated. Therefore, an attempt was made to incorporate PN and PP transport as soil absorbed constituents, by introducing a process-based sediment erosion, transport, deposition and associated pollutant load simulation procedures. This modeling results indicate that PN and PP loads were better correlated with suspended solids (SS) in the stream and the model forecasting capabilities are noticeably enhanced, as verified based on the results obtained for simulation years 2001-2002 using pre-collected data (SS, PN and PP), signifying major pathways of nutrient losses in the basin (Rajapakse, et al., 2010) [13].

The diagram of the model structure within a grid cell utilized is shown in Figure 2. The areal average of water and heat fluxes from all land uses in a grid cell produces the averaged fluxes in the grid cell. Land use is at first divided into three groups, namely a water body group, a soil–vegetation group and an impervious area group. The soil–vegetation group is further classified into bare soil, tall vegetation (forest or urban trees) and short vegetation (grass or crops). The impervious area group consists of impervious urban cover and urban canopy. For the soil–vegetation group, nine vertical layers, namely an interception layer, a depression layer, three upper soil layers, a transition layer, an unconfined aquifer and two confined aquifers, are included in the model structure. The energy balance of each land use is also analysed. The interaction of radiation between soil and vegetation is considered by use of the fraction of transmitted short-wave radiation of vegetation, whereas the interaction between urban cover and urban canopy is considered by using the sky view factor of urban cover. The diagram of the model horizontal structure within a watershed is shown in Figure 3 (Jia, et al., 2001) [10].

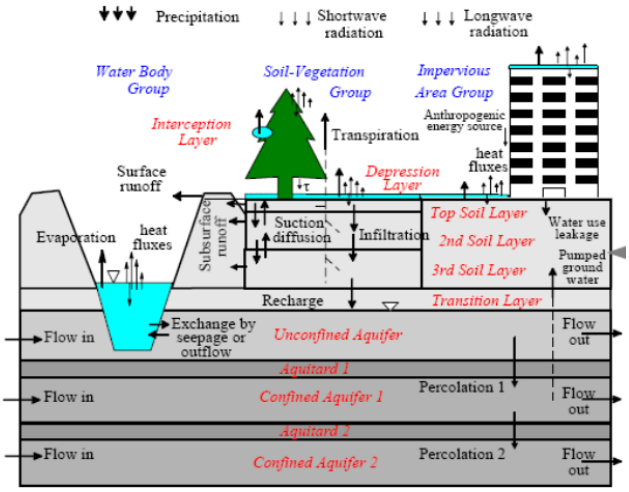

Fig. 02. The Structure of the WEP Model - Vertical Structure within a Grid Cell

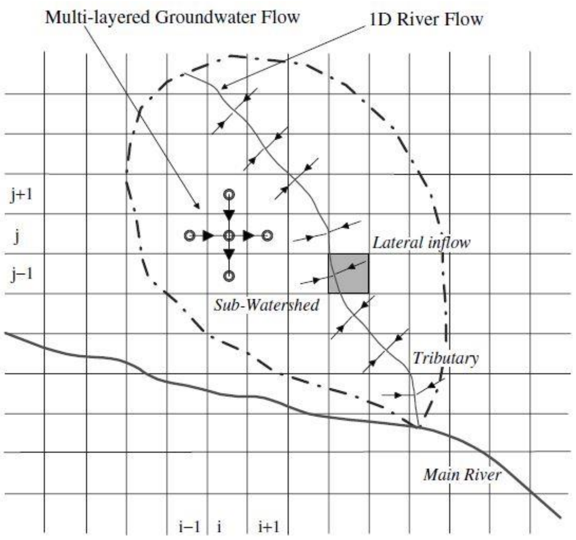

Fig. 03. The Structure of the WEP Model - Horizontal Structure

4. Identified Research Gap

1) Even though several studies have been undertaken on the water quality parameters in few locations of the water of the North Central Province of Sri Lanka, none have been conducted to quantitatively study and analyse the effects of particulate matter pollution in those waters. Most of the researches that have been completed thus far related to this topic are qualitative in nature. This study will set the baseline for commencing and continuing quantitative studies regarding this subject.

2) No studies have been done to study the behaviour of the pollutants including their conveyance and spatial and temporal accumulation patterns after they have been added to the waterways, in the North Central Province of Sri Lanka.

3) Based on the findings of the study, water resources management alternatives and measures to address issues related to the degrading water quality in the basin, due mainly to excessive use of agro-chemicals, can be recommended.

4) No distributed hydrological model analysis has previously been conducted on the Nachchaduwa watershed, to gain a better insight to the behaviour of the water quantity and quality.

5) Not enough studies have been accomplished, in order to regulate the over-usage of agrochemicals and fertilizers or to develop a guideline to the proper usage of fertilizers in that area.

6) Particulate matter pollution density maps for the waters in that region has not yet been developed.

7) Even though the excessive usage of agrochemicals in the North Central Province has been suspected as one of the reasons for causing the Chronic Kidney Disease of Unknown aetiology (CKDu), it has not been quantitatively proven. The particulate matter pollution density maps can therefore be overlapped with the CKDu

affected patient density maps to find out whether the two aspects have a correlation between them.

8) CKDu has caused lot of social issues in Sri Lanka. Hence the long term water resources development and optimal use of agrochemicals will benefit the society comprehensively by addressing the water stress related issues as well as the health problems related to CKDu.

5. Results and Identified Trends

Nachchaduwa catchment consists of several land use types, which include; chena, forests, home gardens/gardens, other cultivations, paddy, rock, scrub land, as well as the water bodies. According to the digital maps prepared by the Survey Department of Sri Lanka, the soil types of the catchment is mainly composed of; alluuvial soils of variable texture and drainage (flat terrain) in the vicinity of the stream paths and, reddish brown earths and low humic gley soils in everywhere else. The entire catchment has been delineated into three sub catchments according to the terrain and stream path distribution. Fig. 04. illustrates the delineated sub catchments.

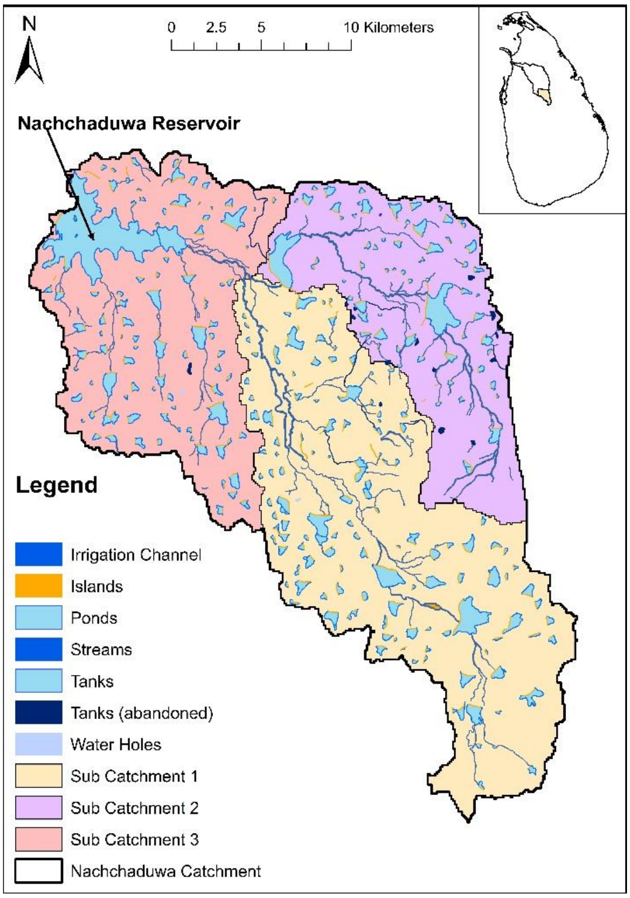

Fig. 04. Sub Catchments of the Nachchaduwa Catchment

Daily rainfall data for stations Anuradhapura, Kahatagasdigiliya, Kekirawa, Maha Illuppallama, Pelwehera were collected from the Meteorological Department. The data was checked for outliers and missing data. Missing data were filled by plotting the single mass curves (by omitting the missing data points) for all these stations. Gradients of the single mass curves were found for the data set(s) up to the missing data points and were used to calculate the missing values. After filling them, the double mass curves for each station were drawn. Then the Thiessen average daily rainfall values were calculated for the catchment.

The stream flow related data and reservoir operation data were collected from the Department of Irrigation, and were checked against the rainfall values. The monthly and annual runoff coefficients were also calculated using those data.

The response of the catchment (total outflow) with precipitation was checked and the resulting graph is shown in Figure 5. The total daily outflow from the reservoir included all the spill and sluice releases. It was noted that during certain years, the rainfall and total outflow from the reservoir do not show a good correlation due to lack of reliable reservoir operation related data. An initial HEC-HMS model [Hydrologic Engineering Center's Hydrologic Modeling System, developed by the United States Army Corps of Engineers (USACE)] analysis was performed by considering the entire Nachchaduwa catchment by using the calculated Thiessen average rainfall values. The SCS (The Soil Conservation Service) curve number method was used as the loss method and the curve numbers were calculated using the land use data for the entire catchment. The SCS unit hydrograph method was used as the transform method. It was considered that there is no base flow, and the initial abstraction was set to zero for the preliminary model runs. The time of concentration and lag time for the catchment were calculated using the Irrigation Department Guidelines (Ponrajah, 1984) [14]. The evapotranspiration was calculated by taking the monthly average values for the Nachchaduwa evaporation station and a pan coefficient of 0.8 was used (Ponrajah, 1984) [14]. It showed a good correlation of the catchment response to the rainfall indicating that the measured spill and total release data are highly underestimated (Figure 6). Therefore, the basin has to be considered as an ungauged catchment when the basin-wide hydrologic modelling is conducted.

The study area has been investigated by conducting field visits. Water quality samples have been collected throughout the stream cascade and they have been tested for the water quality parameters, according to the Standard Methods for the Examination of Water and Wastewater (American Public Health Association, et al., 2005) [15]. Table 1 summarises the water quality sample details, which were collected during the dry season (Yala season) and Table 2 summarises the water quality test results. The mean and standard deviation of the upstream and downstream NH_4^+ - N concentrations determined from descriptive statistics are 13.75±7.50 ppm and 22.75±8.62 ppm, respectively. Hence, the NH_4^+ - N concentrations tend to increase towards the downstream. Single Factor ANOVA values for NH_4^+ - N concentrations are; F =2.483, P =0.166 and $F_{Critical}$ =5.987, respectively.

The mean and standard deviation of the upstream and downstream PO_4^{3-} - P concentrations determined from descriptive statistics are 0.37±0.15 ppm and 0.34±0.06 ppm, respectively. Therefore, the PO_4^{3-} - P concentrations tend to decrease towards the downstream. Single Factor ANOVA values for PO_4^{3-} - P concentrations are; F =0.076, P =0.792 and $F_{Crtical}$ =5.987, respectively.

Nevertheless, from these ANOVA results it can be concluded that the differences between the upstream and downstream concentration values of the water quality parameters are not statistically significant, despite the slightly increasing or decreasing trends shown from upstream to downstream sites.

The NO_3^- - N and NO_2^- - N concentrations were below the minimum measurable limit of the apparatus. Fig. 07. represents a bubble diagram of the water quality test results, with the sampling locations.

Additional sampling for the measured parameters will be continued covering both wet and dry seasons (high flow and low flow conditions) to further investigate spatial and temporal trends and associated seasonal variations.

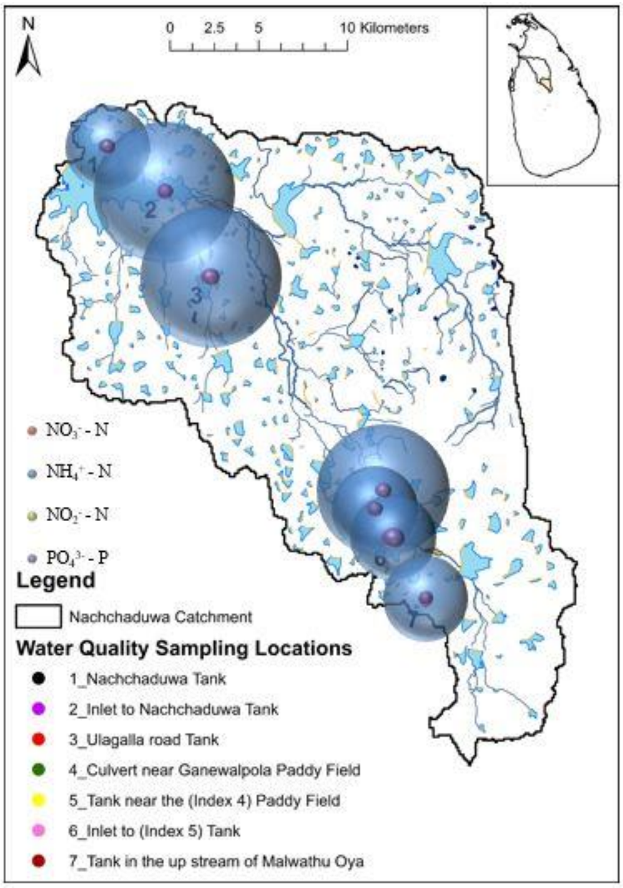

Fig. 07. Water Quality Test Results with the Sampling Locations

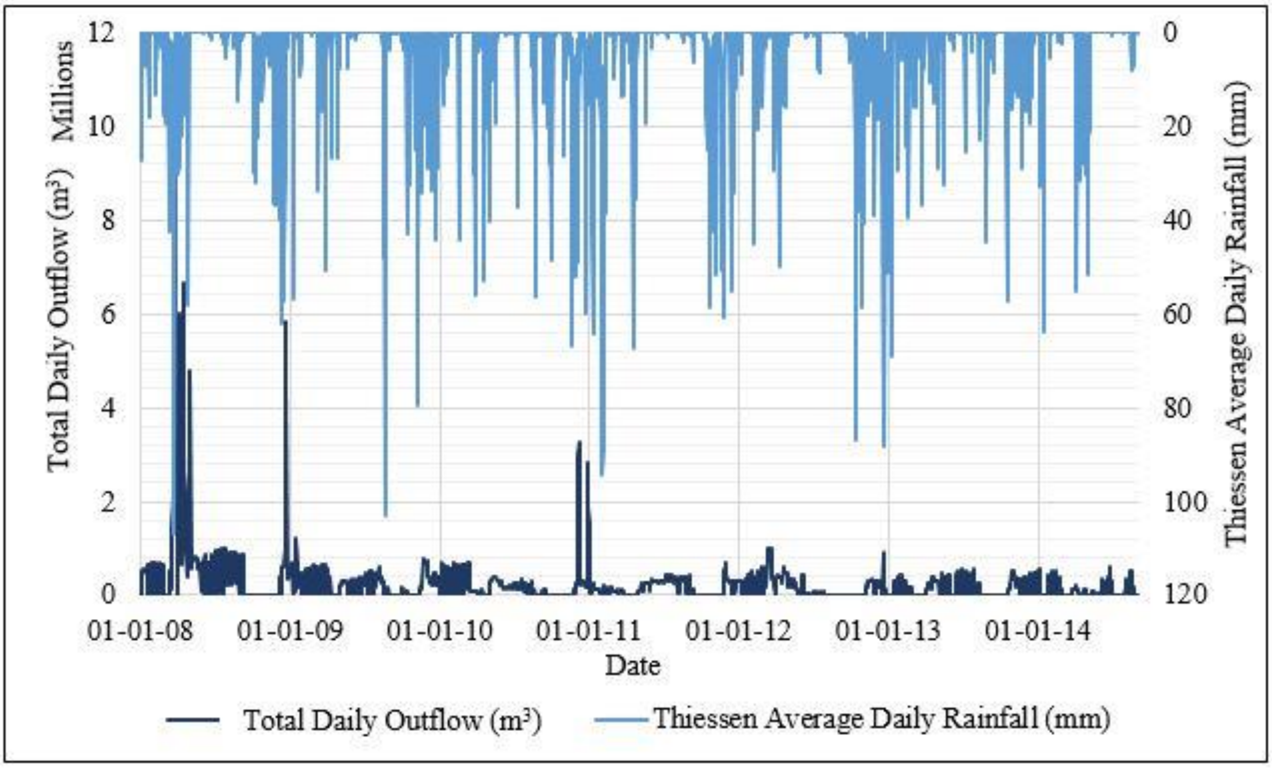

Fig. 05. Thiessen Average Daily Rainfall (mm) and Total Daily Outflow (m3)

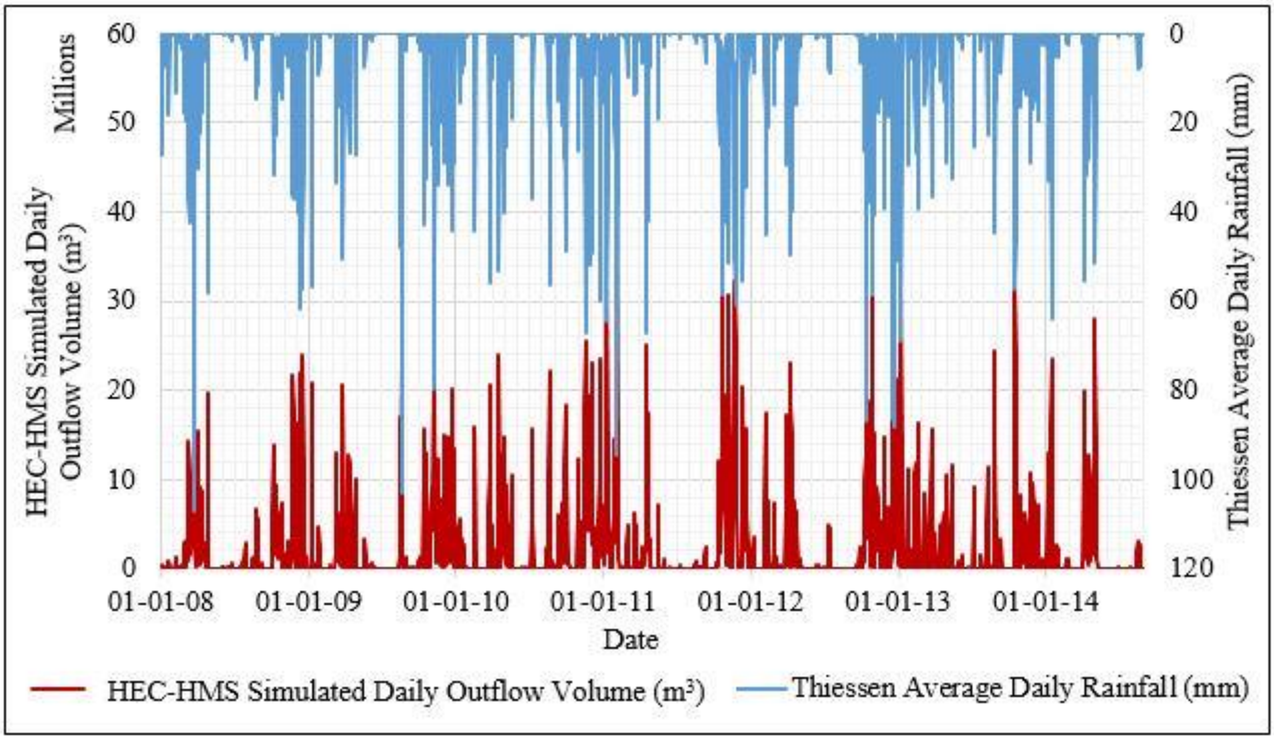

Fig. 06. HEC-HMS Simulated Daily Outflow Volume (m^3) and Thiessen Average Daily Rainfall (mm)

1	Nachchaduwa Tank	(8.268254, 80.491571)	12.10pm	1	Sunny, no wind, shady area
2	Inlet to Nachchaduwa Tank	(8.245356, 80.521026)	12.44pm	2	Sunny, lot of vegetation in the water
3	Ulagalla road Tank	(8.201681, 80.544532)	1.17pm	3	Sunny, shaded by a tree, some vegetation in the water
4	Culvert near Ganewalpola Paddy Field	(8.0917695, 80.6336567)	2.40pm	4	Sunny, culvert, shaded by a tree
5	Tank near the (Index 4) Paddy Field	(8.0822030, 80.6291160)	3.00pm	5	Sunny, no wind, muddy water
6	Inlet to (Index 5) Tank	(8.067624, 80.638727)	3.50pm	6	Cloudy
7	Tank in the upstream of Malwathu Oya	(8.036215, 80.655543)	4.45pm	7	No wind, some vegetation

Table 01: Water Quality Sample Details for Samples collected on 07th April 2016 (Yala Season)

Table 02: Summary of Water Quality Test Results

Bottle ID	NO_3^- - N concentration (ppm), measured on 11/04/2016	NH_4^+ - N concentration (ppm), measured on 19/04/2016	NO_2^- - N concentration (ppm), measured on 11/04/2016	PO_4^{3-} - P concentration (ppm), measured on 11/04/2016
1	below 0.05	10	below 0.05	0.327
2	below 0.05	28	below 0.05	0.287
3	below 0.05	28	below 0.05	0.426
4	below 0.05	25	below 0.05	0.334
5	below 0.05	10	below 0.05	0.288
6	below 0.05	10	below 0.05	0.581
7	below 0.05	10	below 0.05	0.258

5. Conclusions

Malwathu Oya, one of the most widely used sources of extracting water for irrigation, water supply and other diversions in the North Central Province Sri Lanka, has now become a seasonally stressed river basin due to over exploitation and water pollution. But no remedial measures have been taken to overcome this problem. The findings of the research study will be useful in identifying possible better water management scenarios and managing the fertilizer/agrochemical usage of this catchment in a more pragmatic manner. This study will set the baseline for commencing and continuing quantitative studies regarding studying the behaviour of the pollutants including their conveyance and spatial and temporal accumulation patterns after they have been added to the waterways, in the North Central Province of Sri Lanka.

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