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Feasibility of Sediment Budgeting in an Urban Catchment with the Incorporation of an HEC—HMS Erosion Model: A Case Study from Sri Lanka

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Abstract This study aimed at studying the feasibility of using a sediment model built in HEC – HMS incorporating Modified Universal Soil Loss Equation (MUSLE) in aiding the separation of sediment contribution as point and non-point, an important aspect in sediment pollution control. The model was developed and verified using a representative sub-catchment and a canal reach of a tropical climate. The field observations and model developed had a good agreement and indicated about 16% and 35% of total sediments in the canal may be from nonpoint sources for the dry and wet seasons, respectively. Results suggested that a major fraction of eroded sediment ended up in the main canal through the dense drainage network across the catchment. This meant sediment trapping should focus tributary drainage ditches or at point source inputs to canal rather than the main canal banks. The study recognized that HEC – HMS is also capable of simulating sediment generation with acceptable errors. Being a free software package, HEC – HMS would be an effective sediment modelling tool for jurisdictions where sediment analysis has been constrained by cost.

Keywords Canal · Point and non-point sources · Sediment Budget · Total Solids · Total Suspended Solids

1 Introduction

Sediments to urban waterways are sourced by natural mechanisms, such as erosion of soils, channel banks, or floodplain deposits by wind effect and water (Taylor & Owens, 2009), as well as by anthropogenic actions, such as construction activities, road surface wear, abrasion of materials (e.g., tyres, vehicle bodies, and road materials), vehicle emissions (Kim et al., 2019), wastewater (Taylor & Owens, 2009), and emissions from industrial sources (Vercruysse et al., 2017). Expansion of impervious lands due to accelerated urbanization results in a higher volume of surface runoff (Gomes & Wai, 2020), which also aids intensified sediment mobility to water bodies (Kim et al., 2019; Vercruysse et al., 2017). Only part of generated sediment travels to water bodies (Russell et al., 2019a; Taylor & Owens, 2009; Vercruysse et al., 2017), with the remainder retained by buffers such as fences, walls, turfed areas, and disconnected topographic low points (Russell et al., 2019b) and/or deposited in temporary sediment storages such as road surfaces, gully pots, and storm sewers (Taylor

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& Owens, 2009). Fine particles retained within the catchment could be remobilized by wind to water bodies (Taylor & Owens, 2009). The fate of sediment delivered to flowing freshwater bodies depends on the grain size of the sediment particles, runoff conditions (Kuksina et al., 2019; Vercruysse et al., 2017), and barriers which hinder sediment movement within the waterbody (Russell et al., 2019a, 2019b a and b).

Sediment yields in urban catchments are on the rise mainly due to rapid land use changes associated with anthropogenic activities that influence sediment generation (Liu et al., 2017). Increased input of sediments can degrade the quality of water bodies in terms of increased turbidity and reduced dissolved oxygen, hence adversely impacting the health of aquatic ecosystems (Vigiak et al., 2017). In addition, concentrations of pollutants such as heavy metals and polycyclic aromatic hydrocarbons associated with urban sediments are significantly higher than those in more natural catchments (Liu et al., 2017), due to the abundance of contamination sources (Taylor & Owens, 2009). Therefore, it is necessary to implement sediment pollution mitigation in urban catchments. In that regard, it is important to understand the sediment sources, quantities, and fates of sediments in terms of transport and storage.

The sediment budget is a framework based on the mass balance of key components (sources, sinks, and outputs) of the sediment delivery system within a catchment, which provides a holistic understanding of the interaction and linkages between sediment mobilization, transport, storage, and yield (Brown et al., 2009; Parsons, 2012; Walling & Collins, 2008). Sediment budget depends on the identification of input sources, and their mass estimation with temporal accuracy (Brown et al., 2009; Walling & Collins, 2008). However, depending on the requirement certain input sources may need to be combined due to practical and theoretical constraints (Parsons, 2012). In the absence of a particular well-defined and universally accepted method, previous studies have adopted various methods, such as field monitoring (e.g., sediment traps, turbidity sensors), sediment tracing using radionuclides or fingerprinting, repeat topographic surveying, geographic information systems (GIS) and remote sensing-based distribution models (Parsons, 2012; Walling & Collins, 2008; Walling et al., 2001). To construct a sediment budget for a suburban catchment in Melbourne, Australia, Russell et al., (2019a) have utilized a monitoring approach alone, by installing custom-made sediment traps. Similarly, Rovira et al., (2005) established a sediment budget for a catchment in Barcelona, Spain adhering only to field monitoring methods. Wheaton et al., (2009) employed Digital elevation models (DEMs) built from repeated topographic surveys in Scottish Highlands for the sediment budgeting. GIS-based sediment models (e.g., The St. John Erosion Model by Ramos-Scharrón and MacDonald, (2007)) and empirical models (e.g., the universal soil loss equation (USLE) by Banasik et al. (2005)) have been applied together with field measured data in sediment budgeting.

This study investigated the feasibility of a constructed sediment budget for an urban catchment in a densely populated South Asian City. The selected canal (Kirulapona canal) is one of the main canals in the characteristic Dutch canal network in Colombo, the commercial capital of Sri Lanka. Colombo is the densest city in Sri Lanka (35th in the world with a density of around 20,000 people/km^2 after Mumbai, India) and is the former capital also. The major objective of this study was to quantify the contribution of the sediment input from point and non-point sources to the selected urban canal and to make recommendations for the soil erosion and sediment management. Our approach was a combination of field measurements (an analytical approach) and the development of an erosion model (a numerical approach). Same as Walling et al. (2001), our study also monitored Total Suspended Solids (TSS). TSS accounts for sediments transported or has the potential to be transported in suspension, and includes particles remained in a standard glass fibre filter paper of 1.6 µm pore size (WEF and APHA, 2005). Furthermore, the total solids (TS) was also measured. TS is the summation of dissolved solids, suspended and settleable solids in water.

Hydrologic Engineering Centre Hydrologic Modelling System (HEC–HMS), is a reliable model developed by the US Army corps of Engineers (Pak et al., 2008). It can simulate the hydrological process of catchments, and undoubtedly most widely used software in world for the modelling of the rainfall-runoff process (Adhikari, 2021). The HEC-HMS models are used in a wide range of catchment hydrology applications such as producing unit hydrographs, hydrologic routing, etc. (HEC-HMS user's manual, 2024). The erosion modelling component is optional in

HEC-HMS, and the usage was not as prominent as its widely used application of rainfall-runoff generation (Adhikari, 2021). The rainfall-runoff models developed in HEC – HMS has been proven to be performing well in South Asia including Sri Lanka (De Silva et al., 2014; Natarajan & Radhakrishnan, 2019). However, no such application was found for erosion modelling (or sediment budgeting) in Sri Lanka, and this was one gap we expected to fill. Here we hypothesized that HEC-HMS would perform well in sediment budgeting. Employing HEC – HMS would not include any software cost as it is free, therefore checking the feasibility is a worthy cause.

2 Materials and Methods

2.1 Study Area

Dutch canal network is an earthen canal network in Colombo that has origins to the Dutch Colonial period (from 1658 to 1796 AC). Most of Colombo had been marshy and was reclaimed for urban development over a period of nearly 500 years (Gomes et al., 2019). Almost all canals as of now are with gabion wall banks (Gomes et al., 2019; Dehini and Gomes, 2022). The canal system is important as a major flood detention zone of Kelani River floodplain where Colombo is located (Fig. 1). Dutch canal network consists of many sub-canals including Kirulapona canal (from 6°53′1.19"N 79°53′32.55"Eto 6°52′43.02"N 79°51′21.57"E). A 1 km long reach of Kirulapona canal was considered for modelling and field sampling. Colombo is characterized by mild slopes ranging from 0° to 30°, with elevations ranging from the sea level to 30 m above it. The climate of Colombo is humid and tropical. Due to heavy precipitation, which occurs in the form of monsoonal, conventional, and depressional rains, Colombo belongs to the wet zone of the country with about 2500 mm mean annual rainfall. Figure 2 shows the daily rainfall in 2019 and 2020.

The selected reach had 30-point source water and/or wastewater inlets (both ditches and pipes; PS1-30 of Fig. 3) and one tributary canal referred to as Dehiwala canal. The selected section is representative of the Dutch canal network as it included many inlets and tributary canals. STN2 of Fig. 1 shows the outflow location of Dehiwala canal to Kirulapona canal. The selected reach was about 20 m wide. A total of 4.4 km^2 catchment area drains into the Kirulapana canal between the starting point (referred to as inlet; STN1) and the endpoint (referred to as outlet; STN3) of the selected reach. Catchments delineated at the inlet and outlet points are drained inland towards Kelani River, which is located about 20 km eastward of the sea outfall of Kirulapana canal (Fig. 1). Thus, a unique feature of this canal is it flows in the opposite direction to the catchment runoff, aided by an artificial slope, and is a common feature in many urban canals. However, the flow direction of the tributary canal is as same as its sub-catchment and is towards the Kirulapana Canal. Some of the drainage ditches start at locations outside of the delineated catchment boundary marked in Fig. 1 (i.e., outside of sub-catchments S1, S2, and S3), resulting in transboundary inflow to the Kirulapana Canal. Land use in the demarcated catchment area consists of 61% built-up areas including paved roads, 32% homestead (human settlements), and the remainder about 7% of previous lands dominated by wetlands. Colombo falls on the Wanni soil complex, one of the four main soil complexes in Sri Lanka (others are Highland, Vijayan, and Kadugannawa) divided based on the lithology, isotope geochemistry, and tectonic–metamorphic history (Dahanayake & Jayasena, 1983). Most of the selected sub catchments (over 90%) are a mix of red yellow Podzolic soils with dark B horizon and prominent A1 horizon. However, the areas close to the sea are with Regosols on recent beach and dune sands, also known as Sandy Regosols (source: Soil Map of Sri-Lanka.—ESDAC—European Commission). The sandy Regosol which can be found in the west is dominant over approximately 52% of the studied sub catchments.

2.2 Field Data Collection and Laboratory Analysis

Samples were collected at the inlet, outlet, junction (where the branch canal connects to the Kirulapana Canal) and at all 30-point source inlets (PS1-30), the tributary canal (STN2) (Fig. 3) between 11 a.m. to 2 p.m., and this period gave flow rates close to the daily weighted average of the dry season. In the dry season days without rain, the peak flow was from 6 a.m. to 7 p.m. During the wet season, the flow rates within a day were relatively constant, an indication of rainfall-dominated flow conditions. Therefore, it was decided

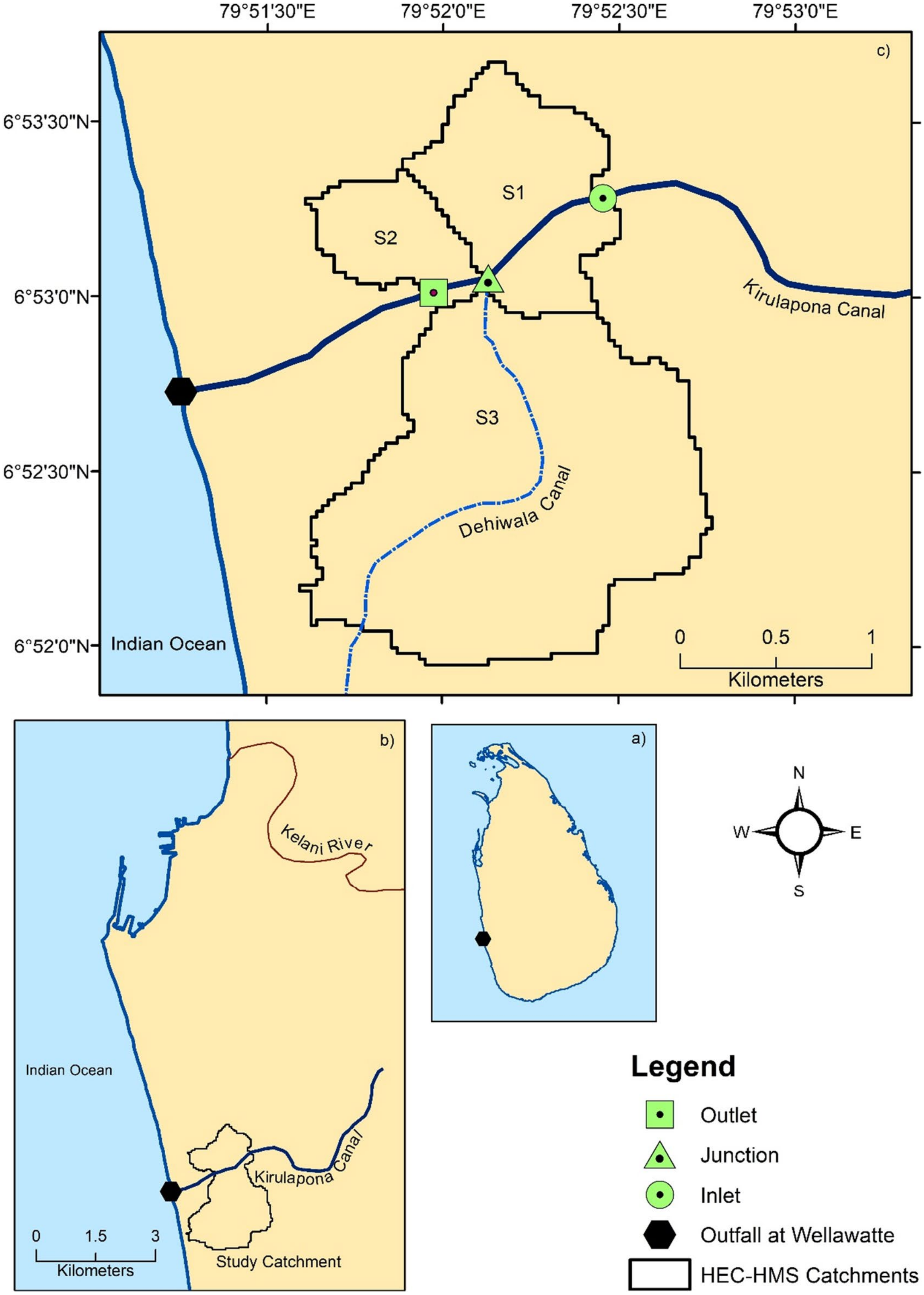

Fig. 1 Study area details: (**a**) Study location on Sri Lanka map; (**b**) Study catchment and the Kirulapona canal; and (**c**) Sub-catchments (S1, S2 and S3), the main canal (Kirulapona) and the tributary canal (Dehiwala)

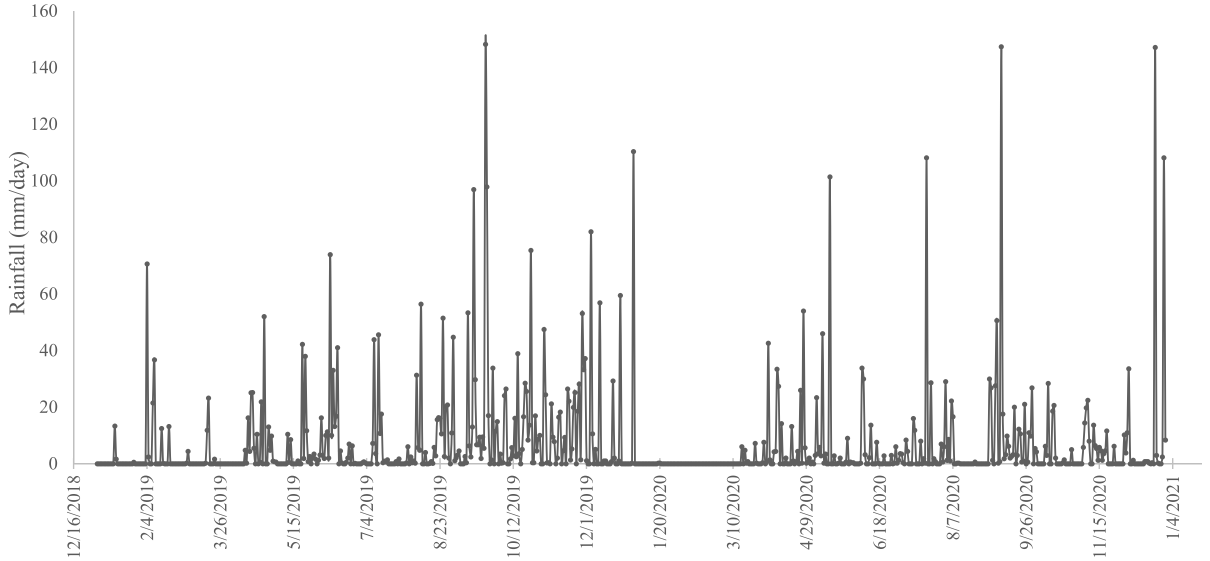

Fig. 2 Rainfall of the study area in 2019 and 2020

to collect wet season samples also between 11 a. m. to 2 p.m. Sampling was conducted every other month starting from April 2019 to February 2020, covering both wet and dry seasons. Specific sampling dates were decided by referring previous days actual rainfall and preceding days forecasted rainfall. Typical dry seasons are from June to August and January to March (these are typical dry seasons of the year and on average each month gets less than 5% of the total annual rainfall). Dry Season sampling was carried out in August (12th and 20th in 2019), December (2nd, 10th and 30th in 2019), and February (4th, 20th and 28th in 2020). Typical wet seasons are in April to June and September to December: during these periods, each month get more than 10% of the total annual rainfall (Dehini and Gomes, 2022). Wet season sampling was carried out in April (27th in 2019), June (9th and 15th in 2019), and October (7th, 23rd and 31st in 2019). During each sampling attempt, flow rates at the inlet, junction and outlet points were measured using the area × velocity method, while flow rates of point sources were measured using the bucket method (Gomes and Wai., 2015).

The concentration of *TSS* and *TS* were measured according to the gravimetric method (WEF and APHA 2005). *TSS* and *TS* loads at each sampling location were estimated as in Eqs. 1 and 2. *TSS* and *TS* are the loads of *TSS* and TS (kg/day), *k* is the unit conversion factor, TSS_c and TS_c are the concentration of *TSS* and *TS* (mg/l) and *Q* is the flow rate (m^3/day).

$$TSS = k \times TSS_c \times Q \; \ldots\ldots \tag{1}$$

$$TS = k \times TS_c \times Q \; \ldots\ldots \tag{2}$$

2.3 Sediment Budget Based on Field Data

Based on field data, *TSS* and *TS* sediment budgets were conceptualised as in Eqs. 3 and 4, respectively. Where TSS_{in}, TS_{in}, TSS_j, TS_j, TSS_{out} and TS_{out} are the loads of *TSS* and *TS* at the inlet (*in*), junction (*j*) and outlet (*out*), (kg/day). *i* is an index denoting a point source, *m* (=31) is the number of point sources (including the tributary canal), TSS_{ps_i} and TS_{ps_i} are the loads of *TSS* and *TS* from the i^{th} point source (kg/day), respectively. ΔS_{TSS} and ΔS_{TS} are the balance *TSS* and *TS* loads (kg/day), respectively (both ΔS_{TSS} and ΔS_{TS} represent sediments in runoff and/or within canal).

$$TSS_{in} + \sum_{i=1}^{m} TSS_{ps_i} + TSS_j + \Delta S_{TSS} = TSS_{out} \; \ldots\ldots \tag{3}$$

$$TS_{in} + \sum_{i=1}^{m} TS_{ps_i} + TS_j + \Delta S_{TS} = TS_{out} \; \ldots\ldots \tag{4}$$

To achieve a more detailed sediment budget than shown in Eqs. (3) and (4), finding the components

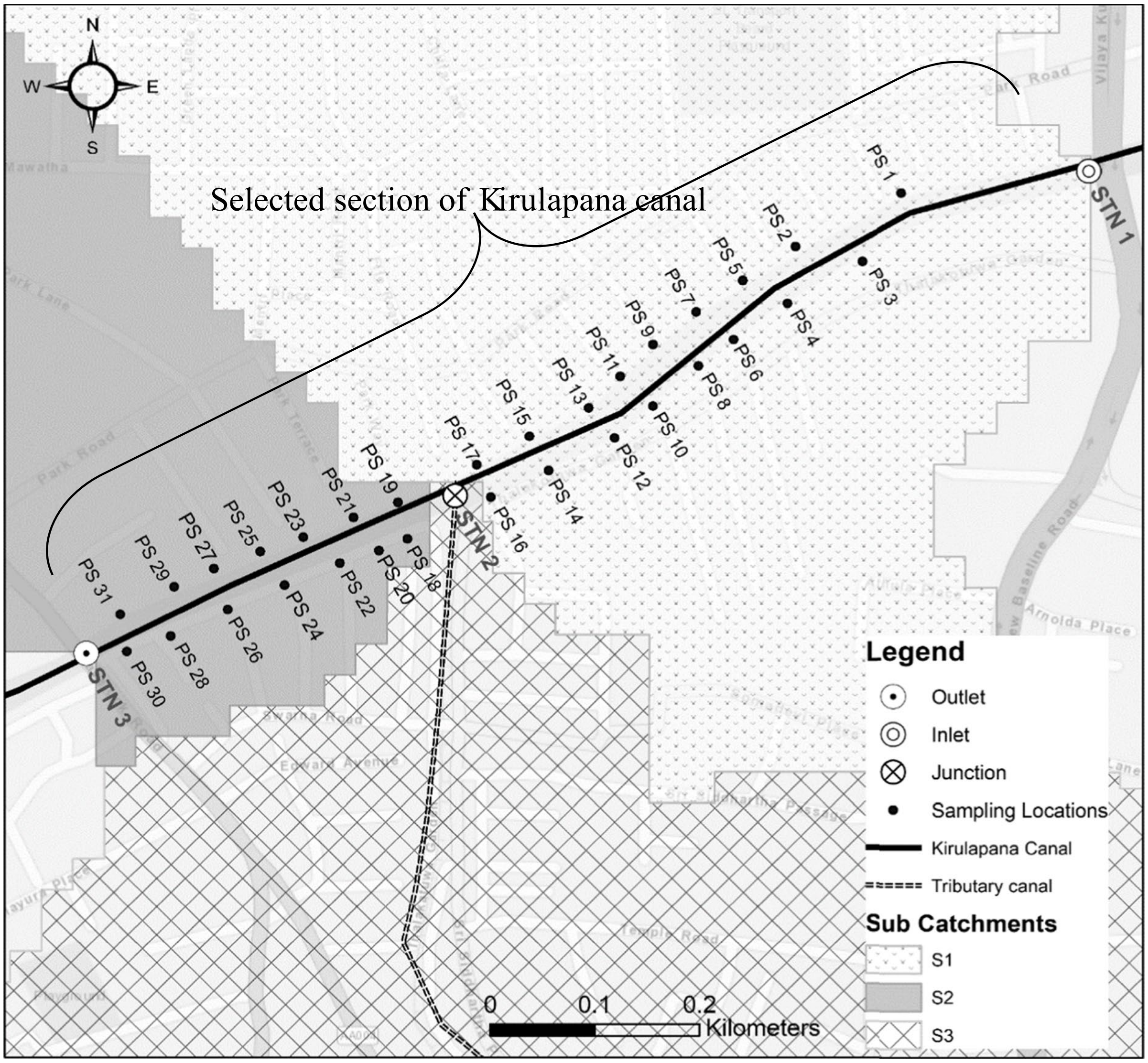

Fig. 3 Sampling locations

of ΔS_{TS} and ΔS_{TS} associated with runoff, field data were integrated through the sediment model developed in HEC – HMS. In this process, the selected section of Kirulapana canal (herein after main canal section) was sub divided in to two. SubSect. 1 is from inlet to junction and subSect. 2 is from junction to outlet (Fig. 1), and computations were done separately for the two sections.

2.4 Catchment Modelling in HEC-HMS

HEC–HMS needs four components: basin model, meteorologic model, control specifications and time series data to develop a model to simulate rainfall-runoff relationship in a catchment (Natarajan & Radhakrishnan, 2019). HEC–HMS 4.9 version, which could delineate catchments for a given outlet point using the inbuilt

Geographic Information System (GIS) and extract catchment physical properties, such as drainage paths, slope and length of reaches. A Digital Elevation Model (DEM) with a resolution of 30 m×30 m (source: US Geological Survey EarthExplorer (https://earthexplorer.usgs.gov/) was used to aid the delineation. Figure 4 shows the delineated sub catchments, reaches and junctions.

In HEC–HMS, any hydrological process in the hydrologic cycle can be represented with a mathematical model (USACE HEC 2022b). In this study, Soil Moisture Accounting, Clark unit hydrograph, and Recession and Modified Universal Soil Loss Equation (MUSLE) options were employed to compute infiltration, surface runoff (transform method), base flow and sediment yield, respectively. Two parameters of Clark unit hydrograph were estimated (Table 1) using the Eqs. 5 (modified after USACE HEC 2022b) and 6 (USACE HEC 2022a), by using HEC–HMS parameter estimation feature (USACE HEC 2022b).

$$T_c = 3.76 \times \left[\frac{L \times L_c}{\sqrt{Slope_{10-85}}} \right]^{0.3} \ldots \tag{5}$$

$$\frac{R}{T_c + R} = 0.65 \ldots \tag{6}$$

where, T_c is the time of concentration (h), L is the longest flow path (km); L_c is the centroidal flow path (km), $Slope_{10-85}$ is the average slope of the flow path represented by 10 to 85 percent of the longest flow path (m/km) and R is the storage coefficient (h). The catchment characteristics: L, L_c and $Slope_{10-85}$ were generated by HEC–HMS. Soil moisture accounting and Recession methods were extracted from De Silva et al., (2014) with necessary modifications accounting for imperviousness; the calibrated parameter values are given in Table 1.

MUSLE is the first surface erosion method added to HEC-HMS (Pak et al., 2008). Parameters that are required for MUSLE are erodibility factor (depends on the soil type), topographic factor (depends on slope length and angle), cover factor (depends on land use type), practice factor (depends on land use type), threshold, exponent and gradation curve. The gradation curve defines the distribution of particle size classes of TSS. Events with a peak flow less than the threshold will have no erosion or sediment yield (USACE HEC 2022b). Tables 2 and 3, respectively display, erodibility factor for different soil types, and cover and practice for different land use types.

Soil and land use type maps of Sri Lanka were obtained from the department of survey, Sri Lanka. Monthly rainfall data observed at Colombo meteorological station for 2019 and 2020 was obtained from

Fig. 4 HEC-HMS model

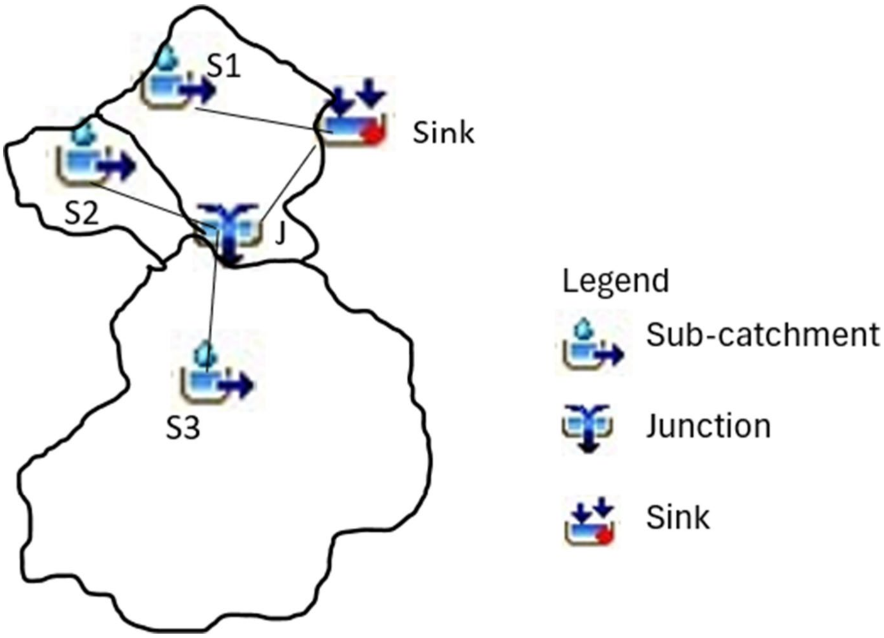

Table 1 Summary of calibrated parameters of Soil Moisture Accounting Loss Method, Clark Unit Hydrograph method and Recession method. (Refer USACE HEC (2022a) for detailed information on parameters)

Method	Parameter	Calibrated values for each Sub catchment		
		S1	**S2**	**S3**
Soil Moisture Accounting Method	Soil (%)	80	80	80
	Ground water 1 (%)	60	60	60
	Ground water 2 (%)	82	82	82
	Maximum infiltration (mm/hr)	2	2	2
	Imperviousness (%)	90	90	90
	Soil storage (mm)	100	100	100
	Tension storage (mm)	60	60	60
	Soil percolation (mm/hr)	1	1	1
	Ground water 1 storage (mm)	100	100	100
	Ground water 1 percolation (mm/hr)	1	1	1
	Ground water 1 coefficient (hr)	400	400	400
	Ground water 2 storage (mm)	150	150	150
	Ground water 2 percolation (mm/hr)	1	1	1
	Ground water 2 coefficient (hr)	400	400	400
Clark Unit Hydrograph	Time of Concentration (hr)	2.55	2.54	5.29
	Storage Coefficient (hr)	1.26	1.25	2.61
Recession	Initial Discharge (m^3/s)	0.1	0.01	0.1
	Recession Constant	0.8	0.8	0.8
	Threshold Type	Ratio to peak		
	Ratio	0.4	0.4	0.4
MUSLE	Erodibility factor	0.28	0.5	0.32
	Topographic factor	0.1	0.1	0.1
	Cover factor	0.62	0.71	0.63
	Practice factor	0.119	0.075	0.084
	Threshold (m3/s),	0.1	0.001	0.1
	Exponent	2	2	2

Table 2 Soil erodibility for soil types of the study. (Source: Fayas et al., 2019)

	Erodibility factor	Area (%)
Red Yellow Podsolic	0.73	47.7%
Sandy Regosol	0.51	52.3%

the Department of Meteorology, Sri Lanka. The model was continuously run from 1st of April 2019 to 31st of March 2020.

Table 3 Cover, Practice for different land use types in the study catchment (Source: Fayas et al., 2019) and the share of each land use type

	Cover factor	Practice factor	Area (%)
Built up area	0.73	0.00	61.1
Homestead	0.51	0.25	31.8
Channel	0.20	0.00	3.4
Paddy	0.43	0.15	3.8

3 Results

3.1 Sediment Budget Based on Field Data

The total amounts of dry season (5 months: July,

Table 4 Summary of the sediment budget based on field measured TSS. Notations are as same as in Eq. 3

	Average daily TSS load (kg/day)	
	Dry Season	Wet Season
TSS_{in}(at STN 1)	169	186
$\sum_{i=1}^{31} TSS_{ps_i}$	225	341
TSS_j(at STN 2)	400	484
TSS_{out}(at STN 3)	231	734
ΔS_{TSS}	(563)	(276)

Table 5 Summary of the sediment budget based on field measured TS. Notations are as same as in Eq. 4

	Average daily TS load (kg/day)	
	Dry Season	Wet Season
TS_{in}(at STN 1)	13,611	14,580
$\sum_{i=1}^{31} TS_{ps_i}$	1975	11,535
TS_j(at STN 2)	801	887
TS_{out}(at STN 3)	23,119	52,296
ΔS_{TS}	6733	25,294

August, January, February and March) and wet season (7 months: April to June, and September to December) TS at the outlet were 3,467,837 kg and 10,982,200 kg respectively, which summed up to an annual TS load of 14,450,037 kg. Dry and wet season TSS loads at the outlet were 34,707 kg and 154,224 kg, respectively. The annual TSS load computed was 188,931 kg.

The summary of the sediment budget (based on average daily TSS and TS loads) is shown in Tables 4 and 5. Total suspended sediment loads (Table 4) from point sources (including the tributary (STN 2)) were 625 kg/day and 825 kg/day in dry and wet seasons, respectively. ΔS_{TSS} took negative values of 563 kg/day and 276 kg/day in dry and wet seasons, respectively. These were indications of sediment deposition on the canal bed. The mass balance indicated that the sediment stored within the Kirulapona canal section in the wet season was about half of the dry season.

Total sediment (Table 5) coming from point sources (including the tributary (STN 2)) were 5923 kg/day and 19,181 kg/day in the dry and wet seasons, respectively. ΔS_{TS}, which is a combined action of nonpoint sources and canal dynamics, were 3585 kg/day and 18536 kg/day in dry and wet seasons, respectively. Positive ΔS_{TS} indicated an addition of sediment in subSect. 2.

As illustrated in Fig. 4, 59% and 28% of TS in the main canal section in dry and wet seasons, respectively were coming from upstream of STN 1. The percentage contributions from point sources to the main canal section were 26% and 37% in dry and wet seasons, respectively. Thus, the remaining 16% and 35% in two seasons should be due to the contribution from non-point sources and/or canal dynamics (e.g., sediment resuspension).

3.2 Predictions of the Erosion Model

Although the model slightly over predicted the sediment loads by 17.50% with a negative bias, total modelled loads and yields agreed with the observed, with a root mean square error (RMSE) of 0.25, demonstrating the model's moderate to high predictive power.

Table 6 Characteristics of sub catchments, simulated sediment loads and yields in each sub catchment (S1, S2, S3), junction (J) and sink

Catchment		S1	S2	S3	J	Sink
Catchment Area (ha)		89	40	285		
Land Use (Area %)	Built up area	51	77	62		
	Homestead	42	7	32		
	Channel	3	2	4		
	Vegetation	4	14	2		
Soil type (Area %)	Red Yellow Podsolic	80	5	64		
	Sandy Regosol	20	95	36		
Soil erosion	Dry Season Load (kg/day)	74	39	475	483	70
	Wet Season Load (kg/day)	148	92	564	640	143
	Annual rate (kg/ha)	473	634	665		

The characteristics and soil erosion of each sub catchment are listed in Table 6, in which the erosion load is the average load of soil eroded per day in a respective season and the yield is the average annual soil erosion per catchment area. S1, S2 and S3 sediment yields were 665 kg/ha/yr, 633 kg/ha/yr and 473 kg/ha/yr, respectively, giving an average of 591 kg/ha/yr soil erosion annually. This average annual sediment yields agreed with the findings of Fayas et al., (2019), who zoned Kelani basin based on severity of soil erosion and identified the area where the upper reach of the Kirulapana canal located as a low erosion zone with sediment yields varying from 0—5 t/ha annually (i.e., about 0 – 4535 kg/ha/yr).

Sediment loads at the junction (STN 2) represent the TS transported to the canal from S3 and S2. Thus, an average of 5.92% and 3.04% of eroded soil did not reach the canal in dry and wet seasons, respectively (Table 6) and must be deposited within the respective catchment. Therefore, out of total soil eroded from the study catchment, a substantial amount of 94.08% in the dry season and 96.96% in the wet season ended up in the canal.

In both canal subsections for both seasons, TSS loads mobilised in point sources were interestingly greater than the soil erosion (or sediment coming with the surface runoff) of the catchment (Fig. 5). Other than subSect. 1 in wet season, in all cases the differences were about two-folds. Figure 6

4 Discussion

4.1 Sediment Budget and Catchment Hydrological Processes

A relatively high and quick runoff is expected owing to the high percentage (about 50%) of imperviousness of the catchments. Even if a rainfall event does not exceed the threshold that would cause erosion, surface runoff would still carry sediments that have been previously deposited on the roads or similar built areas (Taylor & Owens, 2009). This sediment-rich urban runoff is intercepted by the dense human-made (lined and unlined) drainage network and is several folders higher than the TSS load of an average dry day (Taylor & Owens, 2009). Horowitz et al. (2008), through an urban sediment analysis in the City of Atlanta, found more than 94% of the transported suspended sediment occurred due to rainfall events lasted more than 20% of the observed duration. Similarly, field observations of this study showed about 3.2 and 2.3 times higher transported sediment load for TSS and TS, respectively in the wet season, compared to the dry season.

Sediment budget based on the observed TSS, produced negative ΔS_{TSS} in both seasons. This indicated the deposition of suspended sediments within the main canal section. The sediment delivery ratios of the canal (i.e., the ratio of TSS load at the outlet to the TSS load received by the canal; Walling

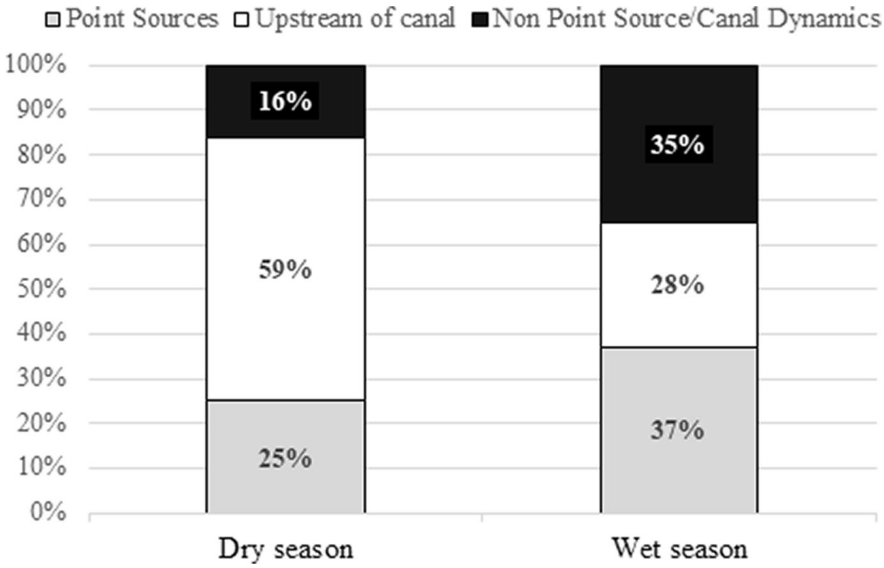

Fig. 5 Percentage contribution to the total main canal section sediment load (TS) by point sources, canal upstream and non-point sources/canal dynamics based on field data

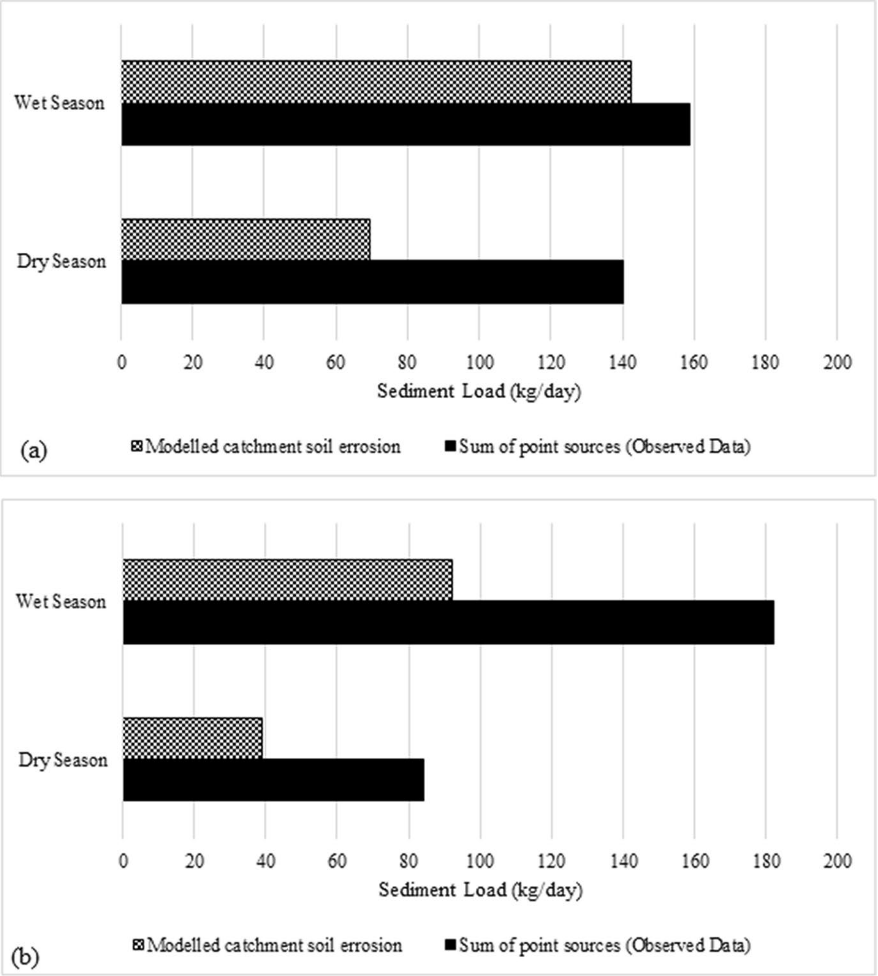

Fig. 6 Comparison of daily TSS loads from point sources (based on field data) and modelled catchment daily soil erosion loads (TSS): a) Subsection 1 (inlet to junction) and b) Subsection 2 (junction to outlet)

& Collins, 2008), in dry and wet seasons were about 27% and 71%, respectively. This exhibited a higher rate of retention per unit length of the canal in the dry season, and high rates of fine sediment transported in suspension in the wet season (Taylor & Owens, 2009). Transported suspended sediment load in fact was a result of sediment deposition and resuspension and depend on flow rate and velocity of the canal (Russell et al., 2019a). As per field observations, velocities ranged 0.15 ± 0.3 m/s in the dry season and 0.21 ± 0.02 m/s in the wet season, while flow rates ranged 5.0 ± 1.3 m^3/s and 8.3 ± 1.7 m^3/s, respectively in dry and wet seasons. Therefore, as low velocities and flow rates do not make much disturbance to the bed load, deposition must have dominated in the dry season, and was the sole reason for the lower sediment delivery ratio in the dry season. As significantly higher flow rates and velocities must had made part of the bed load in wet season to be suspended in the water column. This together with sediment carried by the runoff resulted in a higher fraction transported downstream than deposited. However, the fraction of transported sediment due to resuspension was considered insignificant than that of runoff, as the studied canal had a consolidated bed. Russell et al., (2019a) elaborated that sediment deposition takes place when the transport capacity is lower than the sediment supply rate. Despite the elevated sediment supply, a higher load of sediment seemed to be carried downstream. Therefore, it was evident that the transportation capacity of the canal was increased by high flow rates in the wet season.

Sediment budget based on the TS revealed that the sediment load at the outlet were significantly greater than the summation of sediment load at the inlet, from the tributary and from point sources in both seasons. This has been resulted in a positive ΔS_{TS}, which could be due to 1) sediment loads adding to the canal via nonpoint sources, i.e., sediments associated with surface runoff (Vercruysse et al., 2017), wind carried sediments (Gomes & Wai, 2020) (within and outside of the catchment) and atmospheric dust deposition (within and outside of the catchment); 2) previously deposited on canal bed; and 3) back flow of sediment due to tidal action (Taylor & Owens, 2009). This study discovered that the contribution of point sources to the TS load of the canal was greater than that of sediment load associated in ΔS_{TS} (i.e., summation of nonpoint sources and bed load) considerably in the dry season, but marginally in the wet season. However, this dominant contribution of point sources could be supplicated by the dense network of drainages that anyway intercept a significant fraction of sediment carried by surface runoff (Vercruysse et al., 2017). In the dry season however, about 59% (majority) of total sediment load travelled from the upstream of the studied canal section. This indicated that downstream sediment loads could be largely influenced by the upstream, reflecting on the strong linkage between upstream erosion and upstream open channel dynamics (Taylor & Owens, 2009; Walling & Collins, 2008). Though it was difficult to explain substantially larger upstream contribution, a few factors such as canal dredging activities, recreational activities on the canal making bedload to suspend and longer response time in the upstream part of the canal may provide clarifications for this observation. In the wet season, contribution from upstream was only about 28% (i.e., one third of the sediment load). This observation agreed with Frings et al. (2014) and was a reconfirmation of the longer response time.

4.2 Key Insights of the Erosion Model

Though the model was expected to underpredict sediment load due to exclusion of certain anthropogenic activities that cause soil erosion and intrinsic sediment sources, the results suggested otherwise. The unexpected results can be due to several reasons associated with the modelling process and field data collection. Firstly, it should be noted that the computation of RMSE and bias for sediment loads were performed considering the simulated results of S3 and observed TSS data at the STN 2 only. However, in the main canal there were sediment coming outside of S2 and S1. Also, sampling was done only at the outfall of the tributary canal to the main canal without detailed sampling along the tributary canal and without observations with respect to sediment resuspension or sedimentation in the tributary. Since only a fraction of generated sediment reaches the catchment outlet (Russell et al., 2019a), it was reasonable to assume the observed value at STN 2 was considerably smaller than the actual sediment generated in S3. Secondly, buffers (fences and walls) and temporary sediment storages cannot be modelled in HEC-HMS, as none of the GIS layers (the DEM or land use type) include detailed and necessary information on buffers and temporary sediment storages. This incapability may have resulted in more sediment load (obtained through simulations) reaching the canal.

The incapability has clearly reflected by the significantly small percentage (less than 10%) of eroded soils being deposited within the catchment, in contrast to the findings of previous studies (e.g., Russell et al., 2019b; Trimble, 1995; Walling et al., 2001). Though not as high as the simulated fraction ($> 90\%$), there still was a possibility that the fraction being transported to the Kirulapana canal be the larger fraction. The disagreement could be due to two reasons. Firstly, a considerably smaller catchment with a highly dense network of drainage ditches. Secondly loose topsoil layer and high intense tropical rainfall in the study area. While these may result in higher sediment generation, generated sediment may not travel far enough reaching waterbodies, because of the large number of interconnected ditches in this comparatively smaller catchment area. Also, as the slope of the study area is mild, the overland flow is expected to be slow and with characteristics similar to a uniform laminar flow (Wang et al., 2014). As a result, more deposition can be expected on the catchment surface. This can be reinforced by Taylor and Owens, (2009) who stated that the initial sediment load tends to weaken with increasing river basin area.

4.3 Sediment Budget Incorporating the Erosion Model

The difference between the observed total sediment load coming from point sources (TSS measured) and modelled sediment load (runoff associated) could be the sediment that entered the main canal section via diffusion (runoff over canal banks). As per the results, this value was less and slightly higher in the wet season. The greater point source sediment load can be explained by reflecting on the sources. As the dense drainage network intercepts surface runoff closer to the sources, the point sources should be part of non-point sources. In addition, some of the transboundary water and/or wastewater open channels bring sediments from out of the study catchment ultimately showing up as point sources in the study area. Remobilized particles of previously stored sediment in the drainage network (Taylor & Owens, 2009) would contribute to the point source sediment load. The negligible contribution from runoff meant that ΔS_{TS} mainly composed of the bed load.

4.4 Implications on Sediment Control

Canal aggradation in the dry season decreases the flow conveyance capacity and is also a reason for poor water quality (in sensu Taylor & Owens, 2009). Therefore, sediment removal via dredging is a must in addition to control of soil erosion, soil mobilization, and remobilization within the catchment. Garbrecht and Starks, (2009) have observed a drastic reduction in the annual suspended sediment yield from Fort Cobb Reservoir watershed in West-Central Oklahoma. The reduction has been related to several soil conservation methods, including land use and management changes (Garbrecht & Starks, 2009).

Point sources dominated other sediment pathways in the wet season; in the dry season, it became second after the upstream sediment load. This highlighted the necessity of controlling sediment coming from point sources. Such controlling measures include side entry pit traps (baskets with mesh fitted below the inlet of point sources to the canal); trash racks (mesh fitted across point source ditches and pipes); concrete-lined sediment traps or gross pollutant traps (GPT); and sediment barriers across point source ditches (Russell et al., 2019b). Since the sediments arising from intrinsic sources, such as sediment on roads are highly polluted (Kim et al., 2019), GPTs would be more efficient than sediment traps. Substantially high dry season upstream sediment load implied the need for sediment barriers across the main canal.

Since the incoming load of sediment via point sources was several times higher than the sediment entering the canal with runoff flowing over the main canal banks, it could also be concluded that the runoff over the Kirulapana canal banks was a comparatively less important pathway in terms of sediment management of the canal.

However, as the surface runoff bringing mobilized catchment sediments is intercepted by the dense network of drainage ditches, introducing sediment control measures, along the banks of such open waterways would also be an effective method. Proving vegetated buffers (Ramesh et al., 2021) at those places would be economical, environmentally friendly, and aesthetically pleasing. This may find more generic implications on sediment management in similar small urban catchments such as in our study area, where the provision of sediment control measures along the banks of the drainage network would be more efficient than along the main canal bank.

5 Conclusion and Recommendations

A sediment budget was successfully developed in an urban catchment based on field data, and a HEC-HMS model. Although the method inherited a few limitations, such as the incapability to model all major catchment sediment sources, this approach provided a decent approximation to sediment dynamics. This approach would aid establishment of proper sediment management strategies. One of the key recommendations of this study is to provide sediment control measures at the inlets of the point sources to the canal since the contribution of runoff over the canal banks was found to be relatively insignificant. Although it was concluded that providing sediment control measures along the main canal bank would be ineffective in controlling sediment loads transporting to the canal, providing such measures along the banks of the drainage network within the contributing catchment that drains to the canal as point sources would be more effective and efficient. Our findings apply to other similar urban catchments with intensive drainage networks eventually connecting to the main canal, which thus have a high density of point sources. Further, this study procedure, which is not cost demanding could be replicated in other urban catchments, especially in developing countries where cost may be a constraint. The impacts of sedimentation in the urban environment depend not only on the quantity but also on the quality. Therefore, it is suggested to incorporate quality aspects in future improvements to this model. Also, it is recommended to compare the vertical distribution of mass of sediment budgeting from the model with observations.

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Declarations

Ethical Approval This article does not contain any studies with human participants performed by any of the authors. All procedures performed in studies involving animals were in accordance with the ethical standards of the institution.

Conflicts of Interest The authors have no relevant financial or non-financial interests to disclose.

Compliance with Ethical Standards All complied with the rules and regulations of the related jurisdiction.

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References

Adhikari, P. (2021). *Application of HEC-HMS to the investigation of soil erosion and sediment yield by surface runoff*. Doctoral dissertation, Flinders University, College of Science and Engineering.

Banasik, K., Barszcz, M., & Branski, J. (2005). Major components of a sediment budget for four river catchments in Poland. Sediment Budgets 2. Proceedings of Symposium S1. Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil, April. IAHS Publication 292: 32–36.

Brown, A. G., Carey, C., Erkens, G., Fuchs, M., Hoffmann, T., Macaire, J.-J., Moldenhauer, K.-M., & Walling, D. E. (2009). From sedimentary records to sediment budgets: Multiple approaches to catchment sediment flux. *Geomorphology, 108*, 35–47. https://doi.org/10.1016/j.geomorph.2008.01.021

Dahanayake, K., & Jayasena, H. A. H. (1983). General geology and petrology of some Precambrian crystalline rocks from the Vijayan Complex of Sri Lanka. *Precambrian Research, 19*(3), 301–315.

De Silva, M. M. G. T., Weerakoon, S. B., & Herath, S. (2014). Modeling of Event and Continuous Flow Hydrographs with HEC–HMS: Case Study in the Kelani River Basin Sri Lanka. *Journal of Hydrologic Engineering, 19*, 800–806. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000846

Dehini, G. K., & Gomes, P. I. A. (2022). Deriving optimal hydraulic, water quality and habitat quality criteria against a predefined reference state of urban canals via an analytical method: Implications on ecological rehabilitation. *Ecological Engineering, 182*, 106697. https://doi.org/10.1016/j.ecoleng.2022.106697

Fayas, C. M., Abeysingha, N. S., Nirmanee, K. G. S., Samaratunga, D., & Mallawatantri, A. (2019). Soil loss estimation using RUSLE model to prioritize erosion control in KELANI river basin in Sri Lanka. *Int. Soil Water Conserv. Res, 7*, 130–137. https://doi.org/10.1016/j.iswcr.2019.01.003

Frings, R. M., Döring, R., Beckhausen, C., Schüttrumpf, H., & Vollmer, S. (2014). Fluvial sediment budget of a modern, restrained river: The lower reach of the Rhine in Germany. *CATENA, 122*, 91–102. https://doi.org/10.1016/j.catena.2014.06.007

Garbrecht, J. D., & Starks, P. J. (2009). Watershed sediment yield reduction through soil conservation in a West-Central Oklahoma watershed. *Ecohydrology, 2*(3), 313–320. https://doi.org/10.1002/eco.55

Gomes, P. I. A., & Wai, O. W. H. (2015). In-stream physical heterogeneity, rainfall aided flushing, and discharge on stream water quality. *Water Environment Research, 87*(8), 758–768. https://doi.org/10.2175/106143015X14362865225997

Gomes, P. I. A., & Wai, O. W. H. (2020). Investigation of Long-Term River Water Quality Trends in Hong Kong to Identify Role of Urbanization, Seasons and Pollution Sources. *Water, Air, and Soil Pollution, 231*, 378. https://doi.org/10.1007/s11270-020-04753-1

Gomes, P. I. A., Fernando, B. A. V. W., & Dehini, G. K. (2019). Assessment of Pollution Sources, Fate of Pollutants, and Potential Instream Interventions to Mitigate Pollution of Earthen Canals of Urban to Rural-Urban Fringe. *Water, Air, and Soil Pollution, 230*, 262. https://doi.org/10.1007/s11270-019-4314-7

Horowitz, A. J., Kent, A. E., & Smith, J. J. (2008). Monitoring urban impacts on suspended sediment, trace element and nutrient fluxes within the city of Atlanta, Georgia, USA: Program design, methodological considerations and initial results. *Hydrological Processes, 22*, 1473–1496. https://doi.org/10.1002/hyp.6699

Kim, D.-G., Kang, H.-M., & Ko, S.-O. (2019). Reduction of non-point source contaminants associated with road-deposited sediments by sweeping. *Environmental Science and Pollution Research, 26*, 1192–1207. https://doi.org/10.1007/s11356-017-0192-y

Kuksina, L. V., & Alexeevsky, N. I. (2019). Suspended sediment yield transportation by rivers of the Kamchatsky

Krai into the Pacific Ocean, the Sea of Okhotsk and the Bering Sea. *International Journal of River Basin Management, 17*(1), 37–47.

Liu, A., Duodu, G. O., Goonetilleke, A., & Ayoko, G. A. (2017). Influence of land use configurations on river sediment pollution. *Environmental Pollution, 229*, 639–646. https://doi.org/10.1016/j.envpol.2017.06.076

Natarajan, S., & Radhakrishnan, N. (2019). Simulation of extreme event-based rainfall–runoff process of an urban catchment area using HEC-HMS. *Model. Earth Syst Environ., 5*, 1867–1881. https://doi.org/10.1007/s40808-019-00644-5

Pak, J., Fleming, M., Scharffenberg, W., & Ely, P. (2008). Soil Erosion and Sediment Yield Modeling with the Hydrologic Modeling System (HEC-HMS), in: World Environmental and Water Resources Congress 2008. Presented at the World Environmental and Water Resources Congress 2008, American Society of Civil Engineers, Honolulu, Hawaii, United States, 1–10. https://doi.org/10.1061/40976(316)362

Parsons, A. J. (2012). How useful are catchment sediment budgets? *Progress in Physical Geography, 36*, 60–71. https://doi.org/10.1177/0309133311424591

Ramesh, R., Kalina, L., Hantushb, M., & Chaudharyc, A. (2021). A secondary assessment of sediment trapping effectiveness by vegetated buffers. *Ecological Engineering, 159*, 106094. https://doi.org/10.1016/j.ecoleng.2020.106094

Ramos-Scharrón, C. E., & MacDonald, L. H. (2007). Development and application of a GIS-based sediment budget model. *Journal of Environmental Management, 84*, 157–172. https://doi.org/10.1016/j.jenvman.2006.05.019

Rovira, A., Batalla, R. J., & Sala, M. (2005). Fluvial sediment budget of a Mediterranean river: The lower Tordera (Catalan Coastal Ranges, NE Spain). *CATENA, 60*, 19–42. https://doi.org/10.1016/j.catena.2004.11.001

Russell, K. L., Vietz, G. J., & Fletcher, T. D. (2019a). A suburban sediment budget: Coarse-grained sediment flux through hillslopes, stormwater systems and streams. *Earth Surf Process Landforms, 44*, 2600–2614. https://doi.org/10.1002/esp.4685

Russell, K. L., Vietz, G. J., & Fletcher, T. D. (2019b). Urban sediment supply to streams from hillslope sources. *Science of the Total Environment, 653*, 684–697. https://doi.org/10.1016/j.scitotenv.2018.10.374

Taylor, K. G., & Owens, P. N. (2009). Sediments in urban river basins: A review of sediment–contaminant dynamics in an environmental system conditioned by human activities. *Journal of Soils and Sediments, 9*, 281–303. https://doi.org/10.1007/s11368-009-0103-z

Trimble, S. W. (1995). Catchment sediment budgets and change. In A. Gurnell & G. Petts (Eds.), *Changing River Channels* (pp. 201–215). Wiley.

United State Army Corps of Engineers Hydraulic Engineering Centre (USACE HEC). (2022a) HEC-HMS Technical Reference Manual. Available at : https://www.hec.usace.army.mil/confluence/hmsdocs/hmstrm. Accessed 15 Sept 2021.

United State Army Corps of Engineers Hydraulic Engineering Centre (USACE HEC). (2022b) HEC-HMS User's Manual. Available at : https://www.hec.usace.army.mil/confluence/hmsdocs/hmsum/latest. Accessed 15 Sept 2021.

Vercruysse, K., Grabowski, R. C., & Rickson, R. J. (2017). Suspended sediment transport dynamics in rivers: Multi-scale drivers of temporal variation. *Earth-Science Reviews, 166*, 38–52. https://doi.org/10.1016/j.earscirev.2016.12.016

Vigiak, O., Malagó, A., Bouraoui, F., Vanmaercke, M., Obreja, F., Poesen, J, …,& Grošelj, S. (2017). Modelling sediment fluxes in the Danube River Basin with SWAT. *Science of The Total Environment* , 599–600, 992–1012. https://doi.org/10.1016/j.scitotenv.2017.04.236

Walling, D. E., & Collins, A. L. (2008). The catchment sediment budget as a management tool. *Environmental Science & Policy, 11*, 136–143. https://doi.org/10.1016/j.envsci.2007.10.004

Walling, D. E., Collins, A. L., Sichingabula, H. M., & Leeks, G. J. L. (2001). Integrated assessment of catchment suspended sediment budgets: A Zambian example. *Land Degradation and Development, 12*, 387–415. https://doi.org/10.1002/ldr.461

Wang, X.-K., Yan, X.-F., Zhou, S.-F., Huang, E., & Liu, X.-N. (2014). Longitudinal variations of hydraulic characteristics of overland flow with different roughness. *Journal of Hydrodynamics, 26*(1), 66–74. https://doi.org/10.1016/S1001-6058(14)60008-1

Water Environmental Federation (WEF) and American Public Health Association (APHA). (2005). *Standard methods for the examination of water and wastewater* (p. 21). American Public Health Association (APHA).

Wheaton, J. M., Brasington, J., Darby, S. E., & Sear, D. A. (2009). Accounting for uncertainty in DEMs from repeat topographic surveys: Improved sediment budgets. *Earth Surf Process Landforms, 35*(2), 136–156. https://doi.org/10.1002/esp.1886