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Original Article

Comparative analysis of the cumulative yield from the adjacent catchment along the ancient Minipe Left Bank Canal, Sri Lanka

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ABSTRACT

Ancient Minipe Anicut, Sri Lanka is world-famous for its engineering excellence. Due to its importance, conserving the ancient anicut, another anicut was constructed downstream in the 20th century. Nevertheless, the water diverted from the ancient anicut to the Minipe Left Bank (LB) Canal was kept as it was due to inherited agricultural importance. This research focuses on studying the contributions made by the adjacent catchment along the Minipe LB Canal. There are several level crossings along the Minipe Left Bank Canal from which the runoff of the local catchment flow into the Minipe LB Canal. Hydrologic Modeling System (HEC-HMS) is used to obtain the yield from each catchment into the Canal, which was compared with the annual diversions from Minipe anicut. The total yield from each stream has been compared with the annual diversion of the Minipe LB Canal from 2014 to 2020. The results obtained from this study reveal that there is sufficient water available for water augmentation in the basin, with an estimated annual average cumulative yield from the catchment of 453.6 MCM. This cumulative yield is 1.7 times the annual average diversion from the Mahaweli River, which is 271.9 MCM. With the findings, it is concluded that there is a potential to augment water from the catchment to address pertaining water shortages conveyance in the command area.

KEYWORDS

ancient Minipe Anicut; digital elevation model; GIS; HEC-HMS; Minipe Left Bank Canal; runoff modeling

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1. Introduction

Irrigation is one of the most widely discussed topics in today's world due to its high importance in the ever-increasing population. Food production is at higher risk due to many reasons including water shortages (Mancosu et al., 2015; Rockström et al., 2009), agricultural land conversion (Appiah et al., 2019; Rondhi et al., 2018), pest attacks (Bruce, 2010; Demay et al., 2023; Elakya and Manoranjitham, 2018; Neuenschwander et al., 2023), soil fertility issues (Çakmakçı and Çakmakçı, 2023; Zhong et al., 2014), and natural disasters (De Haen and Hemrich, 2007; Gimpel et al., 2021; Klomp and Hoogezand, 2018). Water-related issues are significant in food production; therefore, planning an irrigation system is highly important (Sojka et al., 2002). Nevertheless, many challenges can be seen in water resources planning even in a world with high technological advances. These challenges were there for thousands of years in history (Haile, 2015; Khan et al., 2006; Li et al., 2020). However, many outstanding works can be found in history to cater to the challenges in water resources management. Many examples can be found all around the world (Brohier, 1937; Li et al., 2020; Vetter et al., 2014; Berking and Schütt, 2021; Oyonarte et al., 2022). On top of them, the ancient irrigation systems in Sri Lanka are extraordinary and amazing to the Civil Engineering world (Brohier, 1937; Fernando, 1980; Gunawardana, 1971; Leach, 1959).

The irrigation works in ancient Sri Lanka is dating back to 400 BCE, in the reign of King Pandukabhaya were under continuous development for the next thousand years. These irrigation systems were some of the most complex and sophisticated irrigation systems of the ancient world. Ancient Sri Lankan kings built several tanks, ponds, canals, and anicuts which are even now spotted throughout the dry zone of Sri Lanka. At the zenith, the irrigation engineering expertise shown by Sri Lankans has been sought by foreign nations as indicated by Kalhana's 12th century historical epic "Rajatharangani" (Britannica, 2020). As far as anicuts are concerned, Sri Lankans excelled appreciably in the construction of Elhera, Thekkam, Angamedilla, and Minipe Anicut. Among these ancient anicuts, the Minipe Anicut was constructed across the Mahaweli River by King Datusena in the 5th Century AD and later rehabilitated by King Aggabodi-I (refer to **Figure 1(a,b)**). It is said that the water of the Mahaweli River was conveyed as far as Trincomalee (100–150 km). Minipe has been a continuous population center until the 17th Century AD. In 1941, the Irrigation Department restored the Minipe Anicut by constructing a low-flow weir across the Mahaweli River (refer to **Figure 1(a,c)**) together with an intake structure to divert water into the Minipe Left Bank (LB) Canal, and in 1962 the length of the LB canal was extended (Karunananda, 2020).

Hasalaka Oya, Berabun Oya, Balawardhana Oya, Heenganga, Hettipola, and Namini Oya are some streams that are falling into the canal (refer to **Figure 2**). These natural waterways create a series of level crossings namely Hasalaka Wewa, Berabun Wewa, Ulpathagama Wewa, Himbutawa Wewa, and Dunuwila Wewa at the confluence of the Minipe Canal. Besides the diversions from river Mahaweli, the yields received by these level crossings contribute to the duty of the canal, which is beneficial to irrigation. At present LB canal carries 22 m^3/s discharge and feeds 7987 ha (Wickramanayake, 2022) of irrigable land in the valley between the LB canal and the Mahaweli River. The length of this canal is 73.825 km.

At present, the flow of water in the Minipe LB Canal fluctuates within a range of about 75% of the design discharge in a day as the LB intake is located at a higher elevation (about 0.7 m) than the RB Canal intake. Therefore, the major portion of water at Minipe Anicut during the low flow

Figure 1. Minipe Anicut: **(a)** Bird eye view (source: Google Earth); **(b)** Ancient anicut (source: Authors' personal photographs); **(c)** New anicut (source: Authors' personal photographs).

period flows into the RB Canal. As a result, farmers at the tail end of the LB Canal are facing a water deficit. Further, the future water resource development in the area such as the proposed water resource development in Heen Ganga and Hasalaka Oya will result in a further reduction in inflows to the LB Canal (Ministry of Irrigation and Water Resources Management [MIWRM], 2014).

The interplay between water, climate, farmers, and agriculture is a complex and critical relationship that holds far-reaching implications for food security, environmental sustainability, and economic stability. Farmers rely on the availability and quality of water to cultivate crops and raise animals, making it a cornerstone of agricultural productivity (Gleick, 1993; Gunaratne et al., 2021; Saumyarathna et al., 2016). Rising temperatures can induce heat stress in both crops and livestock, while altered rainfall patterns can lead to droughts or floods. In regions where water resources are limited, competition for water resources among agriculture and other sectors can escalate conflicts and worsen food insecurity. Therefore, the imperative to introduce sustainable water management practices is essential to sustain both food security and the livelihoods of farmers. In addition, the rapid population growth, urbanization, drastic changes in land use and growing industrialization are threatening water resources with the increasing water demand. The changes in the aforementioned

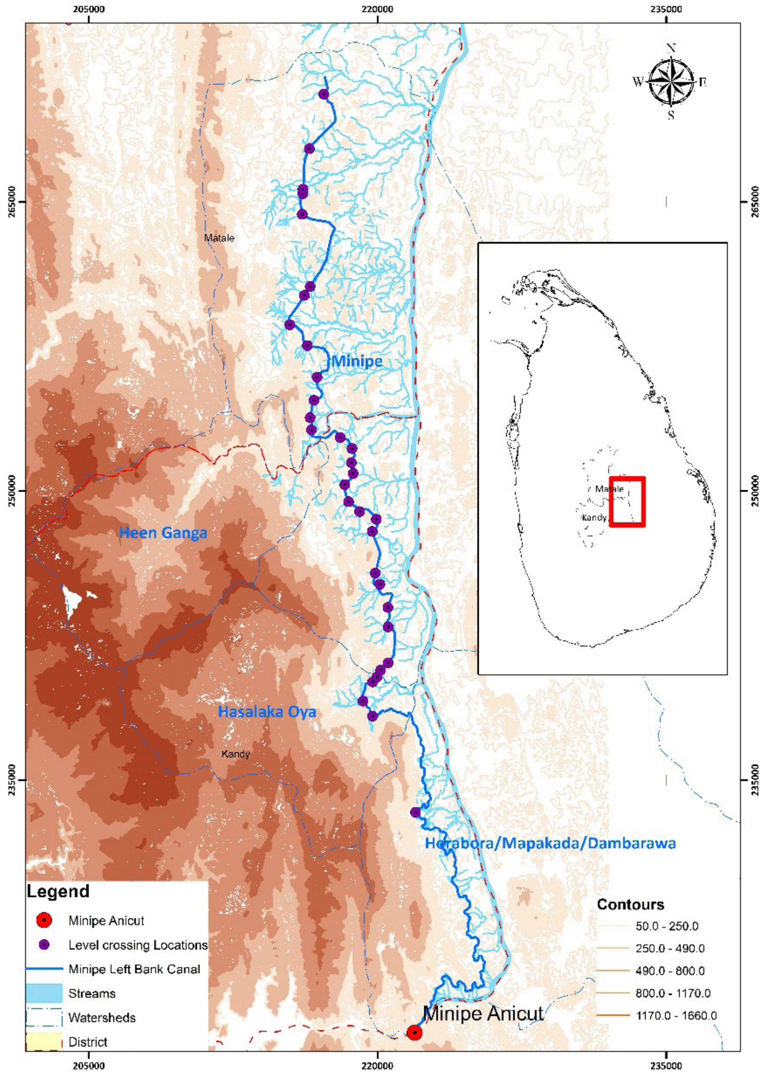


Figure 2. Minipe Left Bank Canal and its command area.

factors directly or indirectly affect the rainfall and stream flow patterns. Hence, estimating stream flow with available rainfall to manage available water is important for water resources management (Dobriyal et al., 2017; Gunathilake et al., 2020; Perera and Wijesekera, 2012). Moreover, with the growth of population and the expansion of cultivating areas, water consumption has been increased. Therefore, it is important to study the contribution of these level crossings to the canal. Furthermore, there have been no prior investigations into an ancient irrigation canal with multiple level crossings. This study serves as an eye-opener for modern Sri Lankan irrigation engineers, highlighting the importance of incorporating indigenous knowledge in water augmentation.

Thus, this research work was carried out to fill the above-identified research gaps. This study aims to analyze the contributions of the yields from level crossings to the water duty of the Minipe Left Bank Canal, Sri Lanka. The research gap showcased in the paper was filled by addressing the research objectives including identifying the geomorphology of level crossings along the Minipe Left Bank Canal, performing hydrological analysis of the level crossings along the Minipe Left Bank Canal, and understanding the relationship between the water duty and the cumulative yield of level crossings.

The modelling to obtain runoff from each sub-basin has been performed using the HEC-HMS software combined with digital elevation modelling which has been used to obtain terrain data.

2. Materials and methods

2.1. Overall summary of the methodology

In the purview of analyzing the yield from each level crossing, a terrain layer for the model has been generated through the Digital Elevation Model (DEM), which is created using 1:10,000 digital contours for the considered area. The rainfall data (obtained from the Department of Meteorology, Sri Lanka) and Land use data (obtained from the Department of Surveying, Sri Lanka) are used for the meteorological model preparation and basin model preparation of the Hydraulic Engineering Center – Hydrologic Modeling System (HEC-HMS). Discharge of each catchment has been obtained by running the model. The total yield from the composite catchment of all level crossings has been compared with the annual diversion from the Mahaweli River to the Minipe Left Bank Canal from 2014 to 2020. The flowchart shown in **Figure 3** summarizes the methodology of this research.

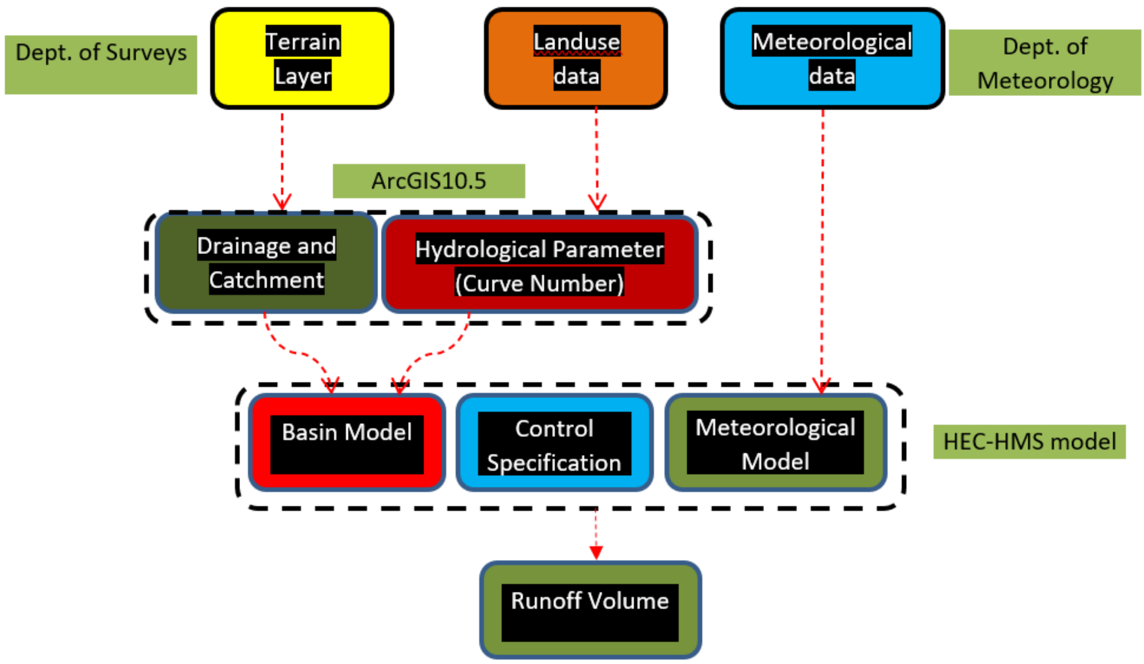
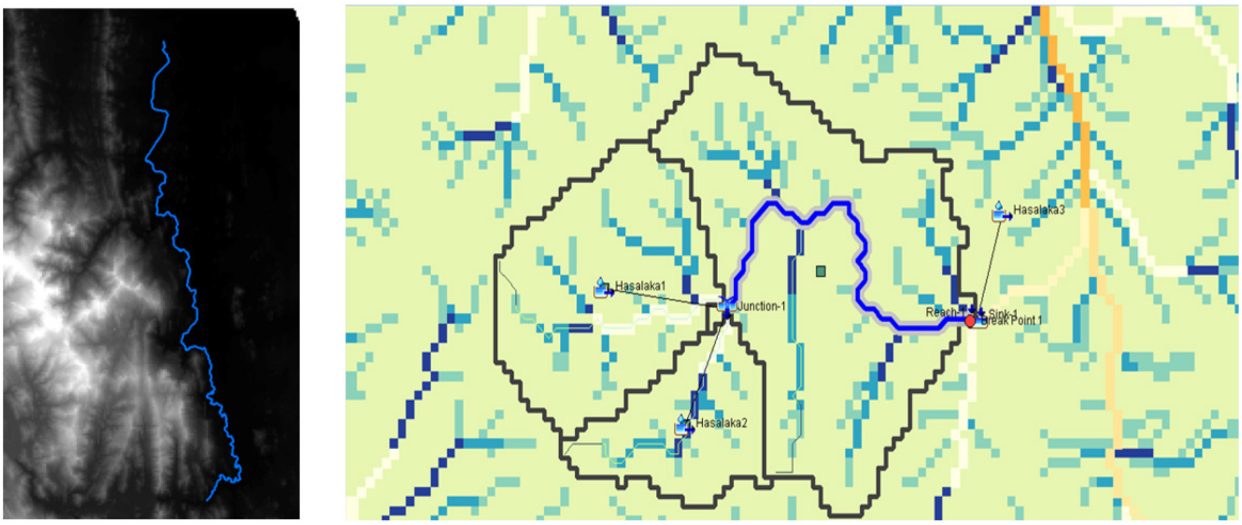


Figure 3. Flowchart of the research methodology.

2.2. Basin model development

The HEC-HMS model setup includes a basin model, a meteorological model, control specifications, and the addition of time-series data (Chathuranika et al., 2022). Version 4.10 of HEC-HMS was used to generate these three models in the main model (Hydrologic Engineering Center, 2023). The locations of level crossings have been identified using Google Earth Pro satellite images and by observing the digital layers (shape files) through the Arc-GIS 10.5 interface. Concurrently, the Digital Elevation Model (DEM) for the study area was generated using 1:10,000 digital contours through Arc-GIS 10.5 by the tools "Create Tin" and "Tin to Raster" (refer to **Figure 4(a)**). Thereafter, the generated DEM is used to develop the Basin Model in HEC-HMS as the terrain layer to delineate the watershed for the considered level crossing. Consequently, some basin models consist of several sub-basins, each of which represents a smaller part of the overall watershed (refer to **Figure 4(b)**). These sub-basins are defined by their own set of physical and hydrological characteristics, such as topography, soil type, land use, and precipitation data.



(a) **(b)**

Figure 4. **(a)** DEM for canal; **(b)** Basin model developed for Hasalaka Oya.

Soil Conservation Service Method (SCS-CN) was considered the loss method in developing the basin model. The identification of the soil type, which is essential to determine the Curve Number (CN) was performed by geo-referencing the soil map of Sri Lanka (Anuruddhika et al., 2022; Jayasinghe et al., 2010). A major portion of the soil in the study area was of Reddish Brown Earth (RBE) and Low Humic Gley (LHG) soils. Further, the Red yellow Podsolic soil with a moderate amount of gravel in the subsoil was found at a few locations. Based on these observations from map cartography, the soil type in the basin was categorized as Group B soil with an Antecedent Moisture Content (AMC) of Type II, which led to the consideration of CN-II values to determine the cumulative CN-II values. The cumulative CN-II was calculated using Equation (1) for each sub-basin.

$$\mathrm{CN} = \frac{\sum \mathrm{A_i CN_i}}{\sum \mathrm{A_i}} \tag{1}$$

where CN is the Cumulative Curve Number, A_i is the area of the i-th land use type within the basin, and CN_i is the CN-II values corresponding to i-th land use type. Six types of land uses were identified from the GIS database in each sub-basin. **Table 1** summarizes the CN-II values utilized in calculating the cumulative CN for each type of land uses identified.

Table 1. CN-II values for identified land uses.

Land use type	Curve number
Water area	100
Bare area	50
Forest area	45
Build up area	85
Rock area	100
Cultivation area	75

The Soil Conservation Service Unit Hydrograph method was used as the Transform Method for the basin model. It is necessary to find the lag (delay between the time runoff from a rainfall event over a watershed begins until runoff reaches its maximum peak) to input for each sub-basin. For that, the first time of concentration was calculated, and after that lag was determined with the help of the time of concentration.

Equation (2) estimates the time it takes for rainfall to travel from the furthermost point of the water to the outlet point (Kenneth et al., 2010). Even though it is not in the real case, it was assumed that the rainfall intensity is uniform throughout the watershed (Faurès et al., 1995; Goodrich et al., 1995; Kenneth et al., 2010; Morin et al., 2006). This is due to the computational complexity of the analysis. However, the outcome would not be severely affected due to spatial regionalization of the area based on the annual rainfalls. The area is considered an intermediate area based on the annual rainfall which is in between the wet zone and dry zone.

$$T_C = \frac{l^{0.8}(S+1)^{0.7}}{1140Y^{0.5}} \tag{2}$$

where T_C is the time of concentration (hrs), l is the lag (hrs), S is the maximum potential retention (inches), and Y is the average watershed land slope (%).

The canal routing is required to obtain the accurate discharge from the catchment in any basin model. The Muskingum method has been employed as the method of Reach for this purpose. This method uses the conservation of mass approach to route an inflow hydrograph. As such, this method can simulate the commonly observed storage increase in channels during the rising side and decreased channel storage during the falling side of a passing flood wave. Parameters that are required to utilize this method within the HEC-HMS model include the initial condition, K (hrs), Muskingum X parameter, and the number of sub-reaches. The Muskingum K parameter is equivalent to the travel time through the reach. The Muskingum X parameter is a dimensionless coefficient that lacks a strong physical meaning. This parameter must range between 0.0 (maximum attenuation) and 0.5 (no attenuation). For most applications, an initial estimate of 0.25 is further refined through model calibration (Hydrologic Engineering Center, 2023), which was used in this basin model as well.

2.3. Meteorological model development

Time series data are necessary for the development of the Metrological Model. This model was created by using daily rainfall data from Hasalaka (7.346680°, 80.942423°) and Hettipola

(7.552420°, 80.905122°) rain gauges, which were recorded from 2014 to 2020. The rainfall data of the Haslaka rain gauge has been used for level crossing numbers 1 to 18 and rainfall values of the Hettipola rain gauge station have been used for level crossing numbers 20 to 33. **Figure 5** shows the annual rainfall variation of these two stations (However, the model was developed using the daily rainfall data).

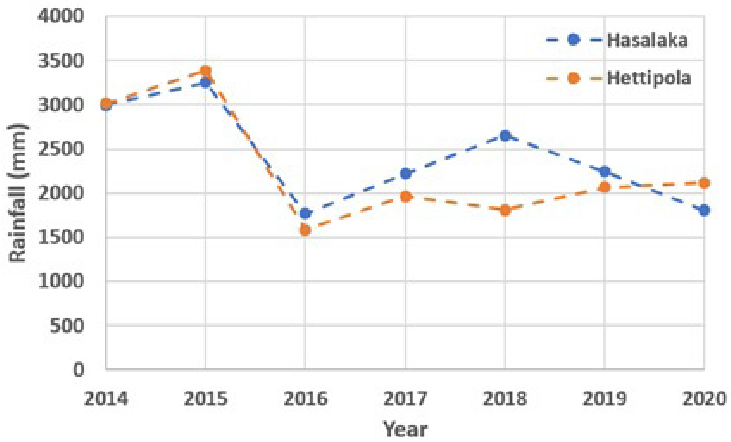


Figure 5. Annual rainfall variation.

2.4. Control specification model

In the control specification, a time duration of a year has been given from the start to the end to run the model. This enables displaying the time series results from the simulation.

2.5. Measurement of diversions from the river to the Minipe Left Bank Canal

The daily diversions from river Mahaweli to the Minipe Left Bank Canal were measured using a calibrated Parshall flume. The daily diversion statistics from 2014 to 2020 collected from the Department of Irrigation, Sri Lanka were utilized to calculate the annual diversions. The collected data is tabulated in **Table A1** of the Appendix. According to this table, maximum diversion from Minipe anicut is performed in every month while it has been minimal during the month of September. Moreover, the annual average diversion to the Left Bank Canal has been 271.9 MCM.

3. Results and discussion

3.1. Locations of sub-basins

According to the method of topographical analysis presented under Section 2.1, 33 sub-basins were identified. The WGS84 coordinates of the outlets of these sub-basins are presented in **Table A2** of the Appendix. This table indicates the coordinates of 33 sub-basins along the canal. Since 1 to 10,000 topographic sheets are used to develop the Digital Elevation Model (DEM), only basins with catchments greater than 0.5 km^2 were identified in the analysis. Therefore, the obtained cumulative yield of the adjacent catchment in the following sections may represent a lesser value than the actual yield.

3.2. Catchment characteristics for the basin model of the HEC-HMS model

The land use data and the soil characteristics, which are essential for the basin model development in HEC-HMS were generated using Arc-GIS 10.5. The cumulative CN values for the basin models for each sub-basin were developed as per the method presented in Section 2.2 and presented in **Table A3** under the Appendix. The other parameters for the basin model namely, Average watershed land slope (Y), maximum potential retention (s), longest flow path (λ), and time of concentration (T_C) were determined and tabulated in **Table A4** in the Appendix.

3.3. Cumulative runoff comparison with annual diversion

The annual cumulative runoffs from the adjacent catchment were estimated after modeling the runoffs for identified sub-basins. Consecutively, the annual diversions from River Mahaweli to Minipe LB Canal were calculated. The calculated results for both annual diversions and catchment runoff are tabulated under **Table 2** and **Figure 6**.

Table 2. Annual discharge from diversions and catchments.

Year	Diversions from the Mahaweli River (MCM)	Cumulative yield from the catchments (MCM)
2014	266	532
2015	273	635
2016	247	332
2017	234	416
2018	205	469
2019	293	433
2020	385	358

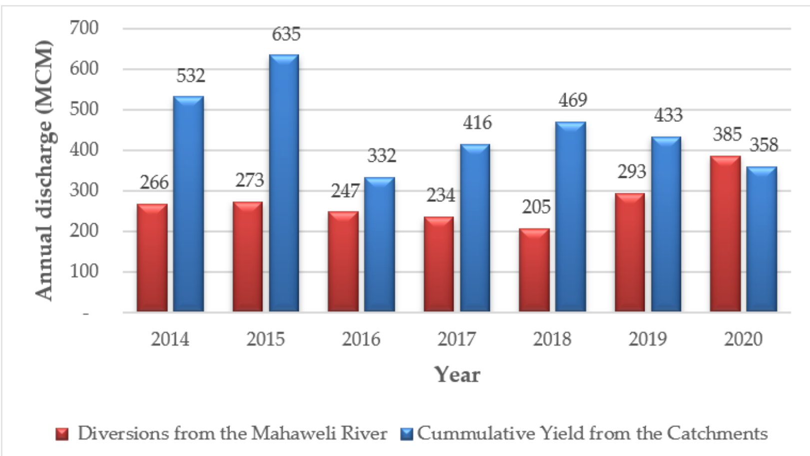


Figure 6. Annual discharges from local catchment and diversion to the Minipe LB Canal.

Figure 6 reveals that the cumulative runoff in the adjacent catchment is greater than the annual diversions except in 2020 (also refer to **Table 2**). There are project proposals to increase the water augmentation in this canal by raising the anicut at the Mahaweli River. The results obtained from this study reveal that there is sufficient water available for water augmentation in the basin, with an estimated annual average cumulative yield from the catchment of 453.6 MCM. This cumulative yield is 1.7 times the annual average diversion from the Mahaweli River, which is 271.9 MCM.

Further, such engineering intervention will avoid water shortages for the command area under this canal. Finally, it is needed to state that the actual runoff from the catchment will be higher than the estimated value because there are unidentified small basins that are lesser than 5 km^2 along the canals not considered in this estimation.

4. Conclusions and recommendations

The nature of the geomorphology of level crossings along the Minipe Left Bank Canal comprises 33 basins whereas in some larger basins, sub-basins can be demarcated. Further, it shows the richness of water heritage in this canal and the reasons for ancient kings to construct such irrigation systems. One of the major conclusions that can be made from this study is that these ancient contour canals are not just water-conveying structures but function as elongated reservoirs.

The annual cumulative yield from the adjacent catchment along the canal was modeled from 2014 to 2020. The total cumulative diversion from the Mahaweli River to the Left Bank Main Canal for the same period has been calculated using the records from the Department of Irrigation. The second conclusion that can be made is that the annual potential yield of the catchment is greater than annual diversions in most instances. Finally, in conjunction with the above-stated conclusions, we state that there is a potential to augment water from the catchment to address pertaining water shortages conveyance in the command area.

Even though annual yields from the catchment are estimated, it is required to develop a scientific water management plan to utilize this water for its inhabitants. Further, a detailed modeling of hydraulic conveyance in the canal is required to identify the delays in water distribution to the farmers. In addition, to improve the model outputs, gauged stream flow data is needed for each stream. The study can be improved further by adding gauged water levels, which is more helpful for each catchment planning and management.

Data availability statement

Data used in this research are only available for research purposes from the corresponding author.

Author contributions

Conceptualization, GNP; methodology, GNP; software, RNJKA; validation, GNP, RNJKA and UR; formal analysis, GNP, RNJKA and UR; investigation, GNP, RNJKA and UR; resources, GNP, RNJKA and UR; data curation, RNJKA; writing—original draft preparation, GNP, RNJKA and UR; writing—review and editing, UR; visualization, GNP and UR; supervision, GNP; project administration, GNP; funding acquisition, UR. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest.

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Appendix

Table A1. Quantity of water diverted from Mahaweli River to the Minipe Left Bank Canal.

Month	Discharge (MCM)						
	2014	2015	2016	2017	2018	2019	2020
January	34	34	18	21	27	33	36
February	35	18	23	19	25	24	35
March	17	17	12	11	10	14	41
April	23	17	27	25	6	20	40
May	25	38	33	57	23	40	48
June	27	37	43	30	10	36	44
July	38	41	41	28	26	43	35
August	14	35	13	8	20	26	7
September	3	1	0	0	0	0	0
October	4	2	15	0	0	0	11
November	27	18	13	14	22	29	45
December	19	15	9	21	36	27	44
Annual discharge	266.35	273	247	234	205	293	385

Table A2. Level crossing location.

Level crossing location	Longitude	Latitude	Level crossing location	Longitude	Latitude
1	80.9728	7.30221	18	80.9426	7.46629
2	80.9525	7.34734	19	80.943	7.47294
3 (Hasalaka Wewa)	80.9481	7.35437	20	80.9374	7.4781
4	80.9526	7.36339	21	80.9239	7.48166
5	80.9547	7.36564	22	80.9232	7.48741
6	80.9565	7.36895	23	80.925	7.49553
7	80.96	7.37238	24	80.9265	7.50636
8 (Berabun Wewa)	80.9599	7.38923	25	80.922	7.52122
9	80.9598	7.39837	26	80.9137	7.53101
10 (Ulpothagama)	80.9561	7.40919	27	80.9206	7.54473
11	80.9539	7.41443	28	80.9233	7.54897
12	80.9525	7.43397	29	80.9196	7.58287
13	80.9544	7.43968	30	80.9198	7.59259
14	80.9465	7.44332	31	80.92	7.59462
15	80.9414	7.44798	32 (Dunuwila Wewa)	80.9229	7.61365
16 (Himbutawa Wewa)	80.9396	7.45597	33	80.9297	7.63923
17	80.9435	7.46118	18	80.9426	7.46629

Table A3. Characteristics of the catchment—The cumulative CN values.

Level crossing number	Sub-basin	Water area (km^2)	Bare area (km^2)	Forest area (km^2)	Build up area (km^2)	Rock area (km^2)	Cultivation area (km^2)	Curve numbers
LC01	Sb 01	0.04	11.80	3.39	0.60	0.51	0.11	52.06
LC02	Sb 01	0.14	13.15	4.25	1.65	0.31	0.60	53.68
LC03	Sb 01	0.08	10.72	6.50	2.17	0.96	7.59	60.17
	Sb 02	0.00	7.14	3.88	0.72	0.05	2.06	54.34
	Sb 03	0.75	19.50	17.04	9.29	1.80	3.09	58.64
LC08	Sb 01	0.16	0.63	0.36	1.58	0.00	0.02	72.63
LC09	Sb 01	0.42	0.06	5.23	1.96	0.10	0.48	59.75
LC12	Sb 01	0.00	4.12	7.54	1.27	0.80	1.49	55.53
	Sb 02	0.00	0.18	0.10	1.26	0.00	0.26	77.75
LC16	Sb 01	0.10	0.12	0.29	0.74	0.00	0.01	73.51
LC18	Sb 01	0.09	0.16	0.09	0.55	0.02	0.05	76.70
LC20	Sb 01	0.05	0.05	0.01	0.33	0.05	0.05	82.46
LC22	Sb 01	0.02	0.43	0.47	0.02	0.00	0.03	50.12
LC24	Sb 01	0.01	0.16	0.02	0.39	0.00	0.02	74.43
LC25	Sb 01	0.01	0.15	0.00	1.10	0.00	0.30	79.87
LC26	Sb 01	0.01	7.99	7.40	1.35	0.06	0.32	51.25
LC27	Sb 01	0.01	0.42	0.00	0.18	0.00	0.13	63.49
LC28	Sb 01	0.01	2.01	0.71	0.01	0.31	0.47	57.03
LC29	Sb 01	0.00	0.79	0.72	0.00	0.01	0.001	47.80
LC31	Sb 01	0.22	10.92	8.79	0.49	0.09	0.23	49.72
LC32	Sb 01	0.34	1.52	13.52	0.18	0.01	0.33	47.77
LC33	Sb 01	0.01	0.04	0.00	0.62	0.00	0.06	82.67

Table A4. Characteristics of the catchment—Equation (2).

Level crossing location	Sub basin	Basin slope (%)	Maximum potential retention (s)	Longest flow path (ft)	Time of concentration (hr)	Lag (hr)
LC01	Sb 01	30.40	9.21	23,054.86	2.50	1.50
LC02	Sb 01	26.35	8.63	33,402.04	3.47	2.08
LC03	Sb 01	32.71	6.62	26,155.18	2.17	1.30
	Sb 02	27.31	8.40	24,680.09	2.63	1.58
	Sb 03	25.02	7.05	47,196.75	4.14	2.49
LC08	Sb 01	11.94	3.77	14,457.25	1.61	0.97
LC09	Sb 01	16.22	6.74	17,831.99	2.30	1.38
LC12	Sb 01	26.31	8.01	16,982.97	1.93	1.16
	Sb 02	6.65	2.61	6635.83	0.95	0.57
LC16	Sb 01	15.51	3.60	4886.29	0.58	0.35
LC18	Sb 01	8.88	3.04	6910.24	0.92	0.55
LC20	Sb 01	3.45	2.13	4011.52	0.80	0.48

Table A4. (*Continued*).

Level crossing location	Sub basin	Basin slope (%)	Maximum potential retention (s)	Longest flow path (ft)	Time of concentration (hr)	Lag (hr)
LC22	Sb 01	20.63	9.95	6035.47	1.09	0.65
LC24	Sb 01	11.20	3.44	5010.63	0.68	0.41
LC25	Sb 01	3.53	2.52	5735.30	1.14	0.69
LC26	Sb 01	16.08	9.51	23,106.37	3.52	2.11
LC27	Sb 01	9.01	5.75	6459.97	1.24	0.75
LC28	Sb 01	2.69	7.53	14,658.83	5.16	3.10
LC29	Sb 01	1.99	10.92	7060.33	4.23	2.54
LC31	Sb 01	12.39	10.11	26,331.04	4.62	2.77
LC32	Sb 01	7.26	10.93	27,878.97	6.65	3.99
LC33	Sb 01	144.36	2.10	4736.19	0.14	0.08