

IRRIGATION DEPARTMENT

**HYDROLOGICAL ANNUAL
2015/16**

**Hydrology Division
Irrigation Department
Colombo 07
Sri Lanka**

***Hydrological Annual 2015/16 – Hydrology Division, Irrigation Department.
57th year of publication***

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Foreword

Hydrological Annual is a publication of the Hydrology Division of Irrigation Department. Content of the booklet is extremely useful for planning, developing and managing water resources of the country. Further it is useful for students and researchers in water and agriculture sectors for monitoring climate change and environmental issues which are crucial for food production and economic development of the country.

Hydrology Division has undergone notable changes during the recent years regarding expansion and modernization of hydrometric network which were carried out under the project 'HMIS' (Hydro-Meteorological Information System), financed by the World Bank. Most of the manual stations were automated while introducing new stations at the locations important for flood forecasting and water management. Original scope of the project was to complete 122 stations with automated data acquisition and transmission facilities with central database management system. Major part of the project could be completed by the end of 2015/16 water year and additional 46 stations were taken up for implementation under the second stage. Ultimate objective of the project is providing reliable and complete hydro-meteorological information covering the entire country to all relevant organizations. Online data received from those stations were extremely useful in managing the critical flood event in May 2016 in the Kelani River basin. This journal also will be improved by additional information through 'HMIS' stations from the next water year onwards.

Similar to previous publications of this series, Part I and II of the journal provide the general information of the river basins and the salient hydrological features pertaining to the current water year. Part III of the journal is allocated for the technical papers and research works carried out by the engineers of the Irrigation Department. Findings of these research works are also useful for those who are engaged in water related development activities.

A critical flood was experienced in the Wet Zone of the country including the Kelani River basin in May 2016. It was considered as the most severe hydrological hazard faced by the people of the Kelani River basin after the devastating flood in 1989. All the important hydrological data pertaining to this flood has been collected and archived by the Hydrology Division for future use.

Three articles have been included in the Part III of the journal. "Flood Frequency Analysis and Selection of Suitable Design Flood for Kelani Flood Bunds" emphasizes the necessity of improving Kelani flood control works and suggests suitable criteria for redesigning flood bunds to cope with future flood events and safeguard the lives and the properties of the area. The second paper provides updated I-D-F (Intensity-Duration-Frequency) curves for Colombo area which will be useful in designing drainage outlets and canal networks for Colombo city area which is frequently subjected to flooding. The article "Subgrade Soil Stabilization through Root Water Uptake" presents the findings of a research in sub grade soil stabilization by reinforcing and suction of water with the living roots of special species of trees. I hope this method can be adopted in strengthening river banks and improving marshy lands which are crucial requirements of this era.

Eng. Ms P. Hettiarachchi,
Director of Irrigation (Hydrology)

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PART I

- **Terminology and Abbreviations**
- **Conversion Factors**
- **River Basin Map and Drainage Area**
- **Hydrometric Stations**

TERMINOLOGY AND ABBREVIATIONS USED IN PUBLICATION

Flood Hydrograph	-	A plot of discharge against time.
Annual Flood Peak	-	Highest value of discharge for the year indicated by the hydrograph
Maximum Flood Peak	-	Maximum observed flood peak during the period of observation.
Average Annual Rainfall	-	Arithmetic mean of annual rainfall values for the period of observation.
Rainfall Intensity	-	Cumulative depth of rainfall during a particular duration.
Annual Runoff	-	The total volume of water measured at a particular point for the year.
Average Annual Runoff	-	Arithmetic mean of annual run-off for the period of observation.
Annual Yield	-	Annual yield is the volume of water available to the tank from its own catchment (without diversions) during the year.
Specific Yield	-	$\frac{\text{Yield (MCM)}}{\text{Catchment Area (Sq.Kms)}}$
Duty	-	Duty is the irrigation requirement (issued from the sluice) during a cultivation season for one hectare
		$\text{Duty (meters)} = \frac{\text{Sluice Issue (ha.m)}}{\text{Area Cultivated (ha)}}$
Evaporation	-	The transfer of water into the atmosphere from a free water surface.
Potential Evapotranspiration	-	The evapotranspiration from vegetal cover and from soil surface when the root zone is saturated.

CONVERSION FACTORS

Length

Imperial		Metric / SI
1 inch	= 1/12 foot	0.0254 m
1 foot	= 1/3 yard	0.3048 m
1 yard	= 3 feet	0.9144 m
1 Engineering chain	= 100 feet	30.48 m
1 mile	= 52.8 chains = 5280 feet	1609 m

Area

Imperial		Metric / SI
1 square foot	= 144 square inches	0.0929 m ²
1 acre	= 43,560 ft ²	4,047 m ² = 0.4047 ha
2.47 acres		1 ha
1 square mile	= 640 acres	259 ha = 2.59 km ²

Volume & Discharge

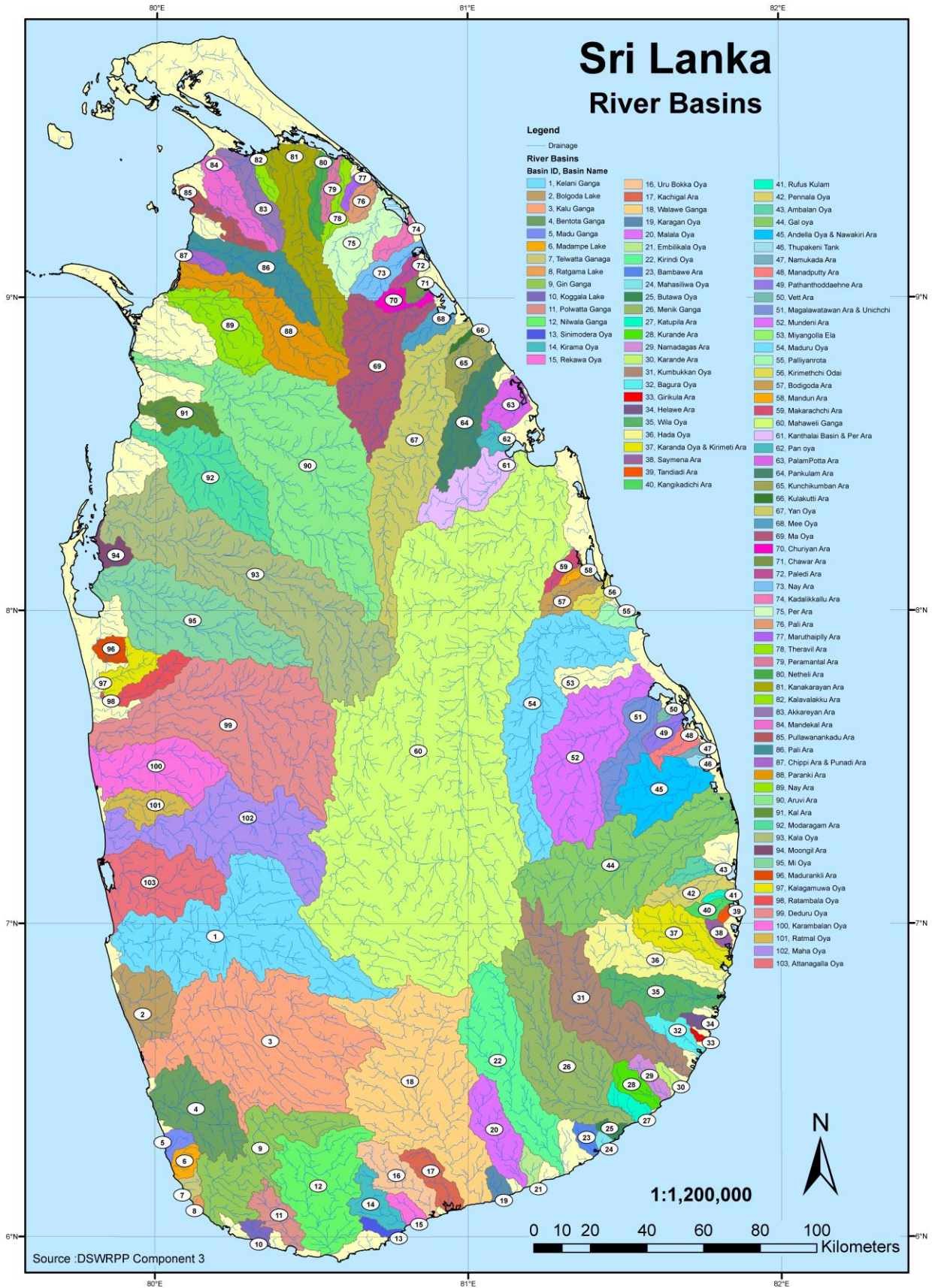
Imperial		Metric / SI
1 cubic foot per second (cusec)		28.317 l/s
1 cusec during 1 day	= 1.983 acre.ft	2,446.57 m ³
1 acre.foot		1,234 m ³
1 acre.foot/day		14.28 l/s = 1234 m ³ /d
1 acre.inch	= 3.630 ft ³	102.8 m ³

Map scales

Imperial		Metric / SI
1 inch : 10 feet		1 : 120
1 inch : 20 feet		1 : 240
1 inch : 66 feet		1 : 792
1 inch : 132 feet		1 : 1,584
1 inch : 264 feet		1 : 3,168
1 inch : 528 feet		1 : 6,336
1 inch : 1 mile		1 : 63,360

Weight

Imperial		Metric / SI
1 pound		0.4536 kg
2.24 pound		1 kg
1 ton		1,016 kg
2,240 pounds		1 Metric Ton = 1000 kg
1 bushel (paddy)		22.88 kg
1 bushel/acre		56.5 kg/ha



RIVER BASINS OF SRI LANKA

	River Name	Drainage Area (Sq.km)	River Name	Drainage Area (Sq.km)
1	Kelani Ganga	2340	41 Rufus Kulam	27
2	Bolgoda Ganga	396	42 Pannel Oya	195
3	Kalu Ganga	2839	43 Ambalan Oya	112
4	Bentara Ganga	667	44 Gal Oya	1911
5	Madu Ganga	69	45 Andella Oya	534
6	Madampe Ganga	90	46 Tumpun Keni	18
7	Telwatta Ganga	41	47 Namakada Aru	12
8	Ratgama Lake	13	48 Mandipattu Aru	90
9	Gin Ganga	915	49 Pathantoppu Aru	101
10	Koggala Ganga	55	50 Vett Aru	22
11	Polwatta Ganga	232	51 Magalavatavan Aru	304
12	Nilwala Ganga	1043	52 Mundeni Aru	1373
13	Sinimodara Oya	35	53 Miyangolla Ela	228
14	Kirama Oya	183	54 Maduru Oya	1439
15	Rekawa Oya	70	55 Pulliyanpota Aru	87
16	Urubokka Oya	373	56 Kirimechchi Odai	89
17	Kachigal Ara	208	57 Bodigolla Aru	132
18	Walawe Ganga	2424	58 Mandan Aru	26
19	Karagan Oya	60	59 Makarachchi Aru	59
20	Malala Oya	409	60 Mahaweli Ganga	10266
21	Embilikala Oya	69	61 Kantalai Aru	437
22	Kirindi Oya	1156	62 Palampotta Aru	97
23	Bambawe Ara	66	63 Panna Oya	164
24	Mahaseelawa Oya	13	64 Pankulam Aru	377
25	Buthawa Oya	37	65 Kunchikumban Aru	245
26	Menik Ganga	1301	66 Palakutta Aru	8
27	Katupila Ara	111	67 Yan Oya	1518
28	Kurunda Ara	99	68 Mi Oya	89
29	Nabadagas Ara	110	69 Ma Oya	1042
30	Karambe Ara	54	70 Churiya Aru	105
31	Kumbukkan Oya	1227	71 Chavar Aru	35
32	Bagura Oya	93	72 Palladi Aru	66
33	Girikula Oya	14	73 Manal Aru	194
34	Helawa Ara	38	74 Kodalikallu Aru	92
35	Wila Oya	472	75 Per Aru	392
36	Heda Oya	615	76 Pali Aru	70
37	Karanda Oya	425	77 Maruthapillay Ary	36
38	Seman Aru	72	78 Thervil Aru	104
39	Tandiadi Aru	20	79 Piramanthal Aru	91
40	Kangikadichi Aru	78	80 Methali Aru	114

81	Kanakarayan Aru	604
82	Kalwalappu Aru	68
83	Akkarayan Aru	244
84	Mandekal Aru	208
85	Pallavarayan Kaddu Aru	311
86	Pali Aru	451
87	Chappi Aru	79
88	Parangi Aru	770
89	Nay Aru	717
90	Aruvi Aru	3291
91	Kal Aru	210
92	Moderagama Aru	1001
93	Kala Oya	2526
94	Moongil Aru	78
95	Mee Oya	1555
96	Madurankuli Aru	128
97	Kalagamune Oya	169
98	Rathambala Oya	244
99	Deduru Oya	2622
100	Karambala Oya	693
101	Ratmal Oya	341
102	Maha Oya	1470
103	Attanagalu Oya	811
	Area of Jaffna Peninsula including Vadamarachchi Lagoon, but excluding islands of Kayts , Kartivu	1018
	Residual area comprising largely, coastal zones intervening between adjacent river basins of Sri Lanka	5049
	Total	65591

Source: Water Resources Planning Project under component 03 of DSWRPP- 2013

HYDROMETRIC STATIONS - 2015/16
(According to River Basin)

Name of Station	River Basin	Coordinates	Catchment Area (Sq.Km)
1. Norwood	Kelani Ganga	(6°50'22", 80°36'42")	97
2. Kithulgala	Kelani Ganga	(6°59'26", 80°24'44")	383
3. Deraniyagala	Kalani Ganga	(6°55'28", 80°20'16")	183
4. Holombuwa	Kelani Ganga	(7°11'07", 80°15'53")	155
5. Glencourse	Kelani Ganga	(6°58'28", 80°10'58")	1463
6. Hanwella	Kelani Ganga	(6°54'34", 80°04'46")	1782
7. Rathnapura	Kalu Ganga	(6°40'42", 80°23'39")	603
8. Ellagawa	Kalu Ganga	(6°43'55", 80°12'36")	1393
9. Millakanda	Kalu Ganga	(6°37'56", 80°11'23")	780
10. Putupaula	Kalu Ganga	(6°36'06", 80°03'26")	2598
11. Baddegama	Gin Ganga	(6°10'33", 80°10'27")	749
12. Thawalama	Gin Ganga	(6°20'31", 80°19'49")	377
13. Urawa	Nilwala Ganga	(6°14'12", 80°34'18")	74
14. Pitabeddara	Nilwala Ganga	(6°12'47", 80°28'31")	332
15. Panadugama	Nilwala Ganga	(6°06'30", 80°28'40")	457
16. Wellawaya	Kirindi Oya	(6°42'35", 81°06'40")	172
17. Thanamalwila	Kirindi Oya	(6°28'06", 81°08'03")	749
18. Kuda Oya	Kirindi Oya	(6°31'29", 81°07'24")	291
19. Katharagama	Menik Ganga	(6°24'56", 81°19'51")	787
20. Nakkala	Kumbukkan Oya	(6°53'42", 81°17'49")	216
21. Siyambalanduwa	Heda Oya	(6°54'18", 81°32'36")	295
22. Padiyathalawa	Maduru Oya	(7°23'01", 81°11'31")	159
23. Thaldena	Badulu Oya	(7°05'27", 81°02'53")	276
24. Calidonia	Mahaweli Ganga	(6°54'07", 80°41'52")	148
25. Demodara	Mahaweli Ganga	(6°56'12", 81°02'03")	78
26. Nawalapitiya	Mahaweli Ganga	(7°02'51", 80°32'04")	176
27. Peradeniya	Mahaweli Ganga	(7°16'03", 80°36'30")	1168
28. Manampitiya	Mahaweli Ganga	(7°54'53", 81°05'10")	7418
29. Horowpothana	Yan Oya	(8°34'39", 80°52'43")	720
30. Thanthirimale	Malwathu Oya	(8°35'14", 80°16'31")	2116
31. Galgamuwa	Mee Oya	(7°58'07", 80°15'34")	299
32. Chilaw	Deduru Oya	(7°36'01", 79°48'57")	2610
33. Giriulla	Maha Oya	(7°19'30", 80°06'53")	1192
34. Badalgama	Maha Oya	(7°18'00", 79°58'47")	1360
35. Dunamale	Aththanagalu Oya	(7°06'56", 80°04'50")	153

PART II

- **Rainfall**
- **Variation of Rainfall**
- **Rainfall Intensities**
- **Evaporation and Evapotranspiration**
- **Stream Flow Data**
- **Runoff / Rainfall Ratio**
- **Flood Hydrographs**

RAINFALL

MONTHLY RAINFALL AT THE PRINCIPAL STATIONS OF METEOROLOGY DEPARTMENT

(In mm)

Upper line : Current year 2015/16

Lower line: Long term average from 1970/71 to 2014/15

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	NEM Total	SWM Total	Annual Total
Anuradhapura (8°21'00", 80°22'48")	389	452	286	32	29	9	114	463	7	14	0	0	1197	598	1795
	245	245	207	83	56	69	168	81	14	28	35	74	904	400	1304
Badulla (6°58'48", 81°03'00")	390	426	273	65	81	47	36	277	5	163	51	1	1281	532	1813
	240	268	277	178	91	100	194	105	36	64	69	126	1155	594	1748
Bandarawela (6°48'36", 80°57'36")	474	219	197	47	50	63	70	183	3	68	34	1	1049	359	1408
	248	244	192	111	67	99	177	108	52	59	57	136	961	589	1550
Batticaloa (7°42'36", 81°42'00")	622	517	343	232	25	63	1	287	0	12	17	30	1802	347	2148
	168	358	434	238	131	73	54	41	32	33	39	71	1402	271	1674
Colombo (6°54'00", 79°51'36")	235	526	377	65	107	91	186	752	132	49	1	29	1401	1150	2551
	335	332	153	69	68	118	246	310	204	120	107	231	1076	1218	2294
Galle (6°01'48", 80°13'12")	316	354	96	41	250	39	76	441	119	128	77	44	1096	885	1981
	316	304	177	86	64	95	223	283	201	155	158	253	1041	1274	2315
Hambantota (6°07'12", 81°07'48")	164	228	125	1	41	25	61	178	10	35	7	0	584	292	876
	128	212	124	64	41	58	93	81	50	35	53	77	627	388	1015
Jaffna (9°40'47", 80°01'48")	76	758	380	16	6	2	1	286	16	0	80	4	1237	386	1623
	239	364	258	74	36	34	63	55	20	28	49	63	1004	278	1281
Katugastota (7°19'48", 80°37'48")	414	386	267	4	30	131	123	519	83	47	39	7	1232	817	2049
	277	291	198	99	71	87	192	134	134	126	101	141	1022	828	1851
Katunayaka (7°10'12", 79°52'48")	276	556	159	3	102	10	43	653	159	22	3	1	1106	879	1985
	357	308	131	50	65	121	215	281	162	88	98	194	1033	1037	2070
Kurunegala (7°27'36", 80°22'12")	283	422	275	2	29	151	307	738	133	85	15	2	1161	1279	2440
	356	312	149	68	71	137	275	182	141	100	88	151	1093	937	2030

MONTHLY RAINFALL AT THE PRINCIPAL STATIONS OF METEOROLOGY DEPARTMENT

(in mm)

Upper line : Current year 2015/16

Lower line : Long term average from 1970/71 to 2014/15

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	NEM Total	SWM Total	Annual Total
Mahailuppallama (8°07'12", 80°27'36")	302	427	244	49	12	16	91	565	8	5	0	0	1049	668	1718
	251	262	199	84	73	69	180	89	15	30	36	95	938	445	1383
Mannar (8°58'48", 79°54'36")	108	608	174	20	1	17	11	400	1	1	0	0	929	412	1342
	162	261	204	49	44	45	93	49	8	13	11	49	764	223	988
Monaragala * (6°51'36", 81°21'00")	411	384	345	26	102	129	66	239	0	38	154	53	1397	549	1946
	234	237	234	142	114	124	210	126	36	43	90	79	1085	584	1669
Nuwara Eliya (6°57'36", 80°45'36")	318	280	265	35	68	68	56	386	84	118	55	35	1035	734	1769
	236	225	188	115	67	67	136	167	187	175	142	171	898	978	1876
Polonnaruwa * (7°54'36", 81°01'48")	459	348	587	147	52	68	35	255	0	40	1	0	1662	331	1993
	322	343	500	258	180	83	123	100	6	35	63	97	1685	424	2109
Potuvil * (6°52'48", 81°49'48")	250	306	359	84	78	76	0	273	7	9	19	33	1151	341	1493
	129	268	316	294	137	78	76	45	13	16	22	57	1222	229	1452
Puttalam (8°01'48", 79°49'48")	300	416	285	10	87	27	55	399	72	0	0	0	1125	526	1651
	226	253	136	52	40	65	168	96	32	22	18	67	772	404	1176
Rathmalana (6°48'36", 79°52'48")	306	356	311	66	7	64	250	676	131	64	6	25	1109	1153	2262
	362	354	165	71	68	119	270	316	202	124	120	250	1139	1283	2423
Rathnapura (6°40'48", 80°24'00")	525	468	292	140	89	194	397	807	220	193	132	102	1708	1851	3558
	453	371	224	123	141	208	364	437	419	296	288	385	1520	2190	3710
Trincomalee (8°34'48", 81°15'60")	394	648	211	101	22	44	4	332	0	81	59	9	1420	485	1905
	206	357	340	138	93	45	53	60	29	57	79	121	1179	399	1578
Vauniya (8°46'00", 80°30'00")	193	403	205	136	18	2	16	477	5	42	24	0	956	564	1520
	229	276	248	89	71	56	136	77	18	44	50	99	969	425	1394

Note :- ‘*’ Denotes Long term average less than specified above. NEM denotes North-East Monsoon. SWM denotes South-West Monsoon.

MONTHLY RAINFALL AT THE PRINCIPAL STATIONS OF IRRIGATION DEPARTMENT

(In mm)

Upper line : Current year 2015/16

Lower line: Long term average from 1989/90 to 2014/15

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	NEM Total	SWM Total	Annual Total
Badalgama (7°18'00", 79°58'47")	398	350	273	0	127	44	157	765	128	42	3	10	1192	1105	2297
	328	253	124	53	56	83	207	200	148	80	106	172	897	913	1810
Calidonia (6°54'07", 80°41'52")	334	369	135	19	25	149	125	456	134	103	122	65	1030	1006	2036
	308	283	140	85	80	115	251	204	262	238	195	164	1009	1314	2323
Deraniyagala (6°55'28", 80°20'16")	691	684	334	10	64	315	582	1722	304	239	153	140	2098	3140	5238
	565	387	174	112	121	217	438	502	461	347	308	432	1576	2488	4064
Dunamale * (7°06'56", 80°04'50")	512	476	268	5	20	46	252	1019	106	66	25	24	1327	1491	2818
	427	267	187	62	76	178	341	321	253	139	160	278	1198	1491	2689
Ellagawa * (6°43'55", 80°12'36")	386	182	38	85	153	144	318	613	158	158	83	129	987	1460	2447
	431	356	155	95	116	205	364	312	308	222	293	372	1358	1872	3230
Galgamuwa (7°58'07", 80°15'34")	372	223	277	36	38	100	261	536	34	3	3	0	1046	837	1883
	232	257	196	74	52	82	233	81	21	24	45	71	892	475	1367
Glencourse * (6°58'28", 80°10'58")	689	426	224	65	192	208	412	1234	163	152	37	65	1803	2061	3864
	517	484	227	101	122	289	403	363	352	224	263	320	1739	1925	3664
Hanwella * (6°54'34", 80°04'46")	444	461	318	130	91	109	442	1007	170	123	21	47	1554	1810	3363
	442	356	209	120	103	167	340	342	273	185	195	308	1397	1643	3040
Holombuwa (7°11'07", 80°15'53")	430	481	371	19	29	138	269	941	154	78	24	35	1467	1500	2967
	463	374	187	90	92	189	358	280	262	184	171	252	1395	1505	2900
Horowpothana (8°34'39", 80°52'43")	294	440	227	249	29	7	25	321	0	142	18	0	1246	506	1752
	193	291	347	148	96	44	94	56	17	24	84	89	1119	364	1483
Kithulgala (6°59'26", 80°24'44")	835	535	318	57	94	220	473	1434	301	245	245	151	2059	2849	4908
	607	355	168	96	119	193	430	554	545	460	395	462	1537	2845	4382

MONTHLY RAINFALL AT THE GAUGING STATIONS OF IRRIGATION DEPARTMENT

(in mm)

Upper line : Current year 2015/16

Lower line : Long term average from 1989/90 to 2014/15

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	NEM Total	SWM Total	Annual Total
Kuda Oya (6°31'29", 81°07'24")	168	264	182	1	29	22	221	257	6	15	1	1	667	500	1166
	209	262	155	88	56	98	167	59	11	13	16	48	868	315	1183
Nakkala (6°53'42", 81°17'49")	366	481	396	51	133	23	20	316	3	58	156	45	1451	597	2048
	266	360	262	168	123	91	185	101	41	52	82	109	1270	570	1840
Norwood (6°50'22", 80°36'42")	450	246	125	85	18	109	286	734	123	108	138	70	1034	1458	2492
	391	301	158	121	89	179	351	277	349	314	234	220	1239	1745	2984
Peradeniya (7°16'03", 80°36'30")	750	359	311	2	10	124	72	796	83	68	39	22	1557	1080	2636
	293	258	168	83	64	88	212	154	164	122	101	128	955	881	1836
Padiyathalawa (7°23'01", 81°11'31")	321	479	471	119	89	50	56	309	0	93	107	30	1528	596	2124
	235	364	456	272	160	71	133	81	38	58	96	132	1558	539	2097
Siyambalanduwa (6°54'18", 81°32'36")	320	269	336	167	133	88	50	189	45	3	188	85	1313	560	1873
	233	378	304	216	124	69	149	87	47	68	60	94	1324	504	1828
Thanamalwila (6°28'06", 81°08'03")	280	260	121	8	28	5	207	255	2	4	3	0	701	471	1172
	200	270	146	81	53	92	173	58	8	10	20	37	843	306	1149
Thawalama * (6°20'31", 80°19'49")	597	483	312	258	227	247	403	737	195	280	170	100	2124	1884	4008
	560	429	332	234	223	290	427	489	383	317	313	479	2069	2407	4476
Urawa * (6°14'12", 80°34'18")	579	355	307	100	80	86	216	559	168	118	54	56	1508	1172	2680
	395	413	299	116	180	207	329	336	189	162	155	301	1611	1472	3083
Wellawaya (6°42'35", 81°06'40")	397	318	244	5	53	126	161	257	0	28	41	0	1144	486	1630
	235	332	169	108	97	133	230	108	21	25	29	97	1075	510	1586

Note :- ' * ' Denotes Long term average less than specified above.

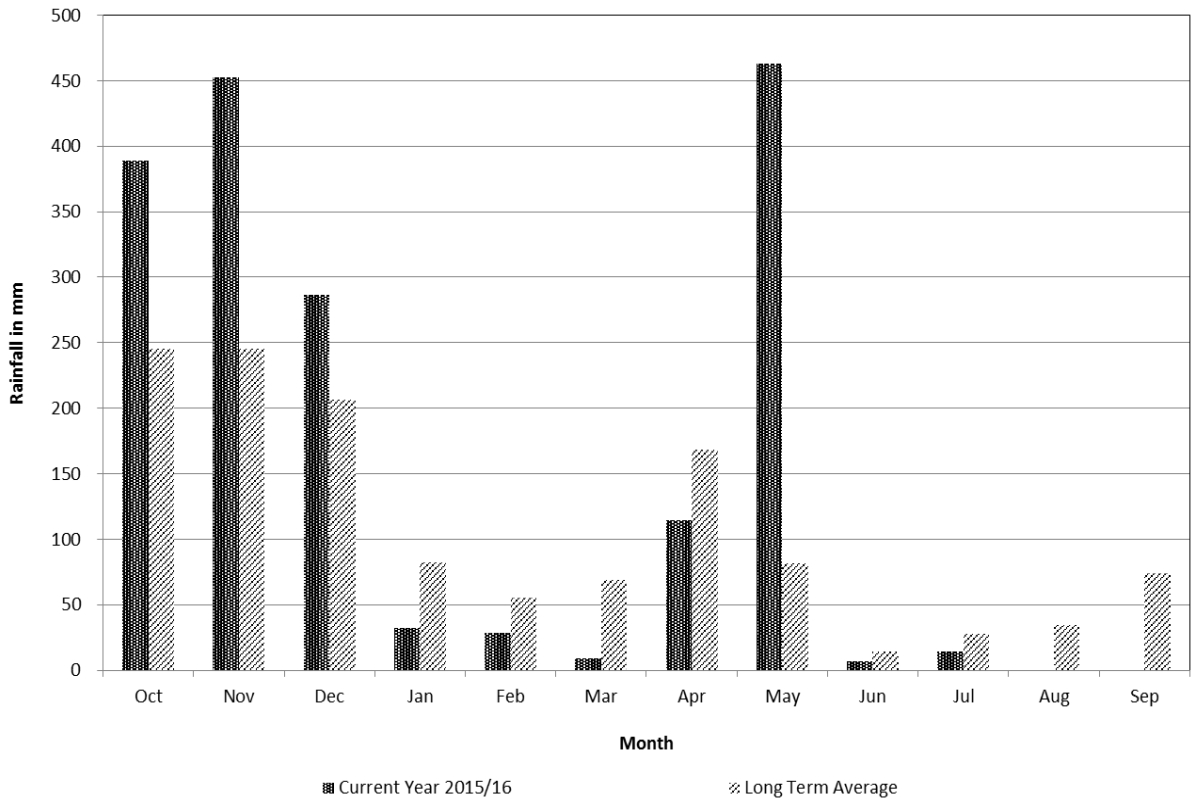
NEM denotes North-East Monsoon. SWM denotes South-West Monsoon.

VARIATION OF RAINFALL

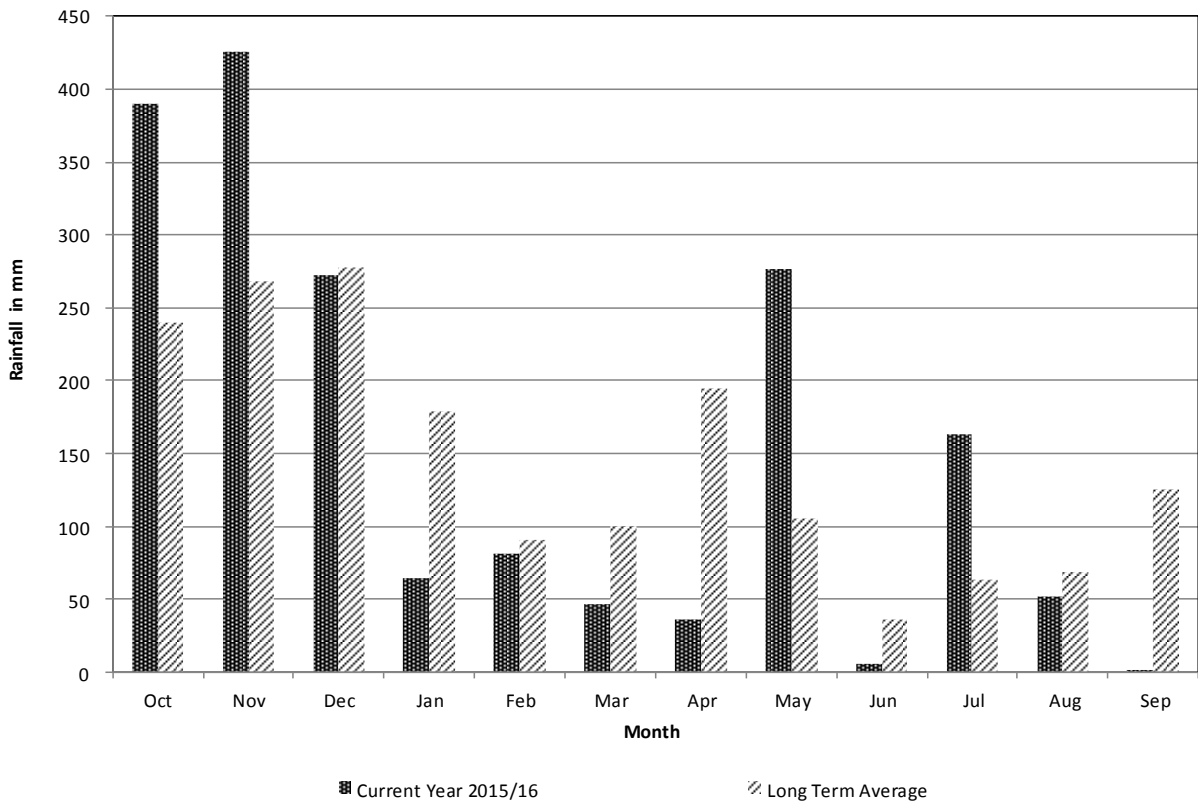
- **Temporal variation of Rainfalls at each station
(Current year versus Long-Term average)**
- **Spatial variation of Rainfalls
(Current year versus Long-Term average)**

**TEMPORAL VARIATION OF RAINFALLS
AT EACH STATION**

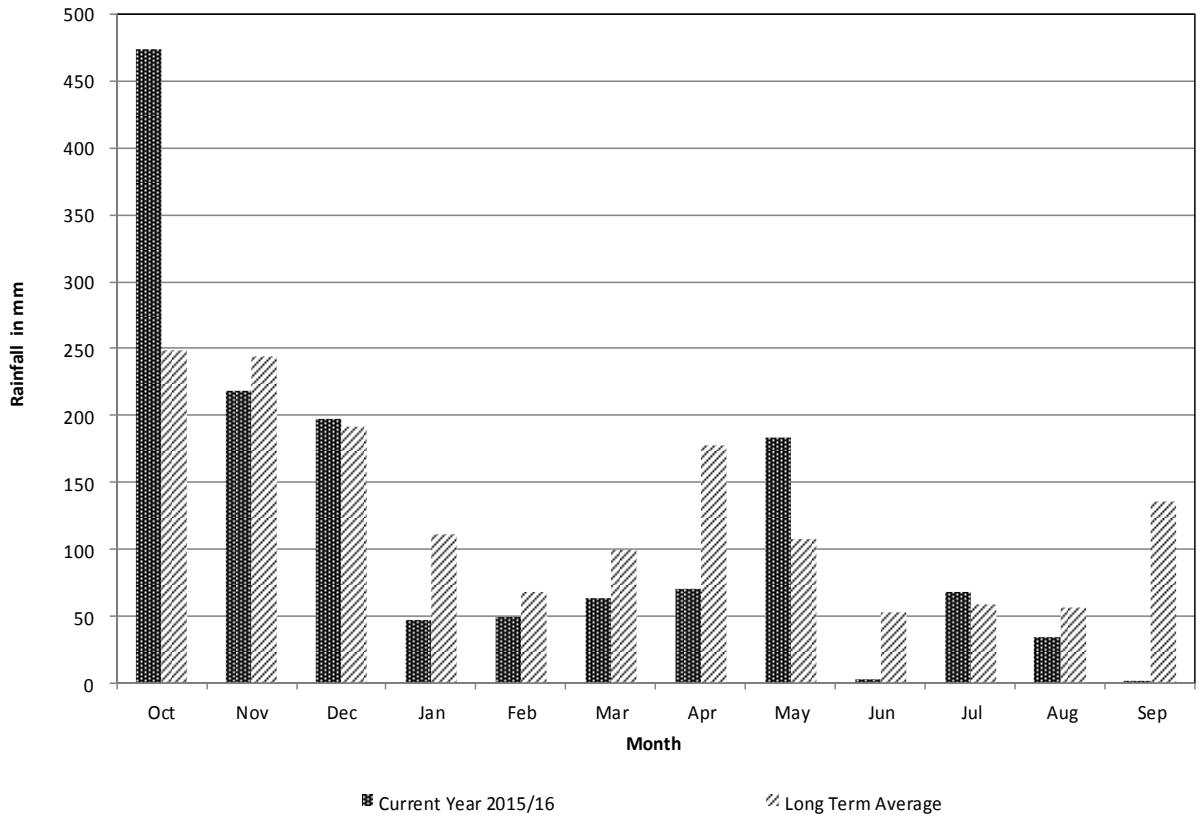
Variation of Rainfall at Anuradhapura



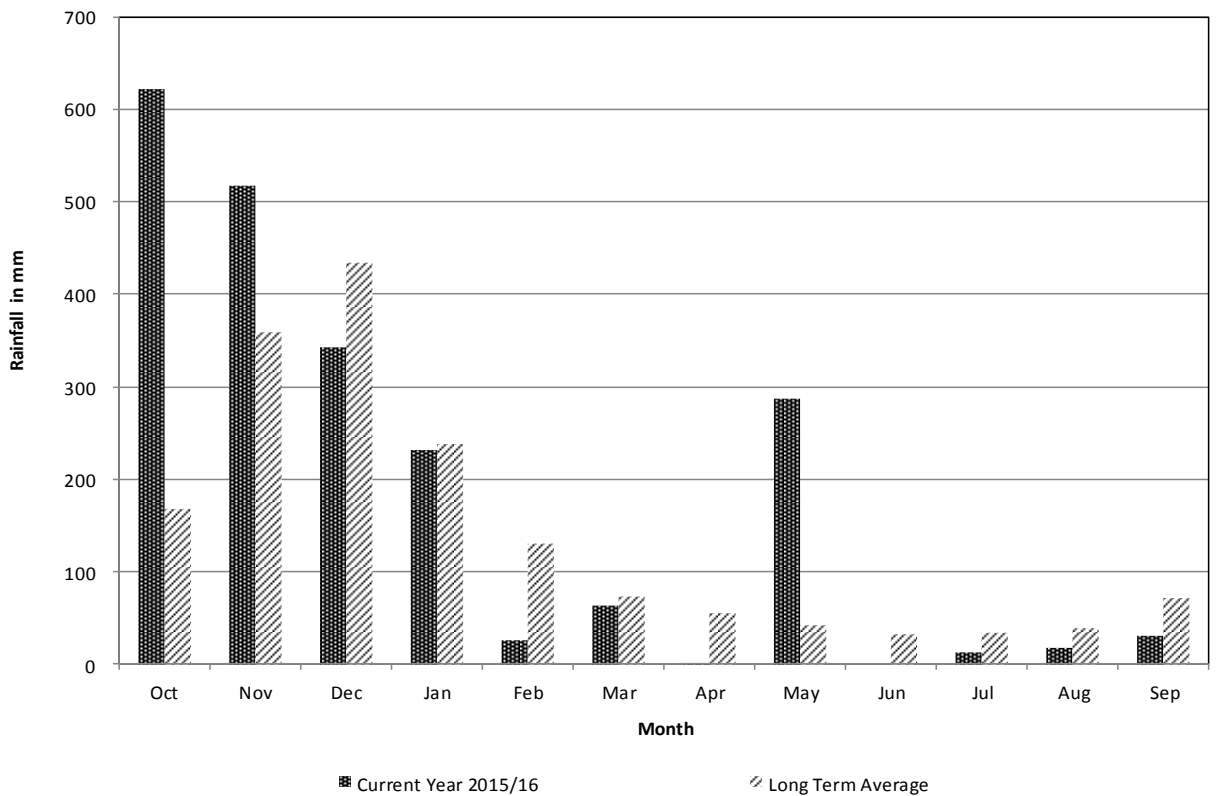
Variation of Rainfall at Badulla



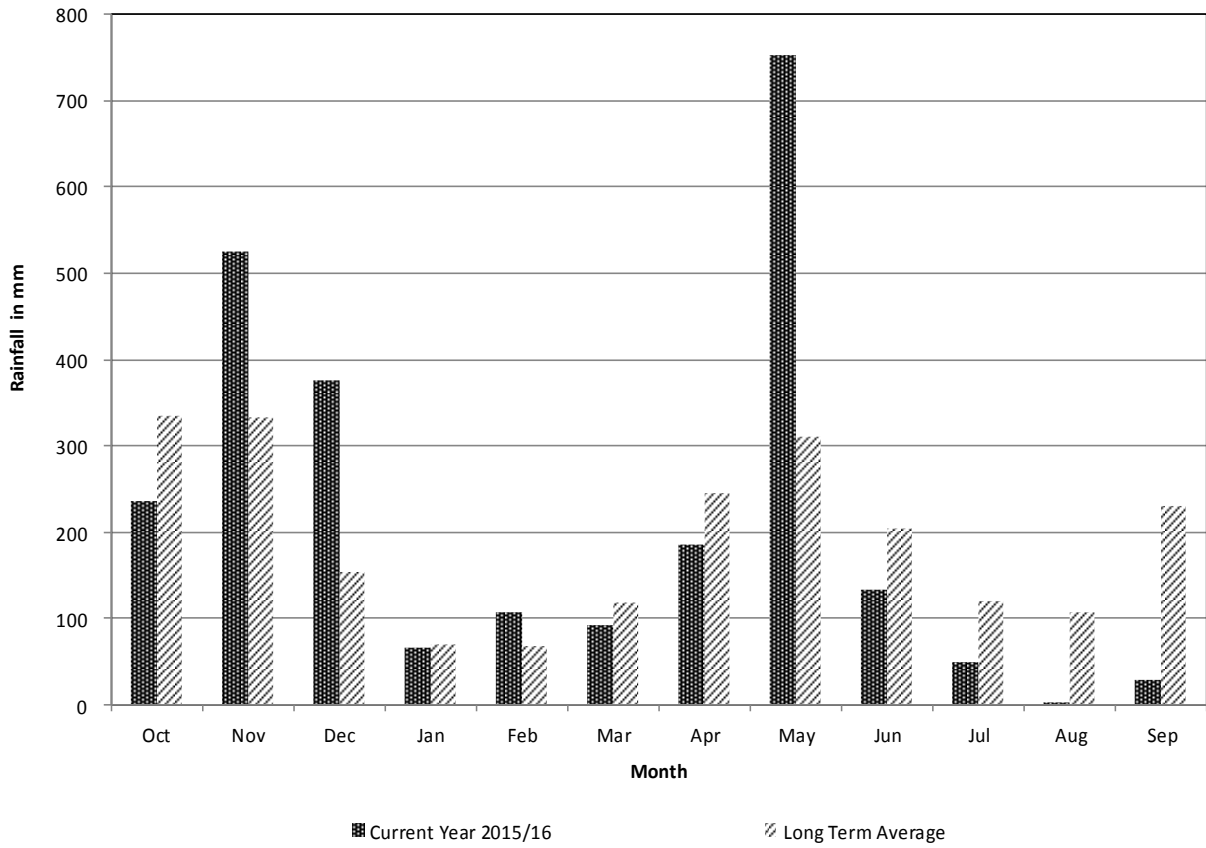
Variation of Rainfall at Bandarawela



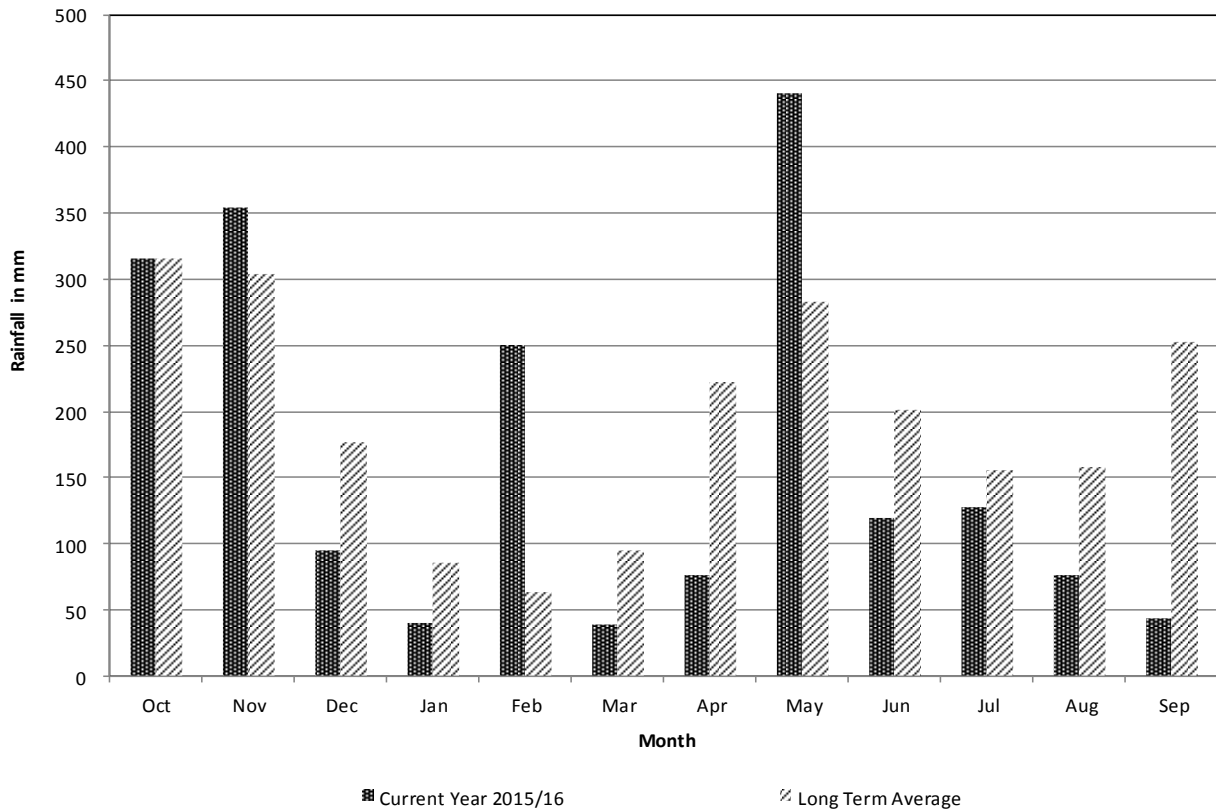
Variation of Rainfall at Batticaloa



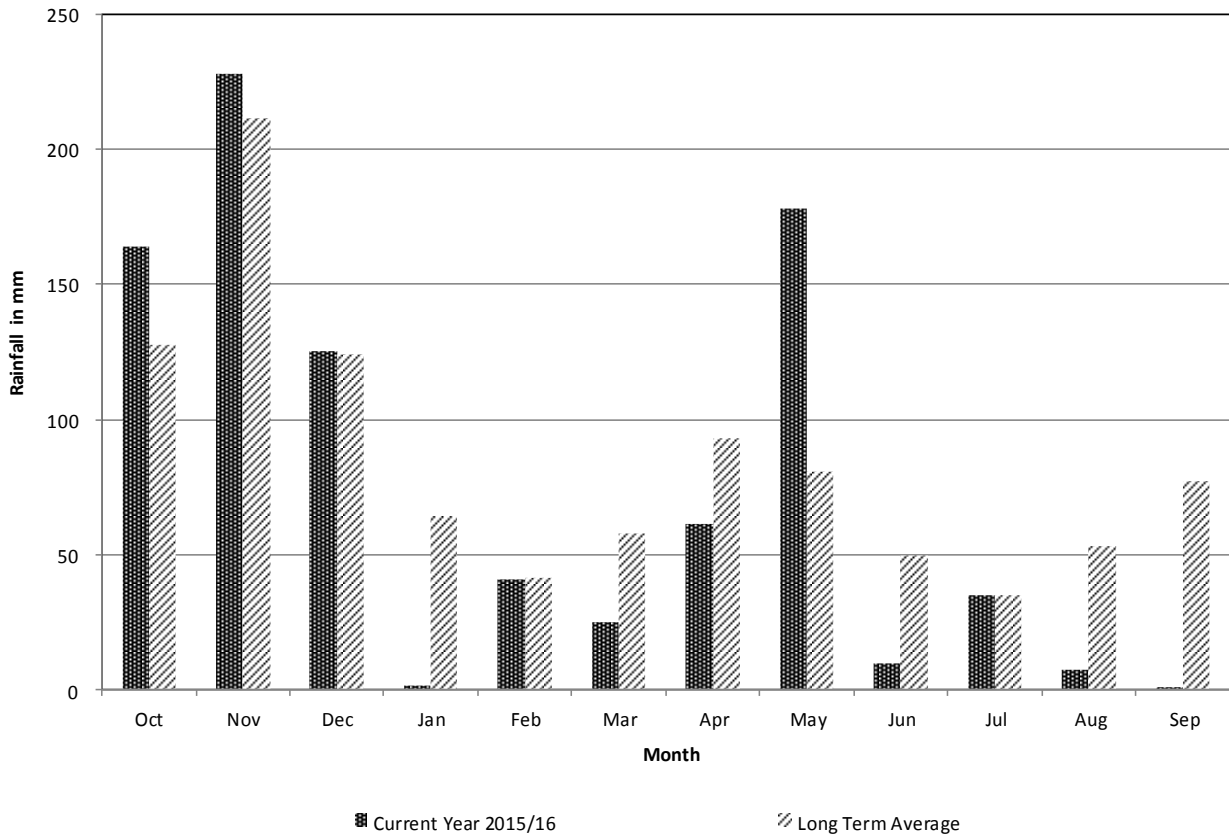
Variation of Rainfall at Colombo



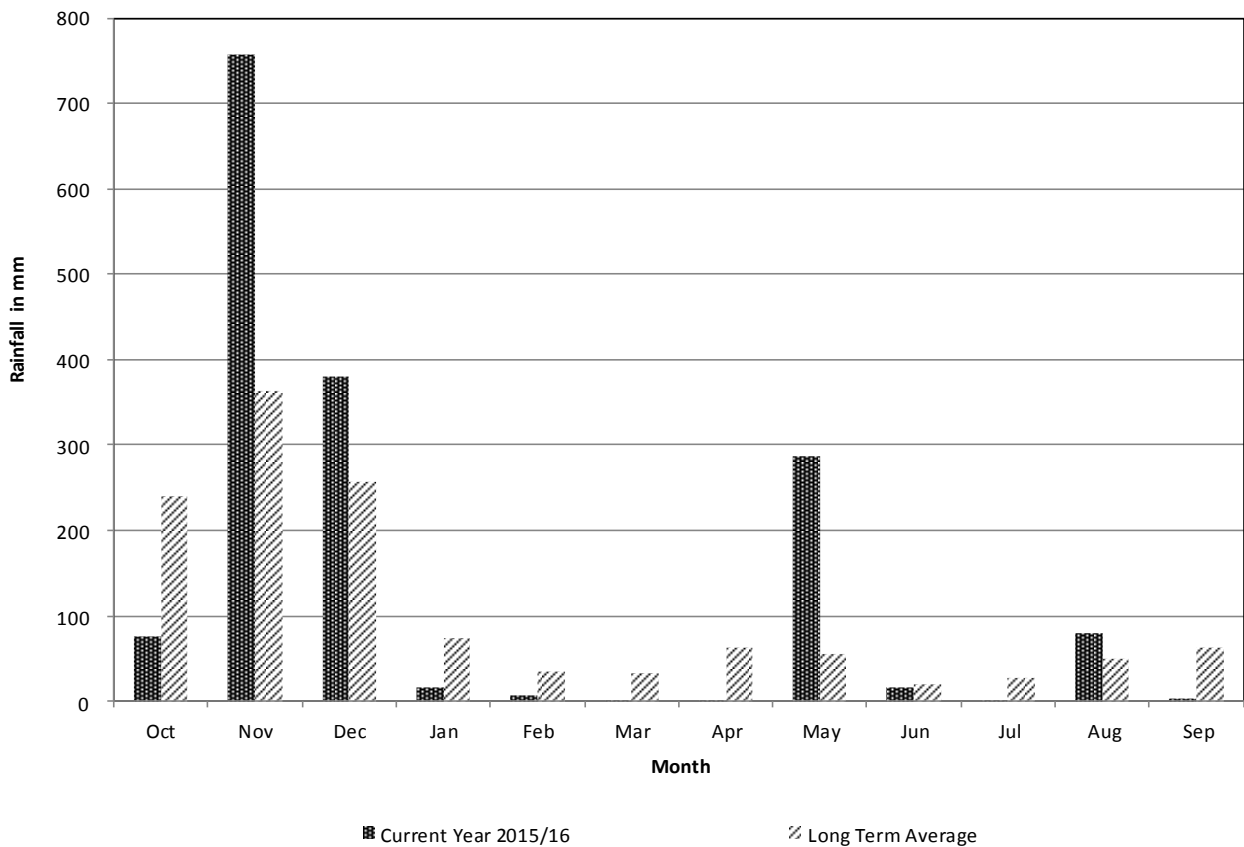
Variation of Rainfall at Galle



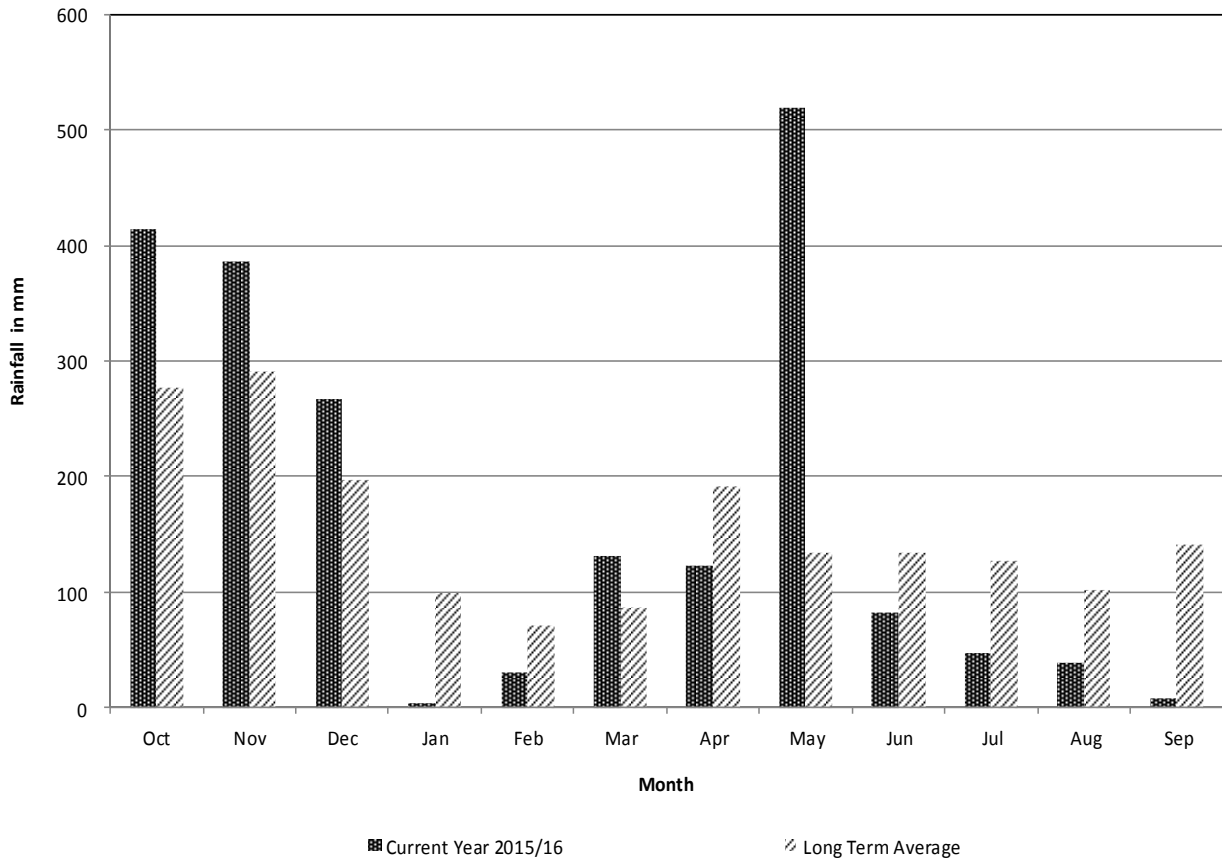
Variation of Rainfall at Hambanthota



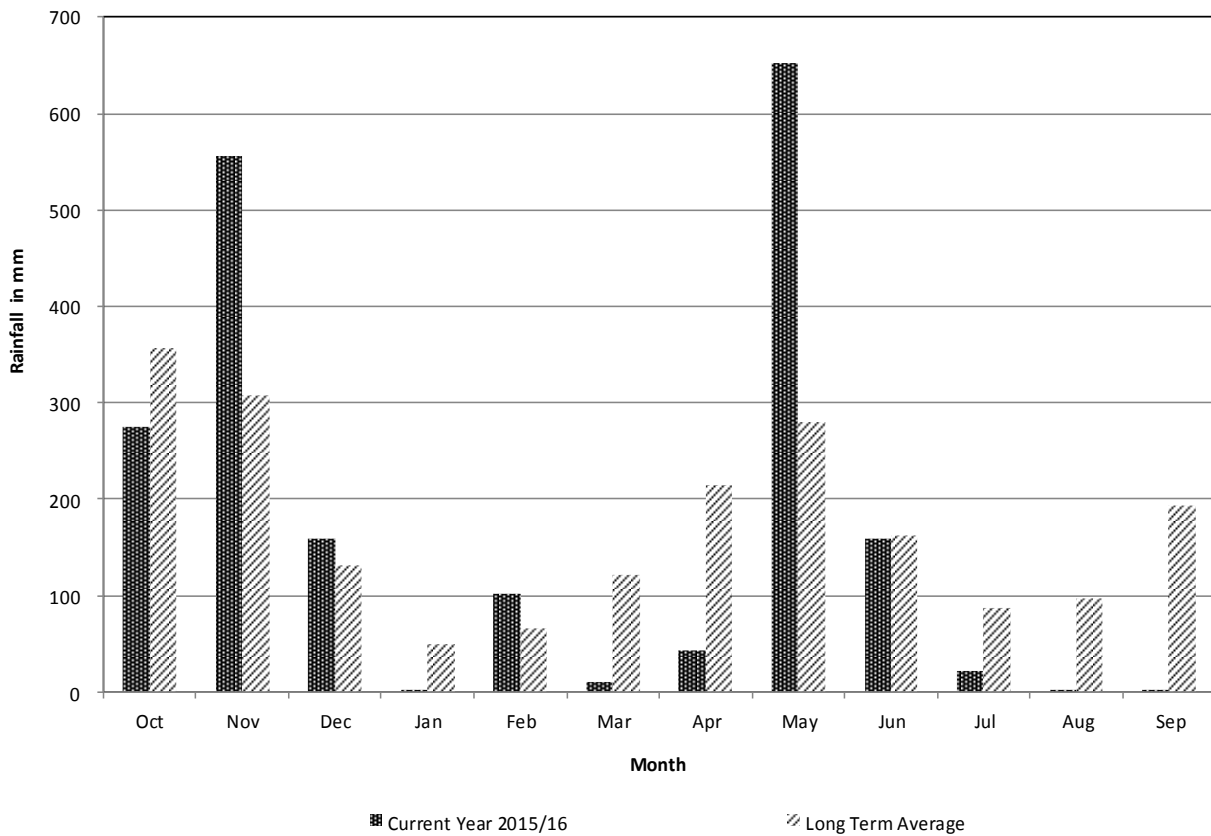
Variation of Rainfall at Jaffna



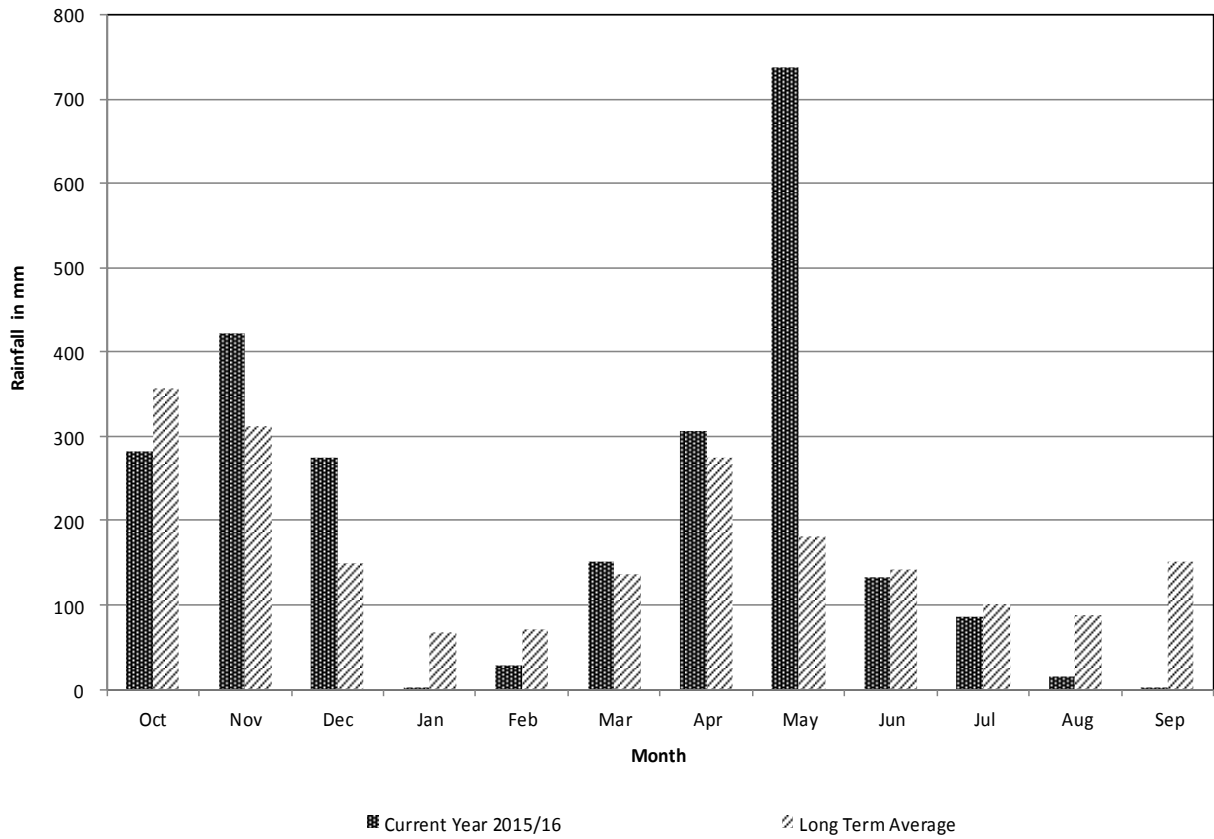
Variation of Rainfall at Katugasthota



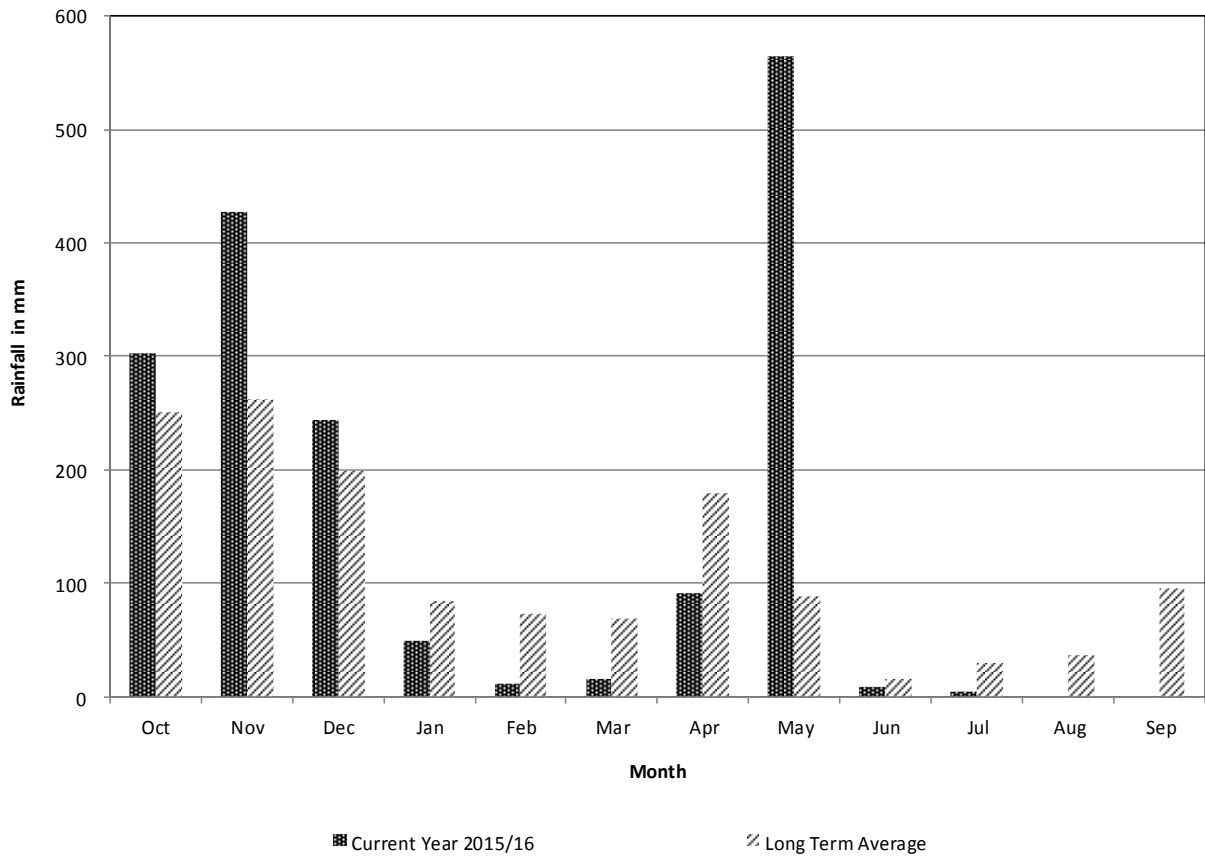
Variation of Rainfall at Katunayaka



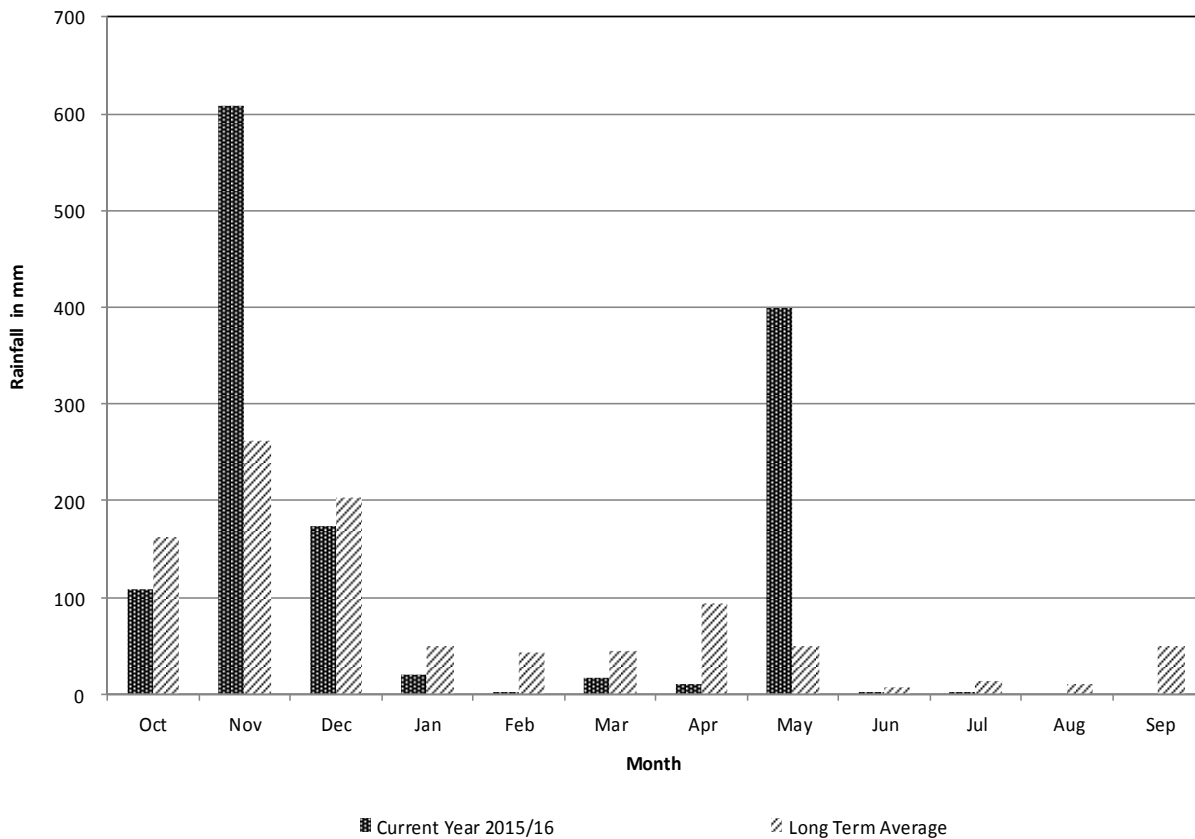
Variation of Rainfall at Kurunegala



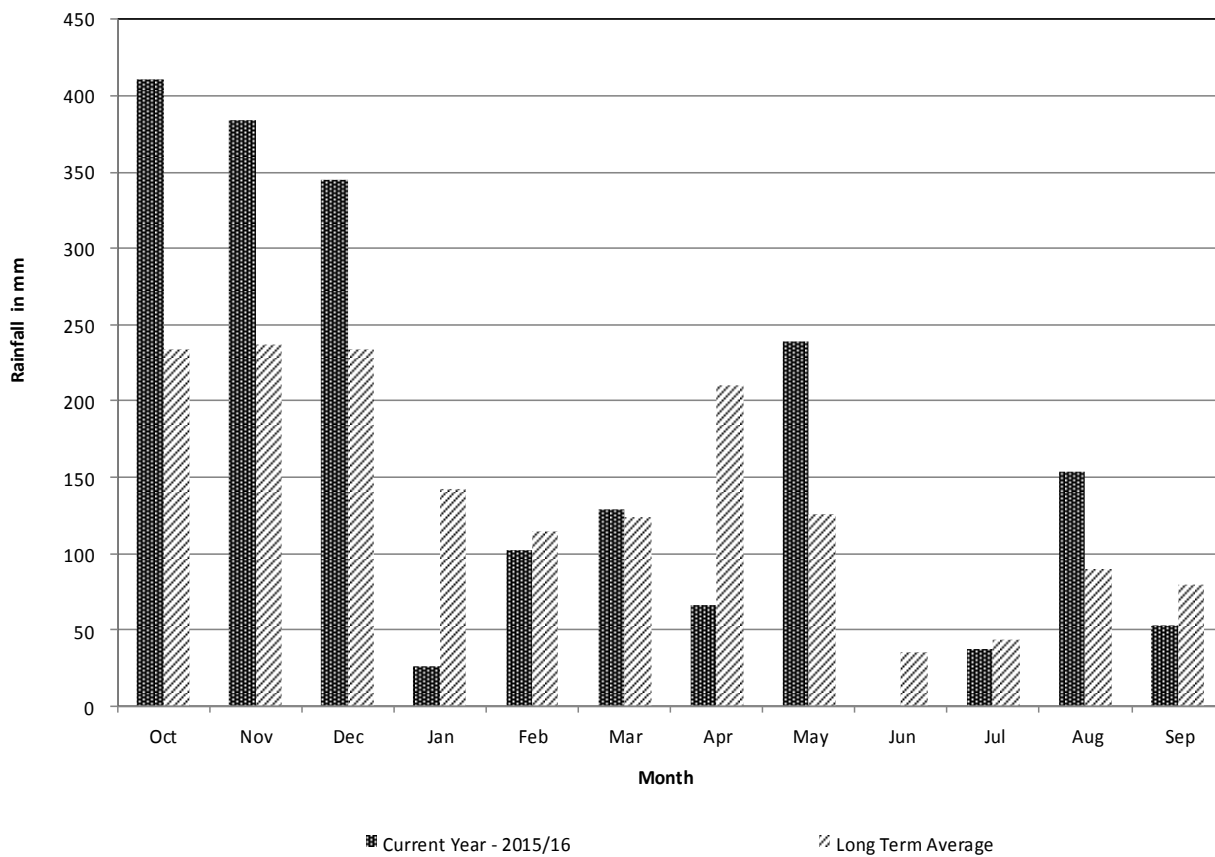
Variation of Rainfall at Mahalluppallama



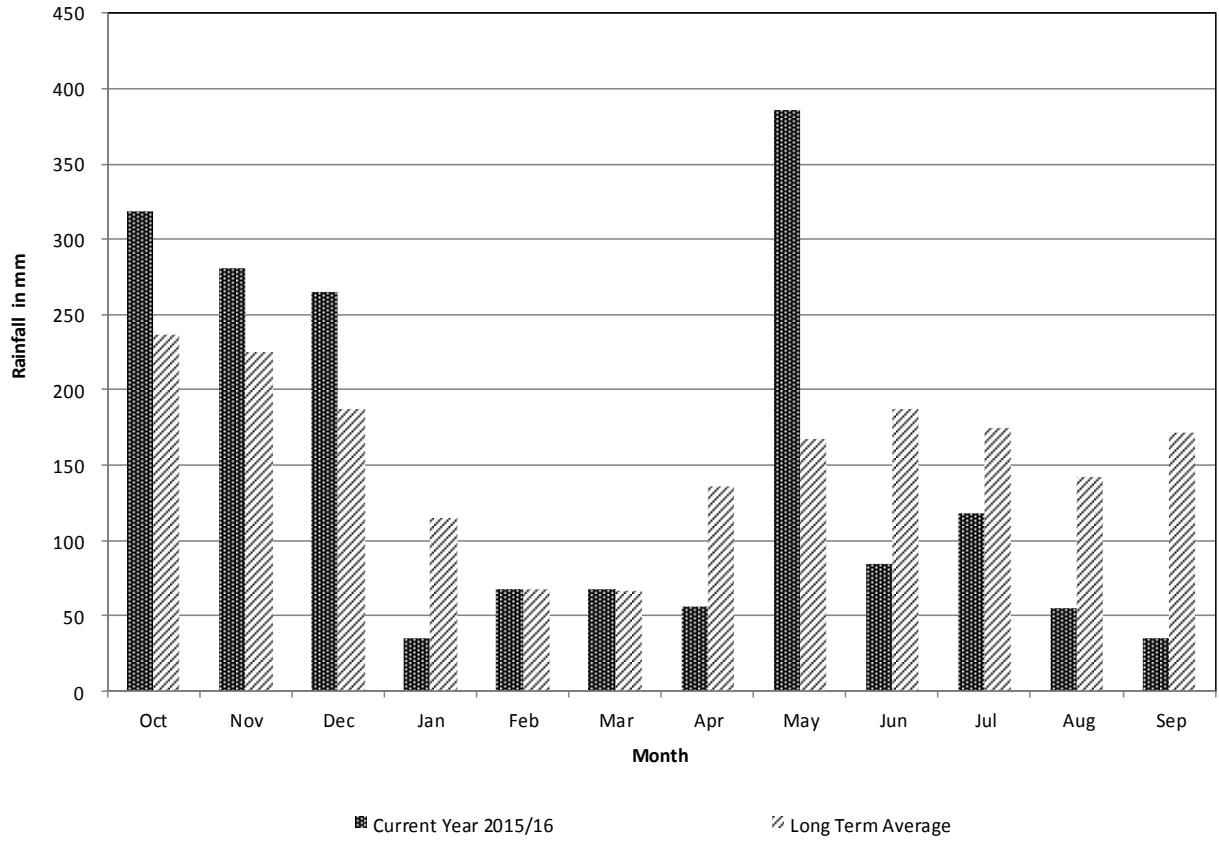
Variation of Rainfall at Mannar



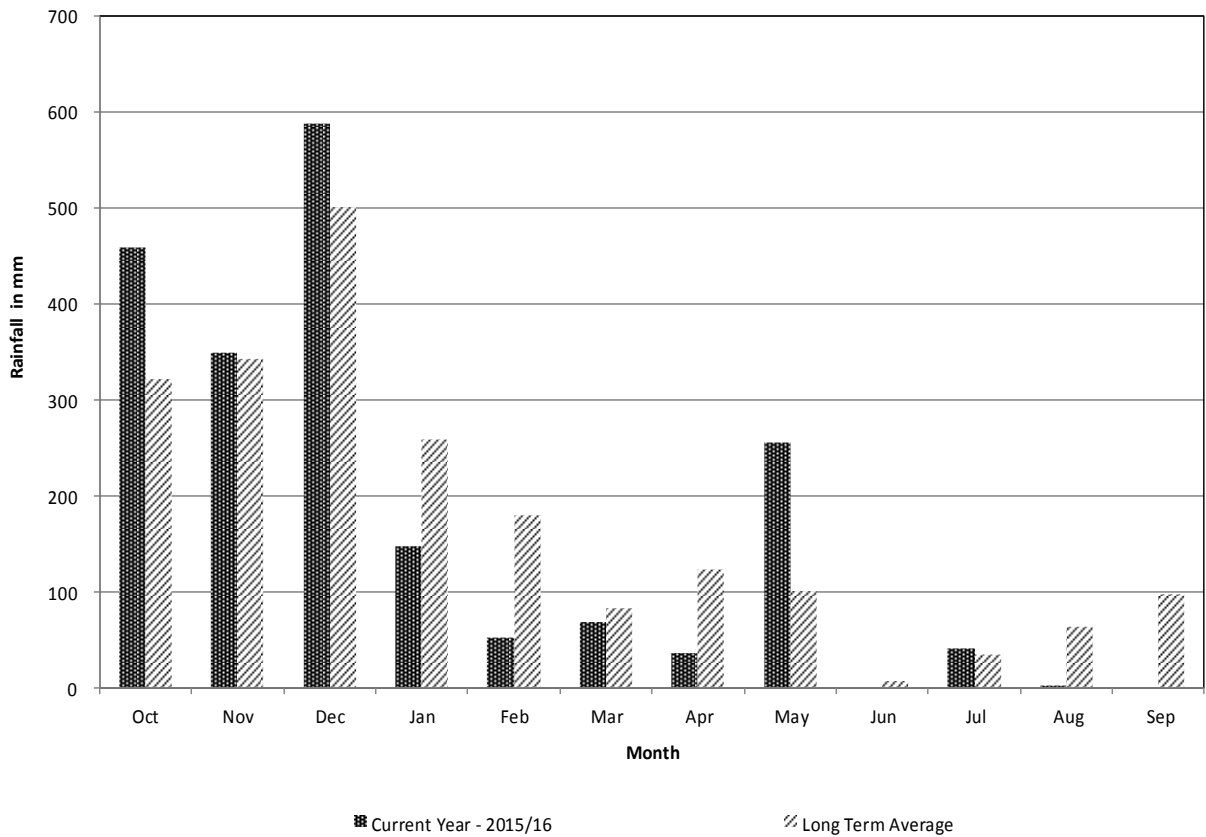
Variation of Rainfall at Monaragala



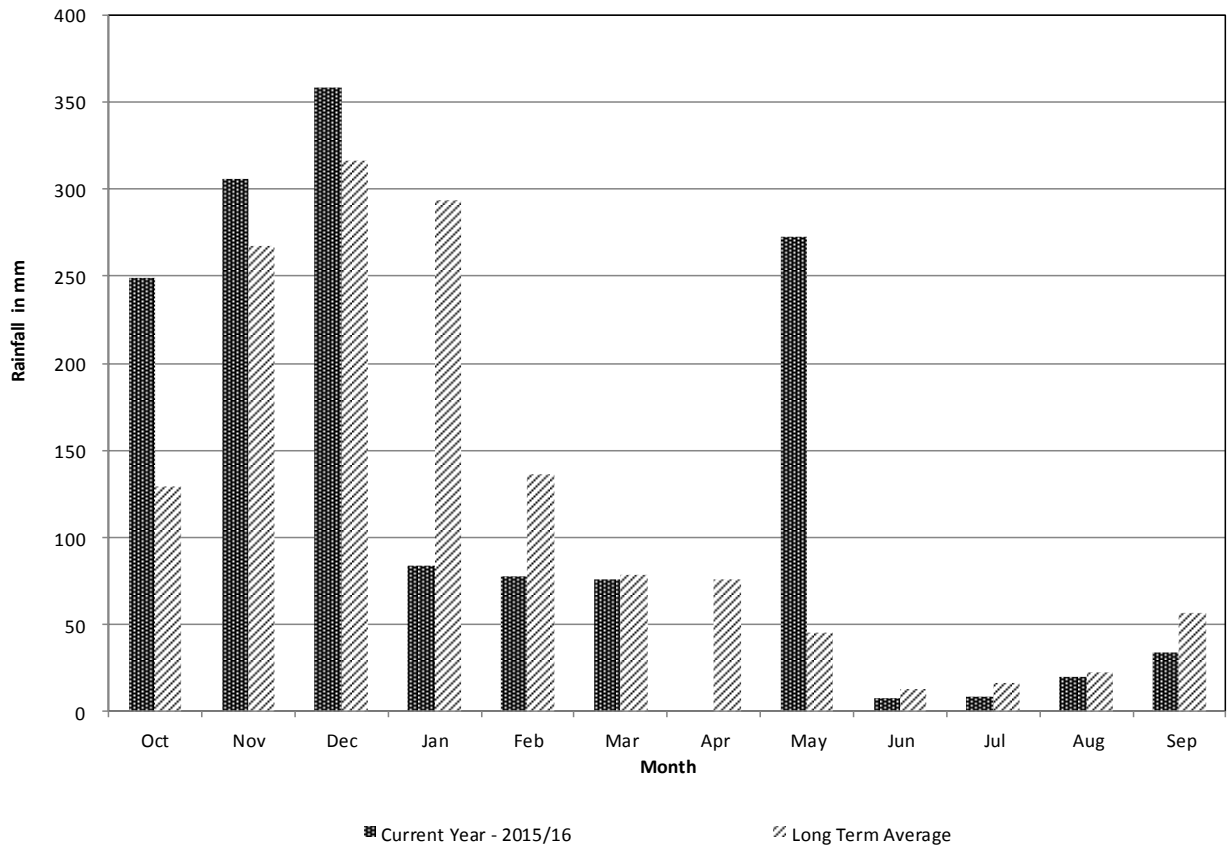
Variation of Rainfall at Nuwara Eliya



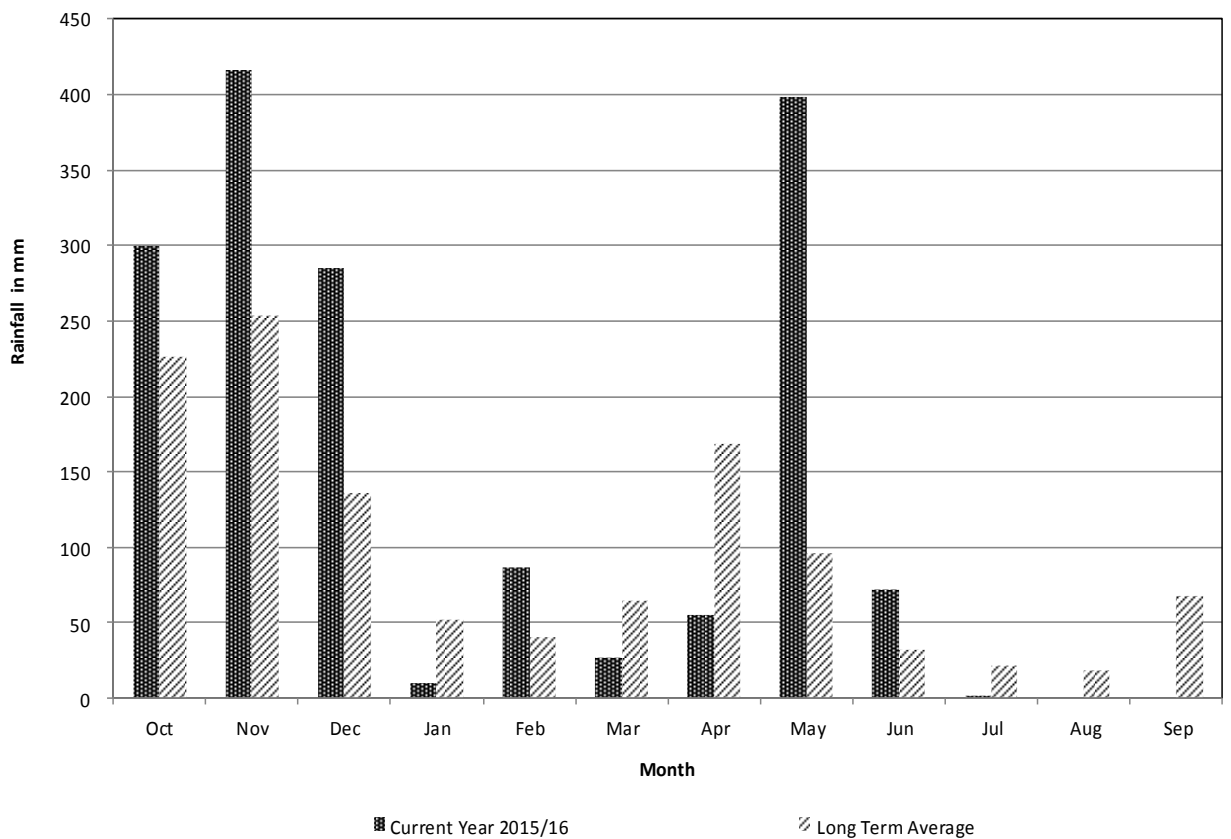
Variation of Rainfall at Polonnaruwa



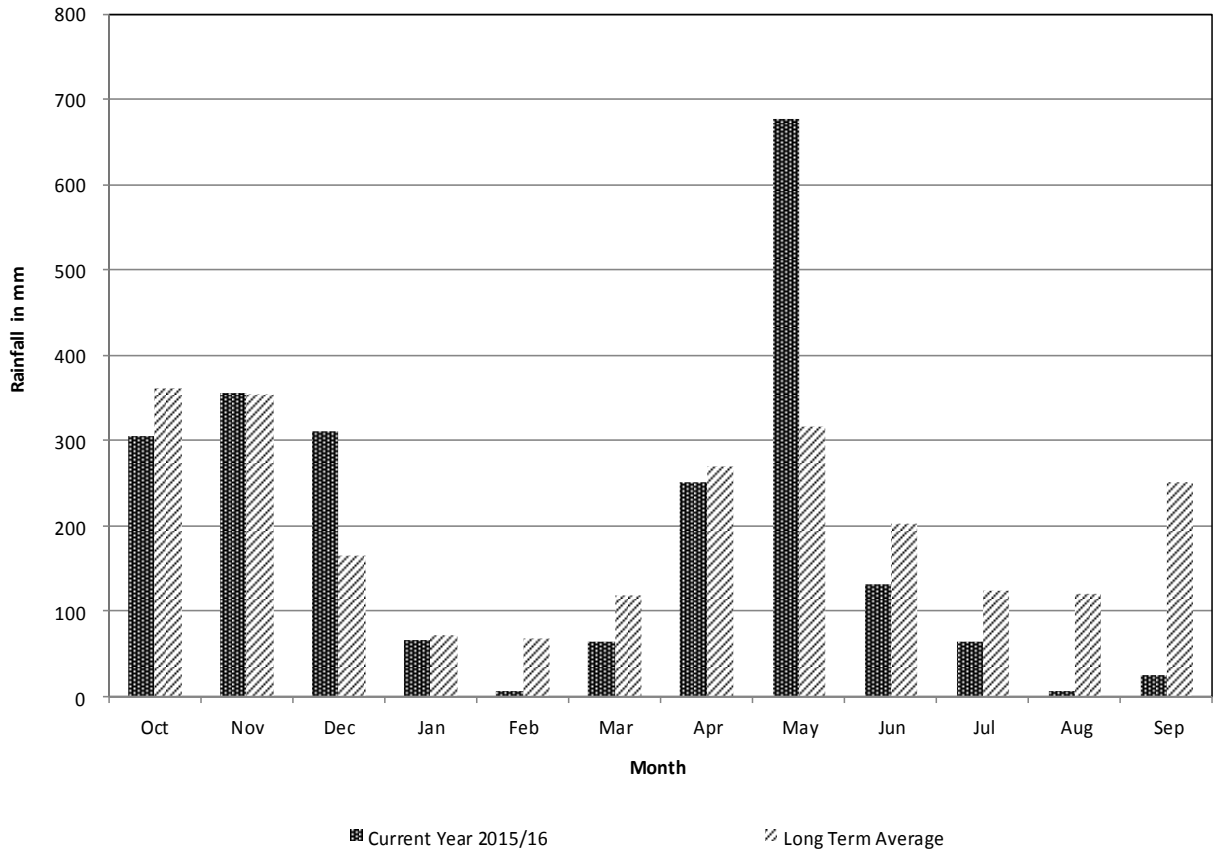
Variation of Rainfall at Potuvil



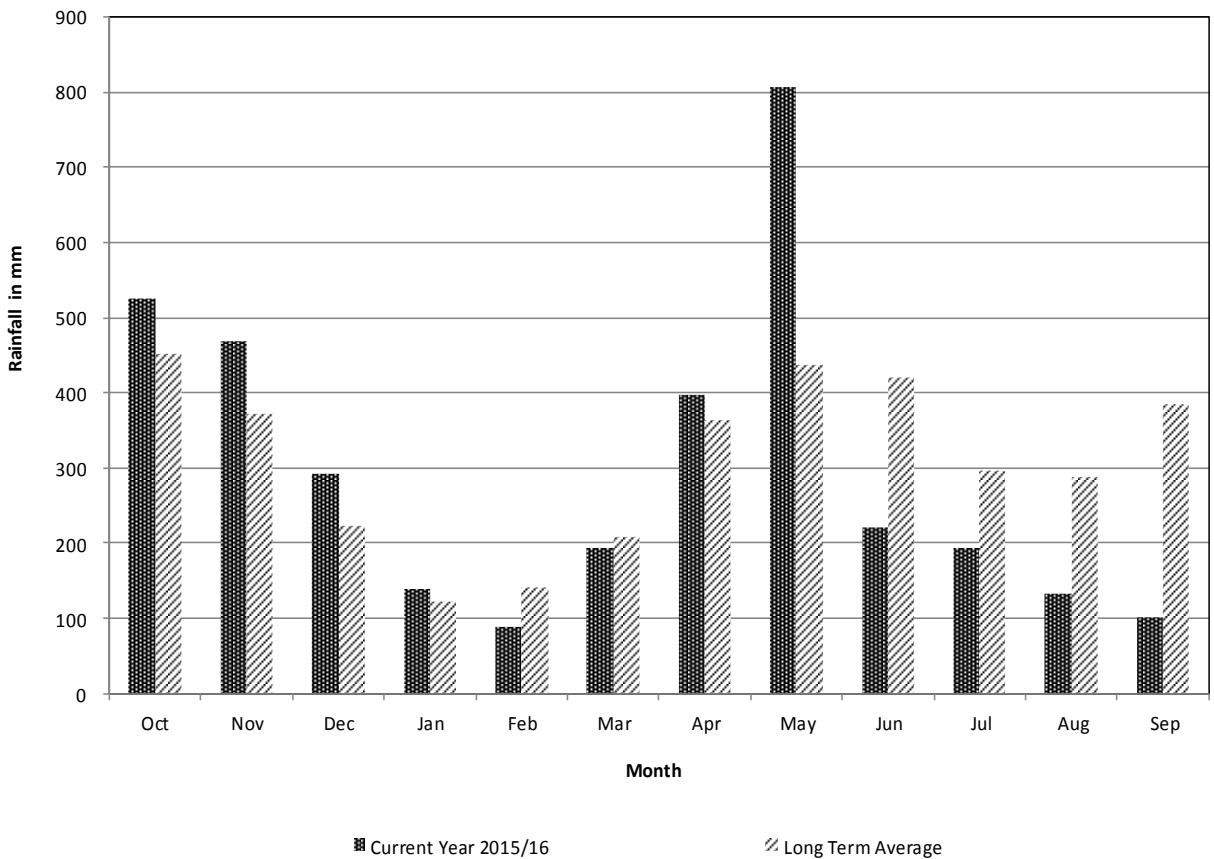
Variation of Rainfall at Puttalam



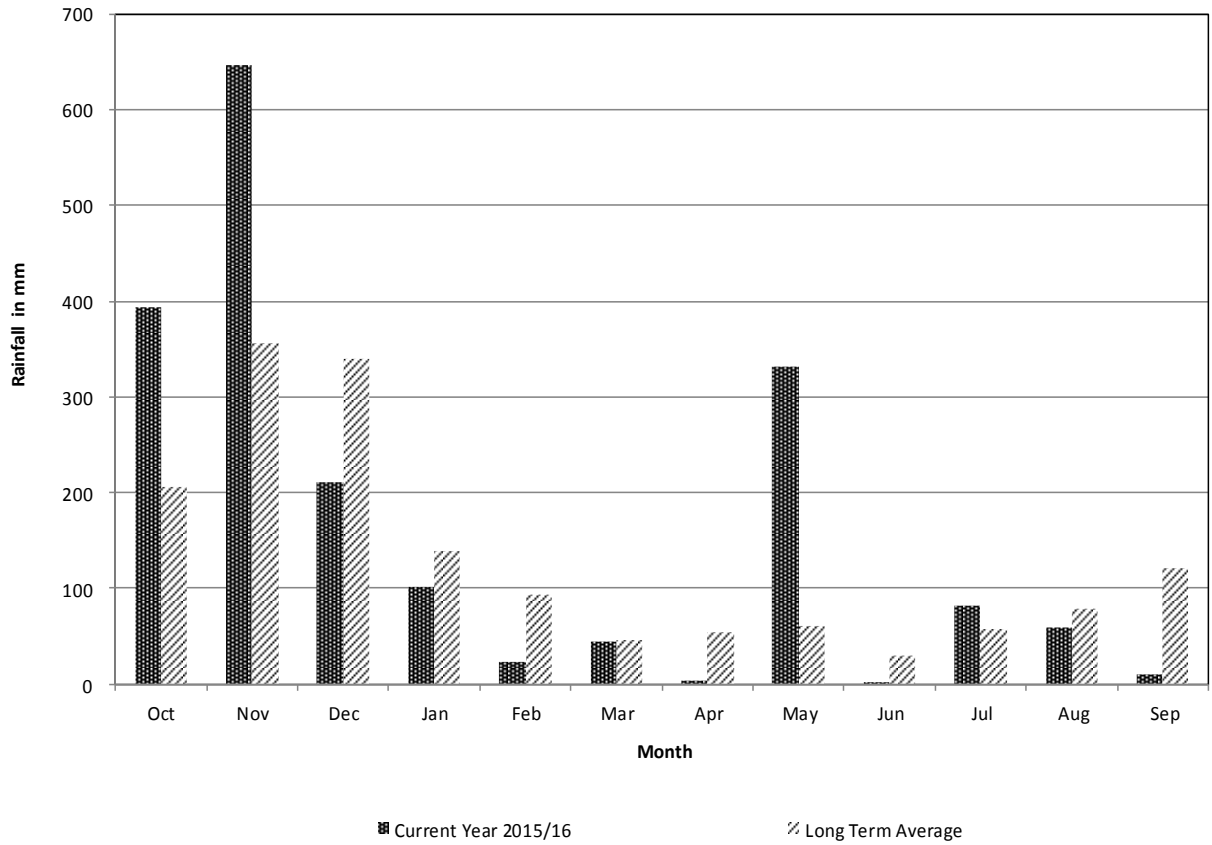
Variation of Rainfall at Rathmalana



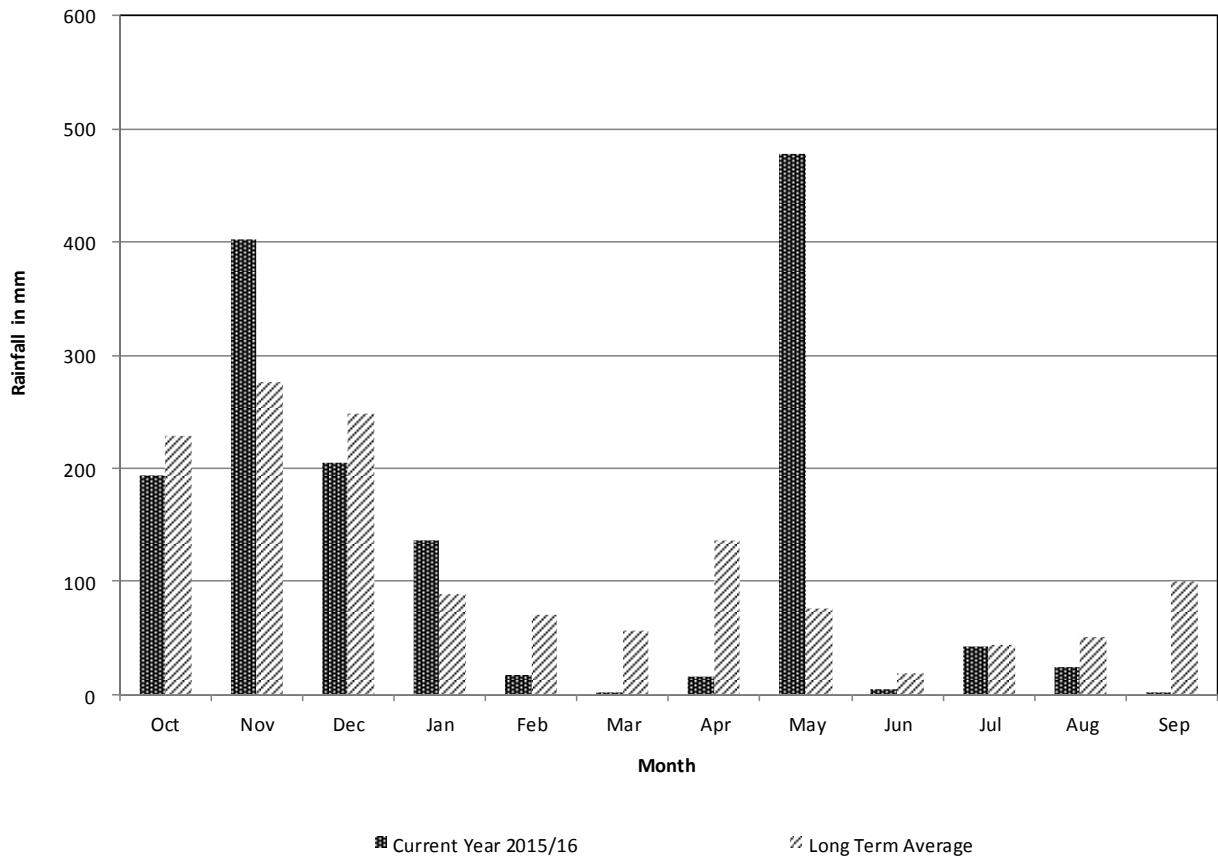
Variation of Rainfall at Rathnapura



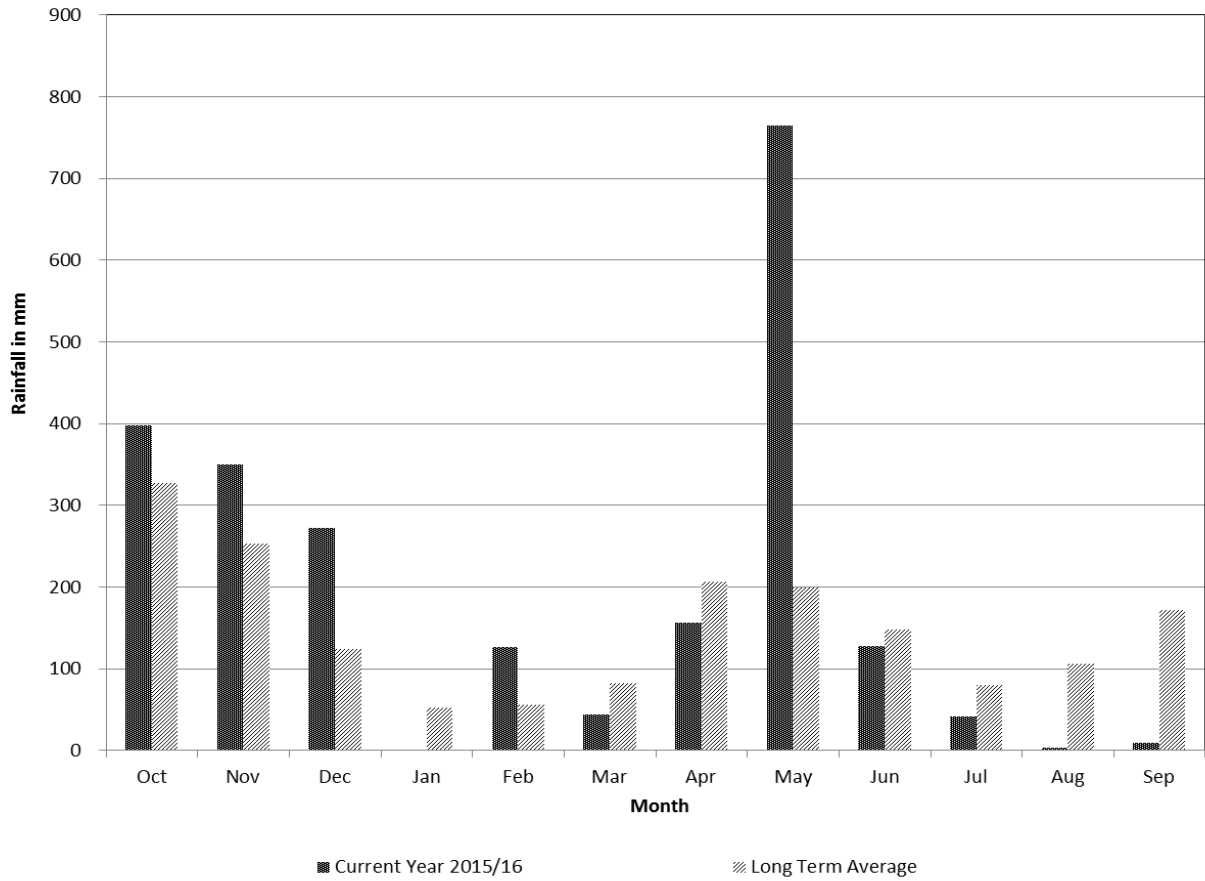
Variation of Rainfall at Trincomalee



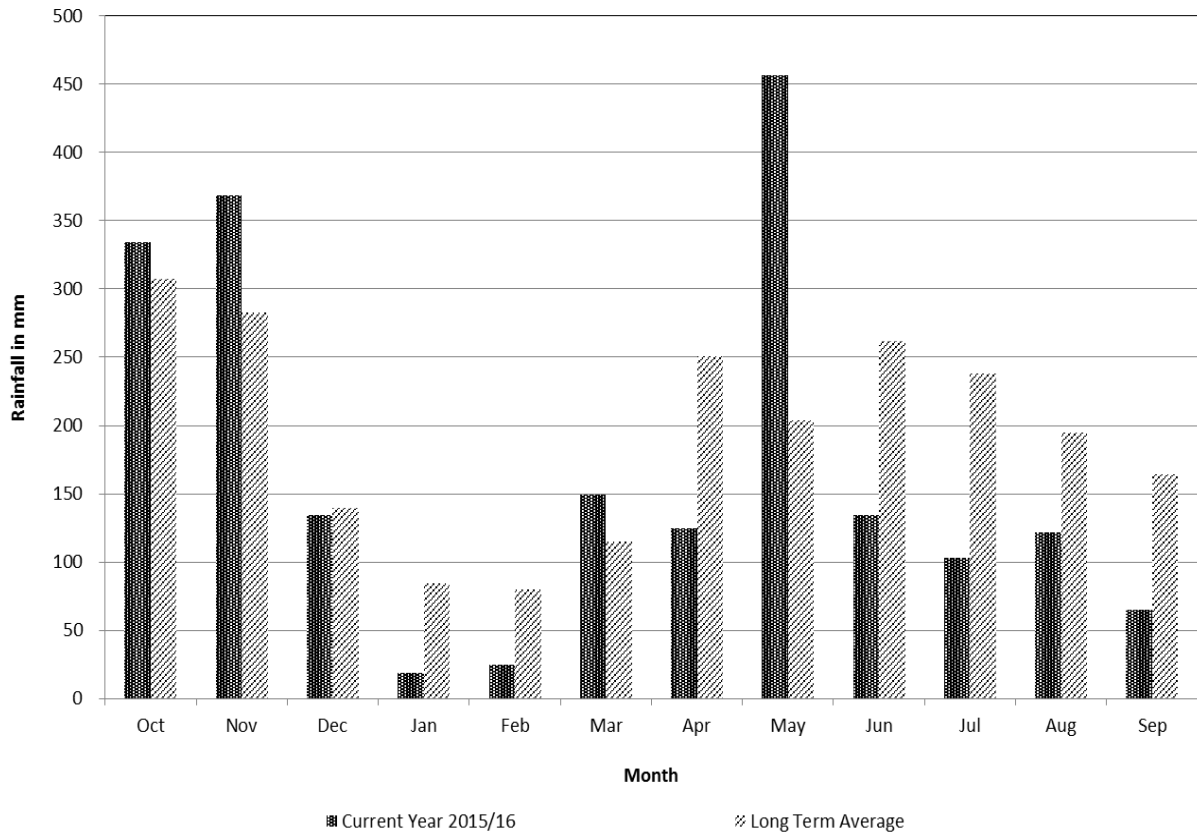
Variation of Rainfall at Vauniya



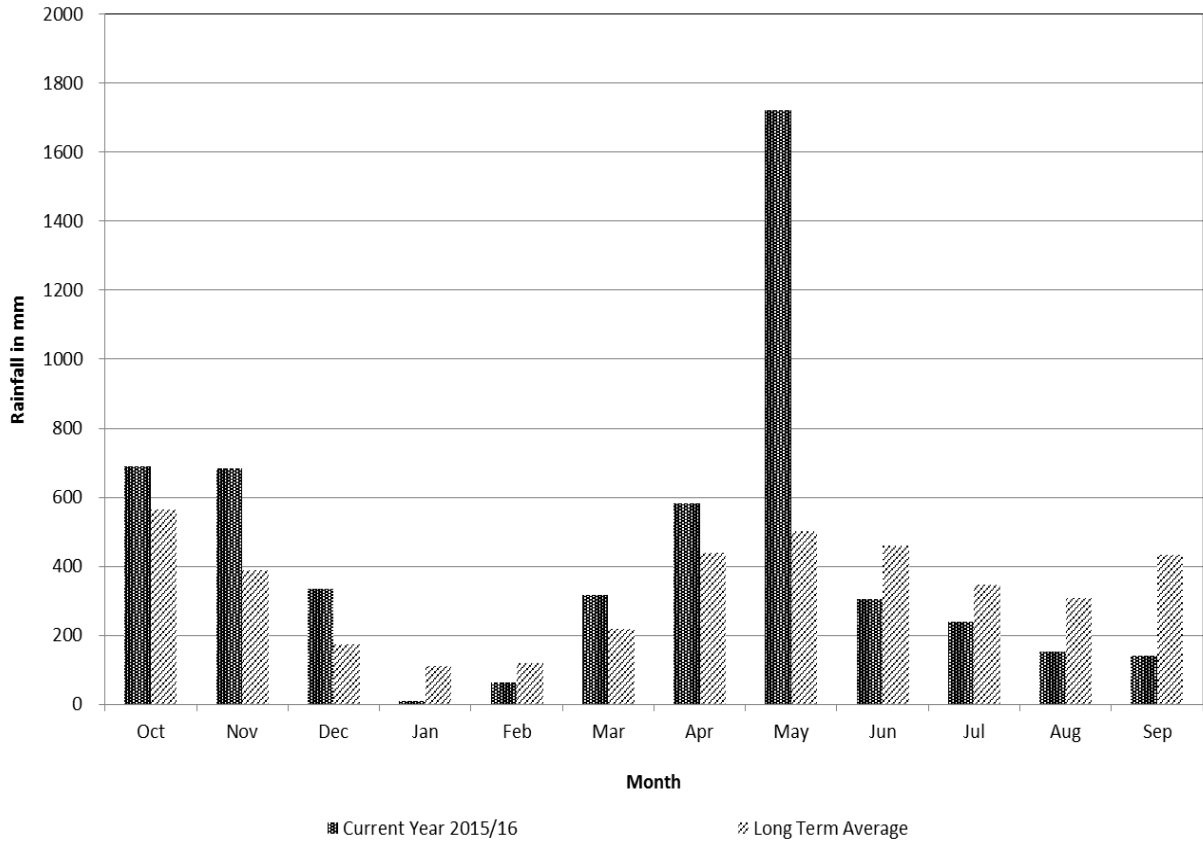
Variation of Rainfall at Badalgama



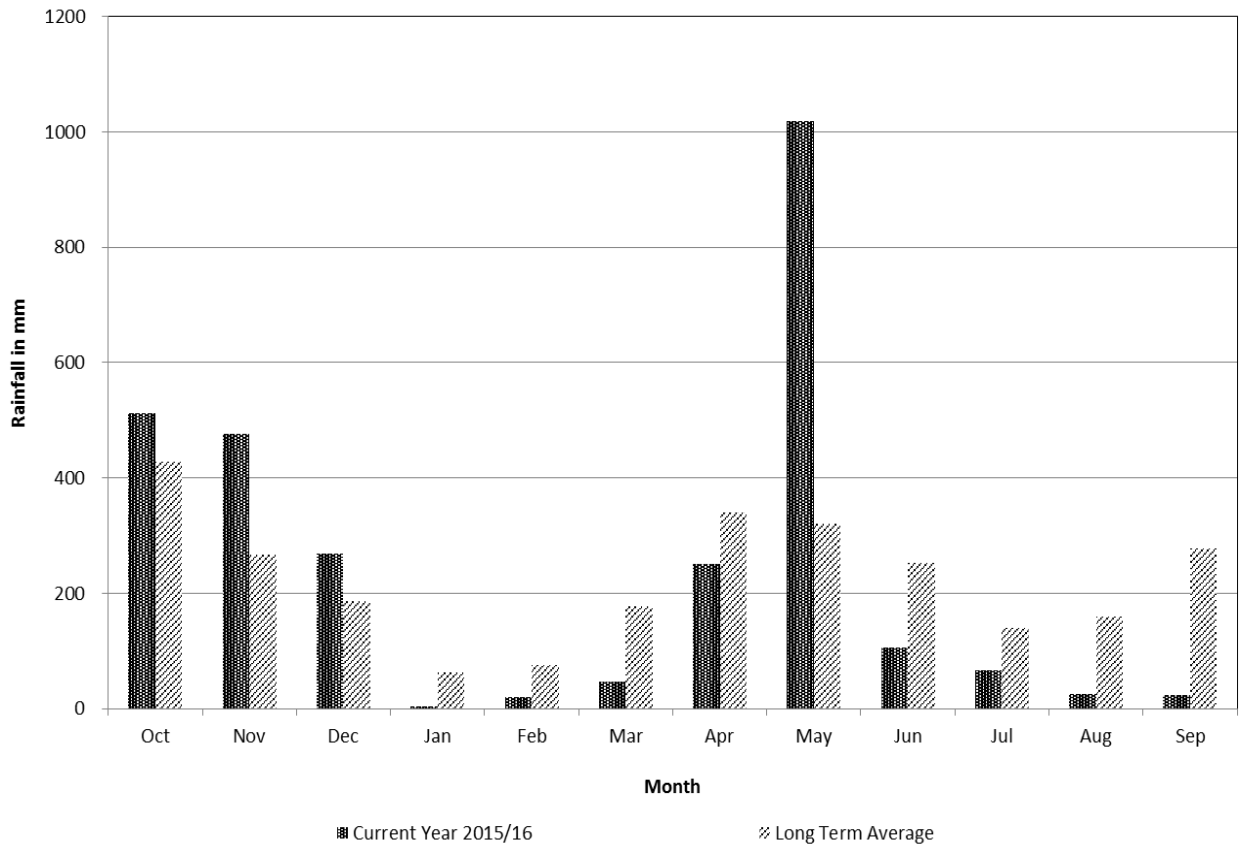
Variation of Rainfall at Calidonia



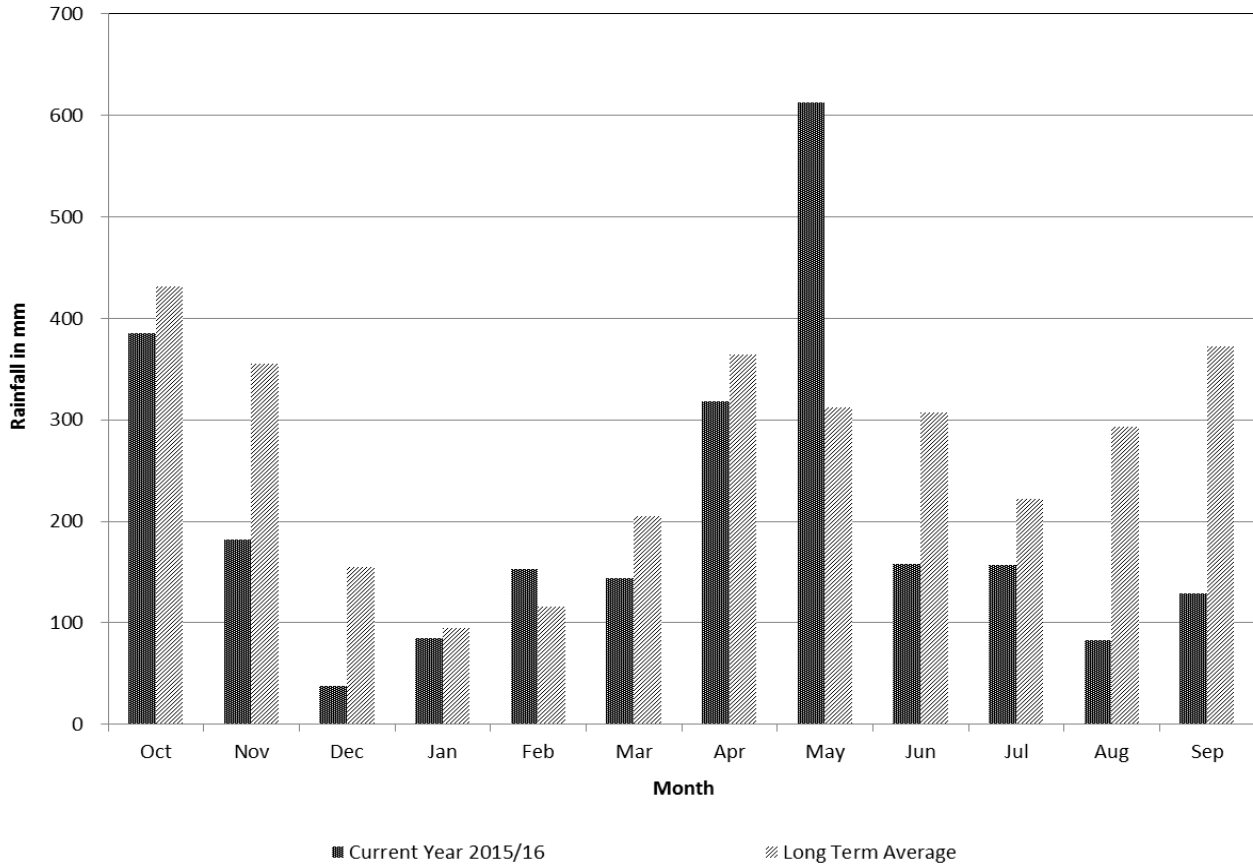
Variation of Rainfall at Deraniyagala



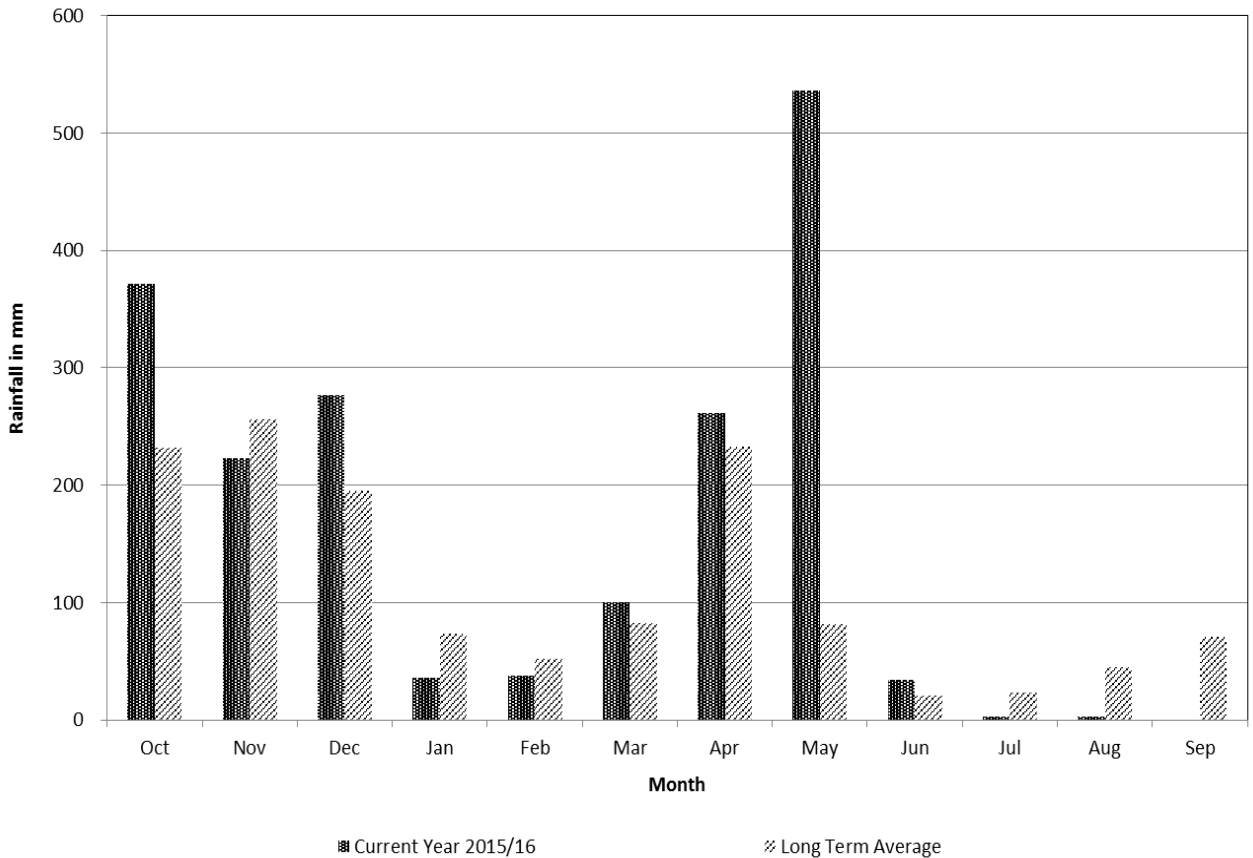
Variation of Rainfall at Dunamale



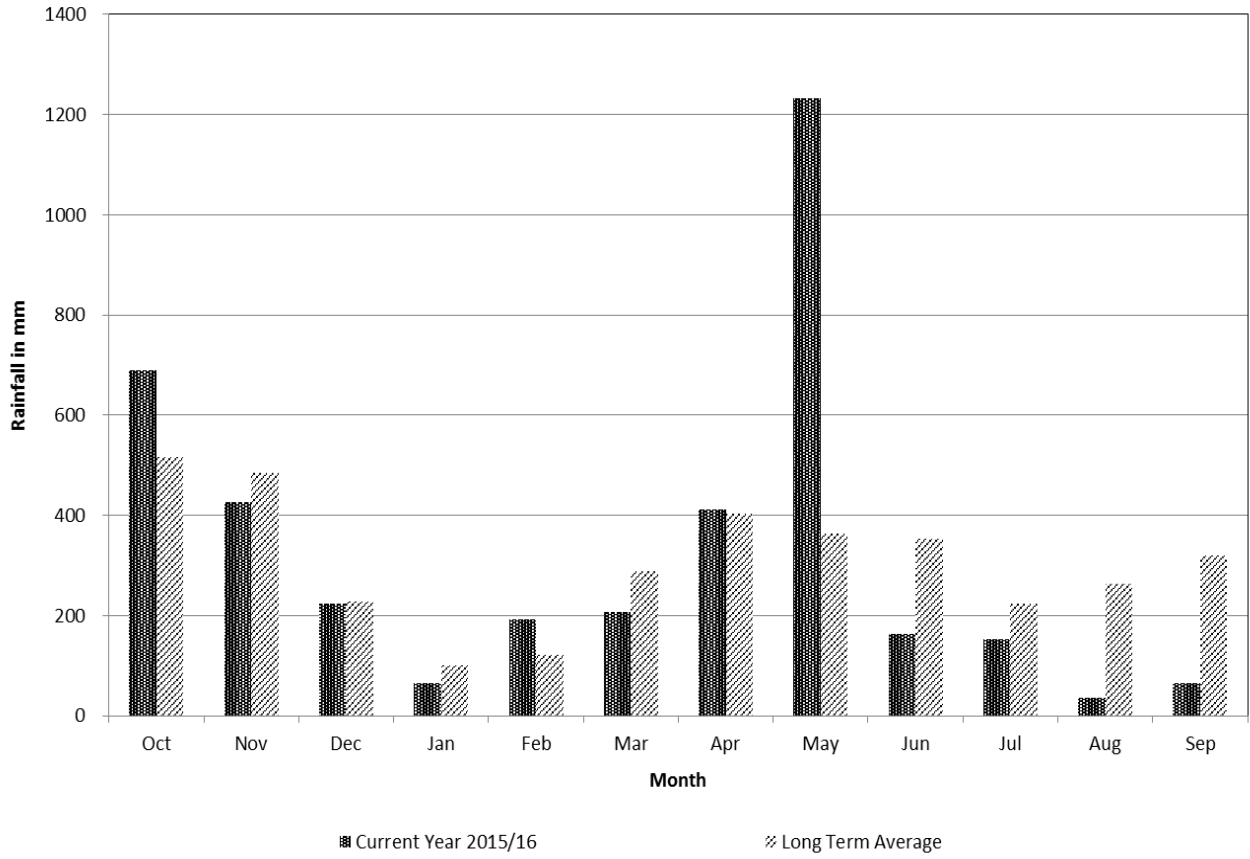
Variation of Rainfall at Ellagawa



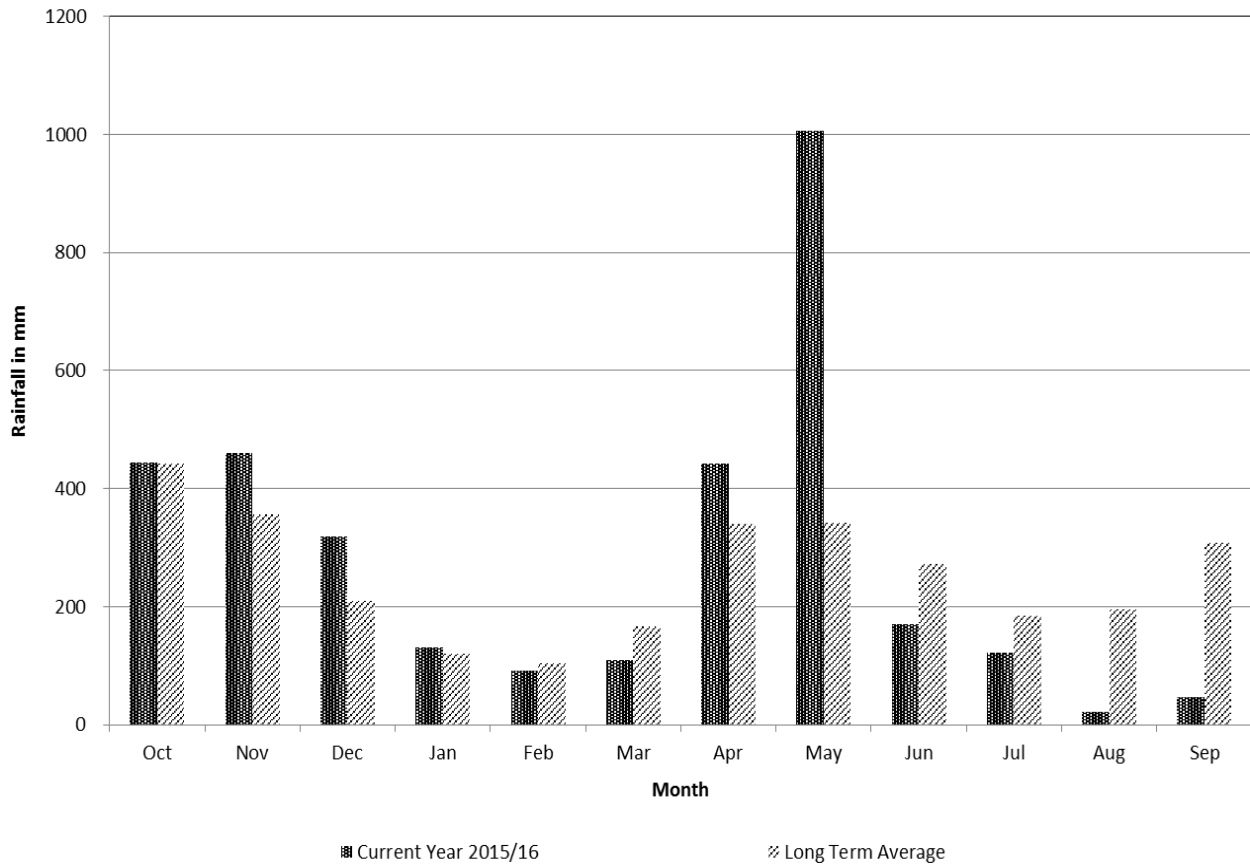
Variation of Rainfall at Galgamuwa



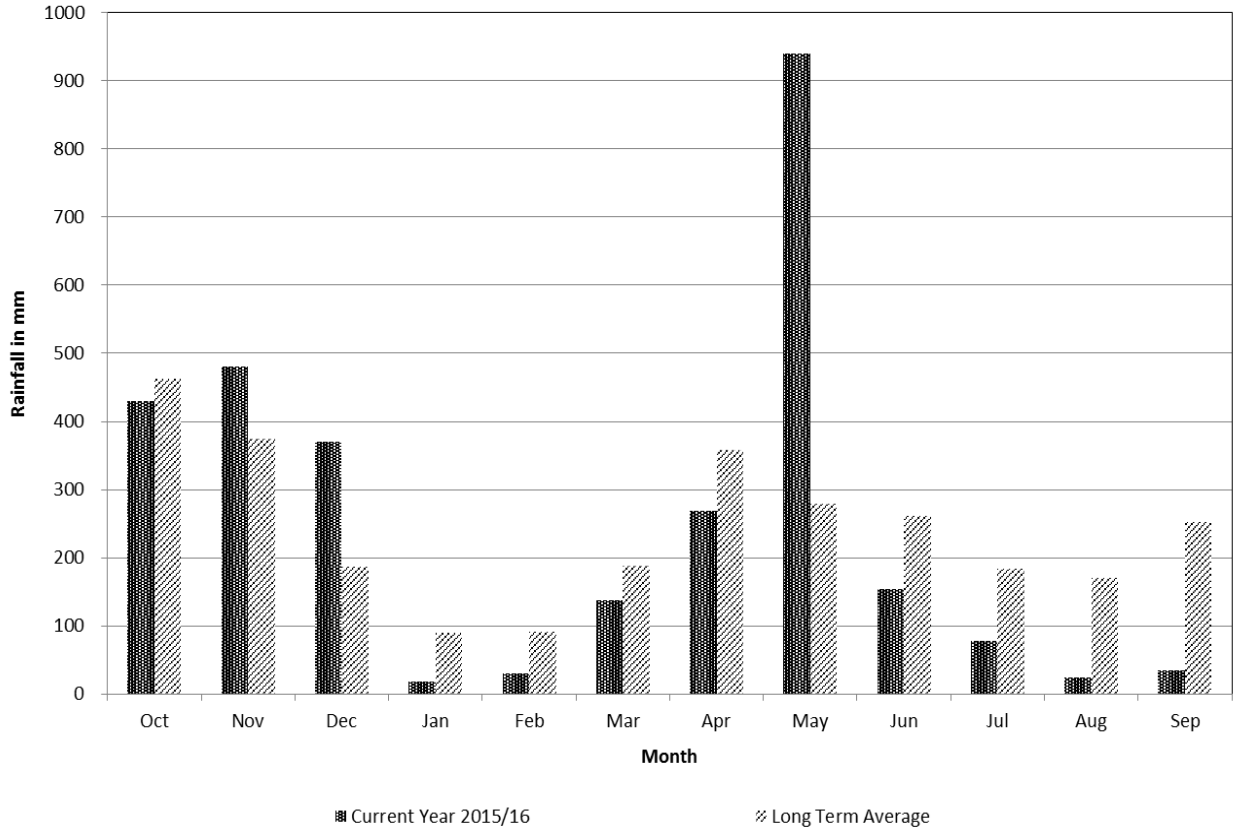
Variation of Rainfall at Glencourse



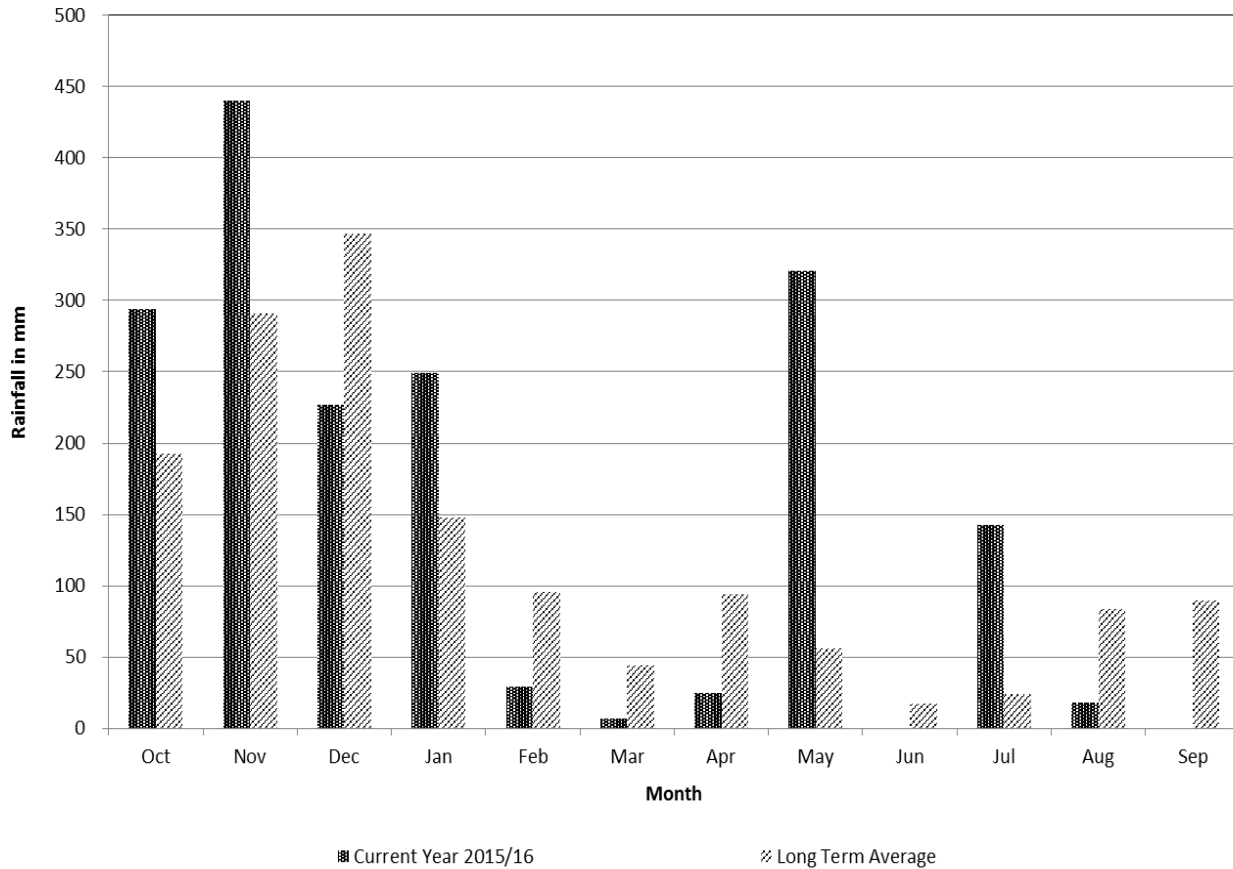
Variation of Rainfall at Hanwella



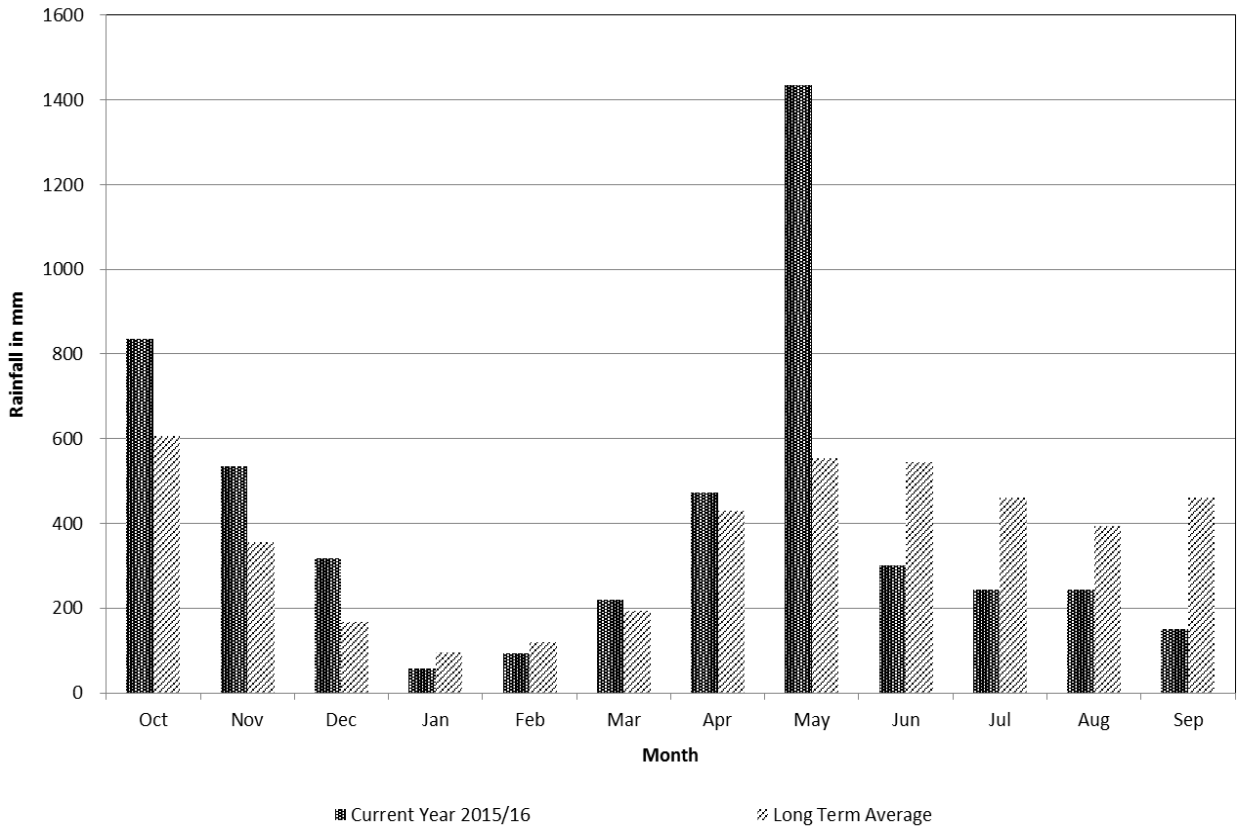
Variation of Rainfall at Holombuwa



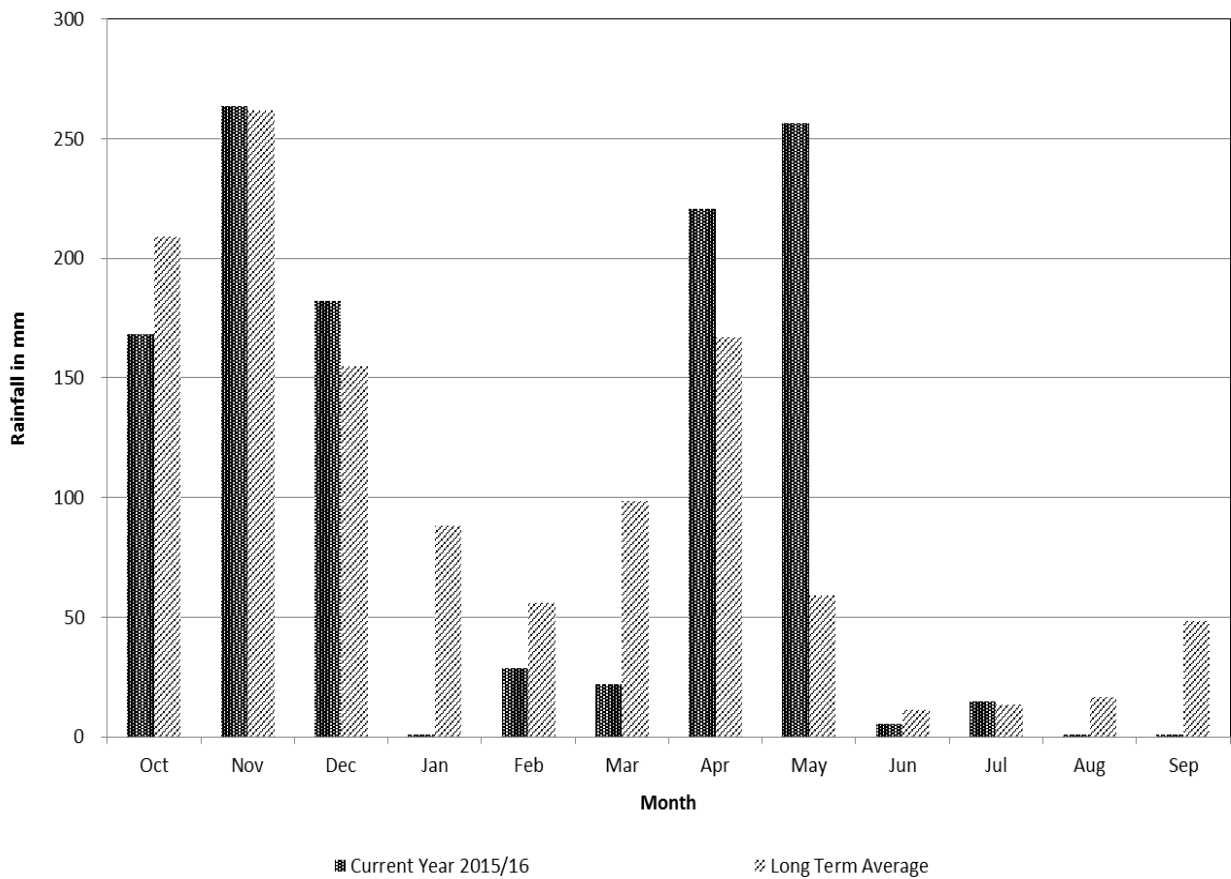
Variation of Rainfall at Horowpothana



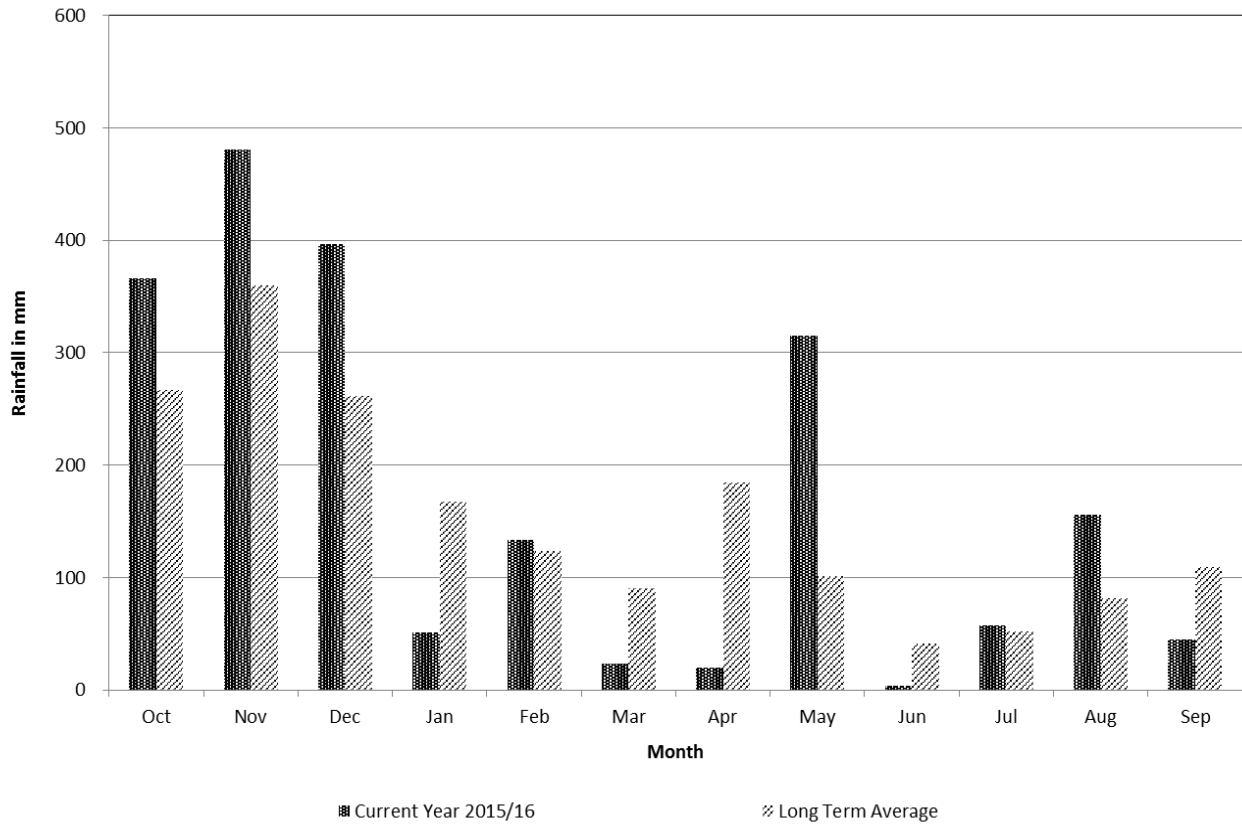
Variation of Rainfall at Kithulgala



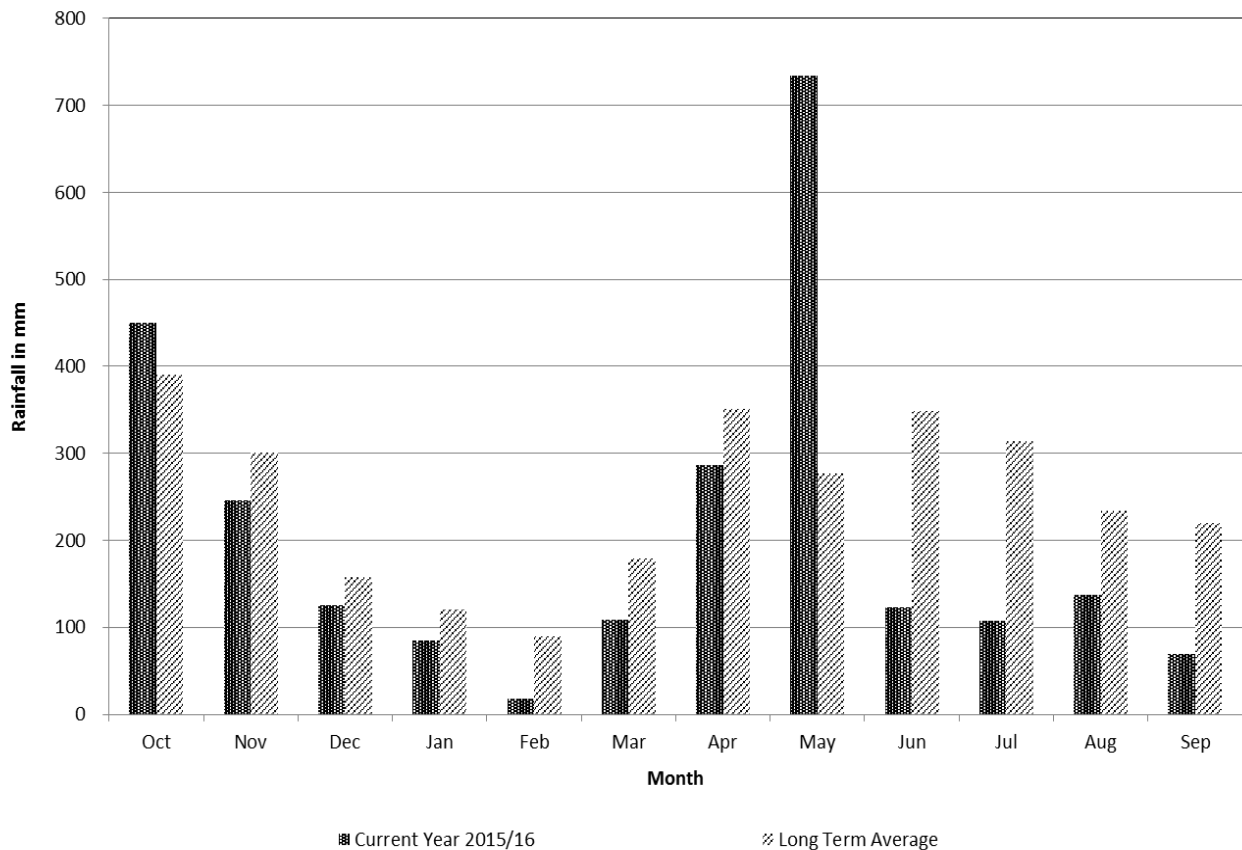
Variation of Rainfall at Kuda Oya



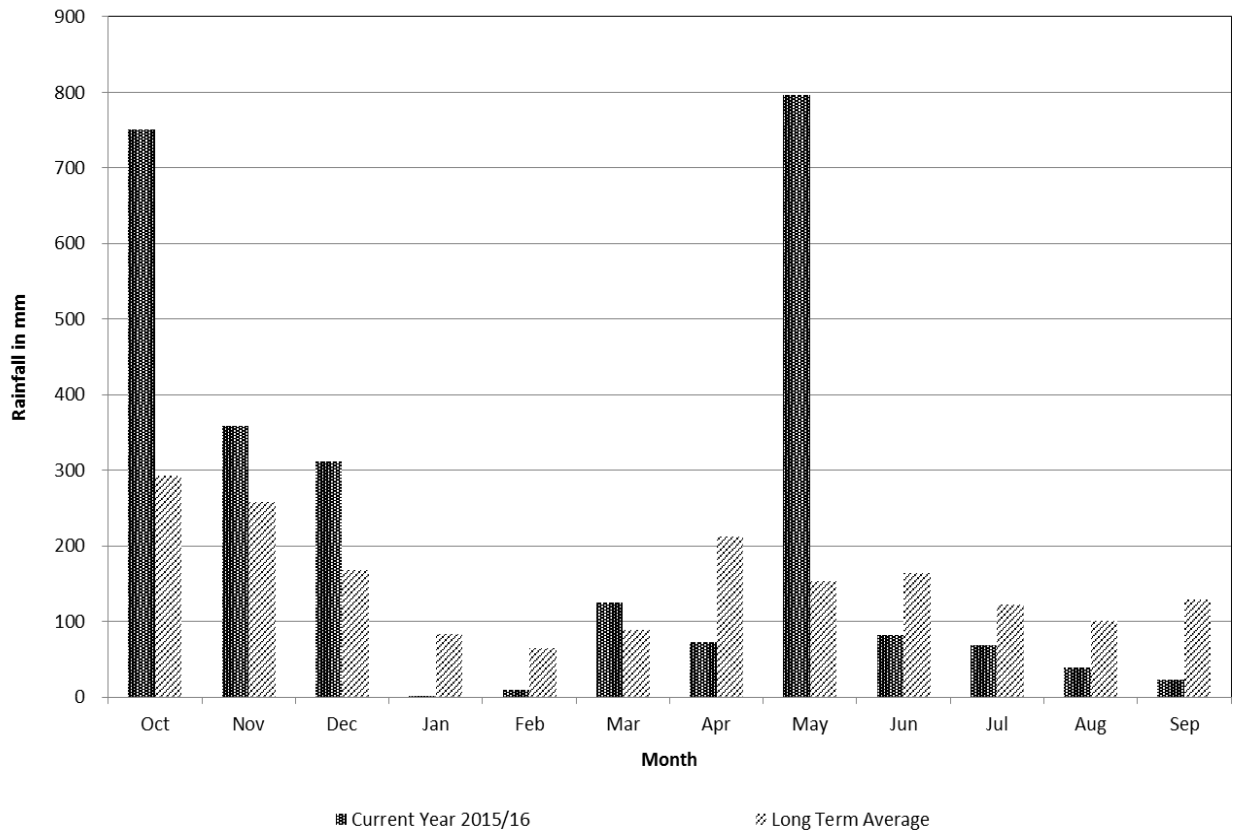
Variation of Rainfall at Nakkala



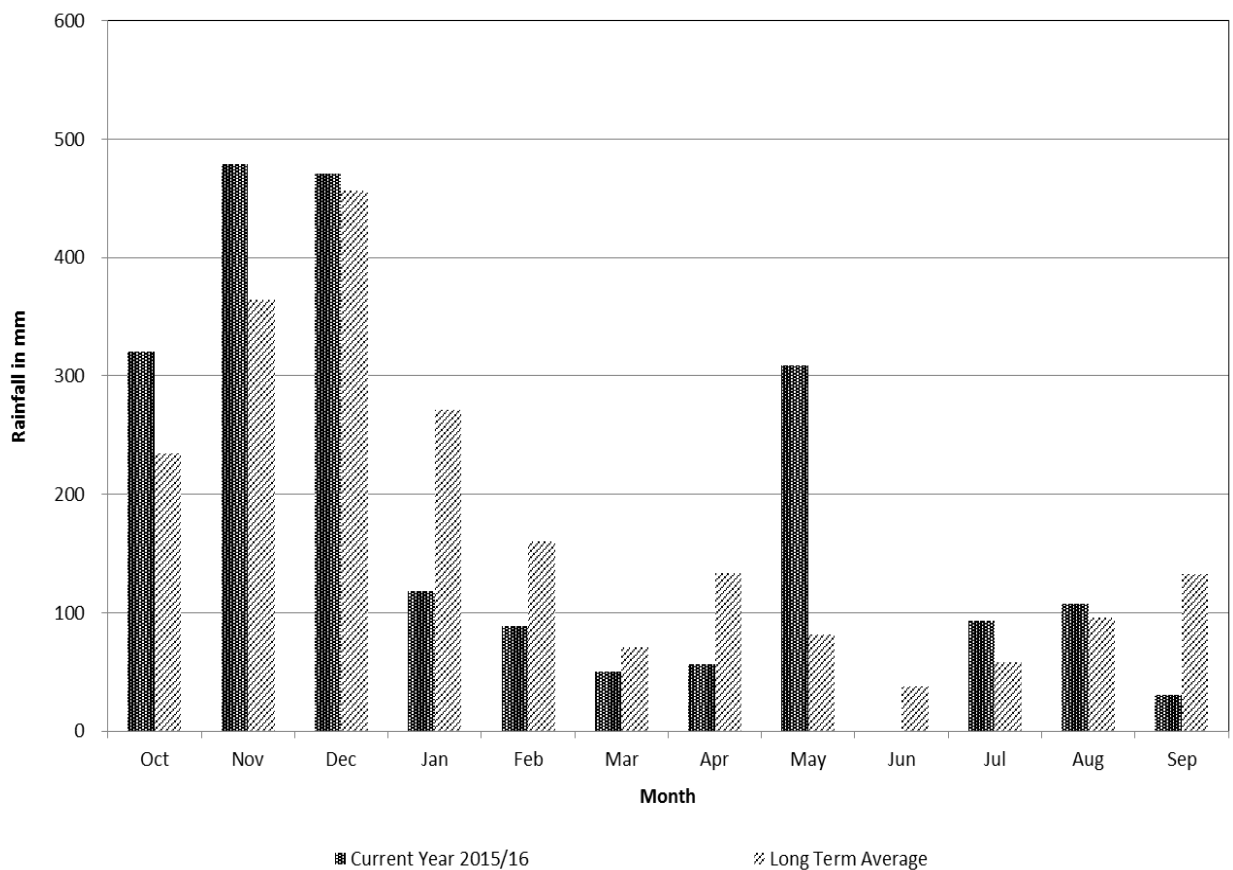
Variation of Rainfall at Norwood



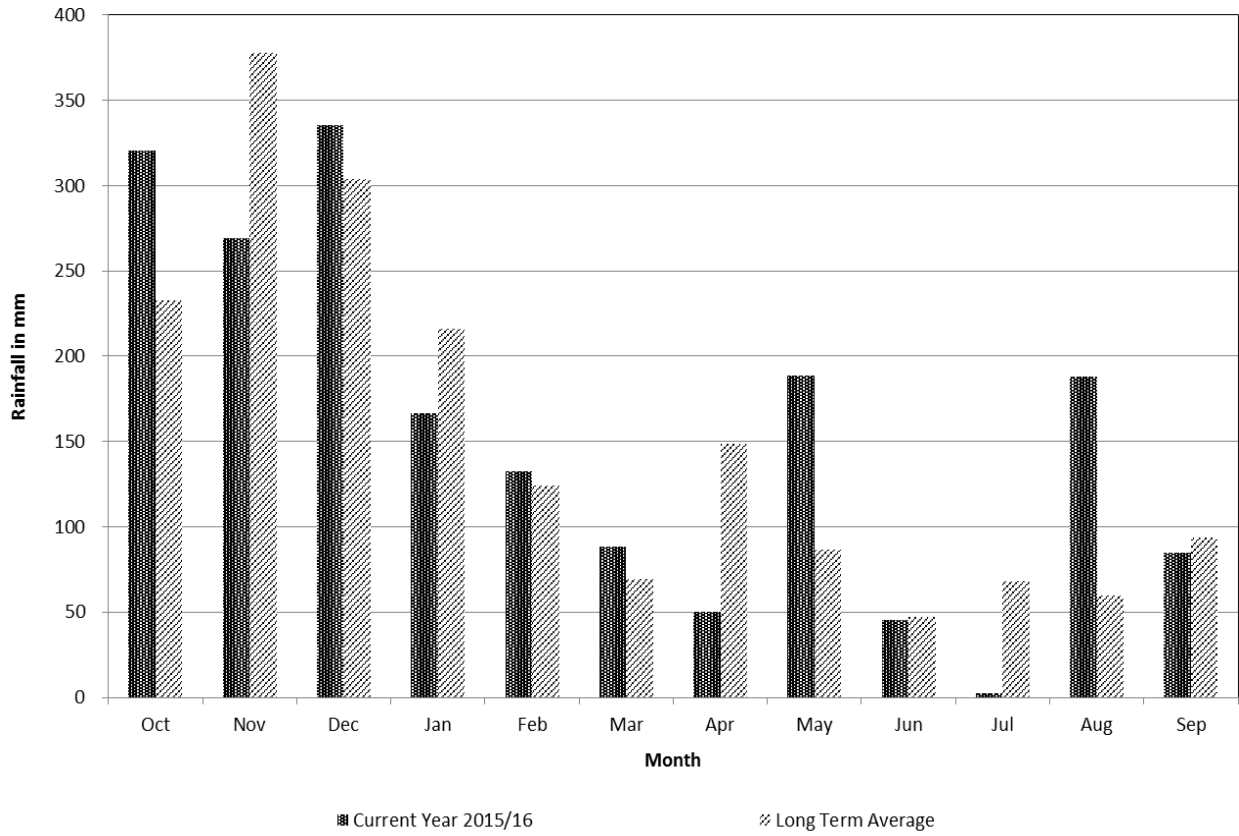
Variation of Rainfall at Peradeniya



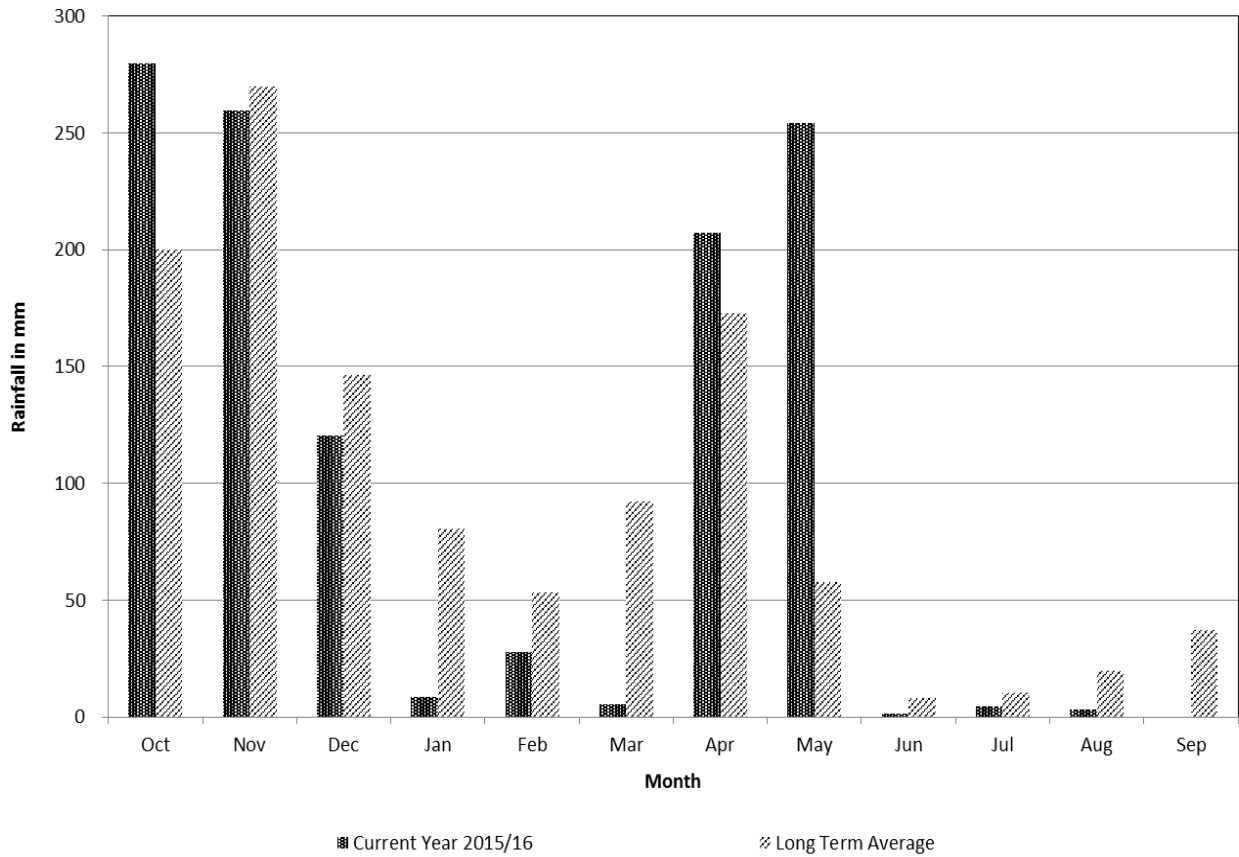
Variation of Rainfall at Padiyathalawa



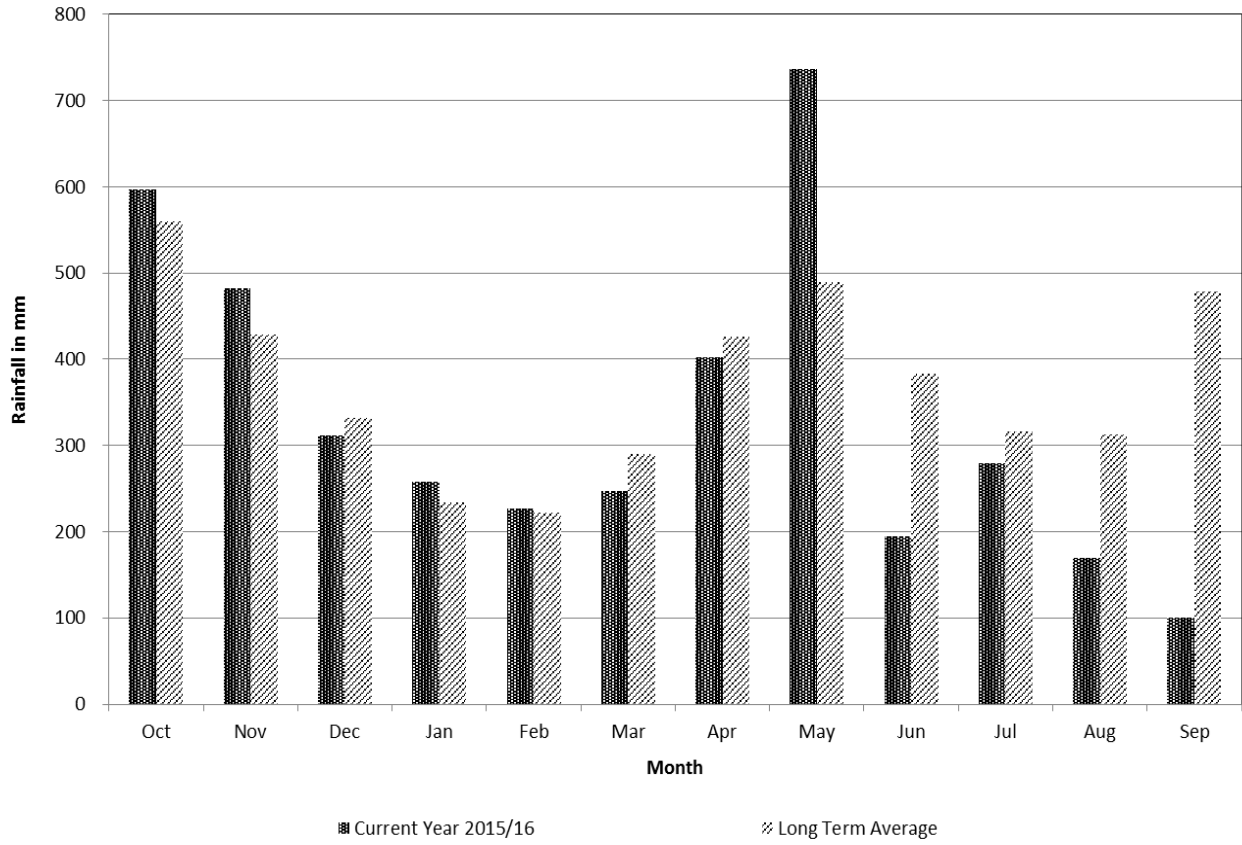
Variation of Rainfall at Siyambalanduwa



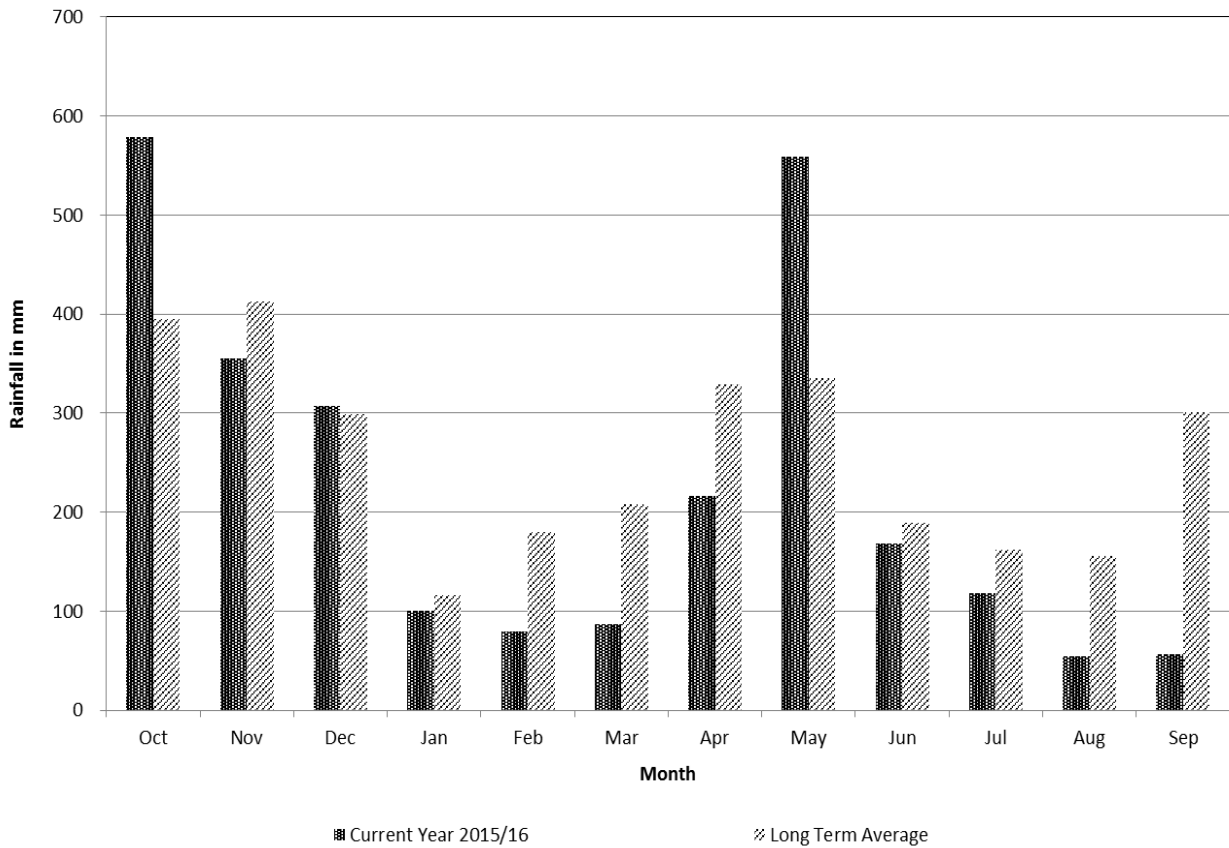
Variation of Rainfall at Thanamalwila



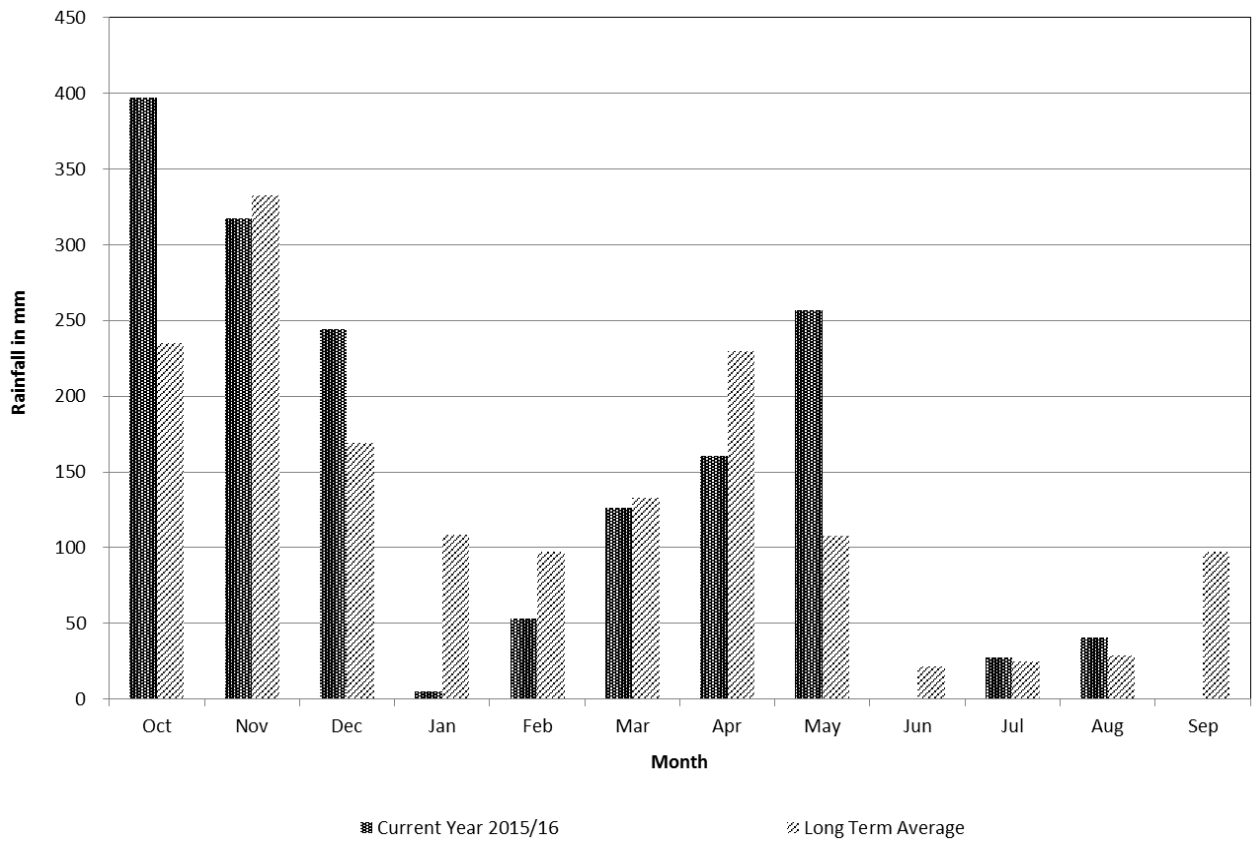
Variation of Rainfall at Thawalama



Variation of Rainfall at Urawa



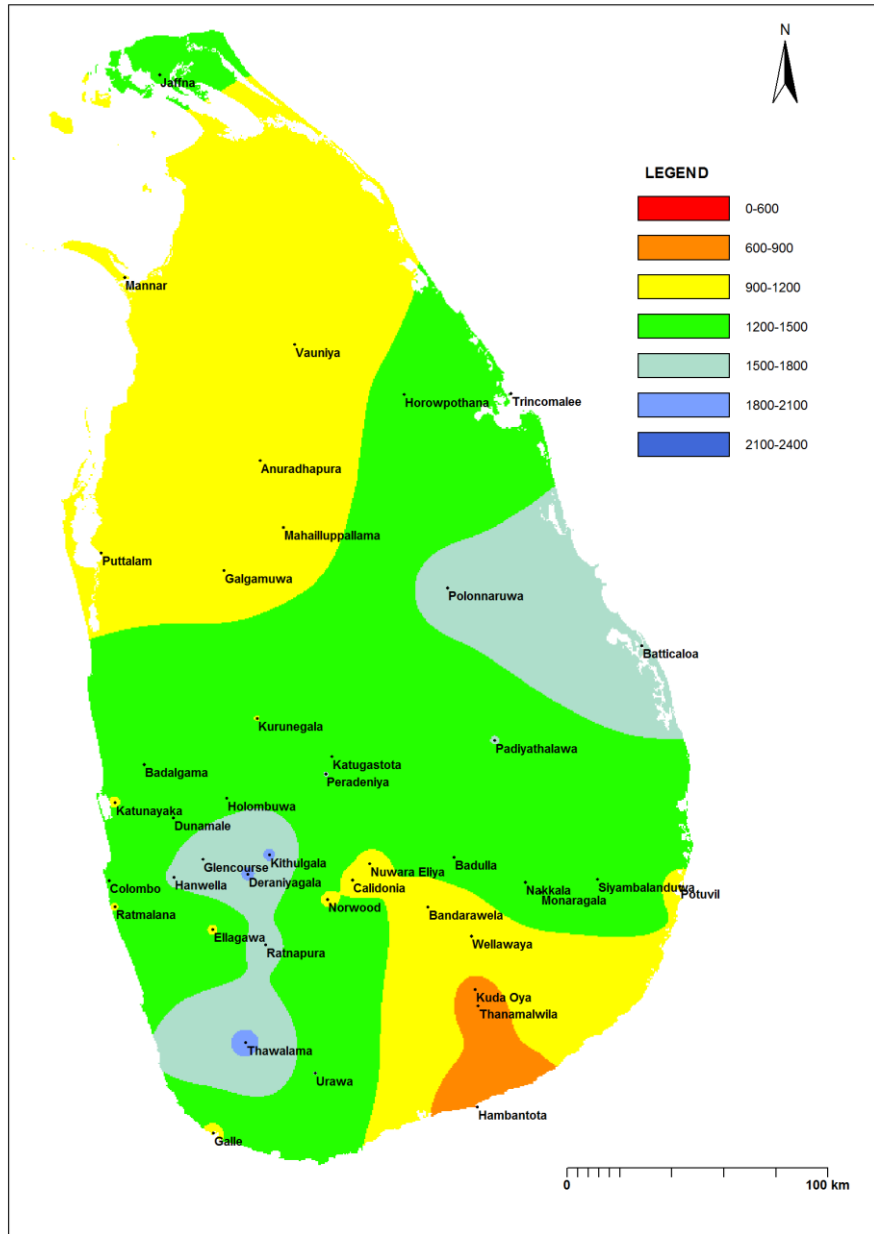
Variation of Rainfall at Wellwaya



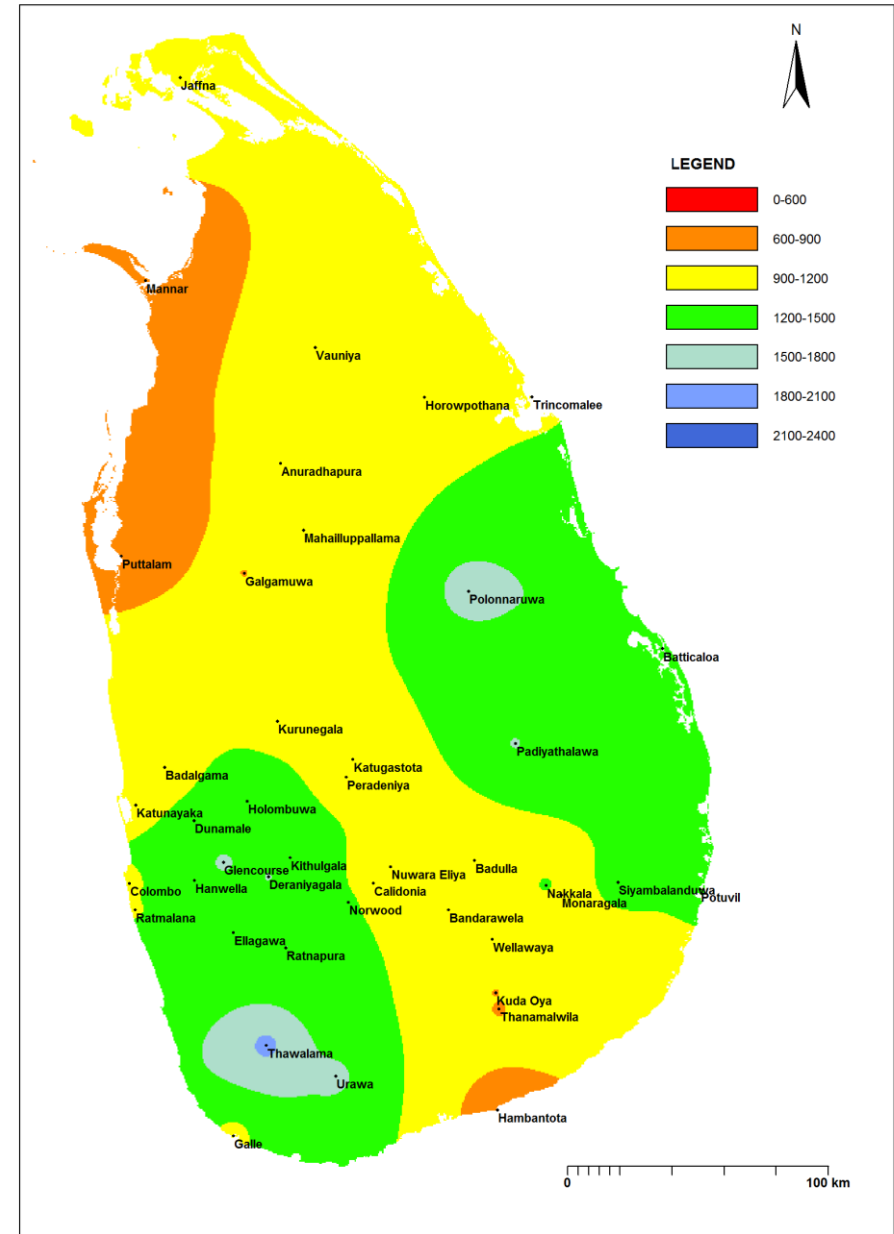
SPATIAL VARIATION OF RAINFALLS OVER THE ISLAND

- **NEM (North-East Monsoon) Rainfall Distribution**
- **SWM (South-West Monsoon) Rainfall Distribution**
- **Annual Rainfall Distribution**

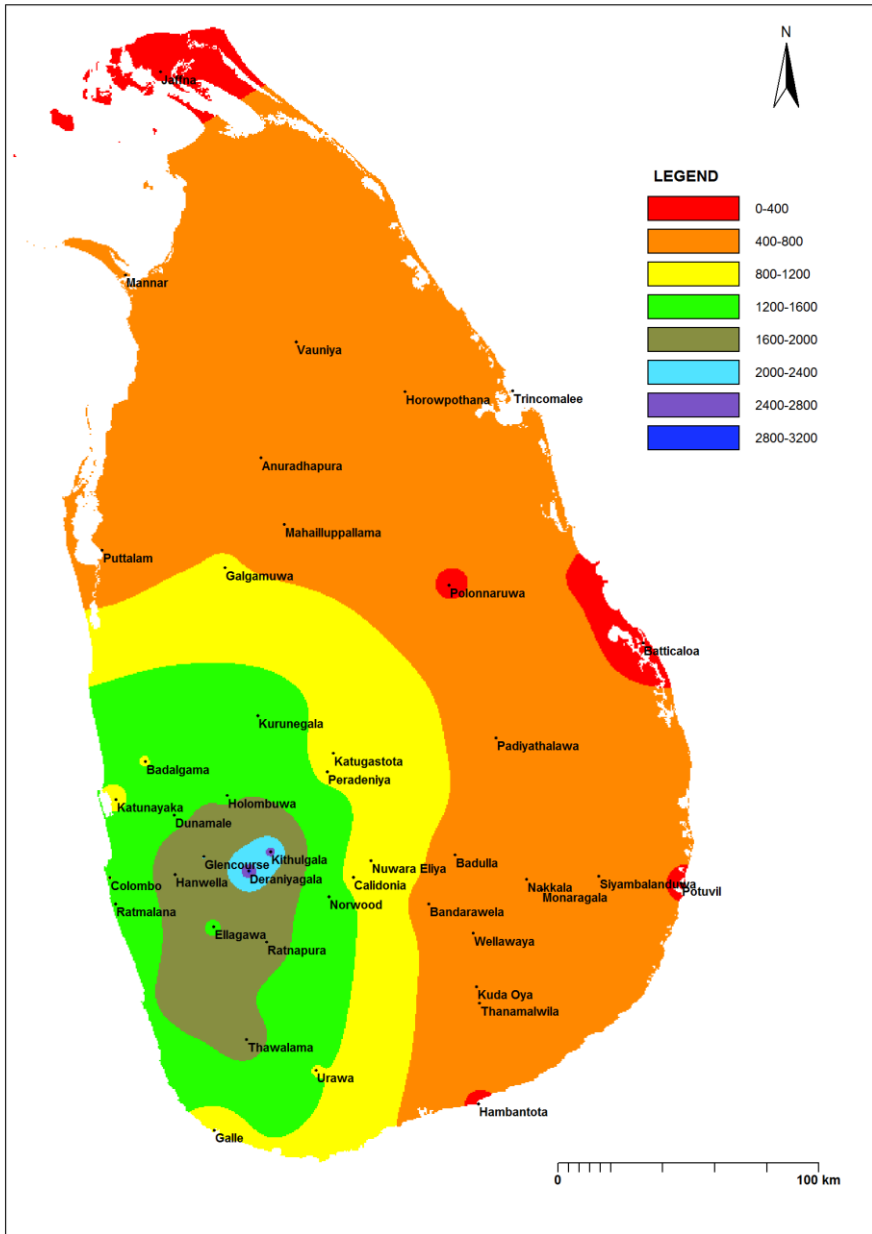
NEM Rainfall Distribution – Current year 2015/16



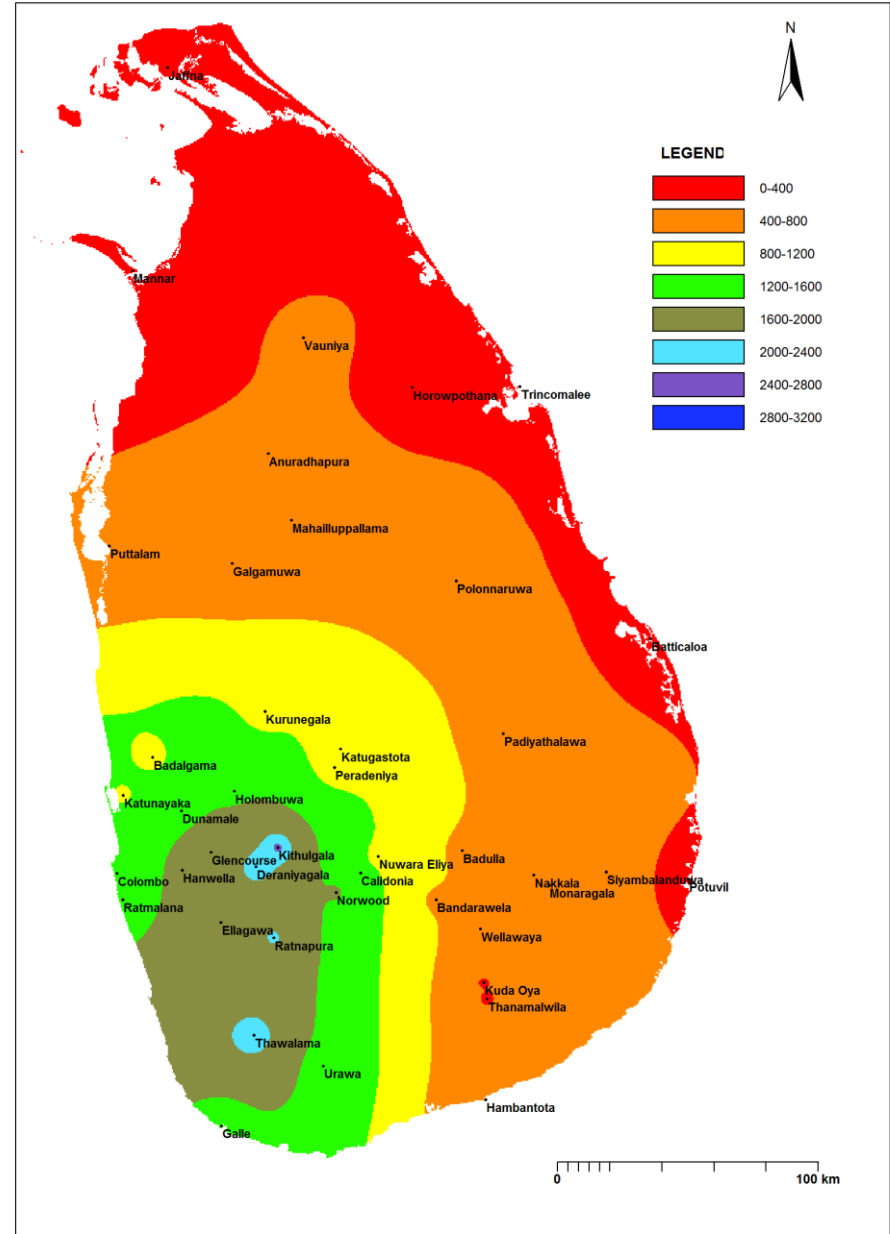
NEM Rainfall Distribution – Long Term Average



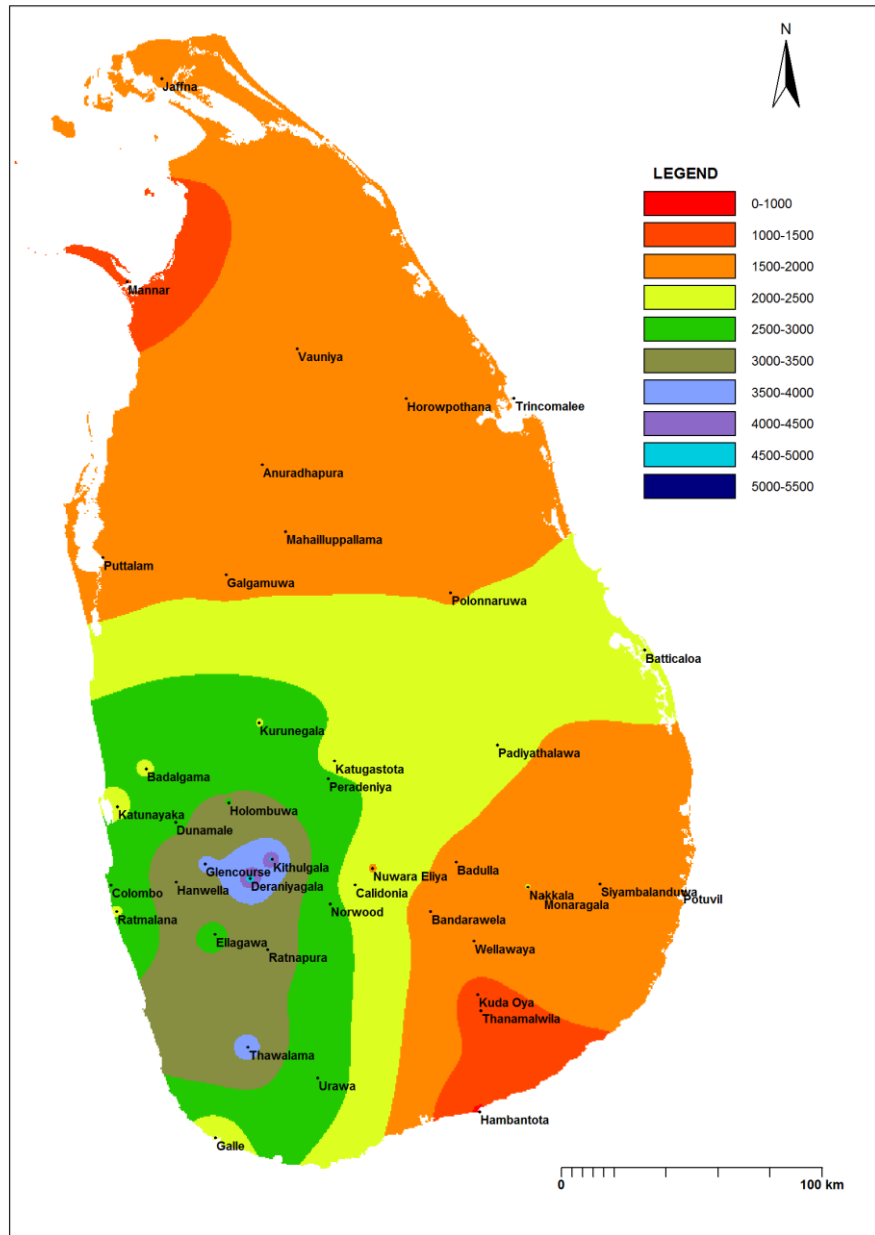
SWM Rainfall Distribution – Current year 2015/16



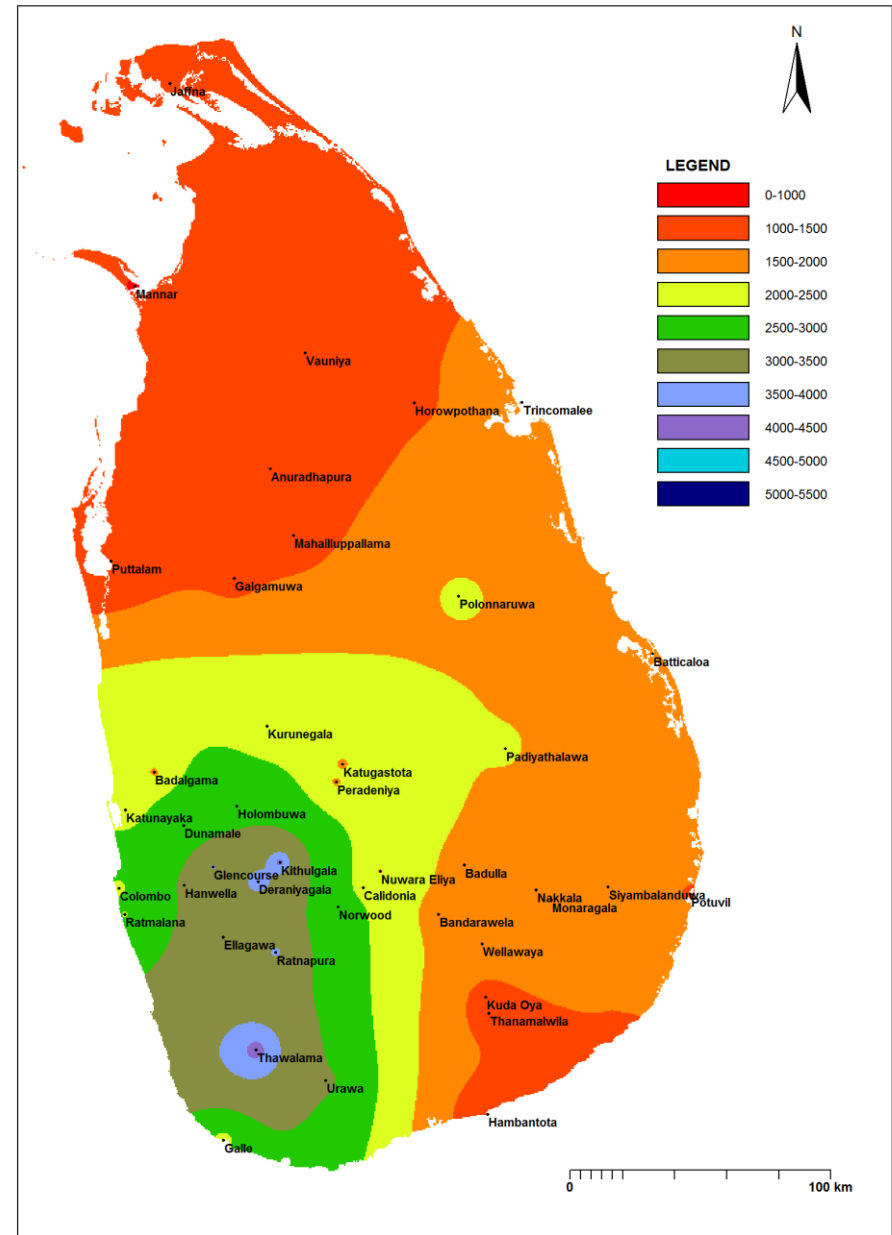
SWM Rainfall Distribution – Long Term Average



Annual Rainfall Distribution – Current year 2015/16



Annual Rainfall Distribution – Long Term Average



RAINFALL INTENSITIES

RAINFALL INTENSITY ANALYSIS
WATER YEAR 2015/16
(MAXIMUM DEPTH OF RAINFALL in mm)

Station	Duration in Hours								
	1	3	6	12	24	48	72	96	120
Badalgama	77	87	106	166	211	247	389	423	437
Baddegama	65	99	99	142	170	190	199	278	280
Calidoniya	39	83	110	143	145	150	163	212	217
Deraniyagala	111	130	170	256	356	454	524	619	719
Dolabodakanda	49	49	76	83	83	124	152	167	211
Dunamale	111	114	120	122	165	211	284	316	389
Galgamuwa	67	91	128	138	149	296	325	346	375
Giriulla	108	123	123	127	128	189	295	358	387
Glencourse	85	94	114	171	226	304	377	403	512
Hanwella	73	112	120	135	170	195	227	240	345
Holombuwa	61	102	107	131	202	306	407	424	461
Horowpothana	62	123	127	192	204	241	268	281	281
Karandagolla	51	51	76	88	98	165	186	196	231
Kithulgala	82	127	181	232	336	406	473	524	663
Kuda Oya	72	85	85	85	85	87	109	128	143
Nakkala	64	95	98	99	99	118	120	163	219
Padiyathalawa	49	82	84	99	109	163	171	177	217
Peradeniya	112	113	113	113	194	306	400	428	443
Pitabeddara	137	137	157	157	157	169	182	260	270
Putupaula	45	72	100	142	177	224	257	277	304
Ranugalla	46	46	79	107	107	160	161	207	282
Rathnapura	50	72	73	77	77	105	148	175	192
Siyambalanduwa	42	57	68	118	123	160	164	164	175
Thaldena	56	74	98	100	118	146	149	201	221
Thanamilwila	72	76	88	89	89	128	158	181	210
Thawalama	74	151	159	159	159	199	248	276	286
Urawa	82	98	106	106	106	176	205	265	294
Wellawaya	57	68	68	71	83	93	133	144	160

**EVAPORATION
AND
EVAPOTRANSPIRATION**

MONTHLY PAN EVAPORATION FOR THE WATER YEAR 2015/16

(in mm)

Name of Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total		
													NEM	SWM	Annual
Agalawaththa	71.1	64.3	67.4	91.3	93.9	102.9	108.2	67.8	84.6	87.4	89.0	84.0	491.0	521.1	1012.0
Badalgama	83.3	71.5	78.5	102.1	98.8	117.4	106.8	68.8	81.5	96.6	116.3	115.2	551.5	585.2	1136.7
Bandarawela*	60.5	60.6	46.5	58.9	72.5	108.5	90.0	86.8	114.0	136.4	102.3	114.0	407.5	643.5	1051.0
Bombuwela*	73.5	74.7	73.2	89.9	89.9	117.8	108.0	77.5	84.0	89.9	96.1	93.0	518.9	548.5	1067.4
Colombo*	101.7	88.8	86.8	114.7	121.8	151.9	138.0	102.3	1.1	114.7	130.2	126.0	665.7	612.3	1278.0
Dunamale	93.0	93.7	81.8	99.1	113.3	133.7	112.7	91.8	94.1	119.7	116.1	134.8	614.5	669.2	1283.7
Galgamuwa	103.0	69.9	69.9	80.0	93.9	148.0	126.2	96.0	95.5	110.6	136.3	138.3	564.7	702.8	1267.6
Girandurukotte*	96.1	57.0	63.6	74.4	89.9	114.7	120.0	117.8	135.0	139.5	-1	151.8	495.7	-1	-1
Horowpathana	89.9	68.1	64.1	65.6	86.7	104.1	130.1	119.5	142.3	149.5	154.4	179.2	478.4	874.9	1353.3
Kanthale	101.9	88.3	96.9	89.8	96.7	122.9	162.7	144.8	151.0	164.5	174.0	204.0	596.5	1001.0	1597.5
Kurunegala*	82.8	68.1	68.8	117.8	121.8	-1	-1	49.6	72.0	86.8	108.5	123.0	-1	-1	-1
Mahailuppallama*	80.6	56.4	56.1	77.5	87.0	130.2	135.0	117.8	114.0	133.3	155.0	147.0	487.8	802.1	1289.9
Padiyathalawa	121.8	106.2	90.3	98.9	120.0	188.3	182.4	150.8	175.4	171.5	186.2	194.4	725.5	1060.6	1786.0
Palugasdammana	88.8	73.0	58.8	89.8	79.4	128.1	139.7	123.0	154.2	168.2	184.2	205.8	517.9	975.1	1493.0
Pelwaththa	92.8	91.4	86.1	126.8	122.2	150.5	120.0	115.5	148.8	154.0	154.3	164.2	669.8	856.8	1526.6
Puttlam*	105.7	76.2	82.5	99.2	110.2	148.8	159.0	133.3	129.0	155.0	164.3	156.3	622.6	896.9	1519.5
Rathnapura*	65.4	66.6	51.2	65.1	69.6	93.0	84.0	55.8	72.0	83.7	80.6	72.0	410.9	448.1	859.0
Sevanagala*	111.9	83.4	104.2	136.4	127.6	173.6	129.0	96.1	147.0	182.9	186.0	156.0	737.1	897.0	1634.1
Seetha Eliya*	60.5	49.8	45.9	71.3	87.0	124.0	102.0	55.8	66.0	68.2	68.2	75.0	438.4	435.2	873.6
Siyamblanduwa	83.5	79.3	144.1	84.2	87.7	113.4	95.9	94.7	103.4	107.7	106.0	113.7	592.2	621.4	1213.6
Thanamalwila	79.1	64.6	72.7	111.0	107.7	126.0	122.1	100.5	135.5	158.4	187.1	203.0	561.1	906.6	1467.7

Note :- Missing data is denoted by -1, ‘*’ Denotes data obtained from Meteorology Department

NEM denotes North-East Monsoon, SWM denotes South-West Monsoon

OPEN WATER EVAPORATION (E_o) & POTENTIAL EVAPOTRANSPIRATION FOR REFERENCE CROP (E_{To}) – 2015/16

Weather Station : **Pelwaththa**
Co-ordinate : **6° 41' N, 81° 12' E**
Altitude : **152 m**

Month	Temp. Avg. °C	Humidity Avg. %	Sunshine hrs	Wind Speed km/hr	E _o mm	E _{To} mm
Oct	28.04	72.86	5.44	1.72	146.26	111.05
Nov	26.82	74.37	4.75	1.55	122.67	92.42
Dec	15.98	78.91	5.17	2.93	113.21	84.40
Jan	16.10	63.48	8.02	5.48	130.21	95.64
Feb	15.71	62.03	7.66	4.71	133.61	92.35
Mar	16.84	63.73	8.78	2.85	151.48	110.17
Apr	28.74	62.72	8.45	1.65	183.74	137.85
May	27.63	66.85	6.82	3.63	172.07	133.00
Jun	27.94	56.26	8.21	4.98	185.46	146.38
Jul	29.12	57.37	8.05	3.66	189.25	147.16
Aug	29.06	55.14	8.16	3.51	193.34	149.89
Sep	29.73	49.34	8.22	4.60	195.60	156.58
Annual	24.31	63.59	7.31	3.44	1916.90	1456.89

Weather Station : **Padiyathalawa**
Co-ordinate : **7° 23' N, 81° 11' E**
Altitude : **100 m**

Month	Temp. Avg. °C	Humidity Avg. %	Sunshine hrs	Wind Speed km/hr	E _o mm	E _{To} mm
Oct	24.09	90.65	5.82	1.42	133.62	101.39
Nov	22.48	90.87	3.66	0.92	100.34	73.19
Dec	26.81	91.74	2.91	1.16	89.58	67.94
Jan	25.53	92.94	4.40	1.05	141.37	116.21
Feb	21.79	89.03	5.65	1.44	122.45	86.27
Mar	24.69	83.48	8.25	1.96	168.62	126.38
Apr	26.04	85.30	8.91	2.08	183.16	137.35
May	25.77	89.74	5.34	1.35	140.01	107.26
Jun	25.98	74.10	5.76	2.82	148.42	112.17
Jul	26.16	78.32	6.15	3.35	155.25	119.02
Aug	26.42	75.74	8.22	2.92	178.60	135.24
Sep	25.89	72.33	8.15	3.41	176.31	132.77
Annual	25.14	84.52	6.10	1.99	1737.73	1315.19

Weather Station : **Palugasdamana**
Co-ordinate : **8° 00' N, 81° 00' E**
Altitude : **52 m**

Month	Temp. Avg. °C	Humidity Avg. %	Sunshine hrs	Wind Speed km/hr	Eo mm	ETo mm
Oct	28.81	84.06	5.13	0.80	140.33	107.42
Nov	28.13	87.35	4.15	0.76	120.75	77.28
Dec	27.46	90.65	3.17	0.72	101.18	47.13
Jan	26.60	93.32	5.02	0.86	118.72	91.46
Feb	26.89	92.10	4.64	1.07	117.88	90.78
Mar	26.78	90.35	7.06	1.23	158.82	121.91
Apr	30.73	82.90	7.97	1.11	183.93	141.75
May	30.11	80.74	5.44	1.76	156.63	121.19
Jun	30.51	70.27	5.57	2.53	155.15	120.00
Jul	29.98	72.71	6.33	2.24	167.37	128.58
Aug	31.12	67.35	7.61	2.81	190.02	146.84
Sep	31.58	66.00	7.48	2.88	183.38	141.89
Annual	29.06	81.48	5.80	1.56	1794.16	1336.23

STREAM FLOW DATA

STREAM FLOW DATA - WATER YEAR 2015/16

Upper line : Runoff in MCM

Lower line : Rainfall in mm

Name of station & River Basin	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	Annul Runoff & Annual Rainfall 2015/16	Long-term Average of Annual Runoff & Rainfall up to 2014/15		Peak Flood for 2015/16 & Observed Maximum Flood Peak up to 2014/15		
														value	**	cumecs	Time	Date
1 Badalgama R.B. 102	135.75	334.24	325.09	19.49	3.69	4.69	16.98	576.36	92.73	13.13	2.88	1.13	1526.17	1268.58	50	1566.40	12:00pm	18.05.2016
	442.6	507.0	430.9	26.0	48.6	149.5	267.5	917.1	165.3	72.0	30.7	24.5	3081.7	2358.4		1982.16	12:00mn	24.09.1971
2 Baddegama R.B. 9	410.30	294.32	184.73	113.37	98.38	110.00	110.46	345.27	203.55	103.32	78.05	83.48	2135.22	2123.03	9	301.95	10:00am	09.11.2015
	496.6	480.2	252.5	187.5	138.4	175.9	336.5	749.0	183.3	176.1	123.0	73.9	3373.0	3743.6		573.43	4:00pm	03.06.2008
3 Calidonia R.B. 60	41.33	53.49	26.24	12.49	7.02	6.61	7.72	27.66	12.43	9.94	8.65	7.71	221.29	212.70	31	167.25	5:00pm	27.10.2016
	278.1	279.6	122.5	35.8	44.9	95.2	134.0	391.6	83.7	106.1	92.3	52.9	1716.8	2058.0		178.48	3:00pm	12.06.2014
4 Chilaw R.B. 99	189.51	231.28	144.94	215.21	172.93	189.79	181.63	372.38	195.50	185.66	203.20	194.53	2476.56	2401.99	25	-1	-1	-1
	343.5	465.5	255.1	7.9	19.8	133.2	177.4	504.3	153.5	28.0	6.1	13.4	2107.7	2025.0		1654.00	6:00am	11.06.1995
5 Demodara R.B. 60	8.38	6.89	6.79	2.03	0.91	0.33	1.09	6.15	0.73	0.19	1.18	0.13	34.79	64.63	24	334.95	4:00pm	19.10.2016
	670.1	369.9	253.8	83.1	78.9	27.7	133.6	389.6	0.0	35.0	96.3	28.4	2166.1	1985.5		662.93	6:00pm	28.10.2014
6 Deraniyagala R.B. 1	83.99	70.23	42.04	14.68	6.71	7.86	25.10	153.15	70.75	30.13	36.24	28.27	569.15	603.68	59	426.53	3:00am	16.05.2016
	668.0	771.2	242.2	21.9	56.3	189.6	306.9	1334.3	488.4	298.8	367.2	250.0	4994.8	5089.4		2313.00	9:00am	31.05.1985
7 Dunamale R.B. 103	47.33	50.83	34.63	4.86	0.38	1.37	6.25	62.52	26.30	6.20	0.98	0.48	242.11	202.04	10	58.66	8:00pm	16.05.2016
	650.3	486.0	266.1	27.8	38.6	121.5	348.4	1111.0	182.1	89.3	24.5	22.2	3367.9	3360.4		58.66	11:00pm	31.05.2008
8 Ellagawa R.B. 3	543.78	-1	-1	93.74	50.12	54.40	148.04	879.69	375.73	93.44	56.14	41.39	-1	3354.43	58	881.33	9:00am	18.05.2016
	514.1	452.3	247.6	114.1	101.6	141.8	240.7	723.8	223.4	140.8	121.0	101.5	3122.9	3727.1		2620.00	4:00am	19.05.2003
9 Galgamuwa R.B.95	5.35	46.27	47.32	6.67	2.67	0.68	3.14	31.04	2.27	1.70	0.86	0.46	148.43	172.08	23	127.69	2:00pm	02.12.2015
	271.7	224.0	247.4	38.6	41.5	92.7	189.8	427.0	57.3	1.9	1.3	0.0	1593.0	1281.4		159.25	1:00pm	19.11.2006
10 Giriulla R.B. 102	84.8	229.0	234.6	9.3	6.1	6.3	8.8	393.8	37.8	8.4	6.3	5.3	1030.5	-1		1558.29	4:00am	18.05.2016
	439.2	515.9	455.6	29.4	42.7	164.7	268.2	941.8	168.1	76.8	33.5	26.6	3162.2	-1		1690.50	4:00pm	26.12.2014

STREAM FLOW DATA - WATER YEAR 2015/16

Upper line : Runoff in MCM

Lower line : Rainfall in mm

Name of station & River Basin	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	Annul Runoff & Annual Rainfall 2015/16	Long-term Average of Annual Runoff & Rainfall up to 2014/15		Peak Flood for 2015/16 & Observed Maximum Flood Peak up to 2014/15		
														value	**	cumecs	Time	Date
11 Glencourse R.B. 1	586.85	603.83	441.02	122.95	97.08	103.30	199.16	1248.94	447.43	174.43	141.47	113.81	4280.27	3914.01	67	1963.33	5:00pm	16.05.2016
	634.5	555.2	283.2	44.1	68.3	162.2	320.0	1149.6	255.3	187.4	178.7	116.3	3954.7	3621.6		3500.00	10:00am	04.06.1989
12 Hanwella R.B. 1	531.99	556.85	388.14	93.54	81.08	87.45	150.59	1415.96	396.49	122.77	100.55	80.92	4006.33	4334.46	31	1619.82	10:00am	18.05.2016
	618.8	530.5	269.6	51.8	76.6	158.7	331.6	1143.8	242.1	180.4	154.2	105.3	3863.4	3714.0		2745.58	8:00am	05.06.1989
13 Holombuwa R.B. 1	32.13	61.50	59.80	8.61	3.72	2.84	5.57	116.35	26.60	7.97	4.06	2.75	331.90	259.92	51	634.46	5:00am	16.05.2016
	710.5	754.5	421.4	38.5	70.5	136.6	204.6	1139.1	170.4	113.4	126.4	72.4	3958.4	3095.5		644.47	7:00am	03.06.1989
14 Horowpothana R.B. 67	13.96	103.28	136.70	85.83	5.90	4.20	3.90	74.40	4.38	4.98	3.88	3.36	444.77	169.54	54	241.30	12:00nn	07.01.2016
	287.6	219.5	250.8	151.0	53.3	29.8	94.0	357.2	0.3	72.0	8.9	0.0	1524.4	1444.4		5662.00	4:00pm	26.12.1957
15 Kataragama R.B. 26	17.84	29.35	27.75	13.92	11.72	11.78	13.08	16.37	10.76	12.42	18.00	16.75	199.74	219.01	70	31.25	7:00am	16.05.2016
	346.9	323.9	274.9	19.1	105.0	45.7	134.9	243.1	0.7	88.7	55.1	8.1	1646.0	1551.1		1365.00	1:00pm	25.12.1957
16 Kitulagala R.B. 1	143.25	154.02	118.57	58.10	77.75	79.07	66.42	176.77	131.31	94.02	75.69	71.37	1246.33	1153.90	67	399.12	10:00pm	16.05.2016
	468.2	335.1	180.2	54.5	51.7	122.8	193.6	814.8	220.1	178.8	212.3	119.5	2951.6	3451.3		2157.00	5:15pm	30.05.1989
17 Manampitiya R.B. 60	148.45	474.42	1364.14	552.68	78.40	39.83	15.53	162.39	11.34	8.62	10.50	2.17	2868.47	4762.86	61	1545.30	10:00am	15.12.2015
	460.4	469.5	259.8	60.0	68.6	100.6	130.7	490.9	119.4	123.8	99.8	55.9	2439.4	2336.1		-1	11:00am	26.12.1957
18 Millakanda R.B. 3	503.39	361.90	223.89	88.85	39.52	37.37	112.22	597.05	261.07	61.81	49.98	31.84	2368.89	2117.75	25	499.68	3:00am	18.05.2016
	696.5	612.6	361.0	167.4	107.5	187.0	400.8	899.0	235.8	186.2	131.4	118.5	4103.6	4315.4		1320.45	12:00mn	01.06.2008
19 Nawalapitiya R.B. 60	83.79	58.45	34.16	16.14	16.28	15.62	19.21	140.50	90.02	53.43	61.19	54.09	642.90	486.04	27	350.71	10:00pm	17.05.2016
	729.8	477.8	211.3	46.1	39.7	216.5	282.8	836.4	320.4	217.3	246.6	145.0	3769.7	3697.5		360.20	4:00am	28.06.1993
20 Norwood R.B. 1	25.61	30.51	17.76	9.38	5.09	5.08	12.38	29.83	11.73	7.84	6.24	5.20	166.65	134.62	30	57.79	10:00pm	17.05.2016
	454.9	316.3	157.7	60.7	7.1	95.0	279.9	634.8	99.2	67.4	82.8	37.3	2293.3	2594.3		180.98	6:00pm	13.05.2013

STREAM FLOW DATA - WATER YEAR 2015/16

Upper line : Runoff in MCM
Lower line : Rainfall in mm

Name of station & River Basin	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	Annul Runoff & Annual Rainfall 2015/16	Long-term Average of Annual Runoff & Rainfall up to 2014/15		Peak Flood for 2015/16 & Observed Maximum Flood Peak up to 2014/15		
														value	**	cumecs	Time	Date
21 Padiyatalawa R.B. 54	17.29	52.02	56.57	22.82	3.47	0.89	0.46	11.06	0.23	0.19	0.19	0.14	165.33	150.64	31	418.46	2:00am	02.05.2016
	404.0	472.8	476.8	118.2	72.1	38.2	51.9	348.3	0.0	76.2	93.5	11.8	2163.7	2135.4		972.30	9:00am	26.12.2014
22 Peradeniya R.B. 60	316.41	365.64	264.66	78.22	81.57	61.86	31.52	376.05	223.16	148.56	125.15	91.24	2164.02	1806.74	67	722.41	12:00mn	17.05.2016
	563.1	420.7	287.9	32.4	146.4	124.1	130.9	721.7	182.9	140.0	131.4	77.5	2959.0	2934.5		5097.71	2:30am	15.08.1947
23 Pitabeddara R.B. 12	132.44	111.13	74.84	29.42	12.98	6.72	22.52	78.23	40.77	16.60	9.13	6.54	541.30	507.62	35	439.08	6:00pm	18.10.2015
	480.4	418.0	228.9	108.6	60.7	40.9	240.1	480.5	136.4	118.1	58.8	44.0	2415.4	2962.7		1292.80	12:20am	18.05.2003
24 Putupaula R.B. 3	676.45	520.84	333.49	225.08	195.23	187.59	204.84	1083.71	421.43	166.52	136.13	129.80	4281.11	6096.84	71	1000.56	4:00am	19.05.2016
	556.7	497.0	269.6	132.8	112.1	154.2	304.9	792.1	221.2	161.0	120.4	104.5	3426.4	3202.1		2829.00	9:30am	16.08.1947
25 Rathnapura R.B. 3	159.61	139.72	88.96	41.65	30.98	29.04	43.60	223.08	89.39	40.83	27.62	23.28	937.76	1037.54	9	296.97	11:00pm	17.05.2016
	492.3	404.1	238.8	107.7	110.7	142.1	200.4	709.0	218.8	129.1	111.2	96.0	2960.1	3146.6		814.10	12:00nn	31.05.1989
26 Siyambalanduwa R.B. 36	2.94	26.93	34.73	15.15	1.10	0.41	0.01	2.77	0.00	0.00	0.00	0.00	84.04	136.54	24	251.50	11:00pm	05.11.2015
	365.7	316.4	340.5	96.5	117.2	108.8	58.2	213.8	22.6	20.1	170.7	69.2	1899.5	1721.7		889.27	4:00pm	12.01.2007
27 Thanamalwila R.B. 22	55.57	97.22	82.35	15.15	7.72	6.77	30.59	54.60	4.86	2.39	2.43	1.16	360.83	258.42	28	613.79	3:00am	20.11.2015
	320.0	338.4	261.7	11.4	42.7	77.4	181.6	308.7	2.8	27.2	31.4	0.7	1603.9	1605.4		824.70	3:00am	24.11.2012
28 Thawalama R.B. 9	182.19	137.77	105.29	52.33	31.20	28.95	71.12	187.25	92.59	38.41	26.91	19.24	973.26	1051.05	35	358.83	12:00mn	08.12.2015
	567.3	396.5	280.0	190.3	183.4	223.9	407.0	773.9	180.5	169.7	103.9	87.1	3563.4	4015.8		1339.07	5:00am	18.05.2003
29 Urawa R.B. 12	18.24	18.55	13.29	4.84	2.56	1.24	2.44	7.56	4.16	1.69	1.09	0.78	76.43	81.61	15	77.11	11:00pm	25.11.2015
	524.3	460.0	252.2	74.2	98.9	55.4	239.4	428.4	122.3	138.5	42.2	41.0	2476.7	3248.4		-1	-1	17.05.2003
30 Wellawaya R.B. 22	37.39	46.24	45.81	15.97	9.72	8.67	16.14	30.12	7.02	4.00	3.44	1.90	226.42	116.8	27	365.39	8:00pm	14.10.2015
	413.5	432.1	364.3	25.8	49.1	103.1	155.6	401.6	2.3	41.2	56.5	1.3	2046.2	2055.2		634.50	8:00pm	21.10.2012

Note :-Missing data is denoted by -1, ** Denotes period of records

RUNOFF RAINFALL RATIOS

RUNOFF RAINFALL RATIOS - 2015/16

Name of River Basin	Station	Annual Rainfall (mm)	Annual Runoff (mm)	Runoff / Rainfall Ratio %
Kelani Ganga	Norwood	2293	1725	75
Kelani Ganga	Deraniyagala	4995	3110	62
Kelani Ganga	Holombuwa	3958	2141	54
Kelani Ganga	Glencourse	3955	2926	74
Kelani Ganga	Hanwella	3863	2248	58
Kalu Ganga	Rathnapura	2960	1555	53
Kalu Ganga	Millakanda	4104	3036	74
Kalu Ganga	Putupaula	3426	1648	48
Gin Ganga	Thawalama	3563	2582	72
Gin Ganga	Baddegama	3373	2851	85
Nilwala Ganga	Pitabeddara	2415	1746	72
Kirindi Oya	Wellawaya	2046	1314	64
Kirindi Oya	Thanamalwila	1604	482	30
Maduru Oya	Padiyathalawa	2164	1039	48
Mahaweli Ganga	Peradeniya	2959	1853	63
Mahaweli Ganga	Manampitiya	2439	387	16
Deduru Oya	Chilaw	2108	969	46
Maha Oya	Giriulla	3162	892	28
Maha Oya	Badalgama	3082	1122	36
Attanagalu Oya	Dunamale	3368	1585	47

MONTHLY DISCHARGES IN MAJOR RIVERS

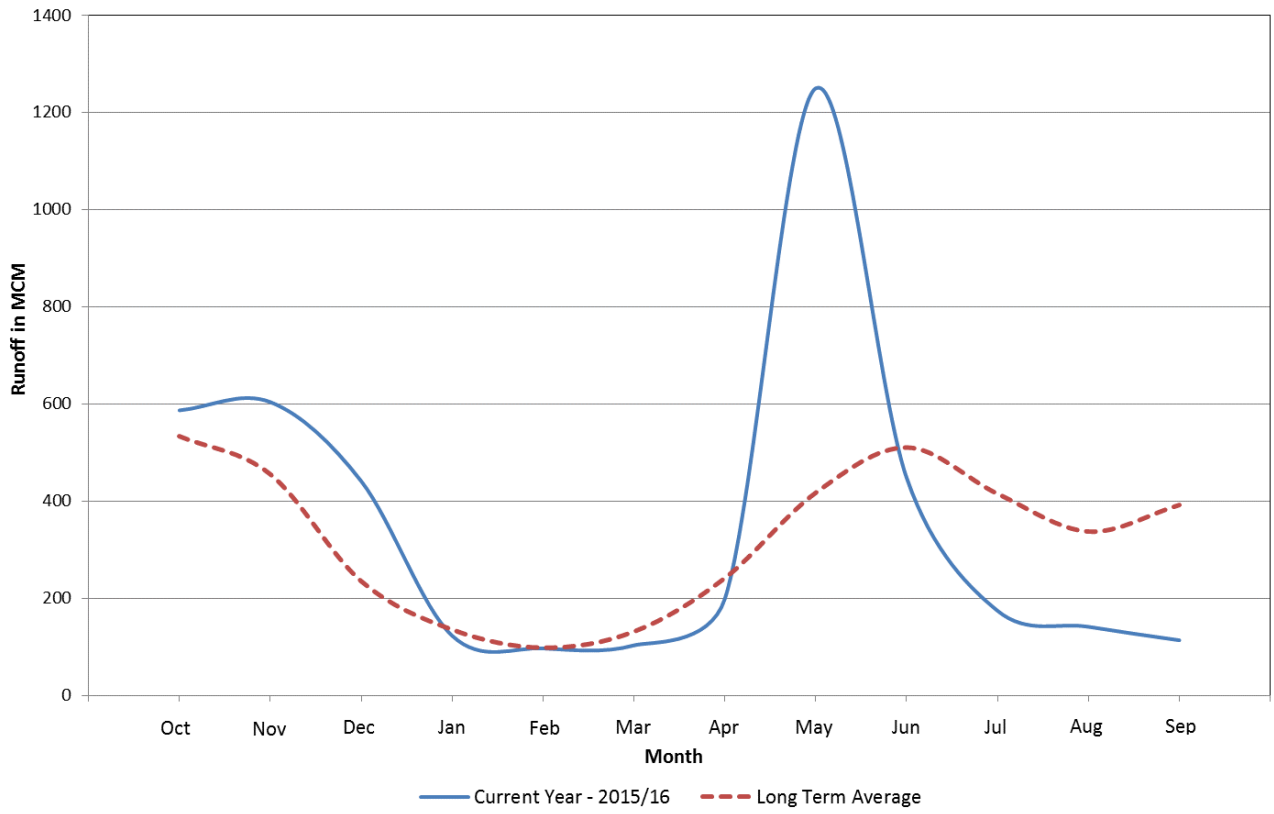
MONTHLY DISCHARGES IN MAJOR RIVERS (in MCM)

Upper line : Current year 2015/16

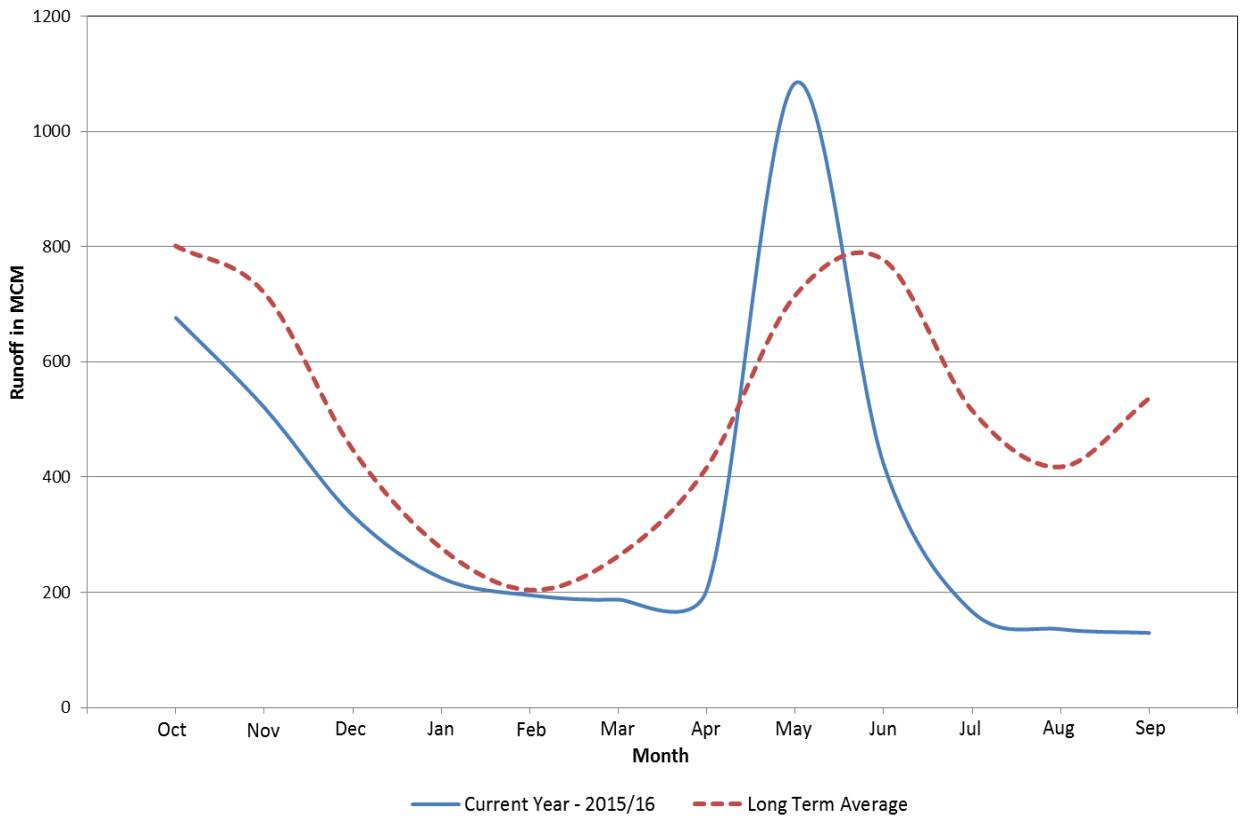
Lower line : Long term average

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Kelani Ganga at Glencourse	586.85	603.83	441.02	122.95	97.08	103.30	199.16	1248.94	447.43	174.43	141.47	113.81	4280.27
	534.31	456.34	236.31	136.63	99.28	132.35	242.48	418.00	511.10	415.86	338.35	393.01	3914.01
Kalu Ganga at Putupaula	676.45	520.84	333.49	225.08	195.23	187.59	204.84	1083.71	421.43	166.52	136.13	129.80	4281.11
	801.90	720.62	448.28	277.13	204.21	263.14	417.15	716.12	777.26	515.76	418.11	537.16	6096.84
Gin Ganga at Thawalama	182.19	137.77	105.29	52.33	31.20	28.95	71.12	187.25	92.59	38.41	26.91	19.24	973.26
	122.24	130.87	92.65	52.56	38.40	47.99	84.71	121.19	118.36	81.36	67.72	93.00	1051.05
Gin Ganga at Baddegama	410.30	294.32	184.73	113.37	98.38	110.00	110.46	345.27	203.55	103.32	78.05	83.48	2135.22
	240.24	271.78	219.43	101.13	96.77	121.52	177.06	228.69	207.19	140.93	122.44	195.86	2123.03
Nilwala Ganga at Pitabeddara	144.31	119.29	77.49	29.24	13.80	8.39	22.73	83.01	40.08	17.57	10.55	8.14	574.60
	53.86	74.32	57.66	33.22	24.23	25.30	39.24	54.26	50.80	31.99	25.89	36.85	507.63
Kirindi Oya at Thanamalwila	55.57	97.22	82.35	15.15	7.72	6.77	30.59	54.60	4.86	2.39	2.43	1.16	360.83
	19.64	55.41	47.17	24.02	14.82	19.89	40.49	25.80	5.24	2.15	1.48	2.31	258.42
Mahaweli Ganga at Peradeniya	316.41	365.64	264.66	78.22	81.57	61.86	31.52	376.05	223.16	148.56	125.15	91.24	2164.02
	220.17	216.70	155.05	86.71	53.99	47.32	77.77	127.18	210.38	224.70	207.52	181.50	1809.00
Mahaweli Ganga at Manampitiya	148.45	474.42	1364.14	552.68	78.40	39.83	15.53	162.39	11.34	8.62	10.50	2.17	2868.47
	320.50	556.87	980.13	816.63	485.72	290.71	243.90	233.54	212.38	213.87	207.58	201.03	4762.86
Deduru Oya at Chilaw	189.51	231.28	144.94	215.21	172.93	189.79	181.63	372.38	195.50	185.66	203.20	194.53	2476.56
	231.84	320.22	229.60	184.45	167.53	181.10	190.51	207.25	179.36	171.94	169.22	168.97	2401.99

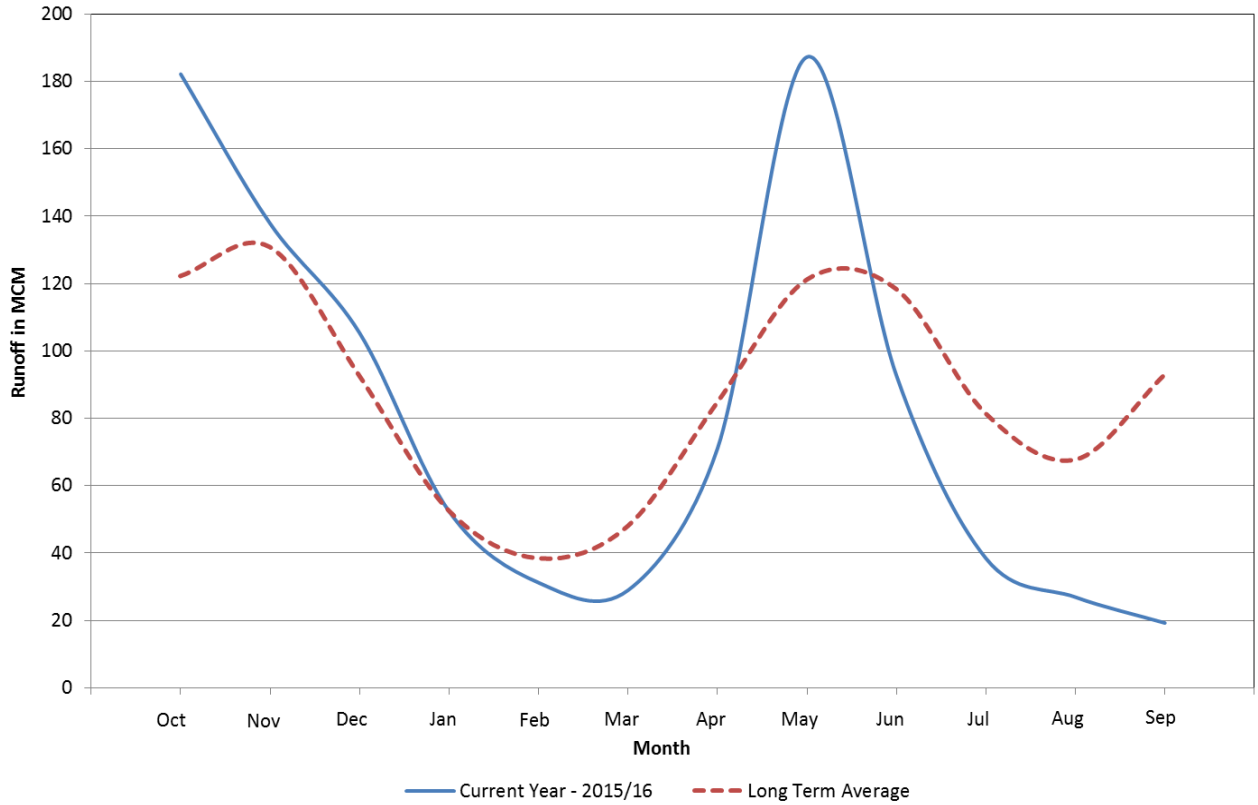
MONTHLY DISCHARGE IN KELANI GANGA AT GLENCOURSE



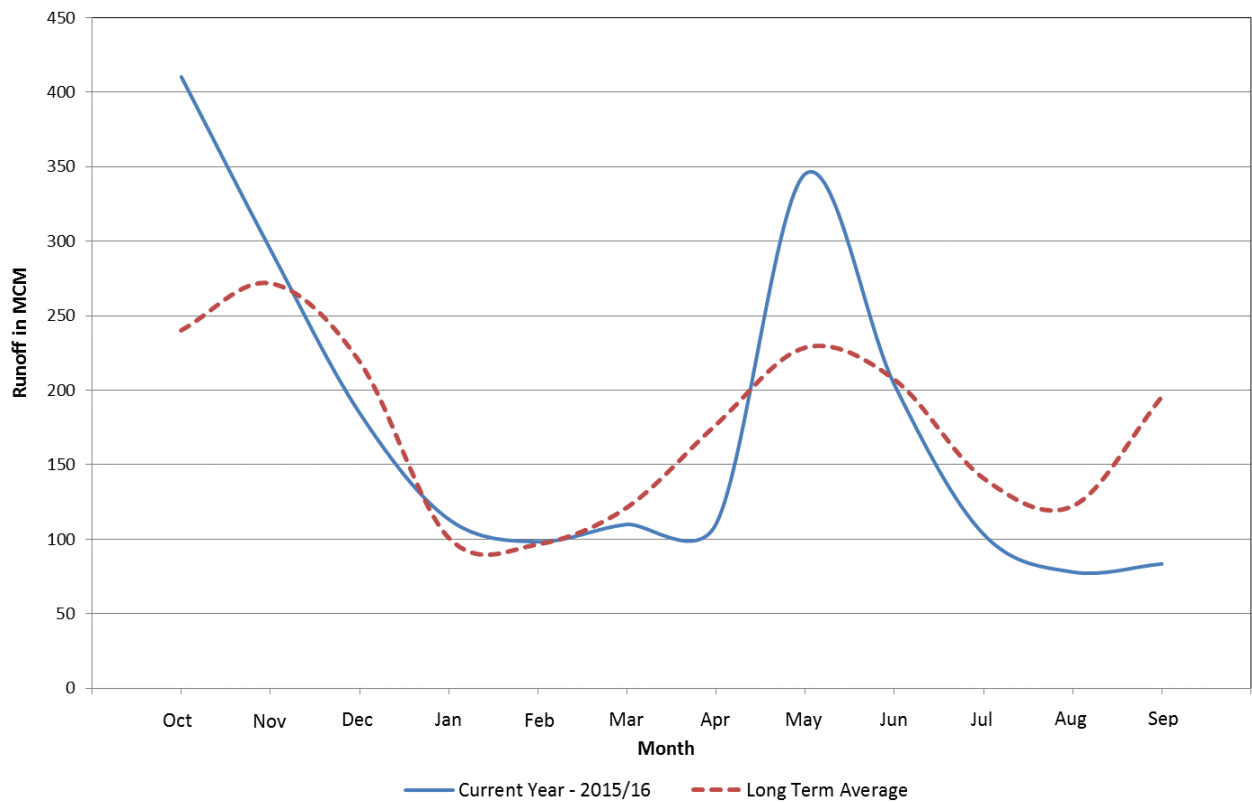
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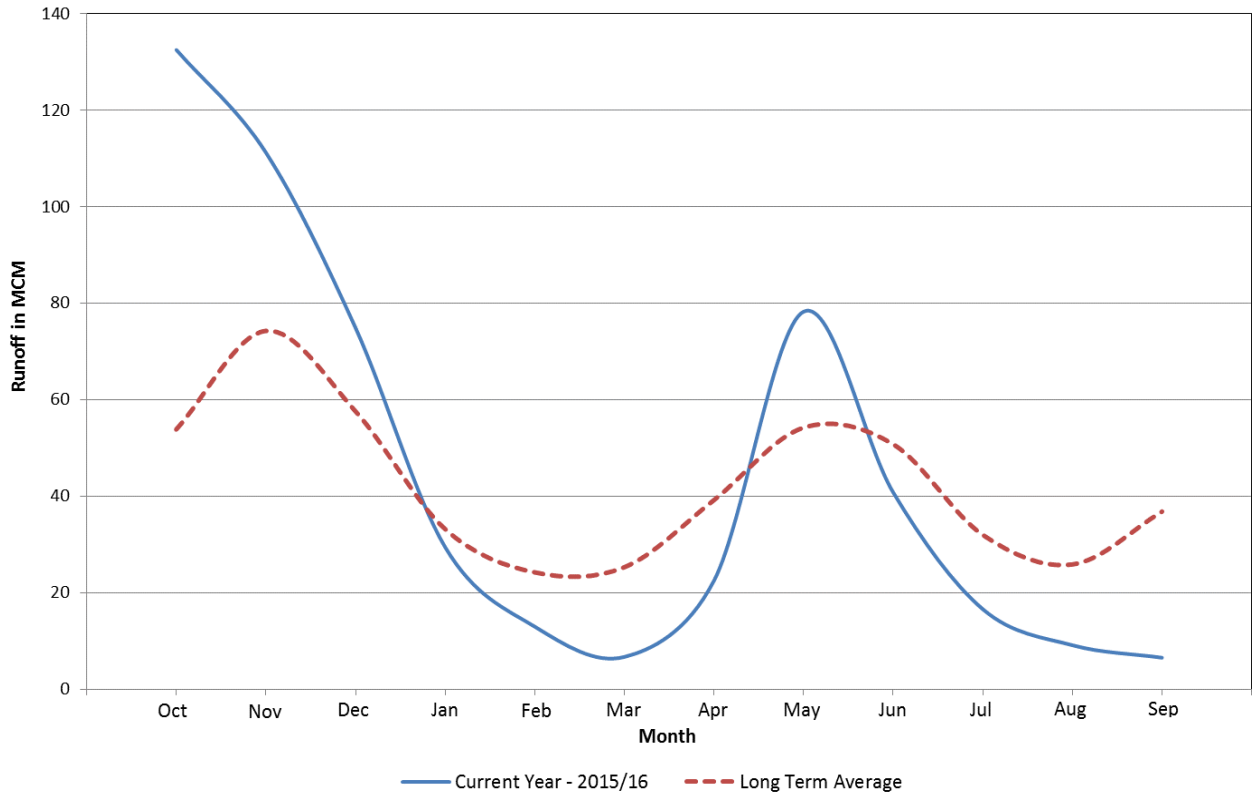
MONTHLY DISCHARGE IN GIN GANGA AT THAWALAMA



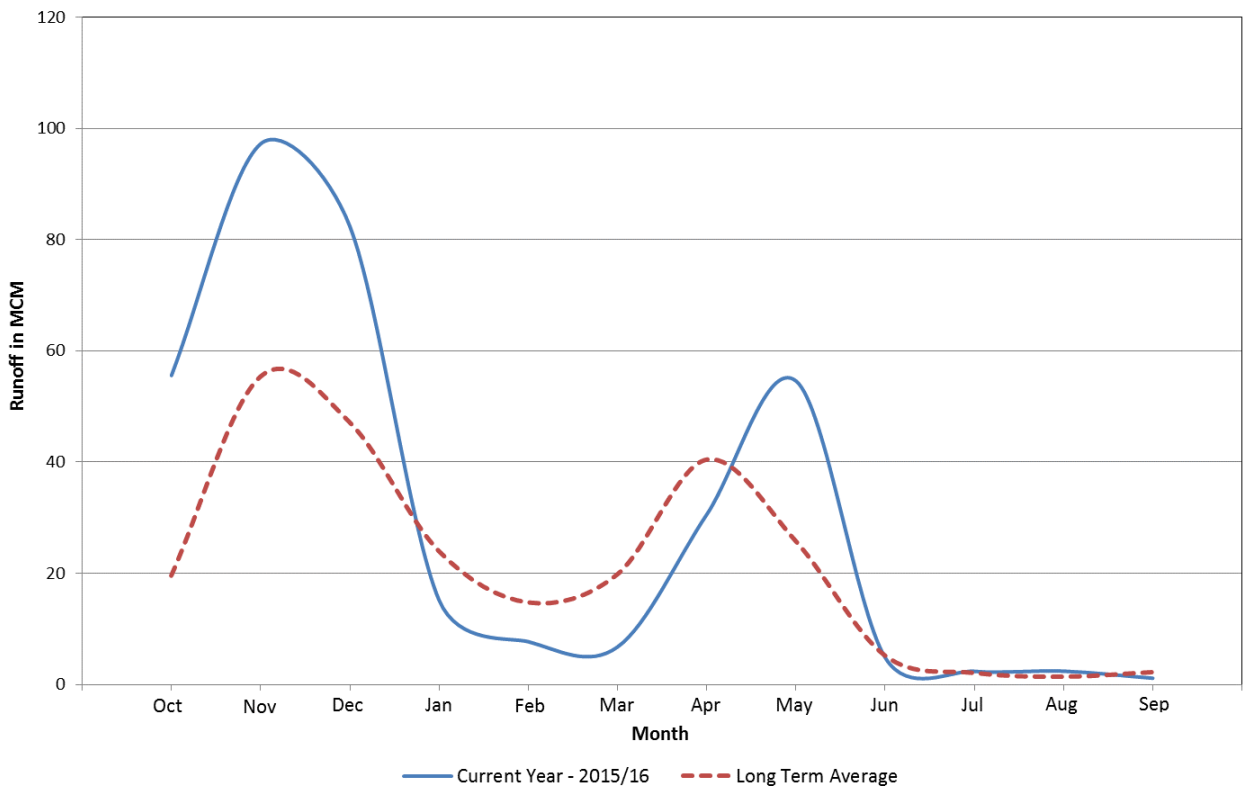
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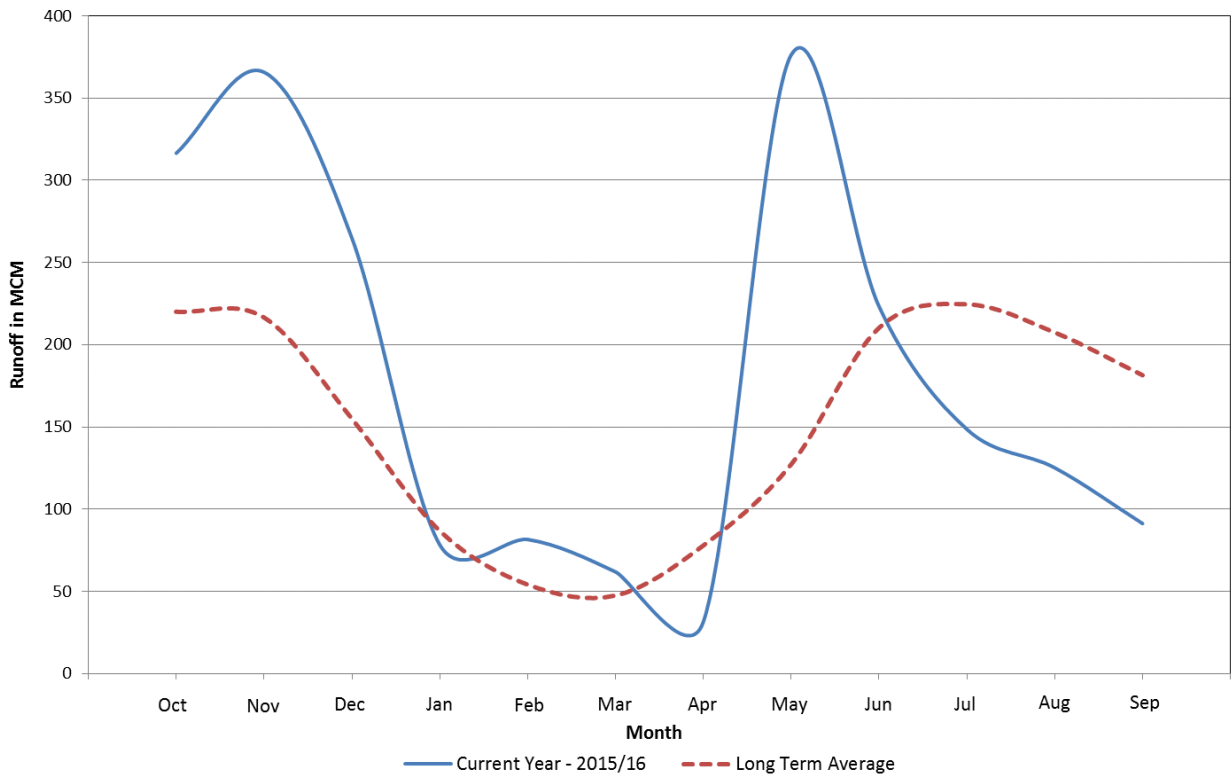
MONTHLY DISCHARGE IN NILWALA GANGA AT PITABEDDARA



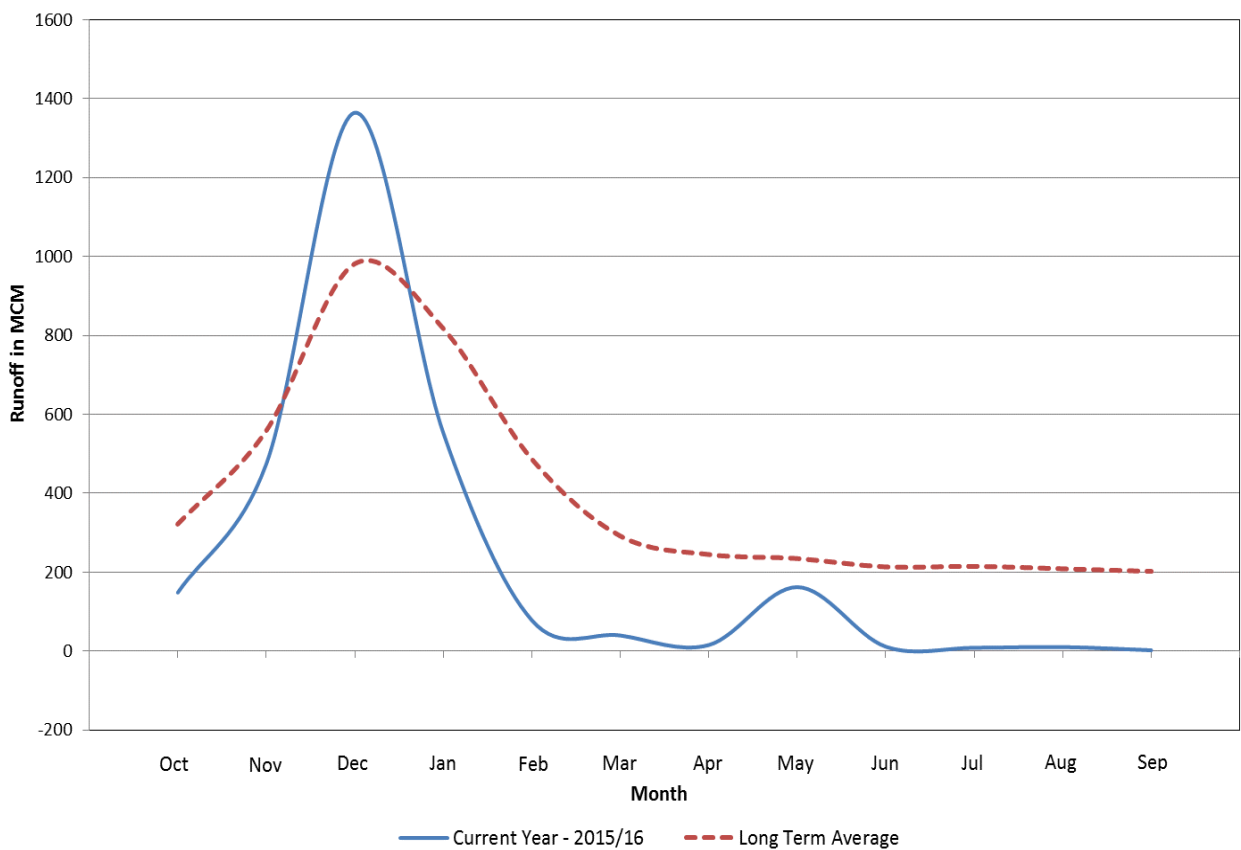
MONTHLY DISCHARGE IN KIRINDI OYA AT THANAMALWILA



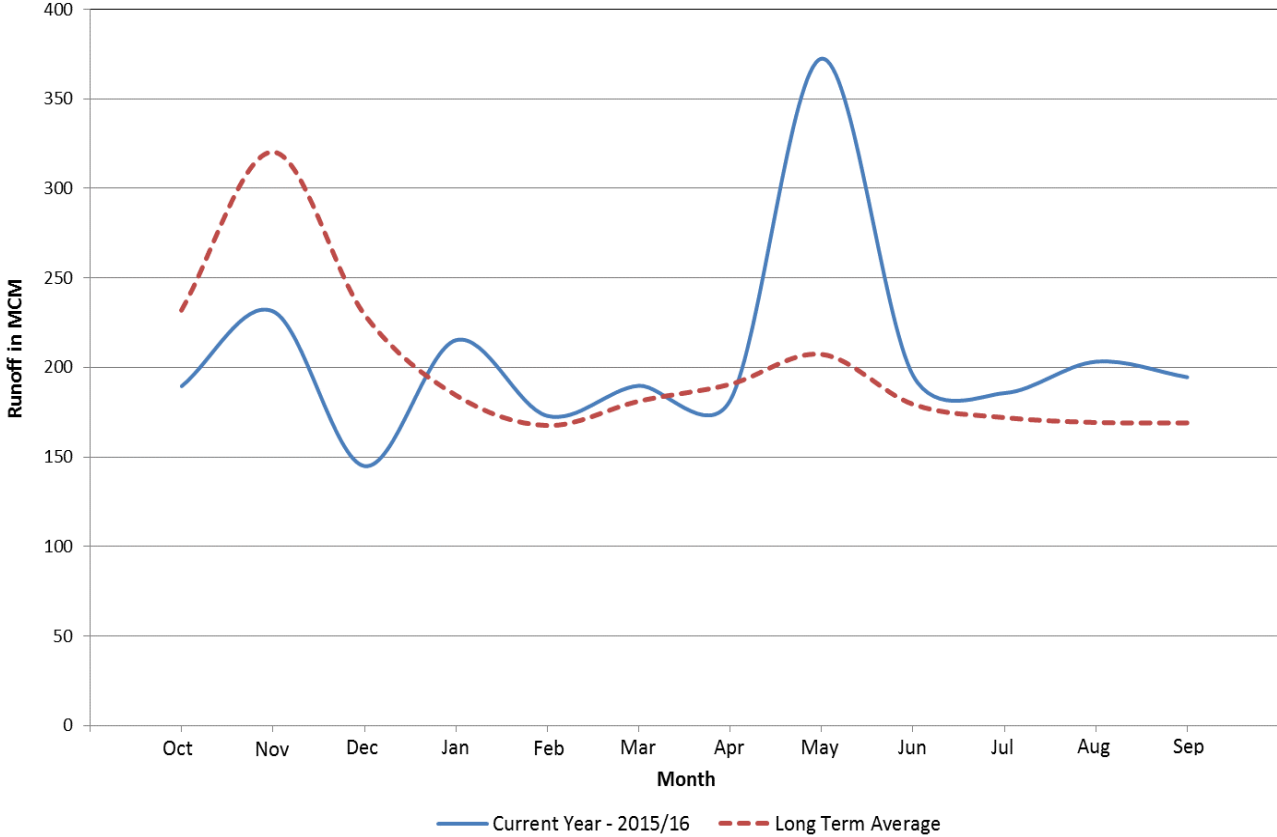
MONTHLY DISCHARGE IN MAHAWELI GANGA AT PERADENIYA



MONTHLY DISCHARGE IN MAHAWELI GANGA AT MANAMPITIYA

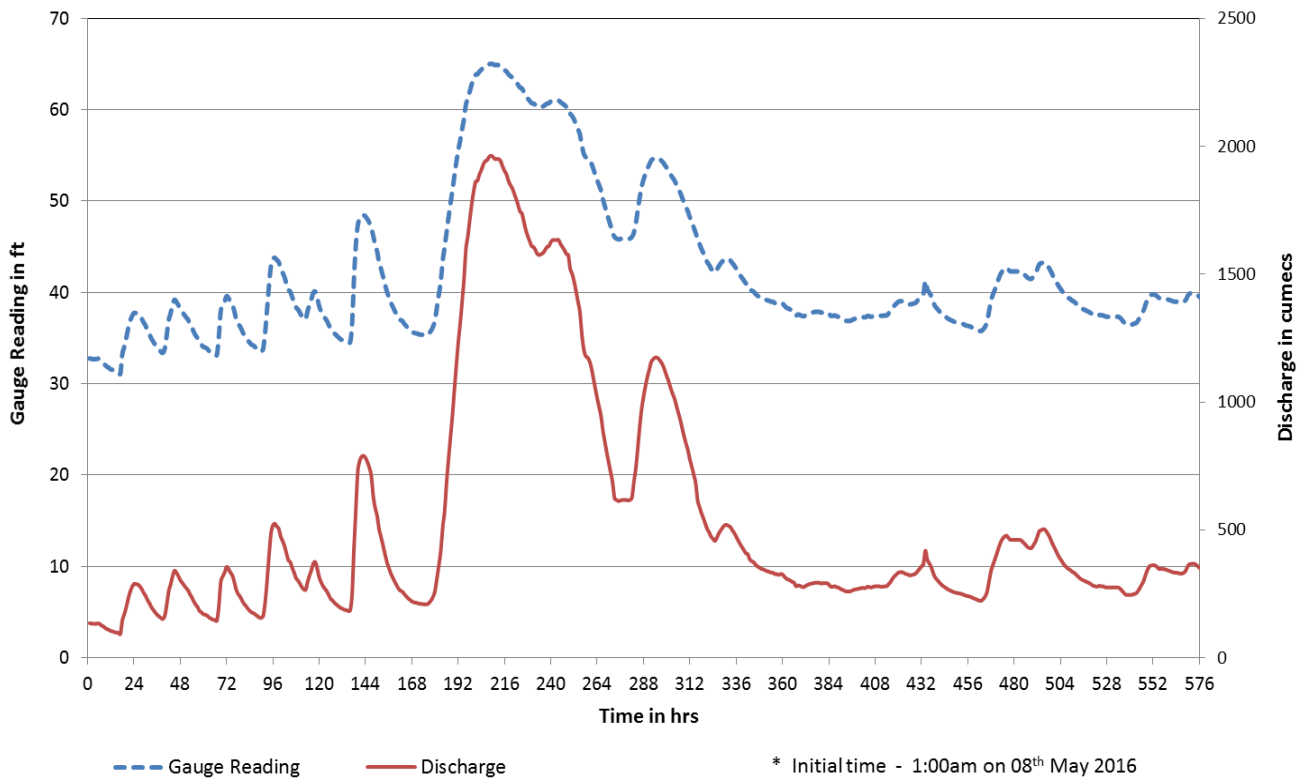


MONTHLY DISCHARGE IN DEDURU OYA AT CHILAW

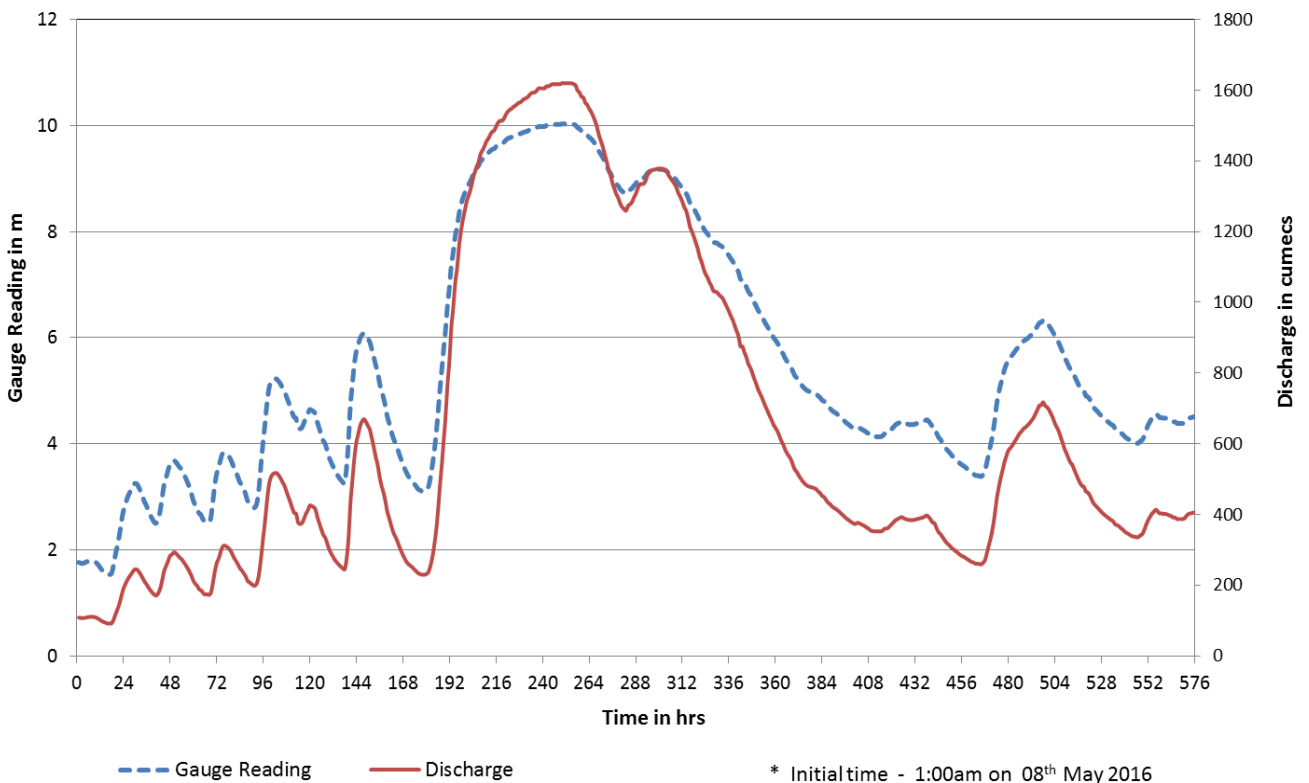


FLOOD HYDROGRAPHS

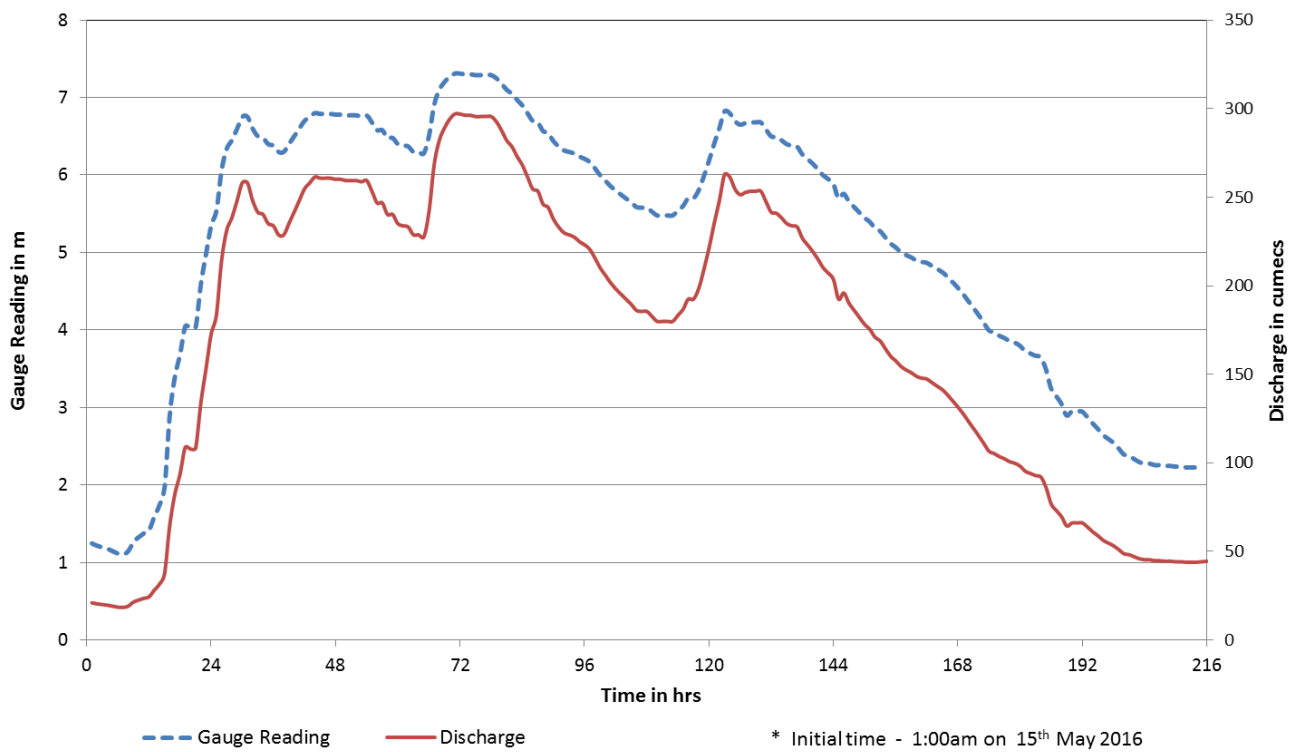
**Kelani Ganga at Glencourse
Maximum Flood During 2015/16
May 2016**



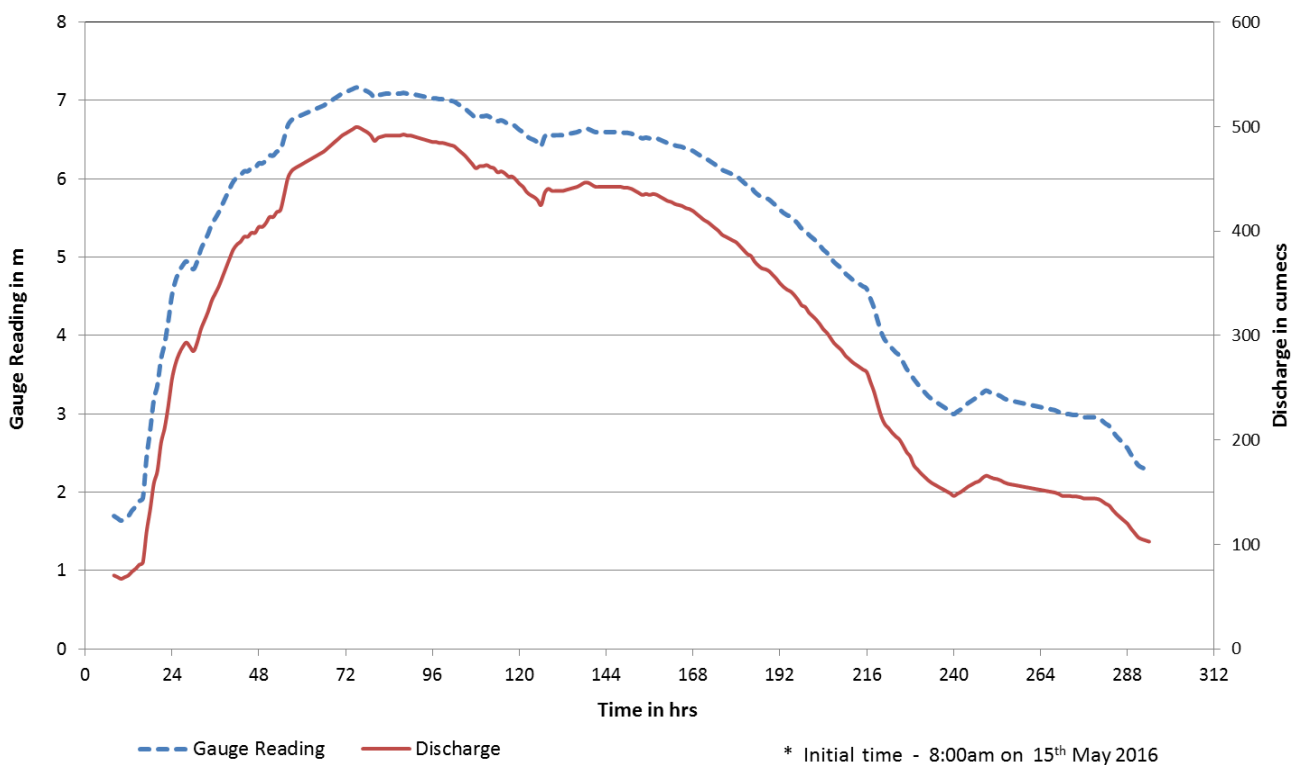
**Kelani Ganga at Hanwella
Maximum Flood During 2015/16
May 2016**



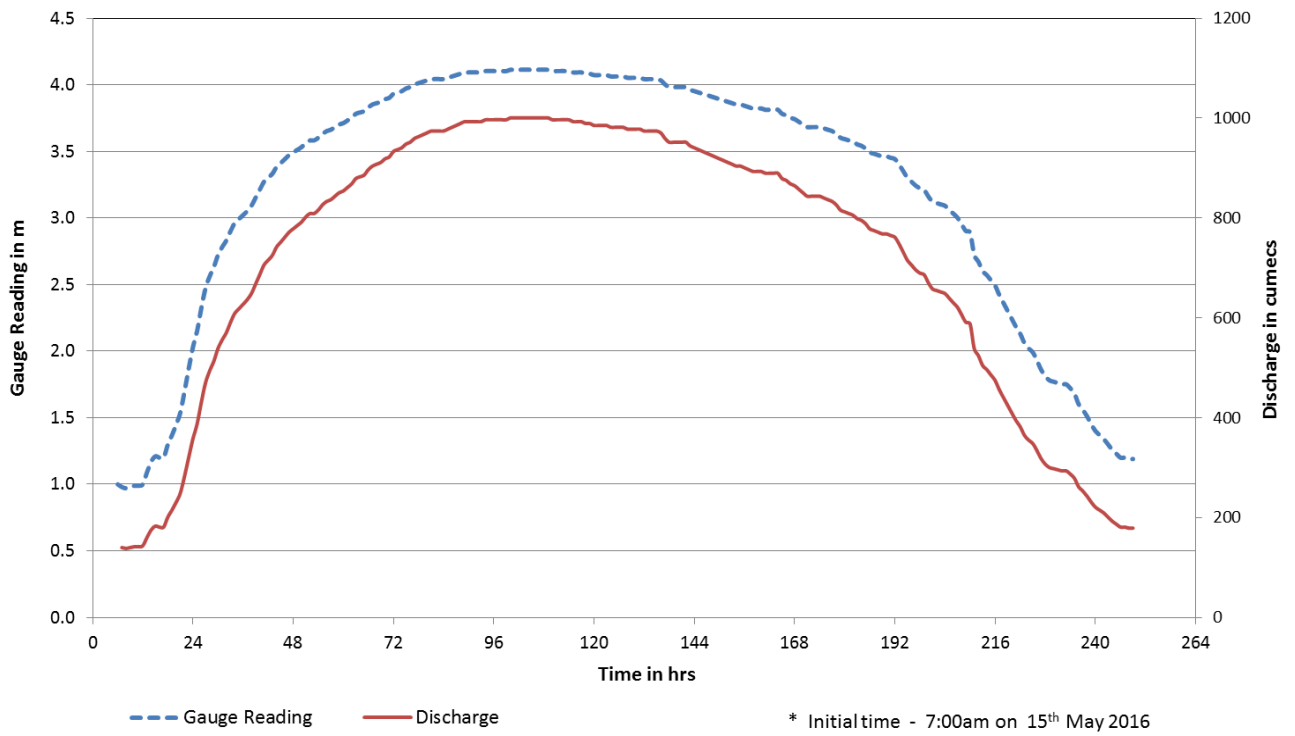
**Kalu Ganga at Rathnapura
Maximum Flood During 2015/16
May 2016**



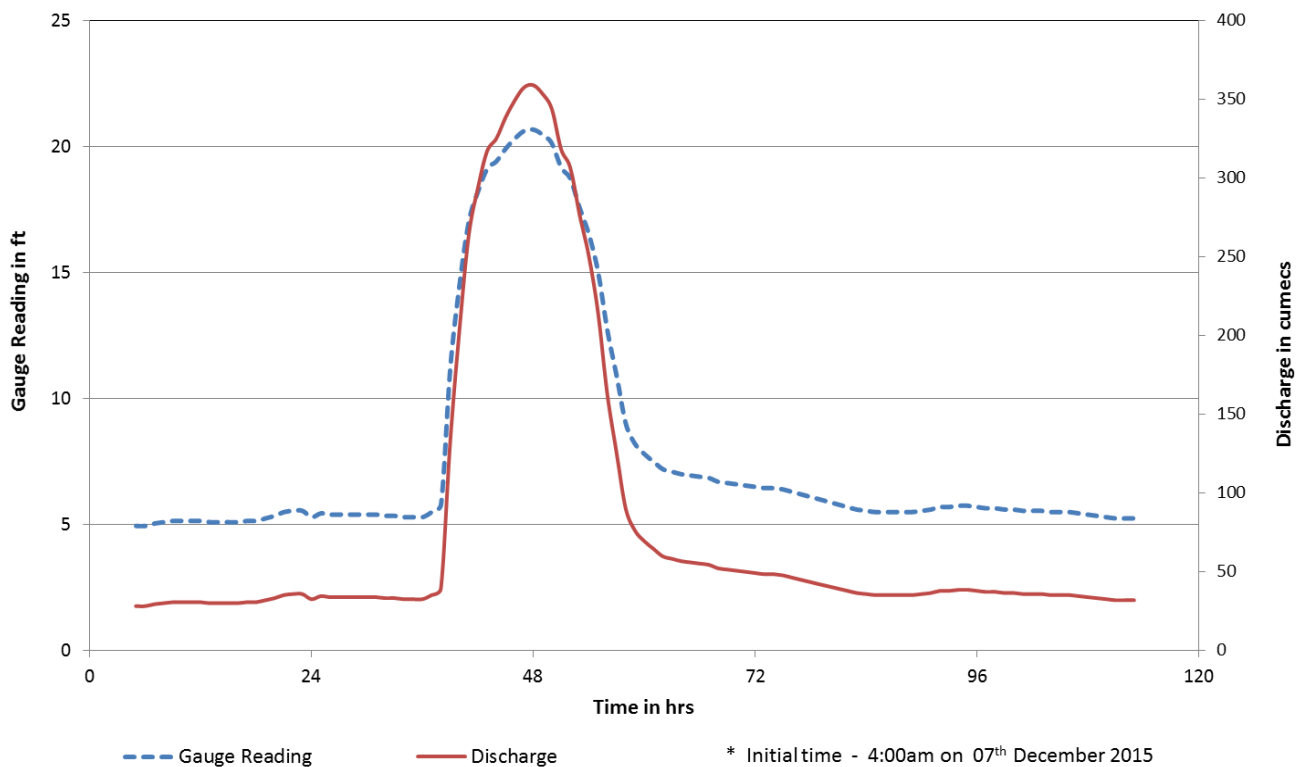
**Kalu Ganga at Millakanda
Maximum Flood During 2015/16
May 2016**



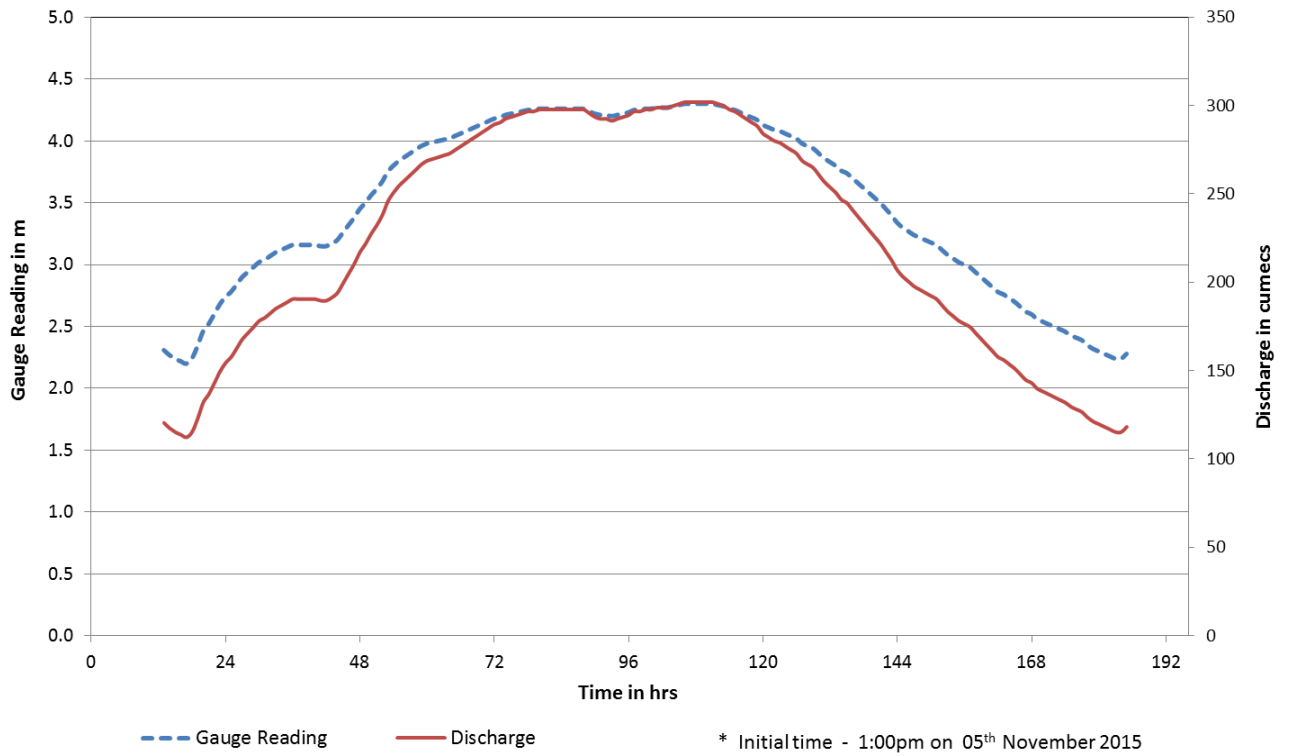
**Kalu Ganga at Putupaula
Maximum Flood During 2015/16
May 2016**



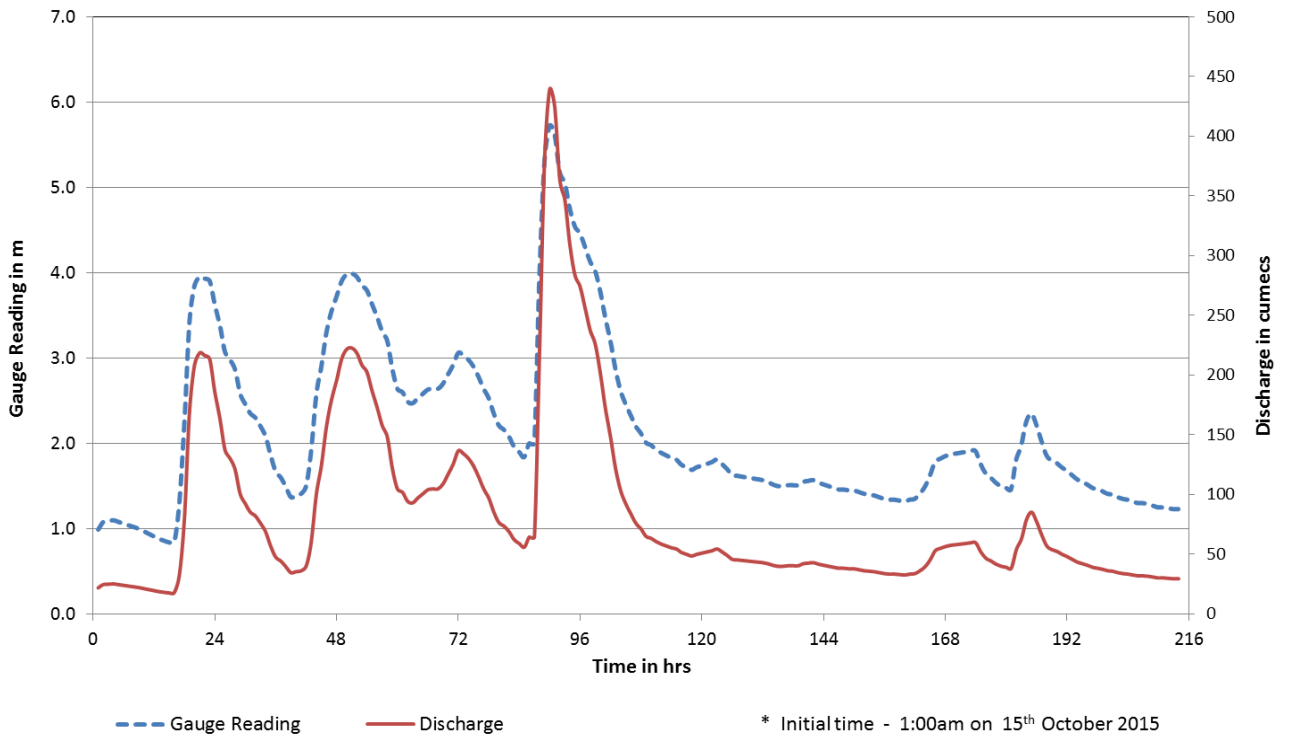
**Gin Ganga at Thawalama
Maximum Flood During 2015/16
December 2015**



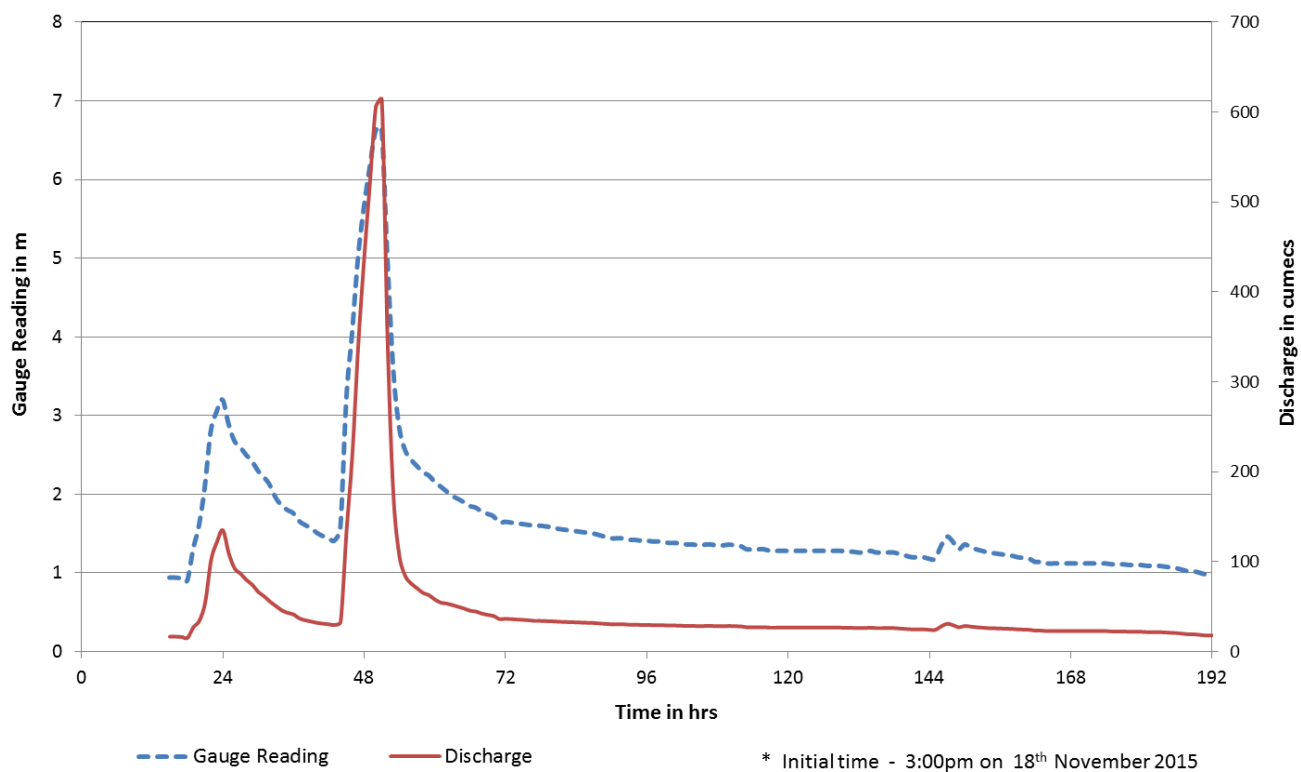
**Gin Ganga at Baddegama
Maximum Flood During 2015/16
November 2015**



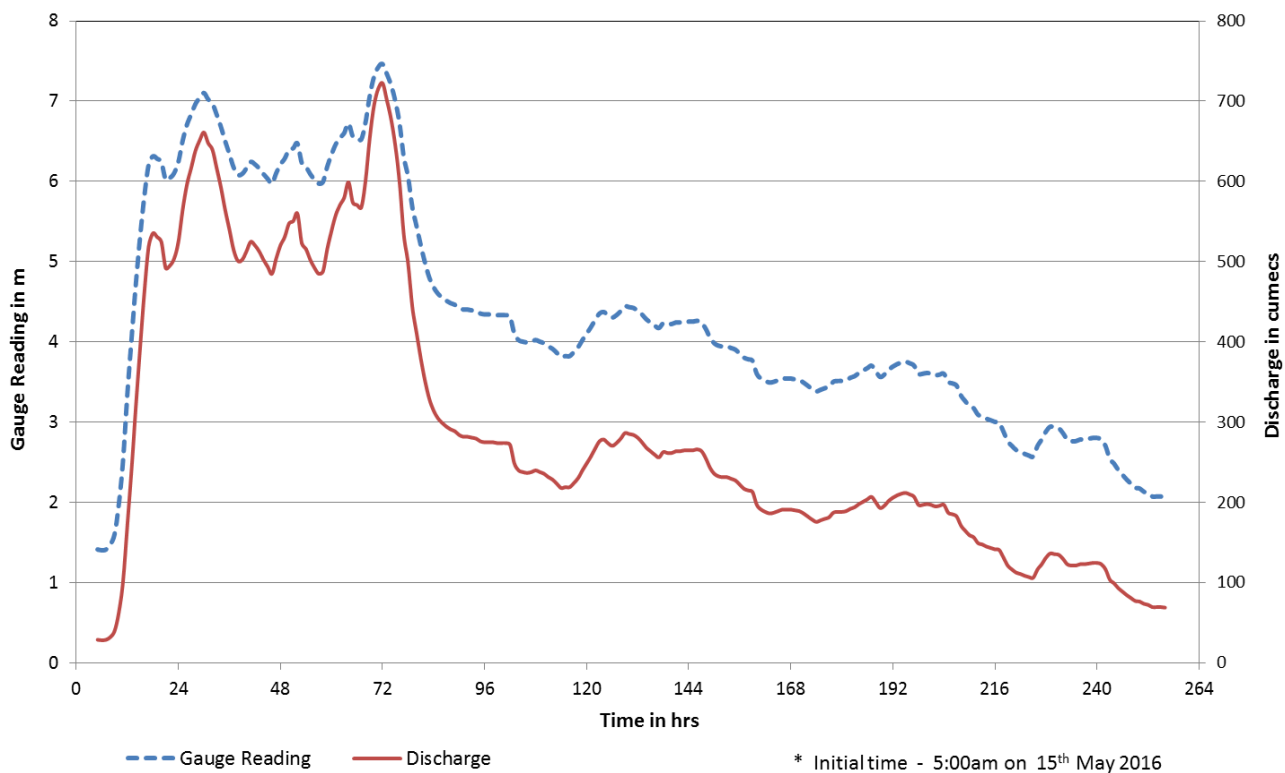
**Nilwala Ganga at Pitabeddara
Maximum Flood During 2015/16
October 2015**



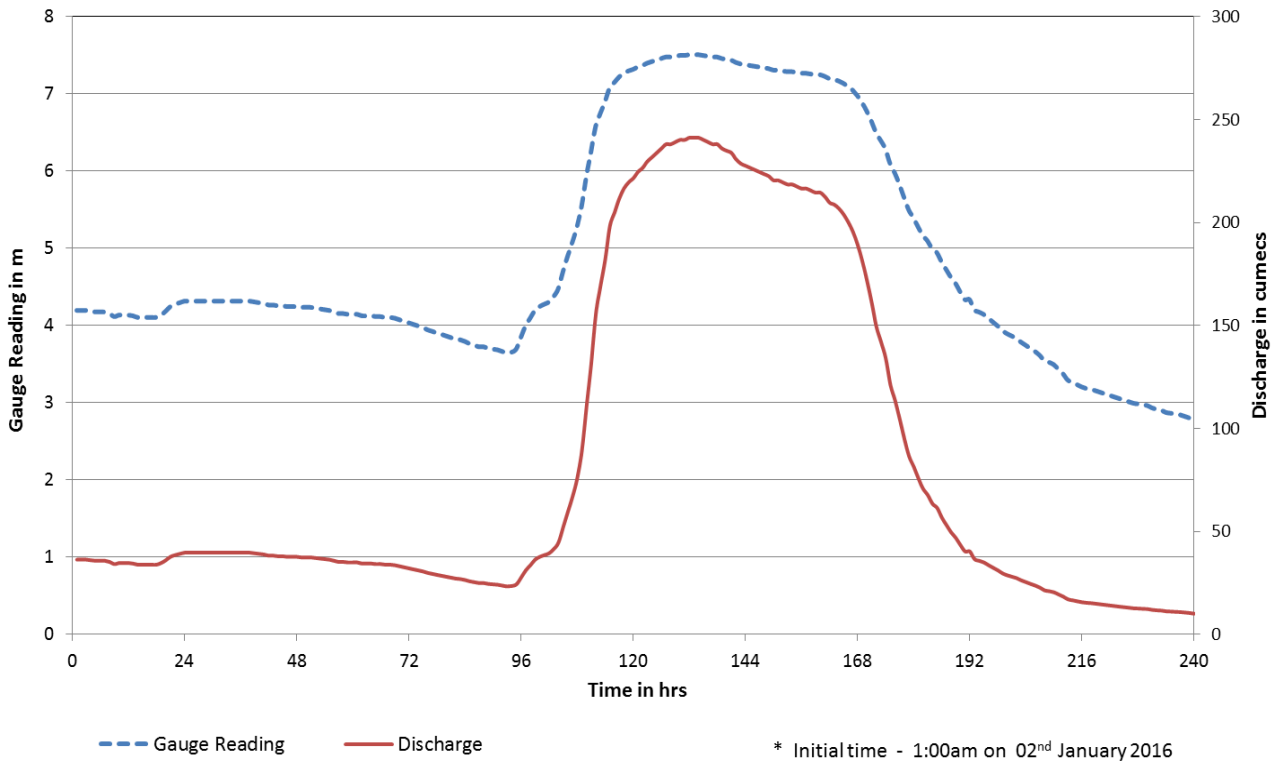
**Kirindi Oya at Thanamalwila
Maximum Flood During 2015/16
November 2015**



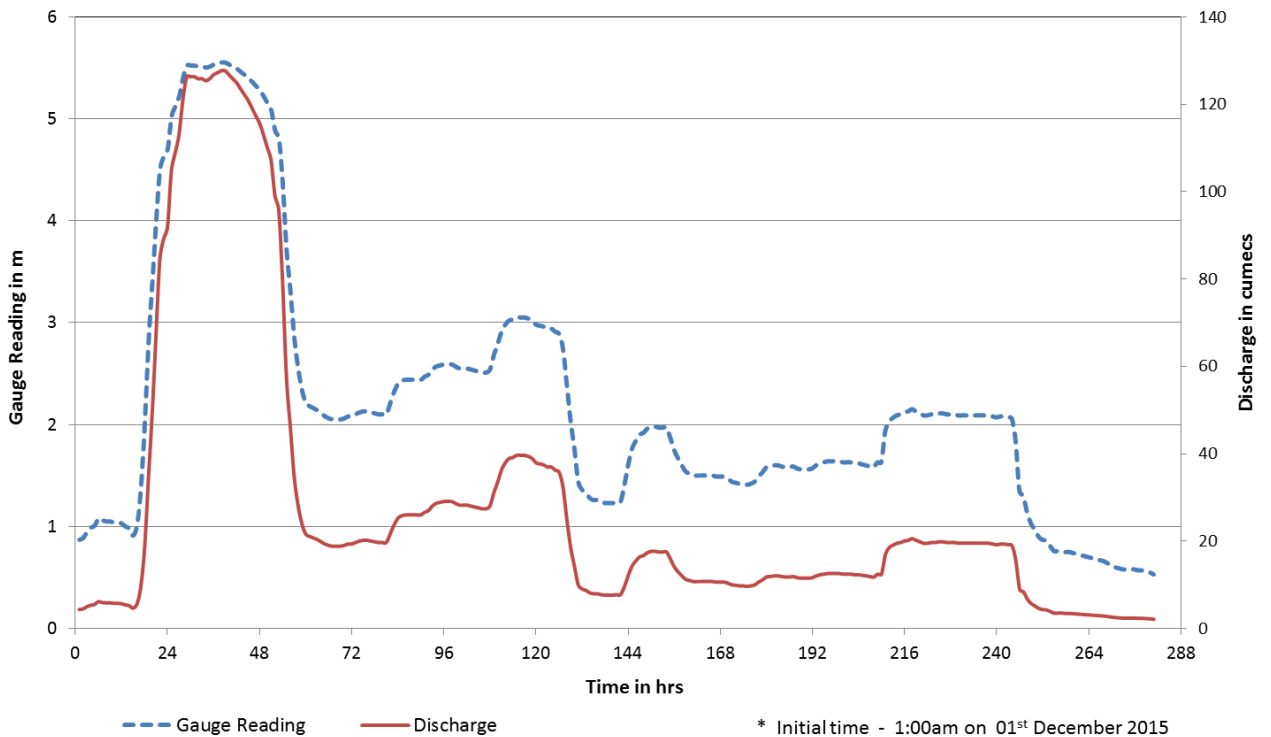
**Mahaweli Ganga at Peradeniya
Maximum Flood During 2015/16
May 2016**



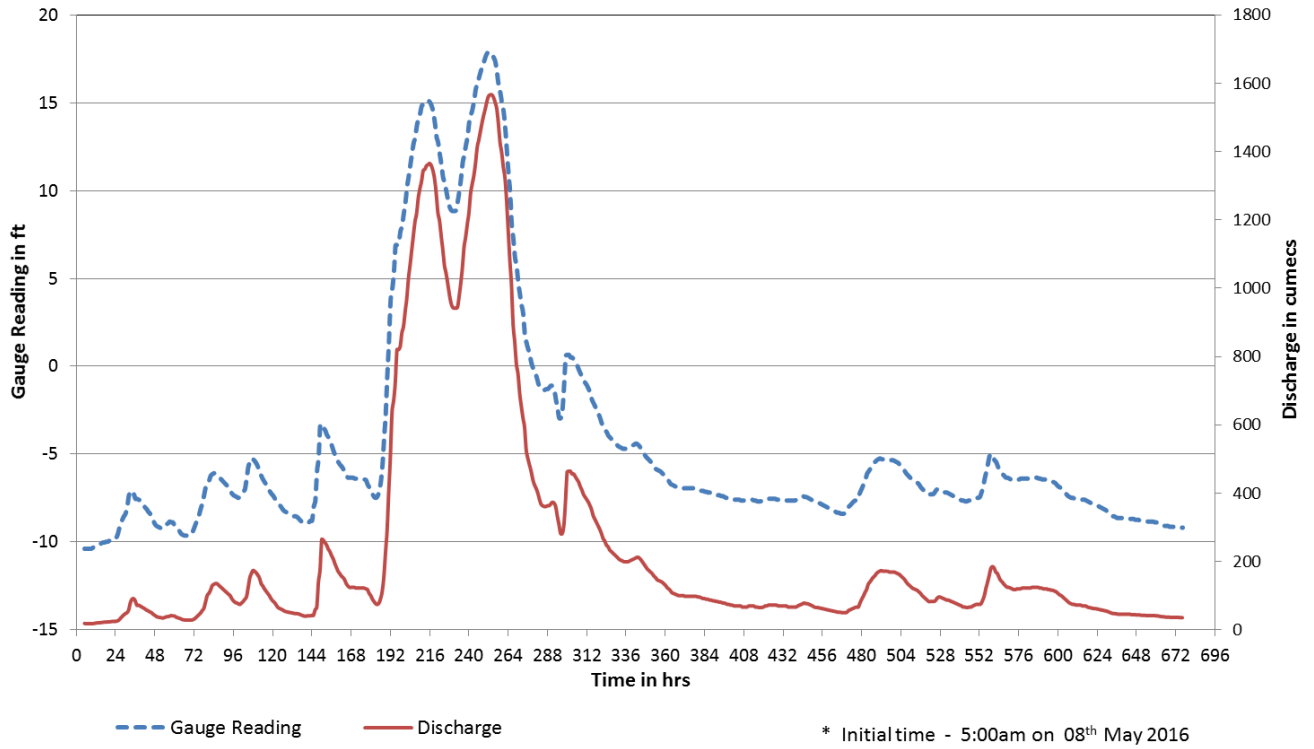
**Yan Oya at Horowpothana
Maximum Flood During 2015/16
January 2016**



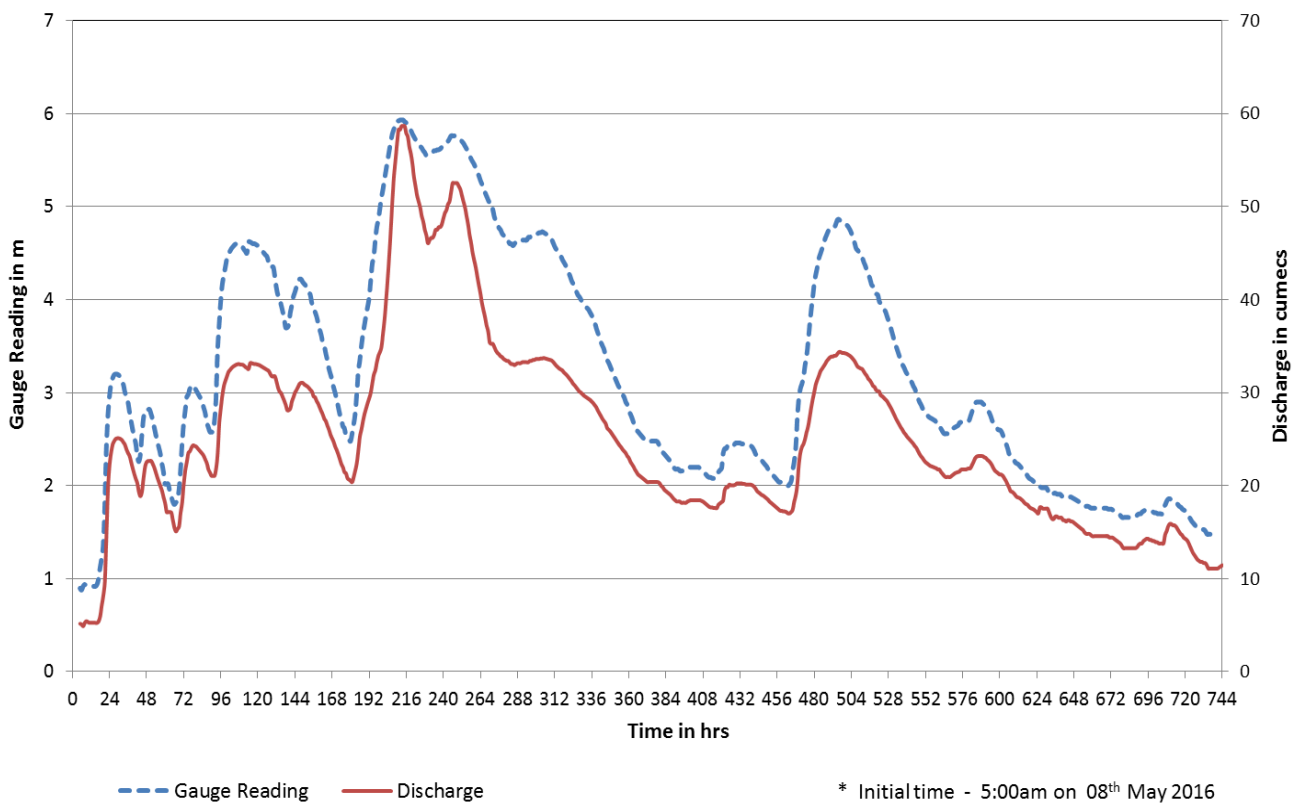
**Mee Oya at Galgamuwa
Maximum Flood During 2015/16
December 2015**



**Maha Oya at Badalgama
Maximum Flood During 2015/16
May 2016**



**Aththanagalu Oya at Dunamale
Maximum Flood During 2015/16
May 2016**



PART III

- **Flood Frequency Analysis and Selection of Suitable Design Flood for Kelani Flood Bunds.**
- **Development of Rainfall Intensity-Duration-Frequency (IDF) Curves for Colombo, Sri Lanka.**
- **Subgrade soil stabilisation through tree root water uptake.**

**Flood Frequency Analysis and selection
of suitable design flood for
Kelani Flood Bunds**

Flood Frequency Analysis and Selection of Suitable Design Flood for Kelani Flood Bunds

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Abstract

The necessity of Kelani Flood Protection Scheme Rehabilitation was highly emphasized after the recent flood in May 2016. The existing schemes which were constructed during the period from 1925 to 1960 had been designed for a wide range of protection levels depending on the situations prevailing and the purpose of protection. Now, these schemes have to be rehabilitated or reconstructed to meet the present requirements. Agricultural lands which were protected then have been converted to residential areas with urbanization and presently require higher level of protection.

The designers of the flood control works are of the opinion that the design return periods of new systems should be between 50 to 100 years. Historical data are available for fairly large periods with respect to all hydrometric stations on the Kelani River. Out of them Glencourse, Hanwella and Nagalagam Street river gauges are most important in analysing Kelani River floods. It is not possible to develop reliable rating curves for latter two stations due to tidal influence and therefore annual maximum water levels were used for frequency analysis. Even the water levels at those two stations show decreasing trends due to various reasons and the results of analysis vary with the data period selected.

Annual Maximum Flow series was selected for the frequency analysis of Glencourse hydrometric station. However, the accuracy of rating curves of this station is also affected by the physical changes of the river channel during the period considered.

According to final results, it was found that the Return Period of 1988/89 flood is between 50 to 75 years while the recent event (2016 flood) is between 15 and 20 years. Flood levels at several stations along the river had been recorded during the 1988/89 flood. Intermediate levels can be estimated using a suitable hydraulic model. The designer can select 1988/89 event as the design flood and use the hydrological parameters of the recent flood for modelling purposes.

1. River Basin Information

The Kelani is a one of major river systems in Sri Lanka. It takes the seventh place in respect to its extent of watershed (2340 km²) and becomes third with respect to water resources aspect (4225 MCM average annual discharge).

The river originates from the central hills near Adam's peak and traverses about 145 km through the south-western slopes of the Island to reach the sea near Colombo.

The Kelani catchment is entirely situated in the wet-zone of the country. The average annual rainfall of the catchment varies from 5700 mm in the upper catchment to 2300 mm in the lower basin. Major portion of the rainfall is received during the South-West monsoon period. However the catchment receives considerable amount of rainfall during the North-East monsoon and inter-monsoonal periods too.

Owing to the heavy rainfall and the steep terrain of the upper catchment, the lower basin of the Kelani River is subjected to heavy floods. The Flood plain is formed below Glencourse gorge which is about 53 km upstream of the sea outfall. Below Hanwella (about 35 km from sea), the flood plain becomes wider following the flat terrain.

2. Hydrometric Network and Availability of Data

Seven hydrometric stations are maintained on the Kelani River to record hourly water levels and rainfalls. Four of them, Nagalagam Street, Hanwella, Glencourse and Kitulgala are located on the main river while the other three (Norwood, Deraniyagala and Holombuwa) are on the tributaries. Nagalagam Street is the lowermost river gauging station which is situated about 4.2 km from the sea outfall. It has the longest record of data from 1920s to date. Hanwella and Glencourse stations were commenced in

1940s and 1950s respectively. At the beginning all these stations recorded daily or twice a day water levels. Gradually, the interval of record was decreased to 1 hour. There were large amount of missing data at the beginning. Nagalagam and Glencourse gauges have records of hourly water levels from the year 1963. Hanwella started hourly recording in January 1974. The Norwood station has the shortest period of data from 1984 onwards. River basin map with all these stations is presented in the Figure 1.

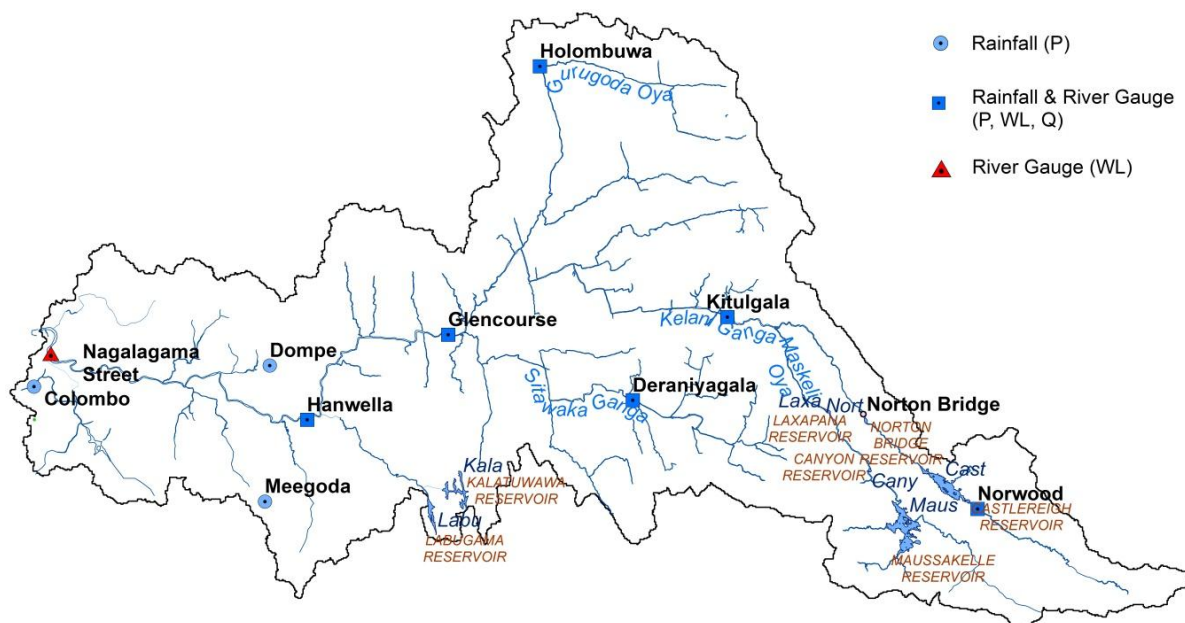


Figure 1: River Basin Map with the Locations of Gauging Stations

3. Historical Floods

Colombo floods have been categorized based on the water levels of the river gauge at Nagalagam Street. Before 1924, this station was only operated during flood periods to record the peak flood levels. Floods above 7 ft. MSL at Nagalagam Street are considered as major floods. Summary of information on historical major floods is presented in Table 1.

Year & Month	W.L. Max. ft. MSL	Year & Month	W.L. Max. ft. MSL	Year & Month	W.L. Max. ft. MSL
1837	13.50	1928 July	9.08	1947 August	12.85
1872	11.90	1930 May	10.91	1952 May	8.25
1891	9.80	1930 Oct.	9.83	1955 Oct.	8.00
1904	9.90	1933 May	9.95	1966 Sept.	8.67
1906	10.80	1936 May	9.43	1966 Oct.	9.00
1913	11.00	1937 May	10.33	1967 Oct.	9.17
1922	12.60	1939 May	9.35	1971 Sept.	7.33
1925	11.50	1940 May	11.00	1989 Jun	9.20
		1942 July	8.17	2016 May	7.65

Table 1. Historical Floods in the Kelani River Basin up to 2016 May Flood

4. Physical Changes in the River Basin during the Period of Observation

Following physical changes in the catchment during the period of observation may affect the stability and consistency of the time series data causing errors in the results of frequency analysis.

4.1 Water Resources Development Works, (Ref: Arumugam [1])

Water Resources Development and Flood Control projects implemented in the Kelani Basin for the last 100 years are listed below. A brief description of the work is given against each of them to understand the impact of those projects on the Hydrology of the river basin.

I. Maussakele Reservoir :-

This was constructed impounding the flow of the Maskeli Oya, a tributary of the Kelani Ganga, for the purpose of development of Hydropower.

Catchment Area	:	130 km ²
Storage Capacity	:	114.8 MCM (93000 acft)
Period of construction	:	From 1966 to 1969

II. Polpitiya Diversion Dam :-

Location	:	about 11 km downstream of Maussakele Reservoir
Capacity	:	0.14 MCM (115 acft.)
Period of construction	:	From 1966 to 1969

III. Castlereigh Reservoir :-

Impounded the flow of Kehelgamu Oya (also known as Hambantota Oya) carrying a discharge through a tunnel for hydropower generation at the Wimalasurendra power house at Norton.

Catchment area	:	115 km ²
Capacity	:	54 MCM (43830 acft)
Period of construction	:	From 1956 to 1958

IV. Norton Reservoir :-

The reservoir formed by the dam regulating the flow of the Kehelgamu Oya for diversion of storage for power generation at Laksapana hydropower plant.

Catchment area	:	168 km ² (including the catchment of Castlereigh)
Capacity	:	0.92 MCM (744 acft)
Year of construction	:	1950

V. Labugama Reservoir :-

Storage reservoir was constructed impounding the flow of the Wak Oya, lower tributary, for the supply of domestic water to the city of Colombo.

Catchment area	:	10 km ²
Capacity	:	8.89 MCM (7200 acft)
Year of completion	:	1886

VI. Kalatuwawa Reservoir :-

A storage reservoir was constructed impounding the flow in Kalatuwawa Ela, a branch of the Wak Oya, for augmenting the domestic water supply to the city of Colombo.

Catchment area	:	13.48 km ²
Capacity	:	17.78 MCM (14400 acft)
Construction Period	:	1958 -1960

4.2 Flood Protection Works (Ref. S. Arumugam)

A large number of drainage and flood protection schemes had been implemented during the period from 1930 to 1960 in order to protect low lands either side of the river from periodic flooding. Inflows from those areas are restricted during the flood periods and release through control gates after the river stages become normal. Impact of these schemes is also significant on the flood levels of the lower basin.

I. Kelani Ganga Minor Flood Protection Schemes in the Left Bank. :-

Eight Minor Flood Protection Schemes (Ambatale, Weliwita, Hewagamuwa, Bomiriya, Ranala, Hempita, Kaluaggala-Berendi, and Akarawita) were constructed on the Kelani Left Bank during the period from 1930 to 1960.

II. Minor Flood Protection Schemes on the Right Bank of Kelani Ganga :-

Ten Minor Flood Protection Schemes (Thalwaththa, Pattiwila, Yabaruwela, Pahuru Oya, Mora Ela, Welgamuwa, Giridara, Nikawela, Pugoda, Minimaru) were constructed on the Kelani Right Bank during the period from 1934 to 1959.

III. Colombo North Flood Protection Scheme :-

This scheme was implemented in the period of 1925 to 1926 with the objective of protecting low lands in Colombo North where densely populated and highly developed. This involved construction of two embankments (Railway embankment and the Kelani North Bund), with four pairs of Lock Gates and storm water drainage system.

IV. Colombo South Flood Protection Scheme :-

The scheme was completed in 1926 with the objective of protecting the city of Colombo from periodic flooding. A flood bund (Kolonnawa Bund) and four pairs of lock gates were constructed to prevent flood water entering to protected lands and evacuation of storm water at the receding part of the flood event.

4.3 Drainage Schemes

The impact of these schemes on the annual maximum flood levels of the Kelani River (lower reach) should not be neglected.

I. Colombo South Drainage Scheme :-

This was implemented to drain the swamps in Kotte, Nawala, Baththaramulla and Thalangamuwa areas.

II. Muthurajawela Scheme :-

Muthurajawela is a marshy land about 6000 acres in extent situated along the western coast lying between the Kelani Ganga and Negombo Lagoon. This scheme was not successful and now in abandoned status.

In addition to above several drainage works and salt water prevention and flood protection works have been implemented in the Kelani Lower basin during the period from 1925 to 1960.

5. Degradation of river bed

Degradation of river bed due to sand mining is a serious issue of the Kelani River. This has adverse effects such as bed erosion, bank erosion, depletion of water table, salt water intrusion etc. This may cause Local reduction of flood levels due to enlargement of river channel. However the discharge capacity of a river highly depends on the hydraulic gradient of the water profile throughout the river and the conditions of the estuary. Therefore, the overall impact of sand mining on flooding is also unfavorable.

Figure 2 shows the long term degradation of river bed on the longitudinal profile from Hanwella to Sea Outfall. Hanwella, Glencourse and Deraniyagala hydrometric stations have been badly affected by sand mining causing reduction of water levels, especially during low flows.

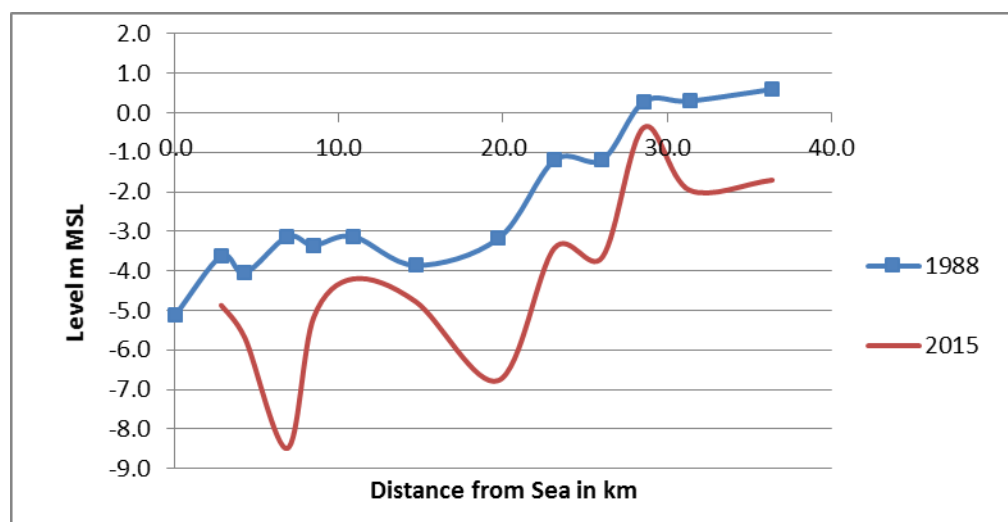


Figure 2: Bed Level Variation, Kelani River from Hanwella to Sea outfall

6. Adequacy and Suitability of Data Series for Frequency Analysis

Hydrology Division has recorded water levels for fairly long periods with respect to all hydrometric stations (Annex 1). However, according to previous chapters, the Kelani River basin has undergone drastic changes during the period from 1925 to 1960 due to implementation of a large number of reservoir projects and flood control works. The impact of individual scheme may not be significant but the overall effect shows high influence on the annual flood peaks of the lower reach of the river.

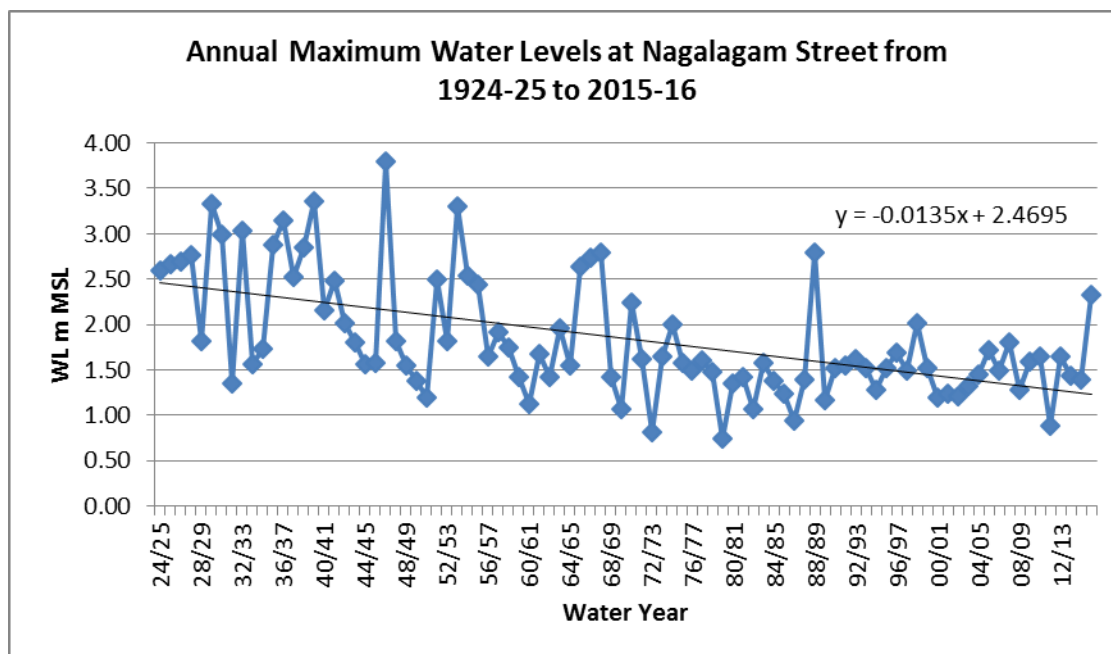


Figure 3: Change of Annual Flood Peaks at Nagalagam Street

The total data set (from 1924-25 to 2015-16) at Nagalagam Street was not much suitable for frequency analysis since appearing significant trend. A similar behavior was shown in the data from Kithulgala, Glencourse and Hanwella also. Sub catchments above Deraniyagala and Holombuwa still remain in the natural status and hence such trends are not appeared.

Most of the construction works in the Kelani basin had completed by 1960. The effect of Maussakele reservoir which was constructed in 1970s was not much significant on Nagalagam Street water levels since the reservoir is situated far upstream from the gauge location. Hence the data from water year 1960/61 to 2015/16 was selected for statistical analysis. Even during this period the data from Nagalagam Street shows small trend as appearing in Figure 4 below.

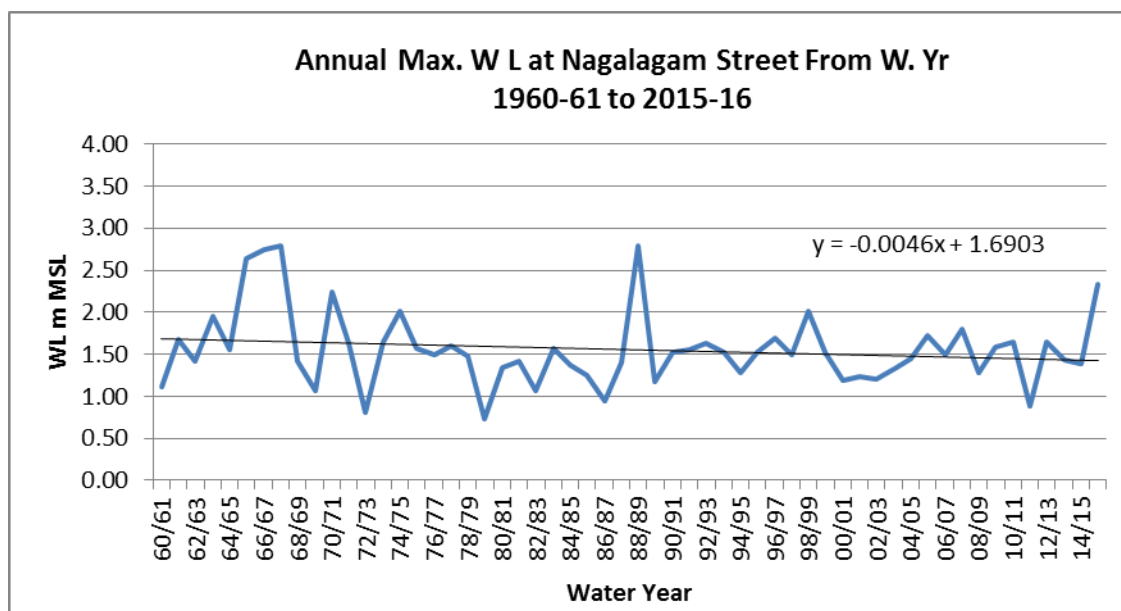


Figure 4: Nagalagam Street, Annual Flood Peaks from 1960-61 to 2015-16

For other stations, only the data from 1970 onwards were considered for the analysis depending on the intervals of recording and the continuity of data. Even with the short series, significant trends were appeared in the data from, Hanwella and Glencourse. This may be due to continuous sand mining in the river resulting depletion of river bed level and enlargement of the river channel.

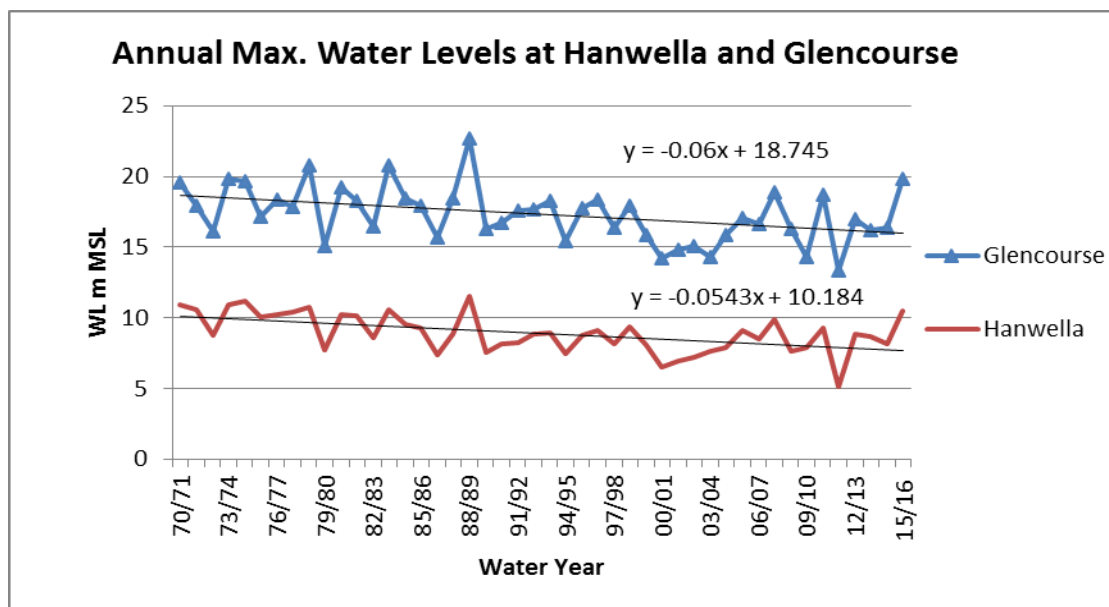


Figure 5: Hanwella and Glencourse Flood Peaks show significant trends

7. Flood Frequency Analysis with Annual Maximum Flood Levels using Gumbel Extreme Value Distribution

The 'Gumbel Distribution of extreme values' denoted by the following equation was used for the frequency Analysis at all 7 stations.

$$F(X_N < X_r) = \exp\{-\exp(-y)\}$$

- Where X_N = the maximum X from a sample size N,
 X_r = a reference value of X_N
 Y = the reduced Gumbel Variate

Graphical presentation of the analysis of Nagalagam Street is presented in Figure 6 and the summary of results in Table 2.

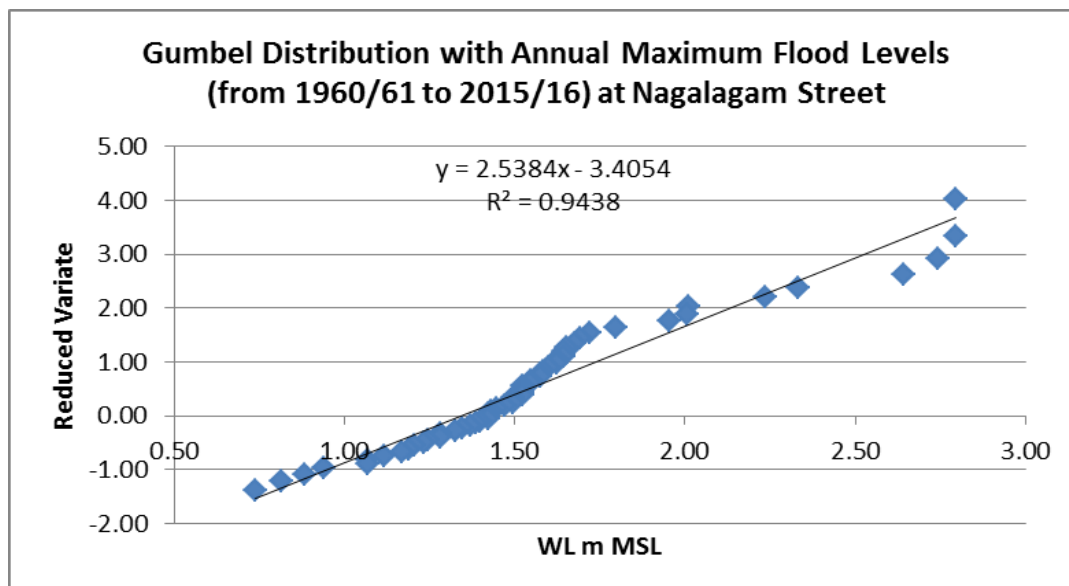


Figure 6: Gumbel Distribution with Water Levels at Nagalagam Street

However it is appeared from the chart this data set is not perfectly fit with the mathematical function. This may be due to the influence of tidal variation of the sea which is only about 4 km downstream to the station.

Return Period (T)	Probability of Exceedance $P = 1/T$	Probability of Non-Exceedance $q = 1-P$	Reduced Variate $Y = -LN(-LN(q))$	Corresponding WL m	Historical Floods Comparable
2	0.50	0.50	0.367	1.49	
5	0.20	0.80	1.500	1.93	
10	0.10	0.90	2.250	2.23	
15	0.07	0.93	2.674	2.39	2015/16
20	0.05	0.95	2.970	2.51	
25	0.04	0.96	3.199	2.60	
50	0.02	0.98	3.902	2.88	1988/89
75	0.01	0.99	4.311	3.04	
100	0.01	0.99	4.600	3.15	1936/37
150	0.01	0.99	5.007	3.31	1929/30
200	0.01	1.00	5.296	3.43	1939/40
500	0.00	1.00	6.214	3.79	1946/47

Table 2. The Results of the Flood Frequency Analysis at Nagalagam Street

Similarly statistical analysis of data series at other two stations was carried out with the same theoretical distribution. Data period selected and the lengths of record used for analysis are tabulated below (Table 3).

Hydrometric Station	Data period selected	Data Period years
Nagalagam Street	From 1960/61 to 2015/16	56
Hanwella	From 1984/85 to 2015/16	32
Glencourse	From 1970/71 to 2015/16	46

Table 3. Data Periods selected for the Analysis

Data series from Glencourse Station was fairly well fitted to the theoretical distribution as shown in the figures 8. However, similar to Nagalagam Street, the data from Hanwella (Fig. 7) shows a pattern of deviation from the theoretical function. These data are influenced not only by the tidal variation but also by the operation of the Salinity Barrier at Ambathale which is about 20 km downstream of the gauging station.

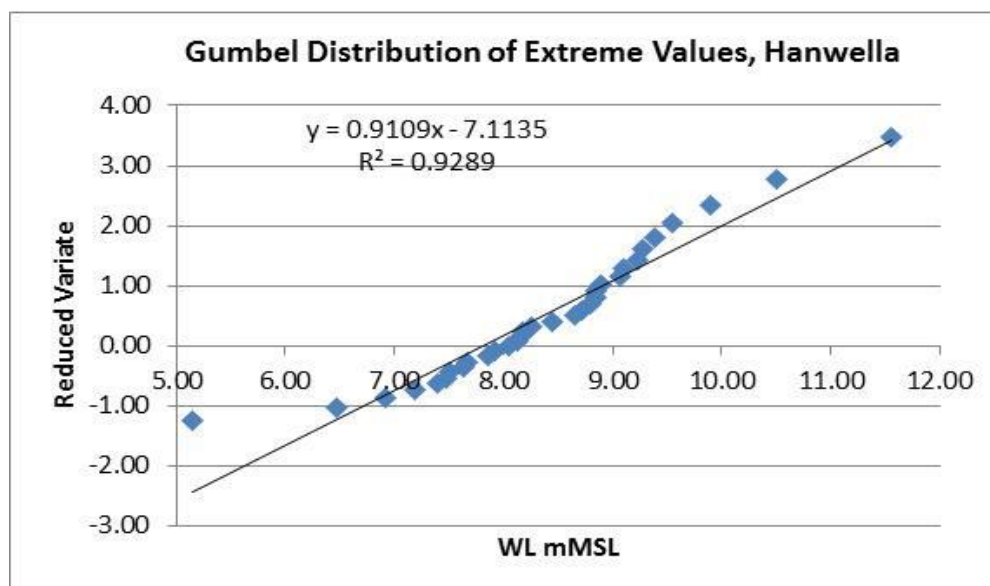


Figure 7: Gumbel Distribution with Annual Max. WL at Hanwella

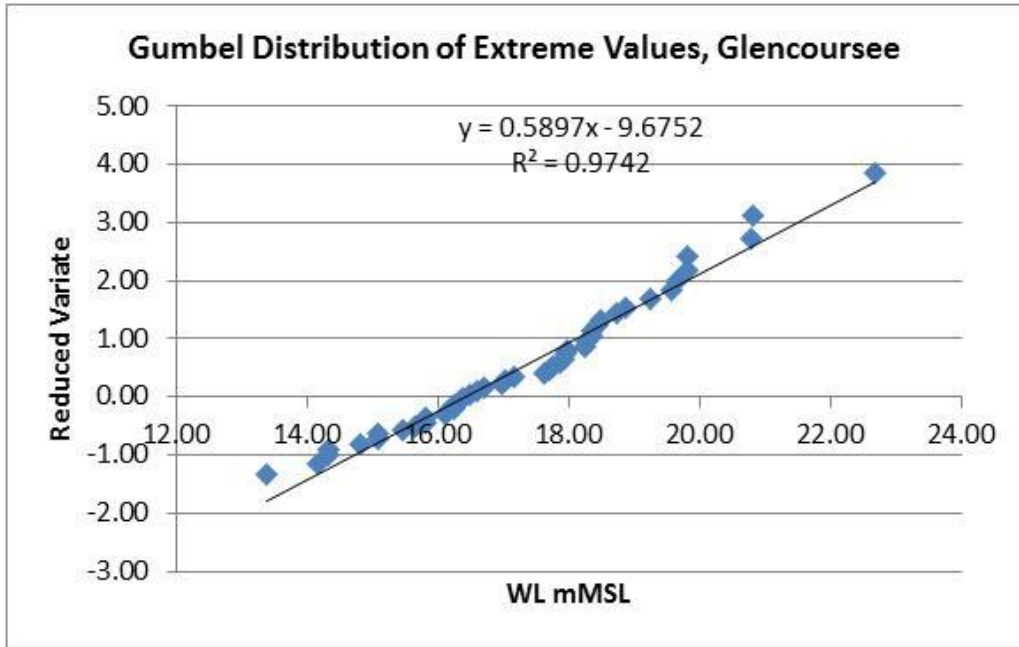


Figure 8: Gumbel Distribution with Annual Max. WL at Glencourse

8. Flood Frequency Analysis with Annual Maximum Discharge using Gumbel Extreme Value Distribution.

Flood Frequency Analysis at Glencourse was repeated with the annual maximum flow series of the same data period using the same theoretical distribution as described below.

A rating curve could be developed with the recent (2004 to 2017) flow measurements to a reasonable accuracy for this station. The problem was how it is adopted to the past periods for which such measurements were not available. According to evidence available, the cross section of the station had undergone drastic changes in the period from 1960 to 2000 (Fig. 9). The heavy erosion during 1988/89 flood was the most significant change. In the absence of reliable ratings for this period, the same rating curve developed for the recent period (From year 2000 onwards) was adopted for the past periods by changing the H_0 (Level at zero discharge) values.

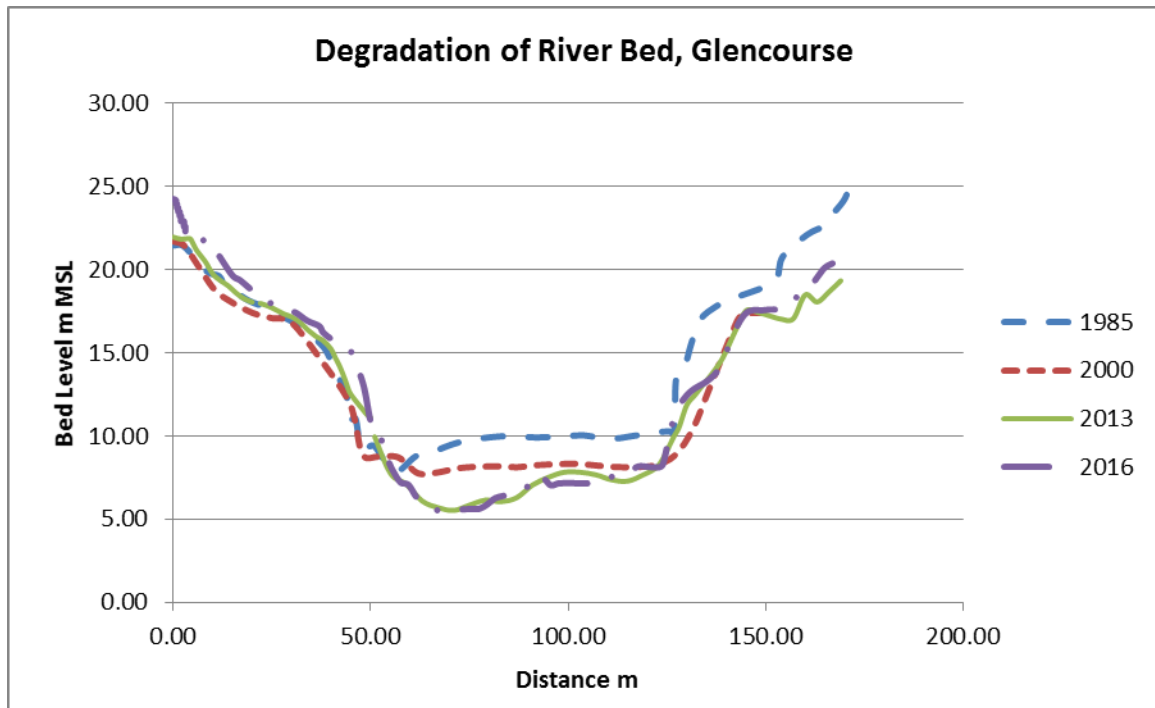


Figure 9: River Bed Variation, Glencourse

Gumbel distribution of the Annual Maximum Discharges at Glencourse is graphically presented in the Figure 10.

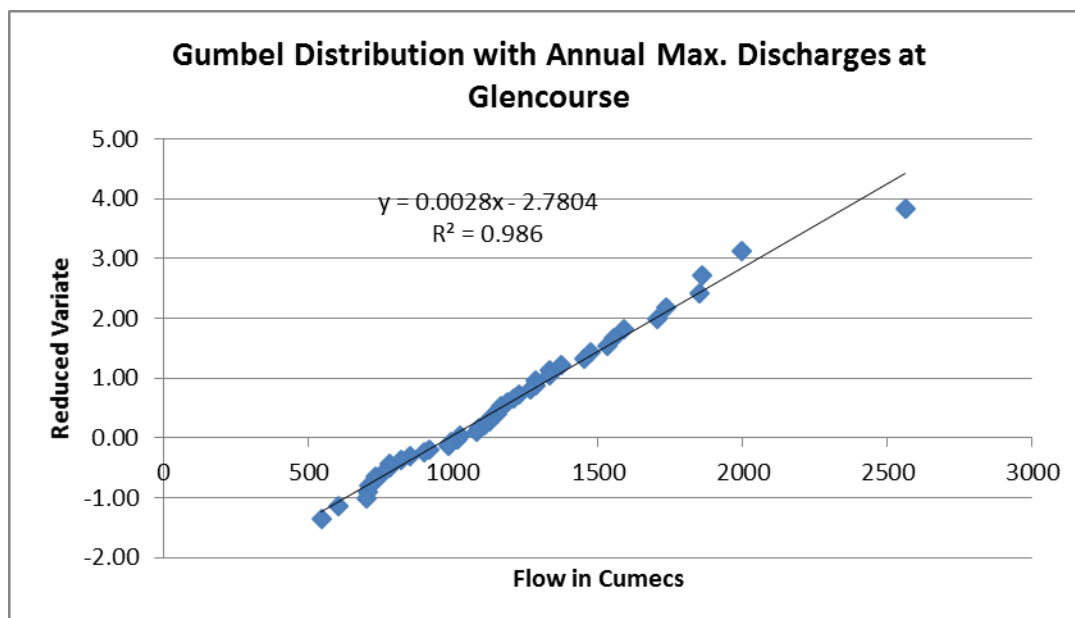


Figure 10 : Gumbel Distribution with annual Max. Discharges at Glencourse

Extreme Values corresponds to different return periods as computed above are summarized in Table 4. Flood Levels at all 3 stations are given in m with reference to Mean Sea Level and the discharges in m³ per second.

Return Period	Nagalagam Street with Annual Max. WL	Hanwella with Annual Max. WL	Glencourse with Annual Max. WL	Glencourse with Annual Max. Discharge
2	1.49	8.05	17.03	1123.90
5	1.93	9.27	18.95	1528.69
10	2.23	10.08	20.22	1796.70
15	2.39	10.54	20.94	2053.78
20	2.51	10.86	21.44	2135.33
25	2.60	11.10	21.83	2305.95
50	2.88	11.86	23.02	2386.55
75	3.04	12.30	23.72	2532.57
100	3.15	12.61	24.21	2635.91
150	3.31	13.05	24.90	2781.32
200	3.43	13.36	25.39	2884.36

Table 4. Extreme Values correspond to different Return Periods at 3 hydrometric stations

9. Return Periods correspond to 1989 and 2016 Floods

It is worthwhile to discuss the return periods of the recent major flood in May 2016 and the previous flood in June 1989 which was subjected for much attention due to the severe damages and loss of properties in both cases. There was no major flood recorded between those two events. However, the Kelani River basin had been subjected to more frequent flooding before 1970 (Table 1). When comparing those two floods (1989 and 2016) it is obvious that the former one is much higher than the latter in respect of the flood levels at all stations. But the damages are somewhat higher in the latter. This is mainly due to the irregular development works taken place in the river basin during the recent past. Secondly the retardation of flood wave due to various constructions on the river by various organizations and private parties. The Salinity Barrier at Ambatale, which was constructed by National Water Supply and Drainage Board, was the most severe obstruction. The flood levels, in May 2016, at

the just upstream of this structure were even higher than the 1989 flood levels [2]. The duration of inundation was also longer than the 1989 flood.

Therefore it is very important to study the hydrological aspects of both floods in designing the flood control works for the Kelani Basin.

Station	Nagalagam Street	Hanwella	Glencourse
1988/89 Flood Level m MSL	2.79	11.56	22.68
Return Period years	50	50	50
20015/16 Flood Level	2.33	10.51	19.81
Return Period (with WL) years	15	15	10
1988/89 Peak Discharge cumecs	-	-	2562
Return Period (with Q) years	-	-	75
2015/16 Discharge, cumecs	-	-	1997
Return period (with Q) years	-	-	20

Table 5. Return Periods of the floods in 1988/89 and 2015/16

Flood frequency analysis is normally done with discharges. The results (Return Periods) got with discharges at Glencourse are higher than the values got with the analysis of water levels. It is recommended to choose the return periods of 75 and 20 for 1989 and 2016 flood with respect to Glencourse station. However it was not possible to do such analysis for Hanwella and Nagalagam Street due to absence of reliable rating curves. Further, the Flood Levels are more important in designing flood protection levees which is the urgent requirement in the Kelani lower basin. Therefore flood frequencies done with water levels more appropriate for Hanwella and Nagalagam Street.

Further, the results of statistical analysis normally vary with the theoretical distribution adopted and also with the data period. 1989 flood is recommended to be used as the Design Flood for flood protection works.

10. Conclusion and Recommendations

When considering the Kelani lower basin (below Avissawella), the return periods 1989 and 2016 floods were between 50 - 75 and 15-20 years respectively. Observed flood level correspond to 1936-37 event at Nagalagam Street is comparable to 100 year flood level. However, only daily water levels were recorded at that period and not possible to get full hydrograph at any of the stations. Further, the upstream river gauges were not in operation and hence it is not possible to develop hydraulic models to simulate flood level variation along the longitudinal profile. The level difference between 1988-89 flood and 1936-37 is only about 0.35 m at Nagalagam Street. Therefore it is recommended to use 1988-89 flood as the design flood and keep suitable free board in order to cater for 100 year flood.

Important hydrological data with respect to 1989 flood had been recorded by Hydrology Division including the flood peaks at 10 stations (Glencourse, Hanwella, Kaduwela, Ambatale, Kelanimulla, Wennawaththa, Kotuwila, Nagalagam Street and Modara) in between Avissawella and the Sea Outfall. The intermediate levels can be computed by using a suitable hydrodynamic model.

References :

1. **Arumugam.S., Water Resources of Ceylon, 1969**
2. **Dharmasena. G.T., Floods in Kelani Ganga, Hydrological Annual 1988/89**

Annex I :

Kelani River, Annual Maximum Water Levels and discharges

Nagalagam Street			Glencourse				Hanwella	
W Yr	WL ft	WL mMSL	W Yr	WL ft	WL mMSL	Dis. Cumecc	W yr	WL mMSL
24/25	8.50	2.59						
25/26	8.75	2.67						
26/27	8.83	2.69						
27/28	9.08	2.77						
28/29	5.95	1.81						
29/30	10.91	3.33						
30/31	9.83	3.00						
31/32	4.41	1.34						
32/33	9.95	3.03						
33/34	5.14	1.57						
34/35	5.70	1.74						
35/36	9.43	2.87						
36/37	10.33	3.15						
37/38	8.30	2.53						
38/39	9.35	2.85						
39/40	11.00	3.35						
40/41	7.08	2.16						
41/42	8.15	2.48						
42/43	6.60	2.01						
43/44	5.90	1.80						
44/45	5.15	1.57						
45/46	5.17	1.57						
46/47	12.46	3.80						
47/48	5.98	1.82					47/48	10.44
48/49	5.08	1.55					48/49	10.52
49/50	4.50	1.37					49/50	9.66
50/51	3.92	1.19					50/51	9.71
51/52	8.21	2.50					51/52	11.13
52/53	5.98	1.82					52/53	10.70
53/54	10.83	3.30					53/54	9.45
54/55	8.33	2.54					54/55	11.03
55/56	8.00	2.44					55/56	11.26
56/57	5.42	1.65						
57/58	6.29	1.92						
58/59	5.75	1.75					58/59	10.42
59/60	4.67	1.42	59/60	54.00	16.46	847.03	59/60	8.87
60/61	3.67	1.12	60/61	52.10	15.88	740.77	60/61	8.59
61/62	5.50	1.68	61/62	53.00	16.15	790.28	61/62	9.96
62/63	4.67	1.42	62/63	54.00	16.46	847.03	62/63	12.40
63/64	6.42	1.96	63/64	62.20	18.96	1381.32	63/64	12.40
64/65	5.08	1.55	64/65	52.70	16.06	773.61	64/65	10.04
65/66	8.67	2.64	65/66	40.15	12.24	217.28	65/66	11.05
66/67	9.00	2.74	66/67	67.60	20.60	1800.28	66/67	11.03
67/68	9.17	2.79	67/68	66.05	20.13	1674.57	67/68	11.46
68/69	4.67	1.42	68/69	60.80	18.53	1281.40	68/69	10.37

69/70	3.50	1.07	69/70	53.90	16.43	841.27	69/70	9.05
70/71	7.33	2.23	70/71	64.20	19.57	1530.27	70/71	10.90
71/72	5.33	1.63	71/72	58.95	17.97	1154.85	71/72	10.54
72/73	2.67	0.81	72/73	52.85	16.11	781.92	72/73	8.72
73/74	5.42	1.65	73/74	65.00	19.81	1591.91	73/74	10.93
74/75	6.58	2.01	74/75	64.50	19.66	1553.25	74/75	11.18
75/76	5.17	1.58	75/76	56.30	17.16	984.49	75/76	10.09
76/77	4.91	1.50	76/77	60.20	18.35	1021.94	76/77	10.19
77/78	5.25	1.60	77/78	58.60	17.86	1131.62	77/78	10.37
78/79	4.83	1.47	78/79	68.30	20.82	1858.50	78/79	10.74
79/80	2.42	0.74	79/80	49.50	15.09	606.05	79/80	7.76
80/81	4.42	1.35	80/81	63.20	19.26	1454.88	80/81	10.27
81/82	4.67	1.42	81/82	60.00	18.29	1225.91	81/82	10.12
82/83	3.50	1.07	82/83	54.10	16.49	852.80	82/83	8.62
83/84	5.17	1.58	83/84	68.20	20.79	1850.12	83/84	10.60
84/85	4.50	1.37	84/85	60.65	18.49	1284.90	84/85	9.56
85/86	4.08	1.24	85/86	58.90	17.95	1151.52	85/86	9.29
86/87	3.08	0.94	86/87	51.40	15.67	703.28	86/87	7.40
87/88	4.58	1.40	87/88	60.50	18.44	1082.58	87/88	8.81
88/89	9.17	2.79	88/89	74.40	22.68	2561.91	88/89	11.56
89/90	3.83	1.17	89/90	53.35	16.26	764.82	89/90	7.51
90/91	5.00	1.52	90/91	54.80	16.70	993.20	90/91	8.14
91/92	5.08	1.55	91/92	57.80	17.62	1167.60	91/92	8.27
92/93	5.33	1.62	92/93	58.10	17.71	1208.16	92/93	8.86
93/94	5.00	1.52	93/94	59.90	18.26	1333.80	93/94	8.90
94/95	4.20	1.28	94/95	50.70	15.45	708.08	94/95	7.48
95/96	5.00	1.52	95/96	58.25	17.75	1333.12	95/96	8.73
96/97	5.55	1.69	96/97	60.20	18.35	1475.88	96/97	9.10
97/98	4.90	1.49	97/98	53.75	16.38	898.54	97/98	8.18
98/99	6.60	2.01	98/99	58.80	17.92	1372.68	98/99	9.39
99/00	5.00	1.52	99/00	51.90	15.82	916.40	99/00	8.05
00/01	3.90	1.19	00/01	46.50	14.17	704.42	00/01	6.48
01/02	4.05	1.23	01/02	48.60	14.81	819.65	01/02	6.93
02/03	3.95	1.20	02/03	49.50	15.09	780.34	02/03	7.20
03/04	4.35	1.33	03/04	47.00	14.32	731.12	03/04	7.64
04/05	4.75	1.45	04/05	51.90	15.82	1017.00	04/05	7.86
05/06	5.65	1.72	05/06	55.90	17.04	1282.90	05/06	9.07
06/07	4.90	1.49	06/07	54.50	16.61	1186.51	06/07	8.46
07/08	5.90	1.80	07/08	61.90	18.87	1736.59	07/08	9.91
08/09	4.20	1.28	08/09	53.35	16.26	1110.01	08/09	7.67
09/10	5.20	1.58	09/10	47.00	14.32	731.12	09/10	7.93
10/11	5.40	1.65	10/11	61.50	18.74	1704.30	10/11	9.24
11/12	2.90	0.88	11/12	43.90	13.38	545.23	11/12	5.15
12/13	5.40	1.65	12/13	55.70	16.98	1268.91	12/13	8.84
13/14	4.70	1.43	13/14	53.05	16.17	1090.45	13/14	8.65
14/15	4.55	1.39	14/15	53.60	16.34	1126.44	14/15	8.16
15/16	7.65	2.33	15/16	65.00	19.81	1996.78	15/16	10.51

**Development of
Rainfall Intensity-Duration-Frequency
(IDF) Curves for Colombo, Sri Lanka**

Development of Rainfall Intensity-Duration-Frequency (IDF) Curves for Colombo, Sri Lanka

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Abstract

IDF curves represent the probability of a given rainfall intensity and duration of storm at a particular location or a climate zone. These curves can be estimated using available rainfall records over a reasonable number of years.

IDF Curves for Sri Lanka were published in the year 1984 in “Design of Irrigation Headworks for Small Catchments” covering the entire island with 6 climatic zones by Eng. A.J.P. Ponrajah of Irrigation Department [1]. It can be considered as a great achievement because at that time even some of the developed countries had not produced IDF curves. Since then Ponrajah’s work has been widely used in planning and design of water resources development in Sri Lanka. After Eng. Ponrajah several engineers have developed IDF curves for selected stations depending on their requirement and availability of data. However updating regional IDF curves was a long felt requirement of the country. Considering this as a responsibility of Hydrology Division Eng.(Ms) Prema Hettiarachchi (Director of Irrigation - Hydrology) has updated IDF curves for Ratnapura in the Kalu Ganga basin and published in Hydrological Annual[2]. Current paper is a continuation of that work and it presents IDF curves which have been developed for Colombo for the durations ranging from 15 min to 3 days using rainfall records over 30-35 years obtained from the Department of Meteorology of Sri Lanka.

1. Introduction

When reviewing literature it is found that the history of IDF curves goes as far back as 1932. Since then many countries have established IDF curves. IDF curves in Australia for any region can be freely accessed through the web site <http://www.bom.gov.au/water/designRainfalls/efd/>. However many developing countries were unable to develop IDF curves yet due to un-availability of long term rainfall data.

Attempt made by Baghirathan and Shaw[3] in Sri Lanka for preparing IDF curves for 19 stations using 8-24 years of data in 1979 can be considered as the initiative. Ponrajah[1] has continued Baghirathan’s[1] work as mentioned above. Later Dharmasena and Premasiri[4] have extended the above study by considering data from 1957-1987 over 10 stations. Ranatunga[5] has recently estimated IDF curves considering 26 stations depending on the availability of data and published in the IESL Transactions in 2001. Considering rainfall data from 1981-2010, Nandalal and Ghnanapala[6] have updated IDF curves for Colombo and published in IESL Journal in 2017. Most of the researchers, all over the world, have confirmed that Gumbel Distribution fits well with annual maximum series.

This paper presents IDF curves developed for Colombo region following “Gumbel Distribution” using rainfall data from 1981-2015 and Log Pierson III Distribution is used to find rainfall depth for different storm duration and return periods to make a comparison with Gumbel Distribution. In the conclusion, the findings are compared with all previous works carried out by many researchers discussed above.

2. Methodology

Annual maximum rainfall for the durations of 15 min to 21 hrs were calculated using pluviographs (for rainfall above 10 mm) from 1981-2010. Similarly hourly rainfall records (digital data) were used to calculate annual maximum rainfall for the durations of 1hr to 21hr for the years 2011-2015. Daily rainfall records from 1980-2015 were used to find annual maximum rainfalls of 1day, 2days and 3 days. (See Annex 01-Annual Maximum Rainfall for different storm durations)

Outlier test was performed for each annual maximum series and the outliers were replaced by statistically acceptable values. Next step was to carryout statistical analysis (Gumbel EV) on each series of data separately to find rainfall for above mentioned storm durations for return periods (years) of 2, 5,

10, 25, 50,100 and 200. Same frequency analysis was carried out with Log Pearson III Distribution for the purpose of comparison.

3. Specimen Calculation and Results

3.1 Gumbel Distribution

3.1.1 Calculation for 45 minute duration

Maximum Rainfall (mm) for each year	Rainfall in descending order (mm)	Probability of Exceedance $p=m/(n+1)$	Return Period yr ($T=1/p$)	$q=1-p$ Probability of non-Exceedance	Y(Reduced variate) $=-\ln(-\ln(q))$
82.50(1981)	104.00	0.03	31	0.97	3.42
64.50(1982)	84.00	0.06	16	0.94	2.71
51.00(1983)	82.50	0.10	10	0.90	2.28
84.00(1984)	81.50	0.13	8	0.87	1.98
73.00(1985)	78.50	0.16	6	0.84	1.74
44.00(1986)	78.00	0.19	5	0.81	1.54
45.50(1987)	74.50	0.23	4	0.77	1.36
78.00(1988)	73.00	0.26	4	0.74	1.21
50.00(1989)	70.00	0.29	3	0.71	1.07
52.00(1990)	70.00	0.32	3	0.68	0.94
40.00(1991)	69.50	0.35	3	0.65	0.82
74.50(1992)	67.00	0.39	3	0.61	0.71
55.00(1993)	66.00	0.42	2	0.58	0.61
63.50(1994)	64.50	0.45	2	0.55	0.51
54.00(1995)	63.50	0.48	2	0.52	0.41
69.50(1996)	63.00	0.52	2	0.48	0.32
61.25(1997)	61.25	0.55	2	0.45	0.23
81.50(1998)	60.00	0.58	2	0.42	0.14
67.00(1999)	55.00	0.61	2	0.39	0.05
70.00(2000)	54.00	0.65	2	0.35	-0.04
63.00(2001)	52.00	0.68	1	0.32	-0.12
51.00(2002)	52.00	0.71	1	0.29	-0.21
46.00(2003)	51.00	0.74	1	0.26	-0.30
52.00(2004)	51.00	0.77	1	0.23	-0.40
66.00(2005)	50.00	0.81	1	0.19	-0.50
70.00(2006)	46.00	0.84	1	0.16	-0.60
78.50(2007)	45.50	0.87	1	0.13	-0.72
60.00(2008)	44.00	0.90	1	0.10	-0.85
41.75(2009)	41.75	0.94	1	0.06	-1.01
104.00(2010)	40.00	0.97	1	0.03	-1.23

Table 1 : Calculations for 45 minutes duration

3.1.2 Gumbel Plot for 45 min duration

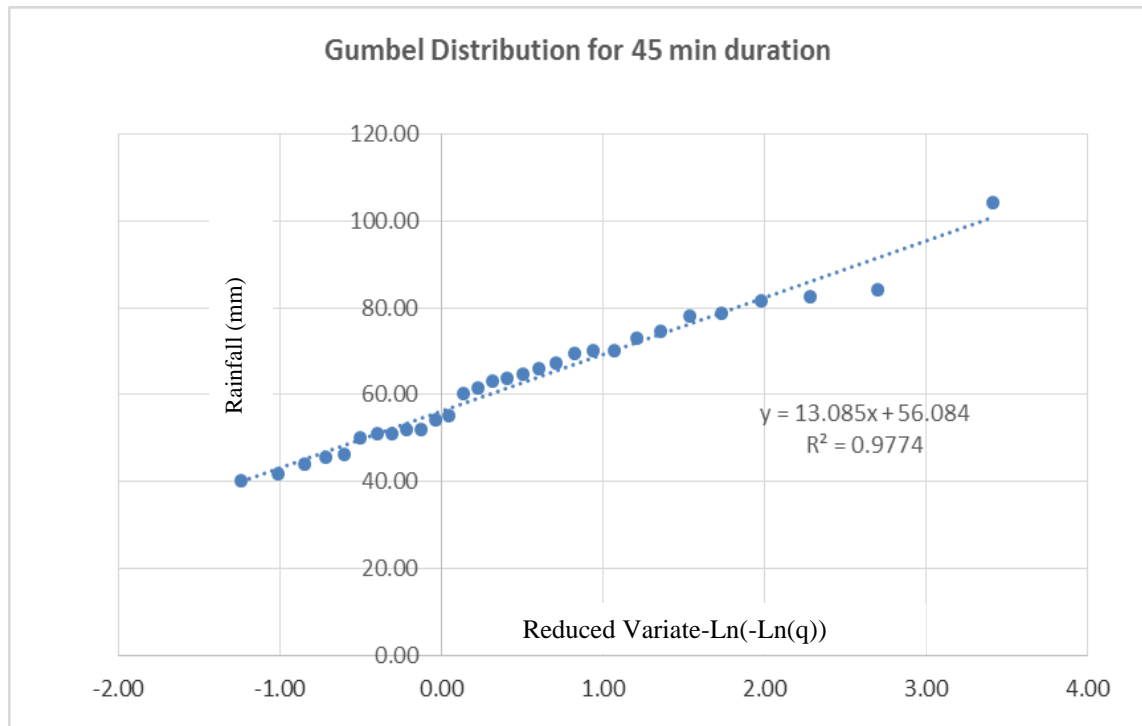


Fig 1 : Gumbel Plot for 45 min duration

3.1.3 Calculation of Rainfall depth for 45 min storm duration for different Return Periods

Equation of trend line for 45 min duration:

$Y = 13.085 X + 56.084$, Where Y= Rainfall in mm

$X = -\ln(-\ln(q))$, reduced variate

$= -\ln(-\ln(1-P))$,

$= -\ln(-\ln(1-1/T))$,

Rainfall depth relevant to 45 min duration for different return periods were calculated and are illustrated in Table 1.

T(Return period in years)	P (Probability)	q=1-P	$x = -\ln(-\ln(q))$, reduced variate	Rainfall Depth for 45 min Duration
2	0.5	0.5	0.37	60.9
5	0.2	0.8	1.50	75.7
10	0.1	0.9	2.25	85.5
25	0.04	0.96	3.20	97.9
50	0.02	0.98	3.90	107.1
100	0.01	0.99	4.60	116.3
200	0.005	0.995	5.30	125.4

Table 2 : Analysis for 45 min rainfall for different return periods

Similarly for other durations the trend lines were obtained and rainfall depths for different return periods are given in Table 3 and illustrated in Fig2.

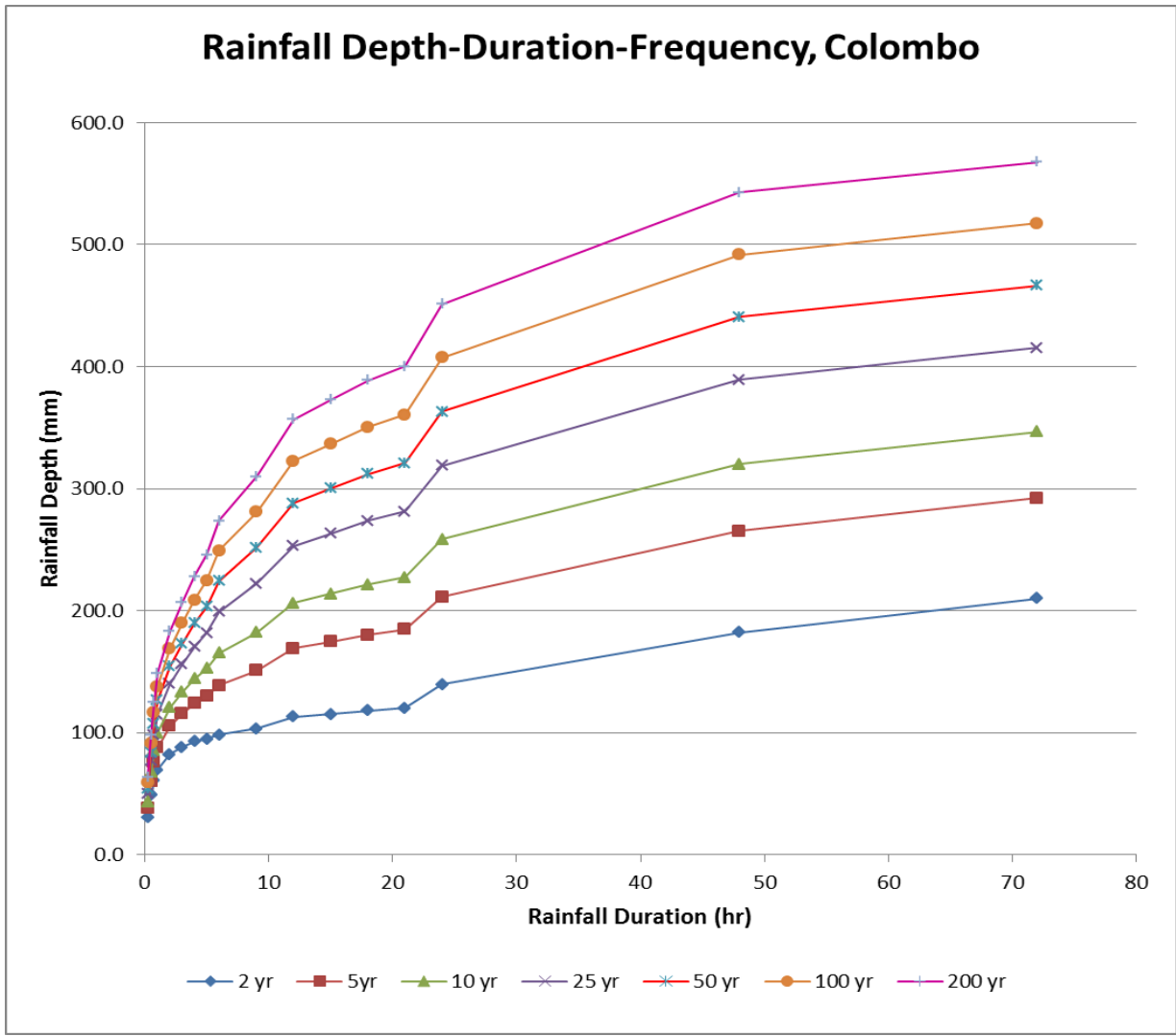


Fig 2: Rainfall Depth-Duration-Frequency Relationship

T	p	q=1-p	x=-Ln(-Ln(q))	Rainfall Duration																
				15 min	30 min	45 min	1hr	2hr	3hr	4hr	5hr	6hr	9hr	12hr	15hr	18hr	21hr	1 day	2 day	3 day
				Y=6.5883 X+28.509 R ² =0.9844	Y=9.958 X+45.052 R ² =0.978	Y=13.085 X+56.084 R ² =0.9774	Y=16.155X+63.478 R ² =0.9822	Y=20.458X+74.595 R ² =0.9724	Y=23.996X+79.358 R ² =0.9503	Y=27.441X+82.628 R ² =0.9474	Y=30.599X+83.829 R ² =0.938	Y=35.629X+85.201 R ² =0.8615	Y=41.917X+87.995 R ² =0.7792	Y=49.471X+94.935 R ² =0.7697	Y=52.302X+96.009 R ² =0.7744	Y=54.965X+97.81 R ² =0.7858	Y=56.798X+99.438 R ² =0.787	Y=63.29X+116.28 R ² =0.8196	Y=73.124X+155.4 R ² =0.9076	Y=72.555X+183.53 R ² =0.9364
2	0.5	0.5	0.37	30.9	48.7	60.9	69.4	82.1	88.2	92.7	95.0	98.3	103.4	113.1	115.2	118.0	120.3	139.5	182.2	210.1
5	0.2	0.8	1.50	38.4	60.0	75.7	87.7	105.3	115.4	123.8	129.7	138.6	150.9	169.1	174.5	180.3	184.6	211.2	265.1	292.4
10	0.1	0.9	2.25	43.3	67.5	85.5	99.8	120.6	133.4	144.4	152.7	165.4	182.3	206.3	213.7	221.5	227.3	258.7	320.0	346.8
25	0.04	0.96	3.20	49.6	76.9	97.9	115.2	140.0	156.1	170.4	181.7	199.2	222.1	253.2	263.3	273.6	281.1	318.7	389.3	415.6
50	0.02	0.98	3.90	54.2	83.9	107.1	126.5	154.4	173.0	189.7	203.2	224.2	251.6	288.0	300.1	312.3	321.1	363.2	440.7	466.6
100	0.01	0.99	4.60	58.8	90.9	116.3	137.8	168.7	189.7	208.9	224.6	249.1	280.8	322.5	336.6	350.7	360.7	407.4	491.8	517.3
200	0.005	1	5.30	63.4	97.8	125.4	149.0	182.9	206.4	228.0	245.9	273.9	310.0	356.9	373.0	388.9	400.2	451.5	542.7	567.8

3.1.4 Rainfall Intensities against Storm Duration for different Return Periods

Rainfall Intensities can be calculated from the rainfall depth (Refer Table 3) for different storm periods over different Return Periods.

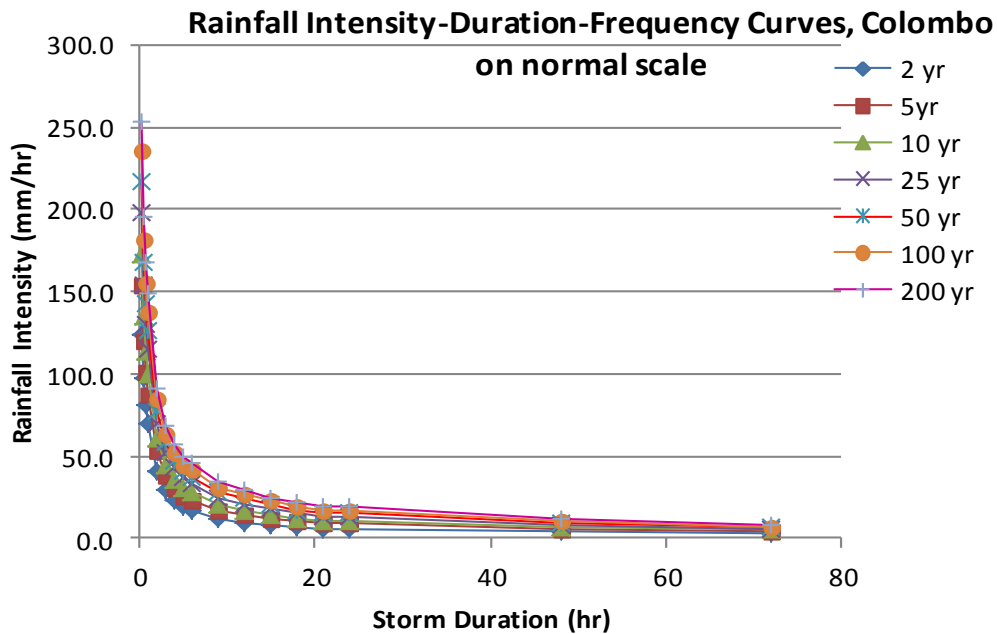


Fig 3 : IFD Curves, Colombo

3.1.5 Rainfall Intensities against Storm Duration for different Return Periods on Log scale

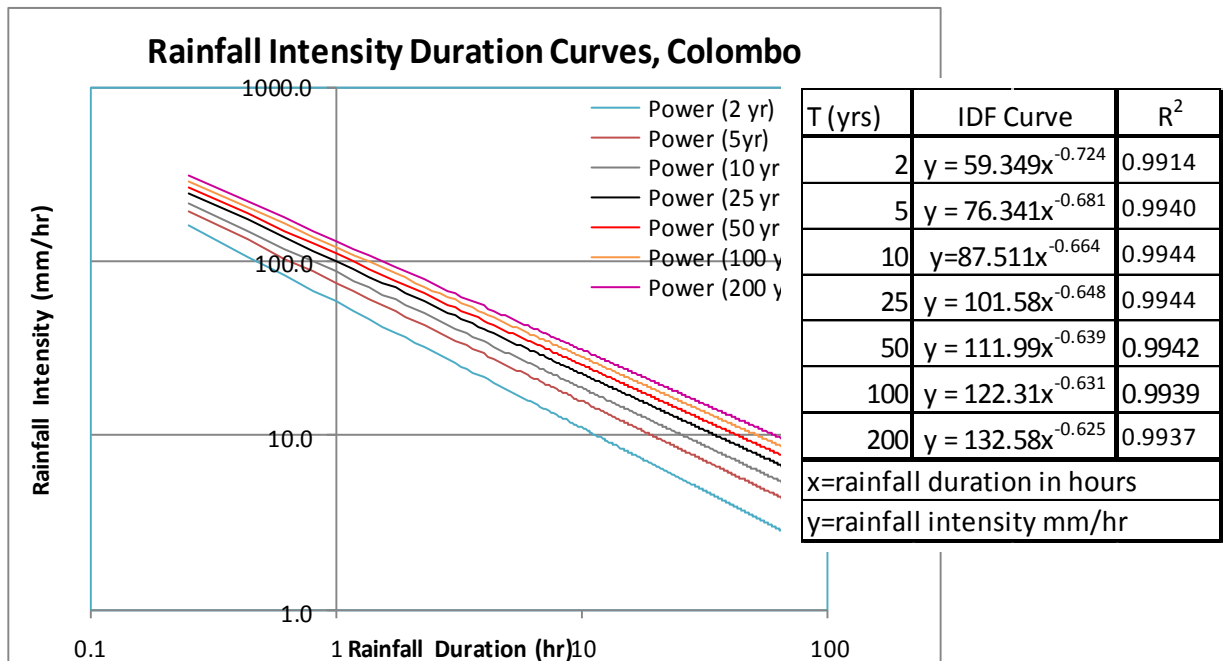


Fig 4 : IDF Curves, Colombo with Equations

3.2 Log Pearson III Distribution

3.2.1 Calculation for 45 min duration

Year	Rainfall (RF) in mm (descending order)	log RF
1981	104.00	2.02
1982	84.00	1.92
1983	82.50	1.92
1984	81.50	1.91
1985	78.50	1.89
1986	78.00	1.89
1987	74.50	1.87
1988	73.00	1.86
1989	70.00	1.85
1990	70.00	1.85
1991	69.50	1.84
1992	67.00	1.83
1993	66.00	1.82
1994	64.50	1.81
1995	63.50	1.80
1996	63.00	1.80
1997	61.25	1.79
1998	60.00	1.78
1999	55.00	1.74
2000	54.00	1.73
2001	52.00	1.72
2002	52.00	1.72
2003	51.00	1.71
2004	51.00	1.71
2005	50.00	1.70
2006	46.00	1.66
2007	45.50	1.66
2008	44.00	1.64
2009	41.75	1.62
2010	40.00	1.60

Table 4 : Rainfall for 45 min duration

Consider Log (RF) series above and following can be calculated.

Average (Log (RF)) = 1.79
 Standard Deviation of log RF = 0.102
 Skew Coefficient = 0.038

Refer Frequency Factors K for log-Pearson Type III Distributions (Haan, 1977, Table 7.7)

T (yr)	2	5	10	25	50	100	200
K	-0.006	0.840	1.286	1.764	2.074	2.354	2.612

Table 5: Frequency Factors K for log-Pearson III Distributions

Log Rf can be calculated from equation shown below. Hence Rainfall (RF) can be obtained.

$$\text{Log RF} = \text{Average (Log(RF))} + K * \text{Standard Deviation of log RF,}$$

T (yr)	2	5	10	25	50	100	200
K	-0.006	0.840	1.286	1.764	2.074	2.354	2.612
LOG RF	1.787737	1.874250355	1.9198578	1.96874097	2.000458	2.029083	2.05542
RF (mm)	61.3	74.9	83.2	93.1	100.1	106.9	113.6

Table 6: Rainfall depths (RF) for 45 min duration storm for different Return Periods

Similarly for other durations, rainfall depths for different return periods were calculated and are given in Table 7.

T (yr)	Duration																
	15 min	30 min	45 min	1 hr	2 hr	3 hr	4 hr	5 hr	6 hr	9 hr	12 hr	15hr	18hr	21 hr	1 day	2 day	3 day
2	31.1	49.2	61.3	69.5	81.1	85.8	89.4	90.9	91.6	92.9	100.0	101.6	104.0	105.8	124.7	171.4	201.0
5	37.9	59.4	74.9	86.3	102.1	111.9	119.6	124.0	128.8	136.2	149.2	152.8	156.5	159.7	184.4	242.7	273.1
10	42.1	65.6	83.2	97.0	116.7	131.6	143.2	150.5	162.3	178.5	199.6	204.7	209.7	214.1	241.6	300.6	329.4
25	47.2	72.9	93.1	110.3	135.7	159.3	177.4	189.6	215.8	252.5	291.0	298.5	305.2	311.8	340.2	387.4	411.0
50	50.8	78.0	100.1	119.9	150.5	182.0	206.2	223.4	265.4	326.5	385.8	395.3	403.6	412.1	437.3	463.0	480.0
100	54.4	82.9	106.9	129.5	165.7	206.6	238.2	261.3	324.8	420.8	510.5	522.0	531.8	542.9	559.8	548.9	556.5
200	57.9	87.7	113.6	139.0	181.5	233.2	273.7	304.2	395.8	541.0	674.7	688.2	699.5	713.6	714.5	646.7	641.5
Skewness	0.108	0.004	0.038	0.158	0.483	0.785	0.873	0.926	1.290	1.637	1.789	1.718	1.685	1.663	1.484	0.874	0.808

Table 7 : Rainfall Depth in mm (Summary of Frequency Analysis with Log Pearson III Distribution)

4. Comparison of Results

4.1 Comparison and Limitations of Present Results

		duration																
		15 min	30 min	45 min	1 hr	2 hr	3 hr	4 hr	5 hr	6 hr	9 hr	12 hr	15 hr	18 hr	21 hr	1 day	2 day	3 day
GUMBLE -IDF Equation(mm)	2	40.5	49.0	54.8	59.3	71.9	80.4	87.0	92.5	97.3	108.8	117.8	125.3	131.8	137.5	142.7	172.8	193.2
	5	49.1	61.2	69.6	76.3	95.2	108.4	118.8	127.6	135.2	153.9	168.7	181.1	192.0	201.6	210.4	262.5	298.7
	10	54.9	69.3	79.4	87.5	110.5	126.6	139.4	150.3	159.8	183.1	201.7	217.4	231.1	243.4	254.6	321.3	368.2
	25	62.4	79.6	91.8	101.6	129.6	149.5	165.5	179.0	190.9	220.1	243.6	263.5	281.0	296.6	310.9	396.8	457.7
	50	67.9	87.2	100.9	112.0	143.8	166.5	184.7	200.2	213.8	247.5	274.6	297.7	317.9	336.1	352.7	453.0	524.4
	100	73.3	94.7	110.0	122.3	158.0	183.5	204.0	221.5	236.9	275.2	306.0	332.2	355.4	376.1	395.1	510.3	592.7
	200	78.8	102.2	119.0	132.6	171.9	200.2	223.0	242.4	259.6	302.2	336.6	366.0	391.9	415.3	436.6	566.2	659.1
PIERSON(mm)	2	31.1	49.2	61.3	69.5	81.1	85.8	89.4	90.9	91.6	92.9	100.0	101.6	104.0	105.8	124.7	171.4	201.0
	5	37.9	59.4	74.9	86.3	102.1	111.9	119.6	124.0	128.8	136.2	149.2	152.8	156.5	159.7	184.4	242.7	273.1
	10	42.1	65.6	83.2	97.0	116.7	131.6	143.2	150.5	162.3	178.5	199.6	204.7	209.7	214.1	241.6	300.6	329.4
	25	47.2	72.9	93.1	110.3	135.7	159.3	177.4	189.6	215.8	252.5	291.0	298.5	305.2	311.8	340.2	387.4	411.0
	50	50.8	78.0	100.1	119.9	150.5	182.0	206.2	223.4	265.4	326.5	385.8	395.3	403.6	412.1	437.3	463.0	480.0
	100	54.4	82.9	106.9	129.5	165.7	206.6	238.2	261.3	324.8	420.8	510.5	522.0	531.8	542.9	559.8	548.9	556.5
	200	57.9	87.7	113.6	139.0	181.5	233.2	273.7	304.2	395.8	541.0	674.7	688.2	699.5	713.6	714.5	646.7	641.5
Skewness	0.108	0.004	0.038	0.158	0.483	0.785	0.873	0.926	1.290	1.637	1.789	1.718	1.685	1.663	1.484	0.874	0.808	

Table 8: Comparison of Rainfall Depths computed by Gumbel and Log Pearson III Distributions

In the present analysis the pluviographs were used to analyze storm durations from 15 min to 21 hrs. In these records the rainfall values which were less than 10 mm were not taken into consideration. To analyze 1 day to 3 day storm periods, the daily rainfall records were used. However there may be missing data (pluviographs) for certain periods. This may be the reason for unsmooth increment of rainfall from 21 hr to 1 day storms as observed in Fig 2.

In Gumbel Distribution skewness of the data series is not considered and the outliers are replaced by statistically acceptable values whereas in Log Pearson III Distribution skewness is considered for the analysis. In general Log Pearson III gives higher rainfalls than the Gumbel Distribution.

4.2 Comparison of Present (Gumbel) Results with Previous Research Studies

The results are tabulated for each storm period and given in Fig 5 to Fig 13..

Rainfall Duration = 15 min			Return Period (Years)					
Researcher	Data Period	Probability Distribution	2	5	10	25	50	100
Present	1981-2015	Gumbel	40.5	49.1	54.9	62.4	67.9	73.3
Nandalal	1981-2010	Gumbel	38.8	45.5	50.8	58.9	63.6	68.2
Ranathunga	1960-1985	Gumbel	32.0	37.5	40.7	45.5	49.5	54.0
Dharmasena &P	1960-1985	Gumbel	31.8	36.8	39.9	45	48.5	51.8
Ponrajah	not given	not given			76.2	94.5	108.4	115.9

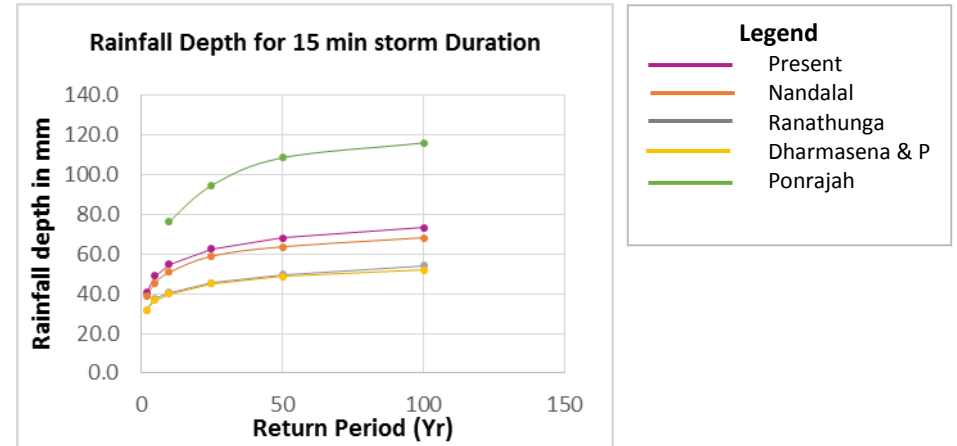


Fig 5 : Comparison of Rainfall depth (mm) for 15 min Storm Duration

Rainfall Duration = 30 min			Return Period (Years)					
Researcher	Data Period	Probability Distribution	2	5	10	25	50	100
Present	1981-2015	Gumbel	49.0	61.2	69.3	79.6	87.2	94.7
Nandalal	1981-2010	Gumbel	59.1	68.0	74.2	84.0	89.7	94.8
Ranathunga	1960-1985	Gumbel	48.2	57.9	63.2	71.6	77.9	85.1
Dharmasena &P	1960-1985	Gumbel	51.3	64.0	71.4	80.0	86.9	94.0
Ponrajah	not given	not given			85.9	105.3	120.7	130.0

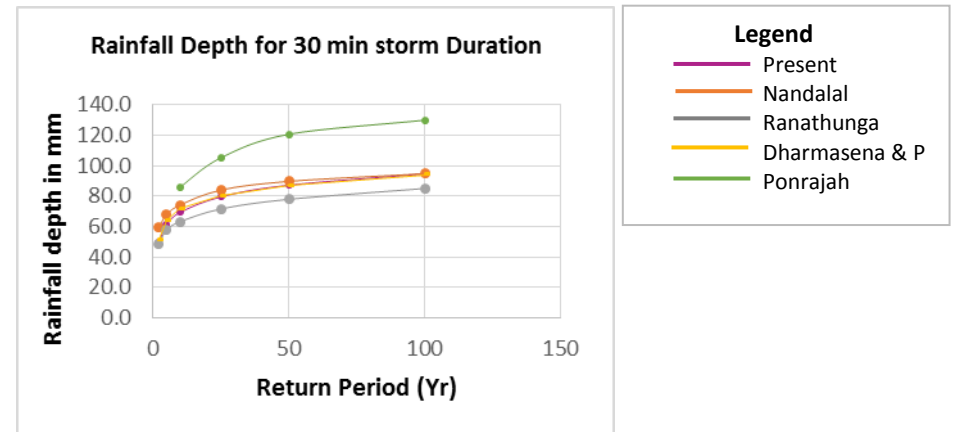


Fig 6 : Comparison of Rainfall depth (mm) for 30 min Storm Duration

Rainfall Duration = 1 hr			Return Period (Years)					
Researcher	Data Period	Probability Distribution	2	5	10	25	50	100
Present	1981-2015	Gumbel	59.4	76.3	87.5	101.6	112.0	122.3
Nandalal	1981-2010	Gumbel	79.2	91.8	101.7	117.4	126.2	134.3
Ranatunga	1960-1985	Gumbel	66.0	81.2	89.3	102.3	111.6	122.0
Dharmasena & P	1960-1985	Gumbel	72.9	91.9	102.4	116.3	127.5	138.4
Ponrajah	not given	not given			96.9	117.3	134.5	145.8

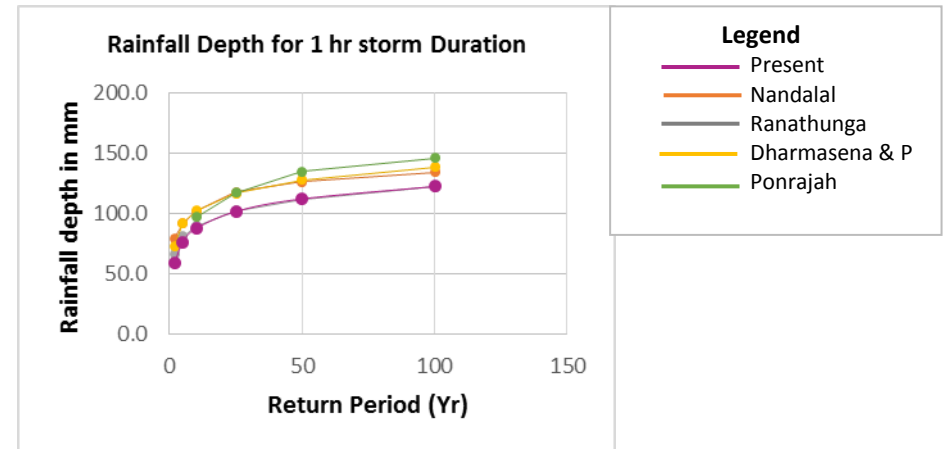


Fig 7 : Comparison of Rainfall depth (mm) for 1 hr Storm Duration

Rainfall Duration = 2 hr			Return Period (Years)					
Researcher	Data Period	Probability Distribution	2	5	10	25	50	100
Present	1981-2015	Gumbel	82.1	105.3	120.6	140.0	154.4	168.7
Nandalal	1981-2010	Gumbel	96.5	114.0	127.2	147.2	161.2	175.6
Ranatunga	1960-1985	Gumbel	83.6	104.7	116.4	134.6	147.2	161.3
Dharmasena & P	1960-1985	Gumbel	79.0	96.0	108.0	124.0	135.9	148.1
Ponrajah	not given	not given			109.2	130.7	149.9	163.6

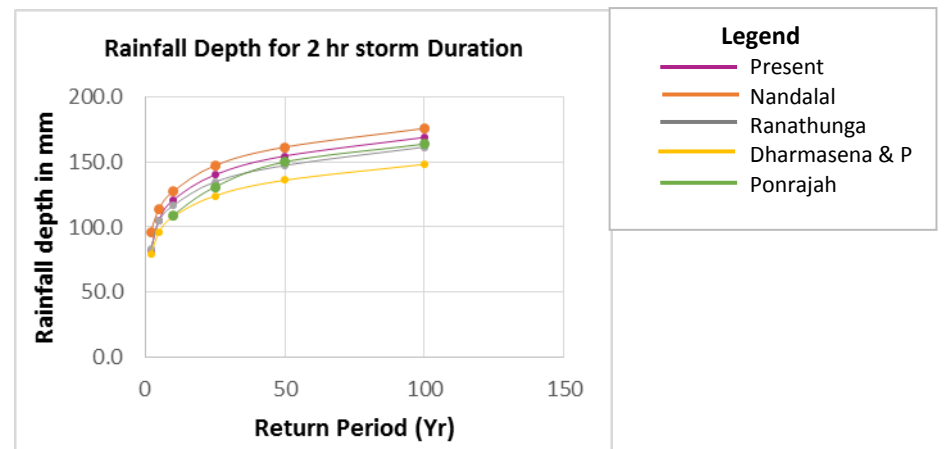


Fig 8 : Comparison of Rainfall depth (mm) for 2 hr Storm Duration

Rainfall Duration = 3 hr			Return Period (Years)					
Researcher	Data Period	Probability Distribution	2	5	10	25	50	100
Present	1981-2015	Gumbel	80.4	108.4	126.6	149.5	166.5	183.5
Nandalal	1981-2010	Gumbel	102.9	123.5	142.2	179.1	203.9	230.3
Ranatunga	1960-1985	Gumbel	93.5	118.1	132.1	153.5	168.1	184.4
Baghirathan & S	1950-1970	Gumbel	79.8	100.3	113.8	130.8	143.5	
Ponrajah	not given	not given			117.2	139.2	159.7	175.0

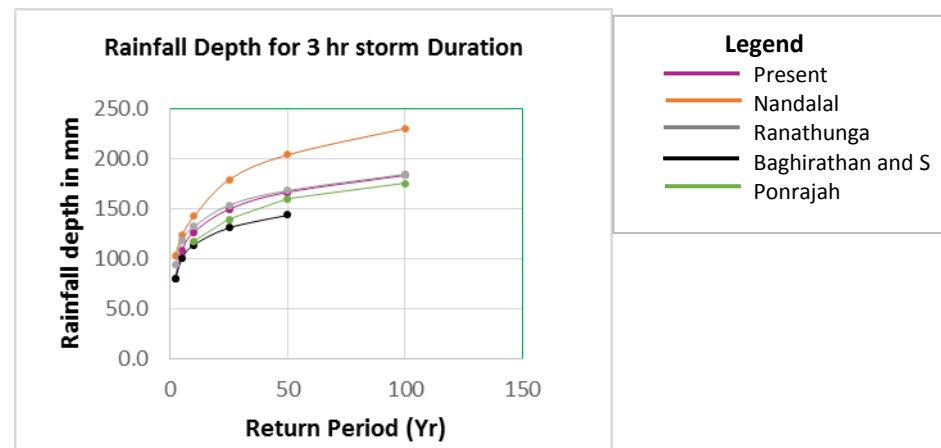


Fig 9 : Comparison of Rainfall depth (mm) for 3 hr Storm Duration

Rainfall Duration = 4 hr			Return Period (Years)					
Researcher	Data Period	Probability Distribution	2	5	10	25	50	100
Present	1981-2015	Gumbel	87.0	118.8	139.4	165.5	184.7	204.0
Nandalal	1981-2010	Gumbel	109.4	135.2	159.0	205.3	243.4	287.2
Ranatunga	1960-1985	Gumbel	100.5	127.4	143.2	166.9	183.0	200.9
Ponrajah	not given	not given			123.1	145.6	167.0	183.6

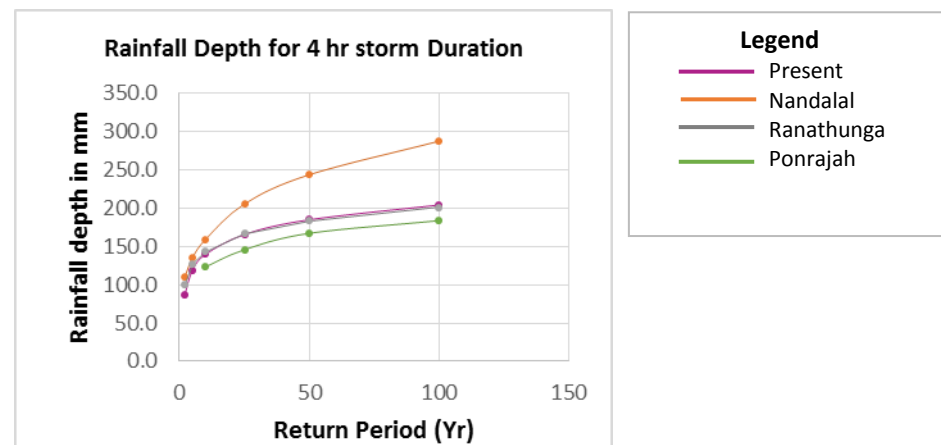


Fig 10 : Comparison of Rainfall depth (mm) for 4 hr Storm Duration

Rainfall Duration = 6 hr			Return Period (Years)					
Researcher	Data Period	Probability Distribution	2	5	10	25	50	100
Present	1981-2015	Gumbel	97.3	135.2	159.8	190.9	213.8	236.9
Nandalal	1981-2010	Gumbel	113.4	144.5	174.9	235.6	285.6	344.2
Ranatunga	1960-1985	Gumbel	110.2	140.4	158.9	185.8	204.1	224.4
Dharmasena & P	1960-1985	Gumbel	95.0	116.8	131.8	151.9	167.9	183.9
Baghirathan & S	1950-1970	Gumbel	100.3	131.6	152.1	178.3	197.6	
Ponrajah	not given	not given			132.1	155.1	177.9	196.4

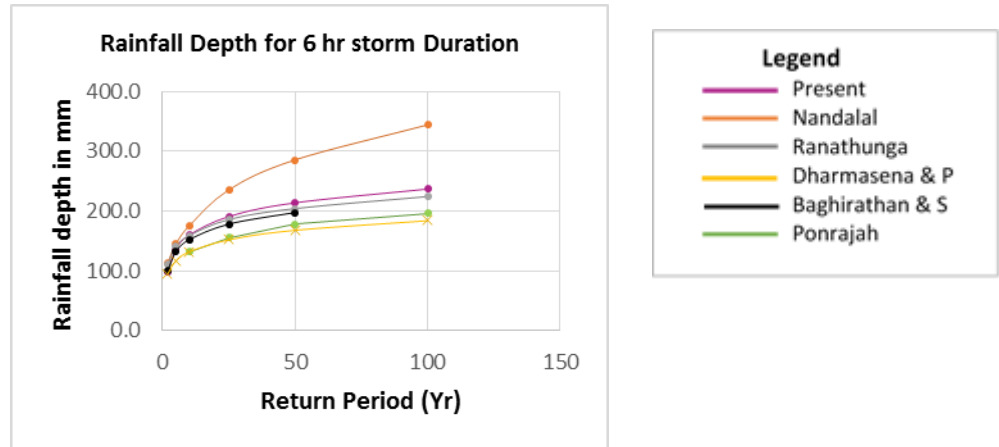


Fig 11 : Comparison of Rainfall depth (mm) for 6 hr Storm Duration

Rainfall Duration = 12 hr			Return Period (Years)					
Researcher	Data Period	Probability Distribution	2	5	10	25	50	100
Present	1981-2015	Gumbel	117.8	168.7	201.7	243.6	274.6	306.0
Nandalal	1981-2010	Gumbel	119.2	161.8	208.2	306.8	394.0	501.1
Ranatunga	1960-1985	Gumbel	126.9	162.6	186.4	219.1	241.3	266.0
Dharmasena & P	1960-1985	Gumbel	122.9	149.9	169.9	198.9	217.9	240.0
Baghirathan & S	1950-1970	Gumbel	116.8	149.1	170.4	197.4	217.4	
Ponrajah	not given	not given			148.9	172.8	198.2	220.3

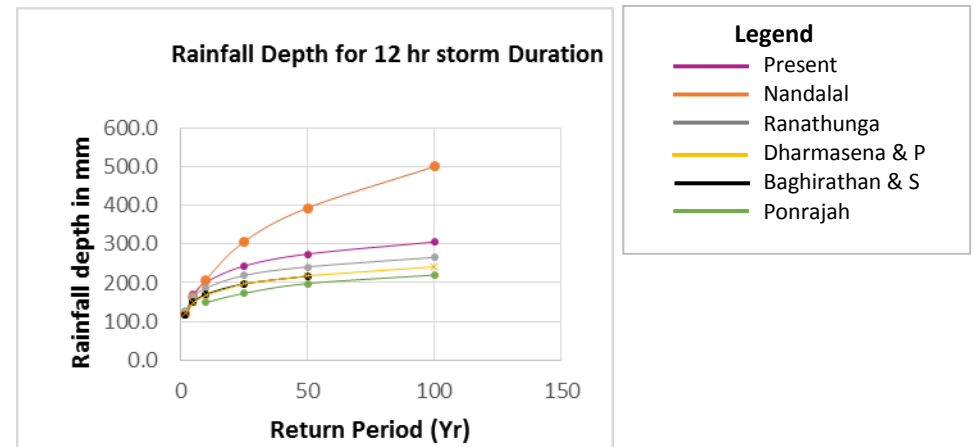


Fig 12 : Comparison of Rainfall depth (mm) for 12 hr Storm Duration

Rainfall Duration = 1 day			Return Period (Years)					
Researcher	Data Period	Probability Distribution	2	5	10	25	50	100
Present	1981-2015	Gumbel	142.7	210.4	254.6	310.9	352.7	395.2
Nandalal	1981-2010	Gumbel	122.8	178.9	245.8	398.6	543.2	730.3
Ranatunga	1960-1985	Gumbel	144.4	185.8	215.7	254.6	281.3	310.9
Dharmasena & P	1960-1985	Gumbel	148.3	187.5	215.6	252.8	282.8	310.9
Baghirathan & S	1950-1970	Gumbel	141.5	186.4	216.2	253.7	281.7	
Ponrajah	not given	not given			167.9	192.5	220.9	247.2

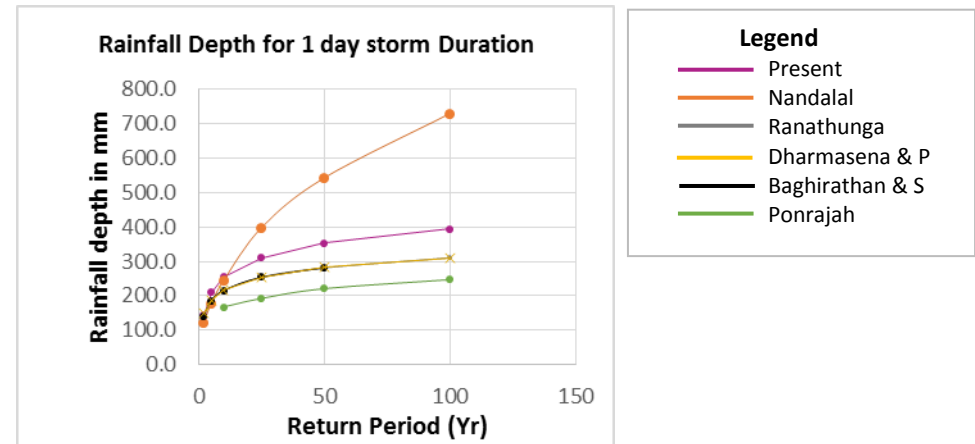


Fig 13 : Comparison of Rainfall depth (mm) for 1 day Storm Duration

5. Discussion

It is observed that previous research work has followed Gumbel Distribution. When considering Ponrajah's analysis, for lower storm durations from 15 min to 1 hr gives the highest values among all. For all the other durations Ponrajah's values are low compared to the others. When considering all storm durations, the present analysis shows gradual increment of expected rainfall depths when compared with all research except the values of Nandalal[5] and Ponrajah's values for low durations.

In the paper "Analysis of Annual Maximum Rainfalls from Principal Stations" published in Hydrological Annual – 2010/2011[7] the analysis for Colombo has been carried out using the data from 1954 to 2013. The rainfall depths computed for one day storm duration [7] are very much similar to the current results.

In recent research work done for Ratnapura[2] shows a similar expected rainfall depths compared to Ponrajah [1]. Colombo is a location closer to the ocean and Ratnapura is a interior station and may have different rainfall trend. Therefore to conclude on rainfall trend with time on a particular region (whether there is climate change) it is necessary to extend this study for some other stations i. Since the present analysis has dealt with recent data, these IDF curves may be used for design and planning work of Water Resource Projects in Colombo area.

Acknowledgements

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Annex I :

Year	15 min	30 min	45 min	1 hr	2 hr	3 hr	4 hr	5 hr	6 hr	9 hr	12 hr	15 hr	18 hr	21 hr	24 hr	
1981	36.00	52.00	82.50	87.50	88.50	89.50	103.00	114.00	114.00	115.00	115.00	115.00	115.00	115.00	115.00	
1982	25.00	47.50	64.50	74.00	81.25	84.50	88.25	91.00	93.75	94.00	94.00	94.00	94.00	94.00	94.00	
1983	21.50	40.50	51.00	53.75	55.75	56.50	56.50	56.75	57.25	57.25	57.25	57.25	62.75	65.25	66.25	
1984	37.00	67.00	84.00	96.00	97.50	97.50	97.50	97.50	97.50	97.50	97.50	97.50	97.50	97.50	104.00	
1985	50.00	65.50	73.00	80.25	83.75	98.50	113.75	115.00	117.75	119.00	120.75	122.25	122.25	131.00	140.75	
1986	24.00	34.00	44.00	53.50	77.00	79.50	81.25	81.50	81.50	83.50	86.75	94.50	94.50	94.50	94.50	
1987	28.50	34.50	45.50	55.50	61.00	64.50	75.25	76.25	77.00	96.00	107.50	110.00	111.50	112.75	112.75	
1988	37.00	60.00	78.00	81.50	113.50	123.50	131.25	136.25	137.75	140.00	141.50	141.50	141.50	141.50	141.50	
1989	36.00	50.00	50.00	54.00	64.75	68.50	71.25	73.00	77.00	80.50	80.50	80.50	80.50	97.25	98.25	
1990	25.00	43.00	52.00	59.00	67.00	70.00	70.25	70.25	70.25	70.25	70.25	70.25	70.25	70.25	70.25	
1991	20.00	36.50	40.00	46.00	62.25	77.00	77.25	77.25	77.25	77.25	77.25	77.25	77.25	77.25	77.25	
1992	38.00	58.50	74.50	92.00	150.00	221.75	262.25	282.25	342.75	436.00	477.50	480.25	482.00	490.25	493.00	
1993	28.00	46.00	55.00	62.00	89.00	92.00	131.00	146.50	148.50	149.00	149.00	149.00	149.00	149.00	149.00	
1994	30.00	48.50	63.50	66.50	70.00	71.00	72.25	72.75	72.75	72.75	81.00	85.75	86.25	86.25	86.25	
1995	23.00	44.00	54.00	62.00	90.00	91.00	92.25	92.25	93.00	93.00	93.00	93.00	93.00	93.00	93.00	
1996	31.50	56.50	69.50	80.25	87.50	91.00	94.50	102.00	114.00	115.75	116.25	116.50	117.75	118.00	118.00	
1997	27.00	43.75	61.25	77.75	104.75	117.75	118.25	118.25	118.25	118.25	118.25	118.25	118.25	118.25	118.25	
1998	43.00	63.00	81.50	84.25	86.25	86.50	86.50	92.25	97.25	106.50	115.75	115.75	119.75	120.50	120.50	
1999	48.00	59.00	67.00	73.00	88.25	104.75	108.00	109.75	113.75	137.75	211.25	211.50	212.75	234.50	238.25	
2000	32.00	52.00	70.00	82.00	94.00	103.75	109.25	110.25	110.25	110.25	110.25	110.25	110.25	110.25	110.25	
2001	30.00	54.00	63.00	66.50	66.50	68.75	71.25	71.75	77.75	78.75	78.75	79.00	92.50	93.00	93.00	
2002	30.00	40.00	51.00	57.75	63.50	64.25	64.25	64.25	64.25	64.25	64.25	64.25	64.25	64.25	64.25	
2003	25.00	45.00	46.00	46.50	66.50	71.25	74.00	76.00	82.00	88.50	106.75	109.00	109.00	109.00	109.00	
2004	28.00	37.50	52.00	70.00	80.25	94.00	95.50	95.50	95.50	95.50	95.50	95.50	95.50	95.50	95.50	
2005	37.00	53.00	66.00	69.00	82.50	93.25	94.50	94.50	98.25	123.50	161.50	206.75	231.25	231.50	231.50	
2006	30.00	60.00	70.00	80.00	110.50	116.25	118.25	118.75	118.75	118.75	118.75	118.75	118.75	118.75	118.75	
2007	35.50	55.50	78.50	98.50	118.25	120.25	120.25	120.25	120.25	120.25	120.25	120.25	120.25	120.25	120.25	
2008	35.00	50.00	60.00	79.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	
2009	22.00	32.00	41.75	51.75	71.00	110.50	137.50	137.50	137.50	137.50	137.50	137.50	137.50	137.50	137.50	
2010	42.50	83.00	104.00	125.00	150.50	154.50	158.75	183.00	242.00	316.00	410.00	416.25	416.25	416.25	416.25	
2011	Data is not available.			45.00	57.60	60.50	64.60	64.60	65.00	78.20	81.10	81.10	81.10	81.40	81.40	
2012				80.90	80.90	80.90	80.90	80.90	80.90	80.90	80.90	101.20	102.30	103.50	110.90	118.40
2013				54.30	54.30	54.30	54.30	54.30	54.30	54.30	54.30	134.00	134.30	166.70	181.90	206.30
2014				69.00	69.00	69.00	69.00	69.00	69.00	69.00	69.00	94.10	94.10	94.10	94.10	94.10
2015				113.30	114.40	114.40	114.40	114.40	114.40	114.40	114.40	114.40	114.40	122.20	122.20	122.40
2016				61.60	81.30	100.90	115.60	121.80	129.20	136.30	161.50	193.00	209.00	211.00	237.50	

Subgrade soil stabilisation through tree root water uptake

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Abstract

Trees absorb water through the root system and lower the ground water table. This natural phenomenon alter the hydrological behaviour of the soil matrix adjacent to the soil. Therefore this can be utilized to stabilize the soil underneath the subgrade structure of most of the infrastructure facilities. Trees grown along rail corridors, major highways and other infrastructure facilities are capable of increasing the matric suction of the subgrade soil via root water uptake, in conjunction with the tree canopy evapo-transpiration. Moreover, these trees are capable of providing significant mechanical reinforcement through the anchoring effect provided by the root network plus the additional cohesive increment due to hair roots generating osmotic suction. Much of the previous research carried out all over the world, to quantify the mechanical strength generated by tree roots has been mainly based on empiricism. In many cases, empirical relations have been developed for a given tree species grown under known soil conditions. The extrapolation of such empirical relations from one tree-soil system to another can be misleading. Furthermore, the effect of transpiration by tree canopy and its influence on the sustained suction equilibrium generated at the root zone for stabilising soft subgrade has not been considered rationally. To accommodate the above natural phenomena, a novel computational model has been developed to quantify the overall suction effect provided by the tree roots and its continual link with the rate and magnitude of canopy evapo-transpiration. Root based suction of a tree improves the shear strength; accelerates the pore water pressure dissipation and it may alter the potential failure conditions of the soil-root system from a saturated to an unsaturated domain. Therefore, it is necessary for the root based suction and the mechanical properties of the root network to be analysed within a coupled multiphase framework. Accordingly, this paper will present the requirement of an advanced shear strength model that captures and combines the root reinforcement effect with both osmotic and matric suction components generated in the soil through naturally coupled osmotic evapo-transpiration phenomenon.

Keywords: soil suction, mechanical strength, shear strength, transpiration

1. Introduction

Green corridor concept in soil stabilisation can be considered as an environmental friendly, economic and expedient method which has been proven the usability by various field studies. When the native vegetation is to be used as a ground improvement method, thorough engineering quantification of its subsequent effects should be carried out. Tree roots are the most important parameter of the soil stabilisation process using native vegetation, and the complexity of the root architecture may lead to unpredictable results if it is not well studied.

Tree roots increase the soil suction during the process of root water uptake in conjunction with evapo-transpiration process (Fatahi et al. 2009). Moreover, tree roots similar to geo fibres provide the mechanical strengthening to the soil matrix by increasing cohesion due to small flexible roots as well as by the anchoring effect due to large stiff roots (Fatahi 2007; Fatahi et al. 2012). Therefore, to determine the true effect of the vegetation on shear strength of the soil, the mechanical strengthening associated with the variation of suction induced by tree roots (i.e. hydraulic processes) as well as the influence of the suction on root reinforcement (i.e. physical reinforcement) have to be taken into account.

Even though the native vegetation is still not very commonly used as a ground improvement method, there have been field studies which demonstrated its potential use for slope stabilisation and erosion control. For instance, Potter (2006) conducted extensive field studies to evaluate the true effect of vegetation and associated matric suction development underneath the railway lines in Miram, Horsham and Wal Wal in Australia. It was reported that the total suction variation underneath a railway

track for a non-vegetated and vegetated condition are distinct and that the latter typically exhibits larger values of suction.

Furthermore, previous research conducted to quantify the effect of mechanical strengthening of tree roots in slope stabilisation have been mainly focused on saturated soil conditions supported by empirical relationships (e.g. Docker and Hubble 2001; Docker and Hubble 2008). In contrast, Fatahi (2009) showed that when a mature tree is under the evapo-transpiration process, tree roots are capable of developing 3MPa root suction at wilting point and this leads to the enhancement and preservation of the vadose zone. Therefore, the sub-soil structure is often under unsaturated condition and the parameters calculated for the saturated condition may not truly represent field conditions. In that case the quantification of the suction generated on soil adjacent to tree roots is important.

Tree physiology, soil condition and other environmental parameters such as temperature, wind speed and humidity affect the suction development in soil by trees (Fatahi et al. 2014). Among these, the parameter that governs the suction development as well as the mechanical strengthening of soil is the spatial distribution of root systems. This is because the distribution of the hair roots (active) in the root system controls the soil suction variation and the distribution of main roots controls the amount of root reinforcement generated. The amount of shear strength generated by means of suction as well as the root reinforcement is accountable by the spatial distribution of root system, which in turn varies according to the environmental factors even among the same tree species. However, it has been proven that the bioengineering techniques can be effectively used in hill slopes where there are risks of landslides as well as for other improvement processes (Bache et al. 1989; Docker and Hubble 2001; Potter 2006; Fatahi 2007)

2. Spatial distribution of a root system

Absorption of water, minerals and nutrients, synthesis of various essential compounds such as growth regulators, storage of food in root crops and anchoring tree to the ground are the main functions of roots. Therefore, the spatial distribution of a root system shows inhabitant behaviours according to the availability and requirement of above parameters. Quantitative understanding of the root system is important since its shape directly affects the shear strength improvement of soil. In addition, different tree species have distinct root systems and properties of the soil also affect the depth and the spatial distribution of the root system. Two main root systems can be distinguished in trees are the fibrous root system and the tap root system. Typically, in well-drained soil conditions roots mainly have a fibrous root system and often results from a combination of lateral and oblique roots with no real tap root. In fact, only a small percentage of tree root systems have a real tap root. (Kramer 1995)

3. Environmental factors affecting the root growth

The environmental factors which affect the growth of tree roots are soil texture and structure; aeration; moisture; temperature; pH; salinity; the presence of toxic elements such as lead, copper, aluminium; competition with other plants and presence of bacteria, fungi and soil inhabiting animals (Weaver 1958). Common variations in shapes of root systems influenced by environmental factors such as soil bulk density, temperature and rainfall amount are illustrated in Figures 1 and 2.

Trees grown in different areas with different environmental factors display severe changes in their root systems, despite the above fact, root based suction applying on adjacent soil by a mature tree, is approximately 10 times greater than the practical vacuum for a prefabricated vertical drain (Indraratna et al. 2008). Therefore, this paper aims to present the model developed to capture the root based suction in conjunction with evapotranspiration and the importance of the combined effect of root reinforcement and suction.

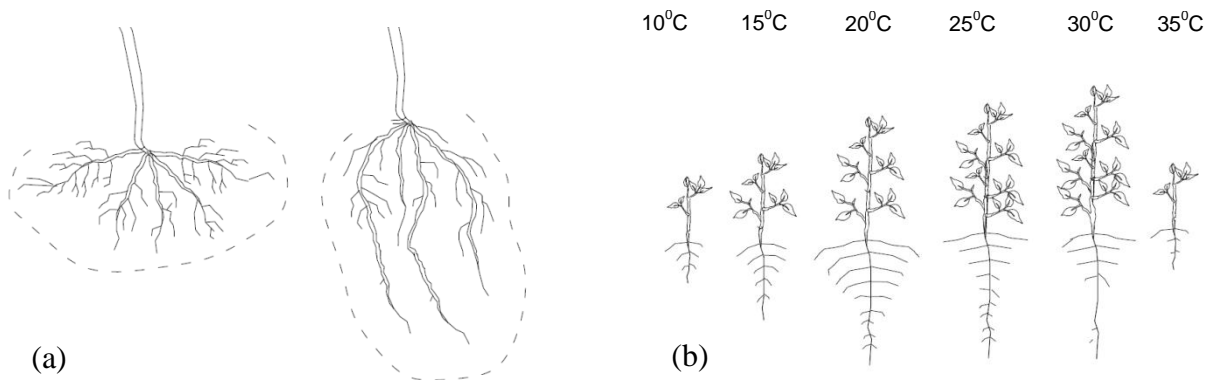


Figure 1: (a) Root system of young barley plants grown in the field in soils with different bulk densities (Left) 1.35 g cm^{-3} ; (right) 1.50 g cm^{-3} (Gilmen 1980) (b) Influence of root zone temperature on root morphology and shoot growth of potato seedlings (modified after Sattelmacher et al. 1990)

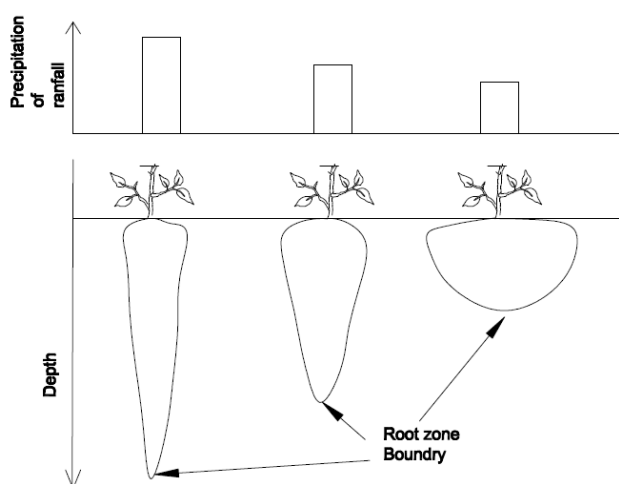


Figure 2: Schematic diagram of the effect of the amount of rainfall on the depth of rooting of winter wheat (very fine sandy loam - silty loam in the Great Plains) (modified after Sattelmacher et al. 1990)

4. Suction effect of tree roots on soil

The root water uptake of a tree increases the matric suction of the adjacent soil due to reduction of the moisture content. This can be very significant as some tree varieties like *Pinus radiata* can absorb water amounts up to its own weight per day and most mature trees can generate suction in soil-root systems up to 30MPa. The main factor that affects the root water uptake is the rate of transpiration of a tree, since the volume of water consumed by plant cells for metabolism is negligible compared to the total root water uptake (Radcliffe et al. 1980).

5. Rate of root water uptake and transpiration

Root water uptake takes place only by active roots of the tree through an osmotic process. The rate of root water uptake in a given time varies from a point to point in a root system according to the spatial distribution of the active roots. The rate of root water uptake has been described considering the hydraulic conductivity of leaves and water potential differences between root and soil (e.g. Gardner 1960; Whisler et al. 1968; Molz and Remson 1970; Feddes R. A. 1974; Hillel et al. 1976). Furthermore, recently Fatahi (2007) developed a more comprehensive approach to evaluate the rate of root water uptake considering transpiration of tree canopy (Eq. 1).

$$S(x, y, z, t) = f(\psi)G(\beta)F(T_p) \quad (1)$$

where, $F(T_p)$ is a factor related to the potential transpiration model developed by Nimah and Hanks (1973) which can be described according to Eq. 2.

$$F(T_p) = \frac{T_p(1+k_4z_{max}+k_4z)}{\int_{v(z)} G(\beta)(1+k_4z_{max}+k_4z)dv} \quad (2)$$

where, $G(\beta)$ is the root density effect which directly depends on tree species and soil condition and k_4 is an experimental coefficient (Fatahi 2010).

The coefficient k_4 depends on the rate of transpiration which is affected by the environmental factors, e.g. humidity, temperature, wind speed as well as soil moisture condition (soil water potential) and tree physiology. The effect of humidity, which is the amount of water vapour in the air, can be computed using Fick's law of diffusion for the rate of transpiration and it is assumed as directly proportional to the difference in vapour pressure between leaf and the atmosphere and inversely proportional to the summation of resistance to water flow encountered in air (Fatahi 2007). Temperature regulates the transpiration to high extend through its effect on vapour pressure, if there is no any inhabitant acclimatization in the plant species. In example, a leaf exposed to full sunlight may experience temperatures reaching 50°C to 100°C. If the leaf stomata remains open, transpiration will occur and vapour will condense once it emerges from the leaf. This phenomenon is called "steaming jungle" and occurs in tropical jungles (Hopkins (1999). Wind speed controls the transpiration through the change of resistance and effective length of diffusion path of water vapour (Nobel 1991). For higher wind speeds, the rate of transpiration increases due to the depletion of diffusion path. Even though the transpiration of tree leaves are affected by wind speed it is also subjected to the inhabitant acclimatization of the plant species.

$f(\psi)$ is the factor related to the soil moisture condition. Soil water potential inversely affects the root water uptake. Soil suction relates to the soil moisture content through the soil water characteristic curve. Therefore, the soil reduction factor is a function of moisture content of soil (Indraratna et al. 2008; Fatahi et al. 2009). A model suggested by Feddes (1974) for root water uptake reduction factor in relation to soil moisture content is shown in Figure 4, where θ_w is the moisture content at wilting point, θ_d is the minimum moisture content at $S = S_{max}$, θ_{an} is the maximum water content at maximum root water uptake. Tree physiology also affects the transpiration and leaf area, number of stomata in leaf and other biological features of tree control transpiration

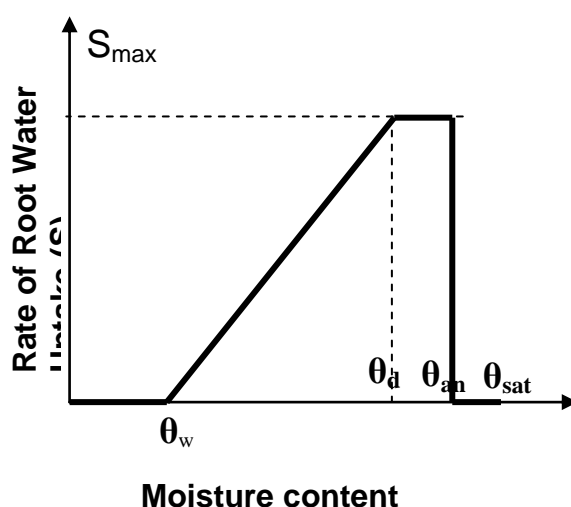


Figure 4 The water uptake – moisture content relationship (modified after Feddes et al. 1974)

The unsaturated flow equation incorporating the root water uptake as a sink term is as follows;

$$\frac{\partial \theta}{\partial t} = \nabla \cdot (k \nabla \psi) - \frac{\partial k}{\partial z} - S(x, y, z, t) \quad (3)$$

where k is hydraulic conductivity ψ is soil suction, z is vertical co-ordinate and t is time. $S(x, y, z, t)$ is root

water uptake. Above equation can be applied for homogeneous as well as heterogeneous media.

6. Mechanical strengthening induced by roots

Tree roots are potentially capable of binding the soil matrix together. Therefore, it gives the fibrous effect to the soil, controls the erosion control and prevents shallow failures within 1.5-2.0m (Bache et al. 1989). Moreover, large tree roots are capable of providing anchoring effect to the soil. The amount of root materials present in the shear plane namely the Root Area Ratio (RAR) is the governing parameter of the reinforcement contribution to the soil (Operstain and Frydman 2000; Docker and Hubble 2001)

$$\text{Root Area Ratio (RAR)} = \frac{\text{Area of Root Along the Shear Plane}}{\text{Area of the Shear Plane}} \quad (4)$$

The effect of tree roots on shear strength increment of soil has been discussed and examined during past few decades by various researchers. Waldron (1977) introduced a model for flexible elastic root extending vertically through a horizontal shear zone and the failure modes of the root system as stretching, slipping and breaking. Furthermore, three different shear strength increment values (ΔS) related to three failure modes were defined and several experimental coefficients relating the bond strength between root and soil, tensile strength of root and other dimensional parameters were introduced (Waldron 1977). According to Waldron and Dakessian (1981), ΔS values can be directly added to the coulomb equation since there is no change in friction angle.

$$\tau = c + \Delta S + \sigma_N \tan \phi \quad (5)$$

The cohesion increment in soil by tree roots can be taken as proposed by Operstain and Frydman (2000) as follows;

$$\Delta C = k_r T_r(r, z, t) \quad (6)$$

where, ΔC is apparent cohesion due to tree roots, T_r is the relative root tensile strength contribution and k_r is an experimental constant.

The value of T_r is influenced by root area ratio and the tensile strength of roots and diameter. In most of the root models, the shear strength development is related to the vertically driven root. Therefore, the practical applications are limited due to the more complex spatial distribution of root systems.

Docker and Hubble (2008) carried out large number of in situ direct shear test for four Australian riparian trees and proved the ability of increasing shear strength using vegetation with empirical equations. It was observed that the amount of shear increment computed by Waldron and Dakessian (1981) model was 50% more than the experimental values. Furthermore, Docker and Hubble (2009) described two types of roots systems according to the generated shear resistance against the block displacement. Figure 6(a) shows two types of root systems and Figure 6(b) displays shear resistance variation of the two types.

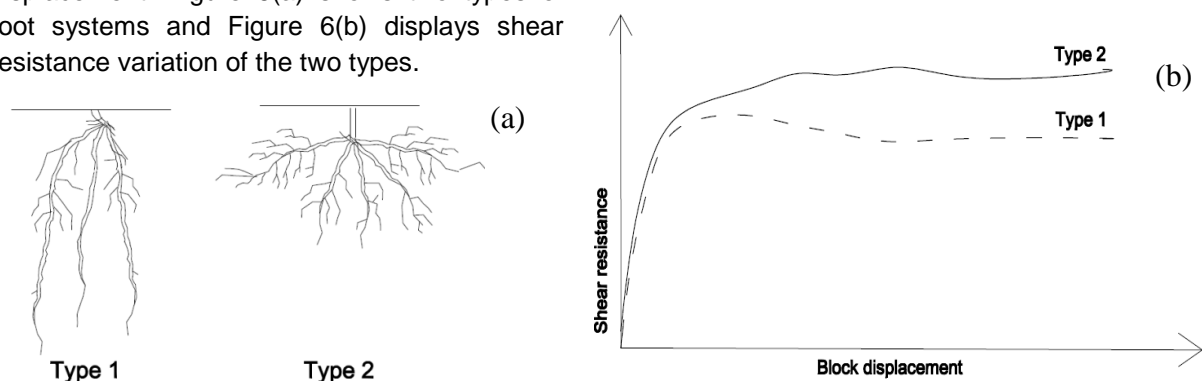


Figure 6: (a) The distinct root morphology through an in-situ shear test-block (b) Diagrammatic representation of two generally distinct root system behaviours at direct shearing (modified after Docker and Hubble 2009)

7. Results and discussion

Initial rate of root water uptake for the parameters of *Poplar tree* was computed by Fatahi (2007) using to the Eq.1 and results are shown in Figure 7(a). Furthermore, two-dimensional finite element analysis has been conducted by Fatahi (2007) for given soil parameters using governing equations and the developed model verification was done for several case studies. Figures 7(b) and 7(c) show the suction values computed using ABAQUS finite element model for the parameters of Fredlund and Hung's (2001) analysis.

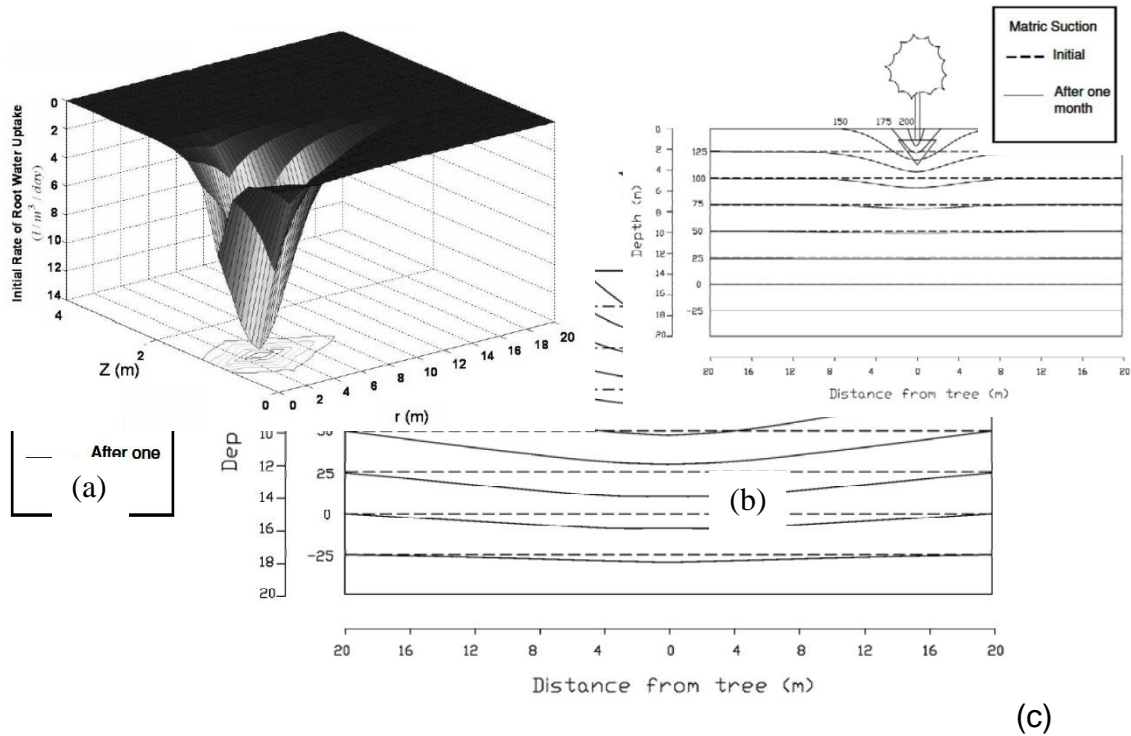


Figure 7(a). Initial distribution of root water uptake of *Poplar tree* (b) Variation of Matric suction after one month. (Fatahi 2007) (c) Variation of Matric suction after one year. (Fatahi 2007)

It is certain that most of the time sub soil remains partially saturated while depth and degree of saturation of the vadose zone are increased by the presence of mature trees. As a result of that, the parameters developed for mechanical strengthening for saturated condition are not realistic. Therefore, a combined effect has to be taken into account and parameters should be defined accordingly. Figure 8(a) gives a general understanding of the improvement in subsoil structure due to the combined effect. Soil element A in Figure 8(a) is directly under the Railway ballast and soil element B is in the root zone. General unsaturated soil mechanics theories are valid for soil element A and therefore Eq. 7 (Fredlund et al. 2012) can be used.

$$\tau = c' + (\sigma_n - u_a) \tan \phi' + (u_a - u_w) \left[\tan \phi' \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right) \right] \quad (7)$$

where, u_a and u_w are pore air and water pressures; θ_s , θ_r , and θ are saturated, residual and instant volumetric water contents and all the other symbols have their usual meaning.

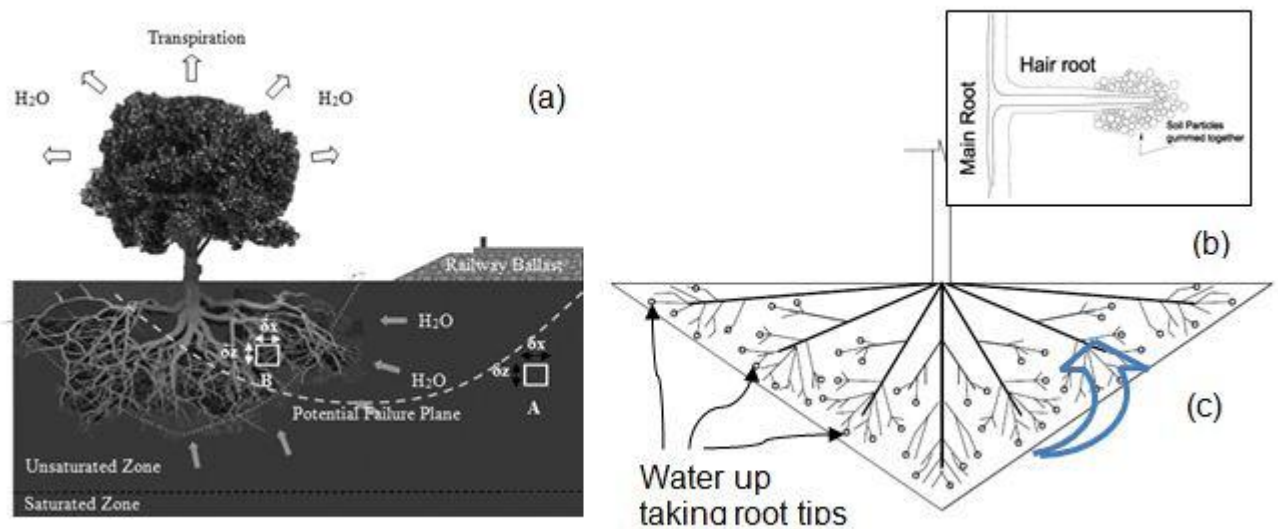


Figure 8 (a) Schematic diagram of root water uptake process and root reinforcement, (b) Schematic diagram of root system with distribution of water up-taking active root tips, (c) Enlarged root tip.

The θ value in Eq. 7 changes with time due to root water uptake and the following equation can be derived considering Eq. 3 and Reynolds differential transport theorem.

$$\frac{\partial \theta}{\partial t} = \nabla \cdot (k \nabla \psi) - \theta \frac{\partial k}{\partial z} - dS(x, y, z, t) + dI(x, y, z, t) \quad (8)$$

In above equation S represents the root water uptake sink term and I is the irrigation source term. The θ is the volumetric moisture content; k is hydraulic conductivity and ψ is matric suction. The usual soil water characteristic curve (SWCC) can be used for element 'A' (Figure 7a), whereas element 'B' has a great effect from root suction and root reinforcement since it is in the root zone of tree. Therefore, the description of the unsaturated soil characteristics which relies on the SWCC cannot be directly applied for element 'B'. Furthermore, the stiffness of the root zone results in an increase of shear strength in soil adjacent to element A. Therefore it is identified as a "shear capacity" of the root area zone which acts as an external stiffener with the effect from root reinforcement and suction (Pallewattha et. al. 2015)

Figure 7(b) shows a schematic diagram of the root zone and water uptake points. According to the enlarged view of root tip in figure 7(c) and according to the classical botanical understanding, process of osmosis at the root tip, binds the soil matrix together. Therefore, the failure patterns described in section 3, may be altered such that it governs by the process of osmosis at root tip. The suction changes the bond strength between root and soil as well as it alters the material properties of root. In this case the failure of root system due to slipping, stretching, breaking or pulling out with soil annulus are greatly affected by suction induced by tree roots as well as the adjacent soil suction. Considering all the above facts, computing the effects from root reinforcement and suction separately and superimposing them may not give realistic answers since suction has an influence on root reinforcement.

8. Conclusions

Tree roots can be used economically in subgrade improvement after an effective analysis of hydrological behaviour of the ground and subsequent effects. Past developed models to compute root based suction and the root reinforcement effect have been contributed considerably for the sub grade improvement, however as described in this paper a comprehensive model which consist of mechanical strengthening as well as root based suction is vital, to have more realistic results. Moreover, most of the trees are not capable of providing the sub-soil improvement due to their shallow root system and deciduous behavior. Therefore, it is essential to select the most appropriate plant i.e. good root system and evergreen. It was shown that it is discernible that the spatial distribution of root has a major role in reinforcing soil. The true tree root system depends on the environmental factors. Therefore, for practical usage, it is essential to compute the parameters considering environmental factors for selected tree species. The model of the shear capacity of tree root zone should comprise the coupling effect of mechanical strengthening of roots and suction and other parameters developed for selected trees. Developing more generalized equations despite the tree species and initial growing condition may not give realistic answers.

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