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Development of a Thornthwaite Moisture Index Map for Trinidad and Tobago

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Abstract. The Thornthwaite Moisture Index (TMI) has been traditionally used as a climatic index parameter to estimate annual moisture status of soils (deficit/surplus), primarily in the agricultural domain. Engineers have also adopted the TMI in efforts to estimate volume change potential in expansive clays, where seasonal (temporal) moisture changes can be correlated to soil matric suction and ultimately volume change via appropriate mechanistic models. In Trinidad and Tobago, approximately 60 % of the islands are covered with over-consolidated clays of medium to high plasticity. When combined with extreme variations in moisture status, these plastic clays have exhibited high volume change potential. This paper investigates the spatial distribution of this climatic index for Trinidad and Tobago, intending to develop an index map for the islands. Within the post-colonial era in Trinidad and Tobago (1962 ~ present), the availability of consistent climatic data is limited to just two recording stations within the islands. The Meteorological Services of Trinidad and Tobago (MET) manages both stations: Piarco, Trinidad and Crown Point, Tobago, where consistent data exists for 36 years (1981 ~ 2018). These two points and their limited data timeframe cannot support the development of a spatial TMI map for the islands. This research addresses this shortcoming by collecting and analysing historical climatic data collected at 28 stations over Trinidad and Tobago over the British Colonial era (1931 ~ 1964). These data are recorded in publications of the Land Capability Surveys of The Imperial College of Tropical Agriculture (ICTA). Data sets of monthly rainfall data from the historical and at present for the Piarco location showed strong statistical coherence, examined through a t-test. Having justified the historical data, TMI values are calculated at all locations. Using the calculated TMI values, a map was developed using the GIS software, Surfer, and interpolation method of Kriging. In Trinidad, the map indicates high TMI at the north-eastern side of the island, with a significant decrease going into the south-western side. Low TMI values are observed in the most western side of Trinidad indicating substantially long dry season period, during which the underlying expansive clay can experience significant shrinkage.

1 Introduction

Highly plastic clays have the potential to shrink and swell, depending on the available moisture at a specific location. Situations can occur where a highly expansive soil can be found in an extremely wet climate or an arid climate, although the overall volume change of the soil may be negligible due to a restriction of moisture variations. Thus, the understanding of our climate regime is essential to better understand the expansive potential of clays in their field conditions.

Thornthwaite [1] developed a climate index (TMI), in which climatic types for varying locations can be accessed by only requiring monthly rainfall, temperature and northing coordinate. TMI maps have been developed for countries, namely in the United States of America [2] and parts of Australia [3-4]. These TMI maps further assist in the research of the estimation of volume change potential in expansive soils, as well as climate change and pavement deterioration [5]. Fig. 1 shows the TMI relationship to equilibrium suction of soils [6] and Table 1 shows the TMI relationship with the depths of moisture change [7]. The depth of moisture changes increases significantly as the TMI values shift from highly positive to highly negative. These relationships assist in foundation designs on expansive soils and have been implemented into building codes.

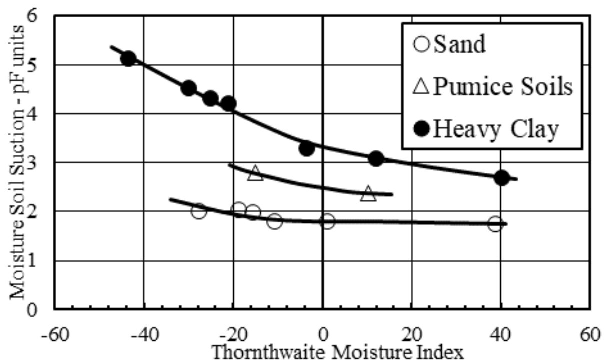

Fig. 1. TMI relationship to moisture soil suction. [6]

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Table 1. Relationship of TMI to seasonal moisture depths. [7]

TMI	Classification	Depth of Moisture Change H_s
>40	Wet Coastal/Alpine	1.5m
10 to 40	Wet Temperate	1.5 - 1.8m
-5 to 10	Temperate	1.8 - 2.3m
-25 to -5	Dry Temperate	2.3 - 3.0m
-40 to -25	Semi-arid	3.0 - 4.0m
<-40	Arid	>4.0m

The design of post-tension slab foundations on expansive soils, uses the TMI values to estimate climate-induced settlement relating to edge moisture variations [8]. In the Australian Standard AS2870 for the design of slabs and footings, the TMI is used to predict surface movements [9].

In Trinidad and Tobago, there are no set building codes relating to expansive soils, and it is left to the discretion of an individual who may seek assistance from a competent engineer. Having 60% of the soils in Trinidad are covered with medium to highly plastic clays [10-11], significant moisture variations could influence the amount of volume change within these soils.

This paper investigates climate variations throughout Trinidad and Tobago and develops a TMI map, which can assist in the design of foundations on expansive clays.

2 Methodology

2.1 Thornthwaite moisture index

The TMI is a single number that classifies the climate regime of an area. It can be computed yearly or for an average number of years using equation 1. The TMI is a combination of two main indices, the humidity index (I_h) in equation 2 and aridity index (I_a) in equation 3. Computing these indices requires monthly Surplus (S), Deficits (D) and Potential Evapotranspiration (PE) at a particular location. Moisture deficits and surplus are calculated from the monthly precipitation and potential evapotranspiration through carrying out a monthly water balance. It is assumed that the field capacity at all sites is 100mm by considering the mean value used by Russam and Coleman [6]. It is also assumed that the ground is fully saturated in December as the rainy season occurs from June to December. The PE is calculated from using the Northing location value and mean monthly temperature at the site in equation 4. The Adjustment (Adj.) factor is obtained through its correlation to the Northing and read off from Thornwaite's tables for corresponding values, with the use of the mean monthly temperature (t), the heat index (I), and correlation factor (a). Although Thornthwaite's determination of PE is simplistic, and there exist advanced methods, most empirical relationships to the TMI were developed using this method. For continuity, PE is calculated using Thornthwaite's method for the proposed TMI map.

$$\mathrm{TMI} = \mathrm{I_h} + \left(0.6 \times \mathrm{I_a}\right) \quad (1)$$

$$\mathrm{I_h} = 100 \times \left(\frac{\mathrm{S}}{\mathrm{PE}}\right) \quad (2)$$

$$\mathrm{I_a} = 100 \times \left(\frac{\mathrm{D}}{\mathrm{PE}}\right) \quad (3)$$

$$\mathrm{PE}(\mathrm{mm}) = \left(\left(\mathrm{Adj.Factor}\right) \times 1.6 \left(\frac{10\mathrm{t}}{\mathrm{I}}\right)^{\mathrm{a}}\right) \times 10 \quad (4)$$

where $\mathrm{I} = \sum_{i=1}^{12} \left(\frac{t_i}{5}\right)^{1.514}$ and

$$\mathrm{a} = \left(\left(6.75 \times 10^{-7}\right) \times \mathrm{I}^3\right) - \left(\left(7.711 \times 10^{-5}\right) \times \mathrm{I}^2\right) + 0.49239$$

2.2 Locations of historical rainfall data

The historical rainfall data sets are taken from Brown and Bally book collection on Trinidad and Tobago Land Capability Surveys [12-15]. In total there are 28 locations having rainfall data for a 30-year mean for each month during the period of 1931 ~ 1964. The name of each location and its coordinates are shown in Table 2 and Fig 2, respectively.

Table 2. Named locations (LOC) for historical data.

LOC	Name	Eastings	Northings
1	Toco	-60.9497	10.83111
2	Valencia	-61.1906	10.69143
3	Arima	-61.2630	10.63853
4	Sangre Grande	-60.9991	10.83006
5	Diego Martin	-61.5552	10.74081
6	Santa Cruz	-61.4713	10.71146
7	POS	-61.5209	10.67072
8	St. Augustine	-61.3992	10.64372
9	Piarco	-61.3479	10.59266
10	Camdem	-61.4480	10.42209
11	La Vega	-61.3461	10.42300
12	Grosvenor	-61.1321	10.55188
13	Spring	-61.4163	10.41684
14	Mayaro	-61.0055	10.29486
15	Guyaguayare	-61.0609	10.13262
16	Moruga	-61.2801	10.08862
17	Barrackpore	-61.4492	10.16986
18	Siparia	-61.5445	10.17707
19	Point Fortin	-61.6597	10.17042
20	Cedros	-61.8058	10.11718
21	Friendship	-60.7941	11.14781
22	Gov. Farm	-60.7511	11.17578
23	Botanic Station	-60.7611	11.17007
24	Moriah	-60.7243	11.23202
25	Hillsborough	-60.6666	11.22807
26	Kendal	-60.6002	11.23367
27	King's Bay	-60.5563	11.26638
28	Hemitage	-60.5844	11.31645

Table 3. Historical rainfall data for the period of 1931 ~ 1964.

LOC	Rainfall (mm/month)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	83.8	75.2	43.7	68.6	121.4	217.2	201.4	207.3	159.5	191.8	208.3	175.3
2	148.8	112.5	76.2	121.4	265.7	412.8	382.0	342.1	263.1	296.7	322.3	297.2
3	85.1	94.2	37.6	76.2	160.5	340.6	301.2	274.8	198.4	209.0	229.1	191.0
4	162.6	104.6	88.6	119.6	200.4	335.0	310.9	337.6	230.6	272.8	332.5	317.0
5	95.5	70.4	53.6	60.5	110.7	201.9	252.0	281.7	214.6	192.3	184.2	166.1
6	139.2	116.6	77.5	55.9	84.3	216.4	269.2	333.2	232.7	164.8	190.0	180.3
7	64.0	44.7	44.2	61.5	99.8	187.2	206.2	252.0	205.7	172.5	192.5	138.9
8	68.1	39.6	33.0	49.0	53.3	224.0	218.4	244.9	182.1	162.8	190.5	158.2
9	72.6	42.4	34.5	55.9	132.8	239.8	226.8	246.9	174.8	157.5	195.8	168.9
10	64.3	40.5	24.0	34.5	68.2	160.6	187.0	218.2	162.5	140.0	166.3	138.9
11	113.9	69.9	40.2	51.5	127.4	308.8	316.1	258.9	202.9	212.8	255.8	215.8
12	157.5	93.1	83.2	96.2	169.9	307.1	316.2	282.3	244.5	265.1	338.8	335.3
13	93.0	64.8	43.1	55.7	97.3	252.3	241.2	260.4	213.7	185.4	219.1	180.3
14	130.0	70.1	60.2	74.4	140.7	246.1	204.5	231.9	159.0	172.7	229.9	233.7
15	156.2	82.6	62.0	100.6	152.7	264.2	231.6	247.9	169.9	191.5	258.6	286.3
16	102.6	55.6	45.0	58.7	135.6	233.7	202.4	189.5	142.7	160.5	203.2	228.1
17	94.2	61.2	45.0	62.0	127.3	224.0	222.3	241.8	158.2	154.4	176.3	156.7
18	87.6	64.8	50.5	57.4	92.7	215.1	177.8	222.5	145.3	139.7	166.4	148.8
19	81.0	85.1	66.3	79.2	105.2	240.3	228.1	281.2	182.6	172.2	189.5	170.7
20	110.2	68.3	63.2	67.6	83.1	182.1	194.8	159.3	113.0	104.1	152.4	146.8
21	57.7	60.5	37.6	49.0	74.4	182.4	173.0	183.4	125.5	176.5	175.3	145.8
22	60.2	54.1	34.0	54.6	110.0	172.2	199.4	197.9	172.2	163.3	210.6	178.3
23	96.3	72.1	43.4	69.1	146.3	223.5	239.3	210.6	197.1	192.0	254.5	200.7
24	103.9	80.5	54.1	50.0	112.3	173.2	195.8	215.9	200.9	240.8	227.1	173.5
25	102.1	102.1	48.5	77.0	118.4	204.5	236.5	216.7	197.4	303.5	266.4	190.8
26	205.0	147.8	94.7	100.6	170.2	328.4	312.9	251.7	283.2	325.4	331.2	283.2
27	129.3	85.1	52.6	79.5	146.8	213.6	226.8	188.7	212.6	201.9	280.9	232.7
28	154.9	90.2	66.3	87.6	163.8	255.8	253.0	233.7	256.3	235.7	326.6	264.9

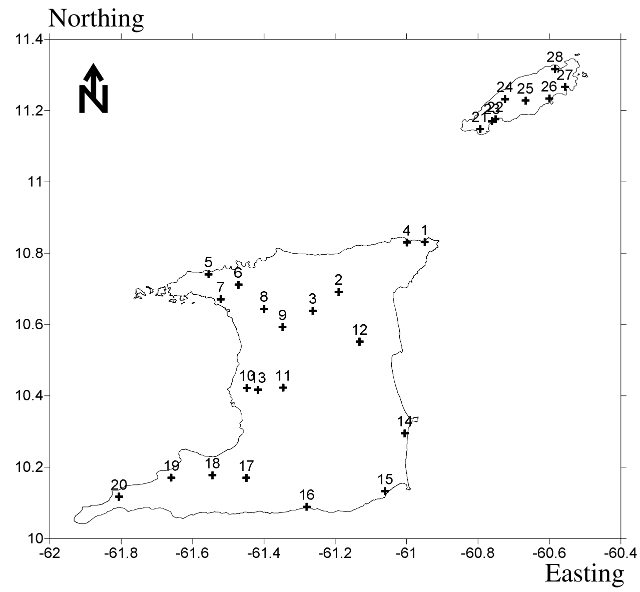

Fig. 2. Locations of historical rainfall data in Trinidad and Tobago.

2.3 Climate data

2.3.1 Rainfall

The historical rainfall data at the 28 locations are given in Table 3. Locations (LOC) 1-9 are from the northern part of Trinidad, LOC 10-13 are from the central part of Trinidad, and LOC 14-20 are from the southern part of Trinidad. LOC 21-28 are from Tobago. The spatial distribution of the locations would help in the interpolation accuracy of the TMI map. Table 4 gives the mean monthly rainfall at the MET office location, Piarco, for a recent period of 1981 ~ 2018 [16]. This set of data is compared with historical data, for the LOC 9 (Piarco), to investigate the coherence and reliability of using the historical data.

2.3.2 Temperature

The mean monthly temperature is also given in Table 4 from the Met Office for the period of 1981 ~ 2018 [16]. It is assumed that these monthly temperature readings are the same throughout Trinidad and Tobago. The temperature data shows a suitable increase in temperatures during May and August but has an overall similar mean temperature throughout the year.

Table 4. Mean monthly rainfall and temperature at the Met Office, Piarco, for the period of 1981 ~ 2018.

Month	Rainfall (mm)	Temperature (^oC)
Jan	72.5	26.27
Feb	38.2	26.89
Mar	26.9	27.39
Apr	30.4	28.14
May	105.2	28.21
Jun	245.4	27.59
Jul	229.5	28.13
Aug	233.9	28.22
Sep	177.12	27.93
Oct	208.8	27.71
Nov	232.8	27.04
Dec	156.9	26.52

2.4 Spatial distribution of TMI

Surfer is a GIS software, used to visualise and analyse data at known locations or points quickly, and can further interpolate data where they do not exist within a specified region. Data processing in Surfer allows for 2D and 3D map generation from the spatial distribution of data.

Calculated TMI values with known coordinates are imported into the GIS Software Surfer from an excel data file. The kriging interpolation method is chosen as the preferred gridding method to generate the spatial distribution of TMI data within the regions of Trinidad and Tobago shown in Fig. 2. The processed data in Surfer is further visualised into blue coloured contours with increments of five TMI. The contours are darker for highly positive values and get extremely light towards the lower values of the TMI.

3 Results and discussion

Fig. 3 shows the comparison of both rainfall distributions for the historical data set and present at the Piarco location. The present set of continuous data is only at one location and cannot be used to examine the TMI throughout Trinidad and Tobago spatially. In order to statistically examine the reliability and coherence of the historical data to the present data at the Piarco location, a t-test (Paired Two Sample for Means) was carried out using the Data Analysis toolbox in Microsoft Excel (2016) [18]. The t-test examined the null hypothesis; there is no statistically significant difference between the mean rainfall data between the selected time periods of (1981-2018) and (1931-1961) at the Piarco Location. The t-test gives a p-value of 0.913, which is greater than the set alpha (significance) level of 0.05, and the t-value of 0.111, which is less than the t-critical = 2.2 for a two-tail analysis. The results of the p-value and t-value from the t-test indicates that the null hypothesis is accepted and cannot be rejected. Also from the t-test, a pearson correlation value of 0.967 was obtained an indicates a strong correlation in comparing both data sets.

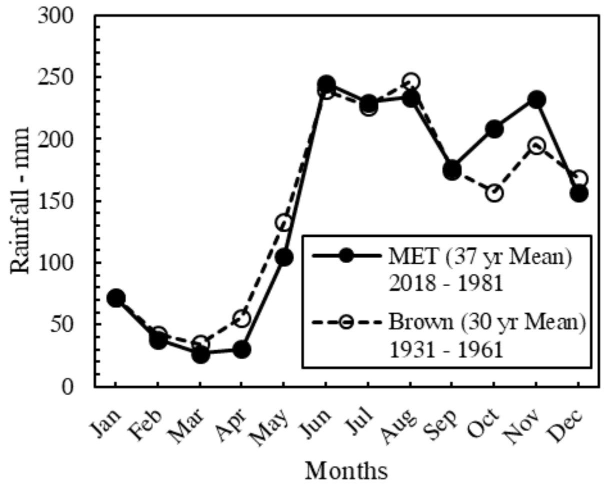

Fig. 3. Comparison of monthly rainfall data sets at Piarco.

Table 5. Calculated TMI values at each location.

LOC	Yearly Deficits (mm)	Yearly Surplus (mm)	PE (mm)	I_a	I_h	TMI
1	-267	225	1874	14	12	3
2	-42	1077	1873	2	57	56
3	-206	530	1873	11	28	22
4	-39	988	1874	2	53	52
5	-269	369	1873	14	20	11
6	-200	446	1873	11	24	17
7	-345	221	1873	18	12	1
8	-416	205	1873	22	11	-2
9	-321	221	1873	17	12	1
10	-468	84	1873	25	5	-10
11	-256	557	1873	14	30	22
12	-92	908	1873	5	48	46
13	-305	389	1873	16	21	11
14	-188	360	1873	10	19	13
15	-136	467	1873	7	25	21
16	-262	224	1873	14	12	4
17	-270	203	1873	14	11	2
18	-306	142	1873	16	8	-2
19	-242	326	1873	13	17	10
20	-428	68	1873	23	4	-10
21	-433	96	1874	23	5	-9
22	-347	152	1874	19	8	-3
23	-233	386	1874	12	21	13
24	-259	237	1874	14	13	4
25	-212	470	1874	11	25	18
26	-44	1004	1874	2	54	52
27	-171	445	1874	9	24	18

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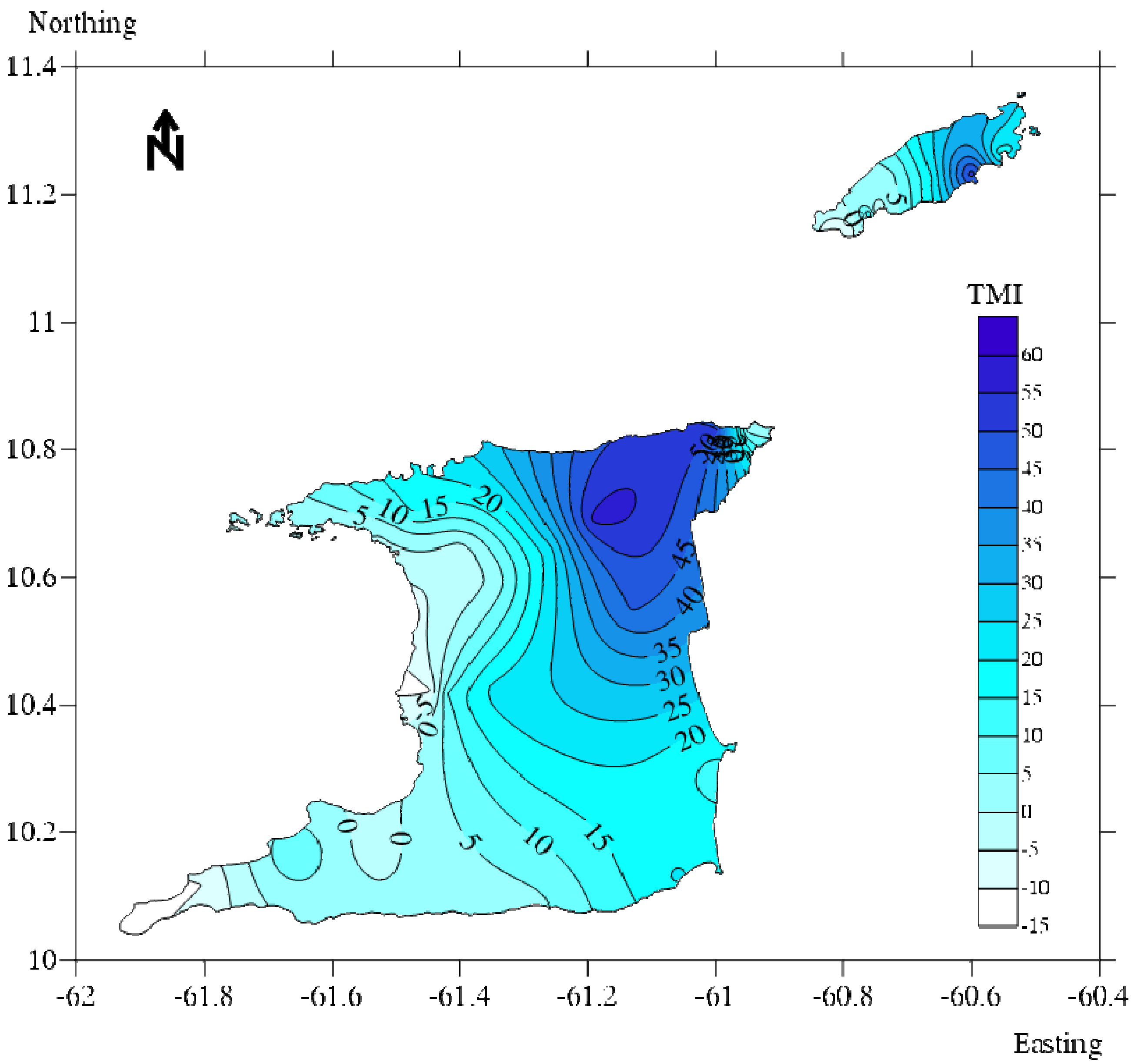

Fig. 4. Proposed TMI map of Trinidad and Tobago

The monthly temperature data at the historic locations are not given, only its average of 26.2°C recorded. Having a high coherence of the rainfall data, it is also assumed that the mean monthly temperature at the Piarco location presently can be used for the determination of PE for all locations.

Calculated TMI values are given in Table 5 using Equations 1-4. Fig. 4 shows the TMI map created using Surfer [17]. The highest value of TMI in the north-eastern side of Trinidad indicates a minimal amount of moisture variations within soils in this region. Coincidentally, in the north-eastern area of Trinidad, one of its largest dams named the Hollis Reservoir is located. The Hollis Reservoir location was most likely selected based on the high record of yearly rainfall. Moving to the southern part of Trinidad, the TMI values decrease towards the south-western tip.

At the central part of Trinidad, on the western side of the island, there is also significantly low TMI values. These low TMI values indicate that, within the western side of the island, moisture variations can be substantial from longer dry seasons. Expansive clays in these areas would be prone to significant volume change and affect shallow foundations resting on them. In Tobago, at both ends on the island, the TMI values are low and a bit higher nearer to its center. Although moisture variations can be high, the soils in this island are generally non-expansive.

4 Conclusion

A TMI map has been developed using the historical data for the period of 1931 ~ 1964. It was observed that, for the Piarco location, the mean rainfall data for the period of 1931 ~ 1964 are similar to the mean values for the period of 1981 ~ 2018. Areas in Trinidad are highlighted where moisture variations are high. This map can be

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used to assist engineers for foundation designs on expansive clays and can be further developed with the availability of spatial data.

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