

Combined Drought Index Using High-Resolution Hydrological Models and Explainable Artificial Intelligence Techniques in Türkiye

Eyyup Ensar Başakın ^{1,2}, Paul C. Stoy ^{2,*}, Mehmet Cüneyd Demirel ¹, Mutlu Ozdogan ³ and Jason A. Otkin ⁴

¹ Hydraulics Division, Civil Engineering Department, Istanbul Technical University, Istanbul 34469, Türkiye; basakin@itu.edu.tr (E.E.B.); demirelmc@itu.edu.tr (M.C.D.)

² Department of Biological Systems Engineering, University of Wisconsin-Madison, Madison, WI 53706, USA

³ Department of Forest and Wildlife Ecology & Nelson Institute for Environmental Studies, University of Wisconsin-Madison, Madison, WI 53706, USA; ozdogan@wisc.edu

⁴ Space Science and Engineering Center, University of Wisconsin-Madison, Madison, WI 53706, USA; jaotkin@wisc.edu

* Correspondence: pcstoy@wisc.edu

Table S1. XGBoost hyperparameter range and optimum values.

Hyperparameter	Explanation	Range	Optimum Value
num_round	The number of rounds to run the training	$[1, \infty]$	100
alpha	L1 regularization term on weights.	$[0, \infty]$	0.01
lambda	L2 regularization term on weights.	$[0, \infty]$	0.03
max_depth	Maximum depth of a tree.	$[1, \infty]$	10
eta	To prevent overfitting, step size shrinkage is used in updates.	$[0, 1]$	0.01
early_stopping_rounds	The model continues to train until the validation score no longer improves.	$[1, \infty]$	30
subsample	Subsampling ratio of the training instance.	$[0, 1]$	0.8

Table S2. XGBoost model performance evaluation results.

Number	Combination	R		RMSE		AIC
		Train	Test	Train	Test	Train
1	TCI_PCI_VCI_GPP_NDWI_SMCi	0.8206	0.6875	30.4915	31.4888	4103.938
2	PCI_VCI_GPP_NDWI_SMCi	0.8144	0.6786	30.5236	31.6834	4107.512
3	TCI_PCI_VCI_NDWI_SMCi	0.8139	0.6574	30.5500	31.5543	4108.237
4	TCI_PCI_GPP_NDWI_SMCi	0.8120	0.6664	30.5656	32.0402	4108.849
5	TCI_PCI_VCI_GPP_NDWI	0.8094	0.6760	30.6307	31.8894	4110.405
6	PCI_VCI_NDWI_SMCi	0.8069	0.6686	30.7620	31.9830	4115.535
7	PCI_VCI_GPP_NDWI	0.8059	0.6646	30.8585	31.9434	4119.295
8	TCI_PCI_GPP_NDWI	0.8059	0.6636	30.8792	31.5025	4120.1
9	PCI_GPP_NDWI_SMCi	0.8047	0.6786	31.0046	31.9521	4124.964
10	TCI_VCI_GPP_NDWI_SMCi	0.8038	0.6764	31.0232	31.5824	4125.683
11	TCI_PCI_VCI_NDWI	0.8034	0.6667	31.0499	31.5258	4126.716
12	TCI_PCI_VCI_GPP	0.8025	0.5986	31.1236	31.7963	4129.559
13	TCI_VCI_NDWI_SMCi	0.8012	0.6620	31.2576	31.6424	4134.715
14	TCI_PCI_GPP_SMCi	0.7997	0.6132	31.2774	31.5412	4135.474
15	TCI_PCI_VCI_GPP_SMCi	0.7955	0.6268	31.3427	32.9441	4137.976
16	TCI_PCI_VCI_SMCi	0.7951	0.6231	31.3489	31.7231	4138.216
17	TCI_PCI_NDWI_SMCi	0.7950	0.6693	31.3911	33.5127	4139.83
18	TCI_GPP_NDWI_SMCi	0.7927	0.6603	31.4493	31.6587	4142.051
19	PCI_VCI_NDWI	0.7925	0.6605	31.5085	32.0796	4144.31
20	VCI_GPP_NDWI_SMCi	0.7921	0.6595	31.5510	33.1200	4145.926
21	TCI_VCI_GPP_NDWI	0.7906	0.6769	31.5692	33.1515	4146.617
22	PCI_GPP_NDWI	0.7871	0.6509	31.6967	32.0128	4151.456
23	TCI_VCI_NDWI	0.7863	0.6700	31.7885	32.5216	4154.924
24	PCI_NDWI_SMCi	0.7859	0.6601	31.8461	31.9596	4157.097
25	GPP_NDWI_SMCi	0.7842	0.6581	31.8970	31.9775	4159.013
26	VCI_GPP_NDWI	0.7836	0.6554	31.9521	32.9480	4161.084
27	TCI_PCI_GPP	0.7831	0.5794	31.9957	32.3918	4162.721
28	TCI_VCI_GPP	0.7827	0.5947	32.0200	31.7643	4163.634
29	TCI_VCI_GPP_SMCi	0.7825	0.6219	32.0728	33.8067	4165.609
30	PCI_VCI_GPP_SMCi	0.7823	0.5374	32.1692	32.0956	4169.211
31	TCI_PCI_VCI	0.7821	0.5971	32.1929	32.3397	4170.097
32	VCI_NDWI_SMCi	0.7819	0.6397	32.3148	33.7662	4174.629
33	TCI_GPP_SMCi	0.7778	0.6165	32.4023	34.5470	4177.877
34	TCI_GPP_NDWI	0.7770	0.6690	32.4688	31.9273	4180.334
35	TCI_VCI_SMCi	0.7749	0.6203	32.5298	33.1235	4182.588
36	TCI_PCI_NDWI	0.7745	0.6467	32.5354	33.2240	4182.795
37	PCI_GPP_SMCi	0.7694	0.5191	32.5435	33.9294	4183.093
38	TCI_PCI_SMCi	0.7691	0.6045	32.5445	33.5117	4183.13
39	PCI_VCI_SMCi	0.7678	0.5257	32.8919	34.8404	4195.872
40	TCI_GPP	0.7669	0.5301	33.0692	34.8666	4202.322
41	VCI_GPP_SMCi	0.7610	0.5132	33.2269	33.1294	4208.031
42	PCI_NDWI	0.7607	0.6289	33.4198	32.8142	4214.978
43	VCI_NDWI	0.7606	0.6261	33.4220	35.7919	4215.059
44	TCI_VCI	0.7582	0.5825	33.5401	32.9283	4219.291
45	PCI_VCI_GPP	0.7578	0.4739	33.6420	35.0156	4222.931
46	TCI_NDWI_SMCi	0.7511	0.6481	33.6598	33.6347	4223.565

47	GPP_NDWI	0.7503	0.6045	33.6752	35.1678	4224.115
48	TCI_PCI	0.7414	0.5084	33.7453	33.4770	4226.608
49	TCI_SMCi	0.7392	0.5577	33.7481	32.7202	4226.711
50	NDWI_SMCi	0.7381	0.6151	33.8158	35.1613	4229.115
51	PCI_SMCi	0.7276	0.4601	33.8267	34.5603	4229.501
52	VCI_SMCi	0.7271	0.4676	33.8429	34.0890	4230.075
53	GPP_SMCi	0.7210	0.4275	34.0262	34.5446	4236.557
54	TCI_NDWI	0.7201	0.6267	34.5137	35.7998	4253.629
55	PCI_GPP	0.7129	0.3797	34.7137	36.6253	4260.562
56	PCI_VCI	0.7101	0.3969	34.7372	35.7031	4261.372
57	VCI_GPP	0.6954	0.3634	34.9224	36.2289	4267.755
58	NDWI	0.6935	0.6059	35.1350	36.0028	4275.037
59	TCI	0.6891	0.5239	35.1973	36.9659	4277.162
60	SMCI	0.6716	0.4157	35.5335	37.1241	4288.57
61	VCI	0.6578	0.4000	35.8195	36.6440	4298.191
62	GPP	0.6406	0.2816	35.8816	37.5655	4300.27
63	PCI	0.6362	0.3116	36.0314	37.9436	4305.27

R is Sperman's Correlation Coefficient, RMSE is Root Mean Square Error, AIC is Akaike Information Criteria

Table S3. CDI weights obtained from PCA of the training set.

District	PCI	TCI	VCI	SMCI	GPP	NDWI
Agacoren	0.11	0.20	0.25	0.10	0.18	0.16
Akoren	0.09	0.20	0.25	0.11	0.17	0.19
Aksaray_Merkez	0.10	0.21	0.24	0.11	0.16	0.17
Ayranci	0.10	0.19	0.23	0.08	0.20	0.19
Celtik	0.10	0.19	0.23	0.10	0.23	0.15
Ciftlik	0.13	0.20	0.24	0.16	0.09	0.18
Cumra	0.07	0.23	0.23	0.08	0.17	0.23
Derbent	0.11	0.16	0.25	0.11	0.23	0.14
Doganhisar	0.11	0.18	0.24	0.10	0.24	0.13
Emirgazi	0.10	0.21	0.22	0.13	0.15	0.18
Eregli	0.08	0.21	0.23	0.11	0.16	0.21
Eskil	0.06	0.23	0.21	0.11	0.19	0.20
Gulagac	0.14	0.23	0.20	0.18	0.01	0.24
Guneysinir	0.09	0.21	0.26	0.09	0.14	0.22
Guzelyurt	0.14	0.20	0.23	0.18	0.06	0.19
Huyuk	0.11	0.19	0.25	0.10	0.24	0.12
Kadinhani	0.09	0.19	0.23	0.10	0.23	0.16
Karaman_merkez	0.09	0.21	0.23	0.09	0.18	0.21
Karatay	0.06	0.23	0.23	0.09	0.21	0.19
Kulu	0.09	0.21	0.24	0.10	0.19	0.17
Meram	0.10	0.19	0.25	0.09	0.21	0.16
Nigde_merkez	0.12	0.21	0.22	0.13	0.13	0.19
Ortakoy	0.10	0.20	0.26	0.09	0.18	0.17
Sarayonu	0.14	0.17	0.22	0.10	0.27	0.10
Sarıyahsi	0.10	0.19	0.24	0.10	0.24	0.14
Seydisehir	0.11	0.19	0.24	0.12	0.23	0.11
Tuzlukcu	0.13	0.18	0.24	0.09	0.23	0.13
Ulukisla	0.13	0.20	0.20	0.15	0.11	0.21
Yalihuyuk	0.13	0.18	0.25	0.11	0.22	0.11
Yunak	0.12	0.19	0.24	0.10	0.22	0.14
Mean	0.10	0.20	0.23	0.10	0.18	0.17

Table S5. Correlation test results between drought indices and crop yield.

District	CDI (SHAP)	CDI (PCA)	CDI (MEAN)	SPEI_1	SPEI_3	SPEI_6	SPEI_9	scPDSI
Agacoren	0.0075	-0.0391	-0.0105	0.0586	0.0812	0.1338	0.1925	0.1534
Akoren	0.4391	0.4165	0.4376	0.3624	0.3684	0.3293	0.2060	0.0632
Aksaray_Merkez	0.6812	0.6361	0.6436	0.5368	0.5744	0.5654	0.4481	0.2301
Aksehir	0.5835	0.3188	0.3895	0.3880	0.5534	0.3714	0.1925	0.2752
Altnekin	0.5474	0.3534	0.3474	0.3729	0.3774	0.4180	0.4301	0.2932
Altunhisar	0.7383	0.7188	0.7158	0.5729	0.6617	0.6737	0.6045	0.3774
Ayranci	0.2692	0.0075	0.0075	0.0902	0.1113	0.2827	0.4256	0.1338
Beysehir	0.6226	0.5910	0.6135	0.2180	0.3068	0.1519	0.1203	0.2000
Bor	0.6436	0.5744	0.5654	0.4556	0.4556	0.3353	0.2586	0.1714
Camardi	0.5038	0.3203	0.3053	0.4767	0.4286	0.3053	0.2752	0.2797
Celtik	0.7008	0.4872	0.4932	0.5053	0.6165	0.6586	0.5820	0.4797
Ciftlik	0.4075	0.4752	0.4827	0.2105	0.2586	0.2556	0.2767	0.2150
Cihanbeyli	0.7624	0.6887	0.6917	0.6692	0.6647	0.5323	0.4241	0.3940
Cumra	0.5579	0.4977	0.4797	0.3805	0.4030	0.2842	0.1158	0.1940
Derbent	0.5729	0.3038	0.3669	0.2286	0.3308	0.2271	0.1835	0.2030
Doganhisar	0.5203	0.4767	0.4165	0.3218	0.3278	0.2000	0.1940	0.2797
Emirgazi	0.8000	0.7008	0.7128	0.6015	0.6120	0.5203	0.3504	0.3233
Eregli	0.2541	0.1549	0.1669	0.0992	0.1594	0.2150	0.2000	0.0316
Eskil	0.5053	0.2677	0.3323	0.2256	0.3955	0.3820	0.3263	0.1744
Gulagac	0.7353	0.6000	0.6617	0.6090	0.6556	0.5729	0.5579	0.4060
Guneysinir	0.1820	0.1203	0.0797	0.0331	-0.0602	-0.1850	-0.2226	0.0767
Guzelyurt	0.3398	-0.0556	0.0361	0.1203	0.1624	-0.0090	-0.0165	-0.1098
Huyuk	0.6887	0.7233	0.7083	0.3850	0.4015	0.3263	0.2722	0.3008
Ilgin	0.7940	0.7594	0.7053	0.5609	0.6286	0.5564	0.4647	0.4677
Kadinhani	0.8286	0.7519	0.7398	0.4932	0.5489	0.4511	0.2917	0.2827
Karaman_merkez	0.7293	0.5489	0.5564	0.3489	0.4511	0.4211	0.4030	0.1233
Karapinar	0.6346	0.4526	0.4541	0.5368	0.7023	0.6767	0.5429	0.4571
Karatay	0.5714	0.4451	0.4677	0.5038	0.4301	0.3940	0.2556	0.2436
Kulu	0.3308	0.4015	0.4301	0.2647	0.3038	0.2060	0.0617	0.1910
Meram	0.4556	0.3654	0.3850	0.3233	0.3759	0.3459	0.3429	0.2556
Nigde_merkez	0.5474	0.4376	0.4406	0.3549	0.4406	0.3865	0.3008	0.1654
Ortakoy	0.5654	0.4436	0.5158	0.2346	0.3098	0.2647	0.2120	0.1293
Sarayonu	0.3774	0.3113	0.2872	0.0150	0.0421	-0.0917	-0.2602	-0.0962
Sariyahi	0.6000	0.5805	0.5383	0.5038	0.4180	0.4602	0.5053	0.4226
Selcuklu	0.6647	0.6030	0.5759	0.3774	0.3805	0.2722	0.1609	0.1504
Seydisehir	0.0015	-0.1098	-0.1143	-0.1579	-0.0105	-0.0541	-0.0060	-0.0662
Tuzlukcu	0.5579	0.5053	0.5504	0.4571	0.5188	0.3233	0.1519	0.2647
Ulukisla	0.6722	0.5925	0.6180	0.5353	0.6105	0.5353	0.3850	0.1805
Yalihuuyuk	0.1278	0.0752	0.1805	-0.0045	0.0406	-0.0737	-0.1218	-0.1293
Yunak	0.6406	0.6391	0.6271	0.5910	0.6331	0.5940	0.4662	0.4541

Table S6. Correlation test results between drought indices and crop yield.

District	CDI (SHAP)	CDI (PCA)	CDI (MEAN)	SPEI_1	SPEI_3	SPEI_6	SPEI_9	scPDSI
Agacoren	0.0075	-0.0391	-0.0105	0.0586	0.0812	0.1338	0.1925	0.1534
Akoren	0.4391	0.4165	0.4376	0.3624	0.3684	0.3293	0.2060	0.0632
Aksaray_Merkez	0.6812	0.6361	0.6436	0.5368	0.5744	0.5654	0.4481	0.2301
Aksehir	0.5835	0.3188	0.3895	0.3880	0.5534	0.3714	0.1925	0.2752
Altnekin	0.5474	0.3534	0.3474	0.3729	0.3774	0.4180	0.4301	0.2932
Altunhisar	0.7383	0.7188	0.7158	0.5729	0.6617	0.6737	0.6045	0.3774
Ayranci	0.2692	0.0075	0.0075	0.0902	0.1113	0.2827	0.4256	0.1338
Beysehir	0.6226	0.5910	0.6135	0.2180	0.3068	0.1519	0.1203	0.2000
Bor	0.6436	0.5744	0.5654	0.4556	0.4556	0.3353	0.2586	0.1714
Camardi	0.5038	0.3203	0.3053	0.4767	0.4286	0.3053	0.2752	0.2797
Celtik	0.7008	0.4872	0.4932	0.5053	0.6165	0.6586	0.5820	0.4797
Ciftlik	0.4075	0.4752	0.4827	0.2105	0.2586	0.2556	0.2767	0.2150
Cihanbeyli	0.7624	0.6887	0.6917	0.6692	0.6647	0.5323	0.4241	0.3940
Cumra	0.5579	0.4977	0.4797	0.3805	0.4030	0.2842	0.1158	0.1940
Derbent	0.5729	0.3038	0.3669	0.2286	0.3308	0.2271	0.1835	0.2030
Doganhisar	0.5203	0.4767	0.4165	0.3218	0.3278	0.2000	0.1940	0.2797
Emirgazi	0.8000	0.7008	0.7128	0.6015	0.6120	0.5203	0.3504	0.3233
Eregli	0.2541	0.1549	0.1669	0.0992	0.1594	0.2150	0.2000	0.0316
Eskil	0.5053	0.2677	0.3323	0.2256	0.3955	0.3820	0.3263	0.1744
Gulagac	0.7353	0.6000	0.6617	0.6090	0.6556	0.5729	0.5579	0.4060
Guneysinir	0.1820	0.1203	0.0797	0.0331	-0.0602	-0.1850	-0.2226	0.0767
Guzelyurt	0.3398	-0.0556	0.0361	0.1203	0.1624	-0.0090	-0.0165	-0.1098
Huyuk	0.6887	0.7233	0.7083	0.3850	0.4015	0.3263	0.2722	0.3008
Ilgin	0.7940	0.7594	0.7053	0.5609	0.6286	0.5564	0.4647	0.4677
Kadinhani	0.8286	0.7519	0.7398	0.4932	0.5489	0.4511	0.2917	0.2827
Karaman_merkez	0.7293	0.5489	0.5564	0.3489	0.4511	0.4211	0.4030	0.1233
Karapinar	0.6346	0.4526	0.4541	0.5368	0.7023	0.6767	0.5429	0.4571
Karatay	0.5714	0.4451	0.4677	0.5038	0.4301	0.3940	0.2556	0.2436
Kulu	0.3308	0.4015	0.4301	0.2647	0.3038	0.2060	0.0617	0.1910
Meram	0.4556	0.3654	0.3850	0.3233	0.3759	0.3459	0.3429	0.2556
Nigde_merkez	0.5474	0.4376	0.4406	0.3549	0.4406	0.3865	0.3008	0.1654
Ortakoy	0.5654	0.4436	0.5158	0.2346	0.3098	0.2647	0.2120	0.1293
Sarayonu	0.3774	0.3113	0.2872	0.0150	0.0421	-0.0917	-0.2602	-0.0962
Sariyahi	0.6000	0.5805	0.5383	0.5038	0.4180	0.4602	0.5053	0.4226
Selcuklu	0.6647	0.6030	0.5759	0.3774	0.3805	0.2722	0.1609	0.1504
Seydisehir	0.0015	-0.1098	-0.1143	-0.1579	-0.0105	-0.0541	-0.0060	-0.0662
Tuzlukcu	0.5579	0.5053	0.5504	0.4571	0.5188	0.3233	0.1519	0.2647
Ulukisla	0.6722	0.5925	0.6180	0.5353	0.6105	0.5353	0.3850	0.1805
Yalihuuyuk	0.1278	0.0752	0.1805	-0.0045	0.0406	-0.0737	-0.1218	-0.1293
Yunak	0.6406	0.6391	0.6271	0.5910	0.6331	0.5940	0.4662	0.4541

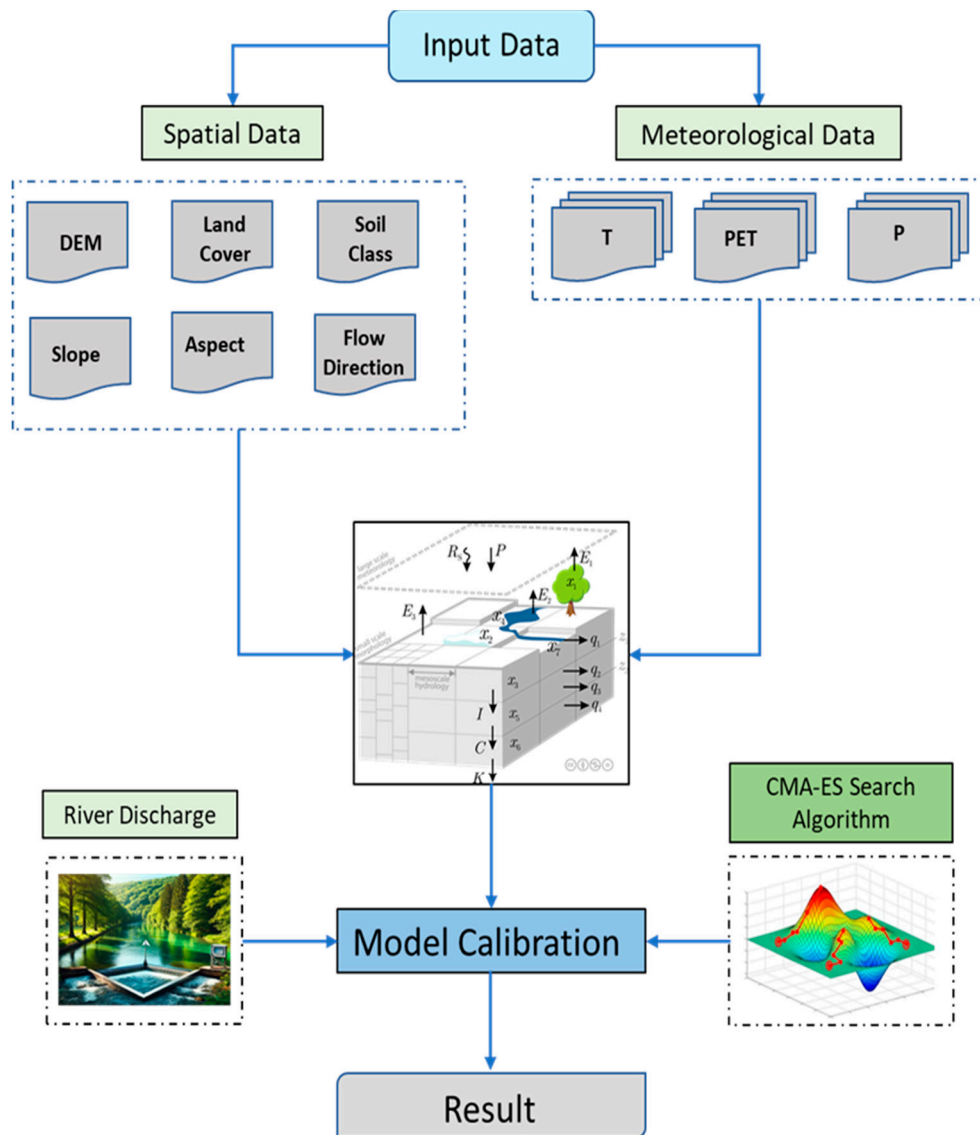


Figure S1. The mHM workflow.

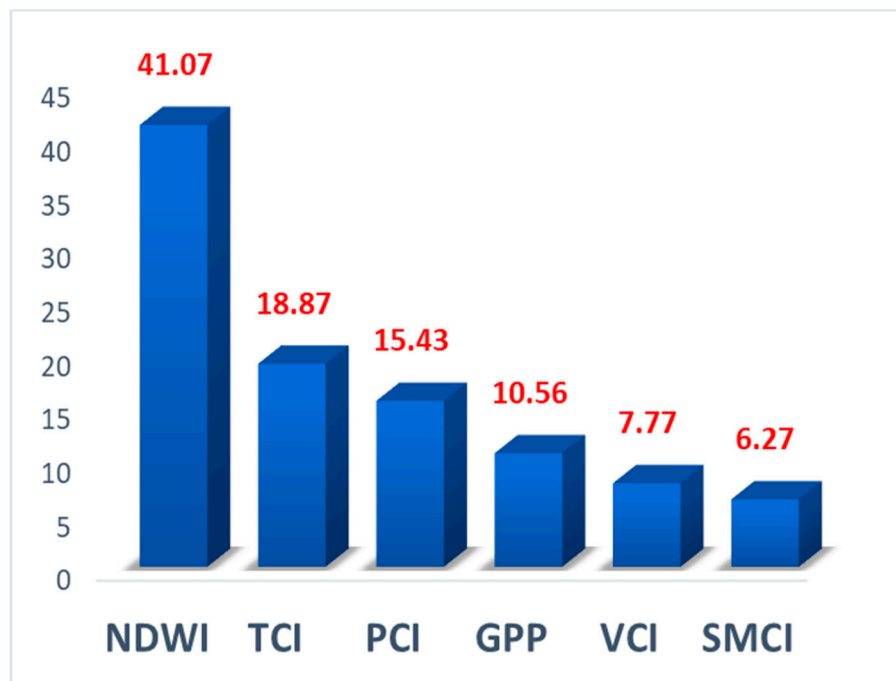


Figure S2. SHAP feature importance graph.