水資源決策與氣候變遷對於水文乾旱影響與分析

Impact and Analysis of Water resources Decision-making and Climate Change on Hydrological drought

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摘要

本研究開發了 改良版水會計系統脆弱性評估 （modified WAVE+）模型。該模型基於水文-社會經濟活動互動及對偶雙系統的概念 (Hydrological-social interaction and dual system)，從供水系統的角度有效評估和量化水文乾旱的多重原因，包括可用水量降低、社會水需求提高、乾枯期差異、與水資源管理政策。本研究使用石門水庫供水系統的歷史數據驗證了 modified WAVE+ 模型在乾旱檢測和診斷方面的性能。這種新方法能夠評估乾旱的嚴重程度、強度和持續時間，表現優於同時考慮了入流量、儲水量、消耗量的兩種乾旱指標：社會經濟乾旱指數 (SEDI) 和改進的多元標準化恢復力和可靠性指數 (IMSRRI) 等現有方法。本研究基於上述討論新開發的模塊化條件數據庫乾旱指數集成了水文乾旱和發生之條件機率，如圖 3 以 8 月為例，條件機率提供了所有可能決策後果的評估以支持用水量和水庫調度的實時政策調整。圖 4 顯示以條件機率變化量展示給定情境決策於不同月份的可能風險。此外，本研究開發了一個對偶雙系統序列模擬過程來評估氣候變化和用水量變化情景下的乾旱事件特徵演變。結果表明，如圖 2(a), (b), (c) 表明，在預測的氣候變化情境（RCP 2.6 和 RCP 8.5）下，台灣北部乾旱事件的發生次數有明顯減少，而乾旱嚴重程度及乾旱持續時間在平均值與變異數相差不大的情況下極端嚴重以及極端長的持續時間有下降的趨勢。

關鍵字: 異常事件偵測及診斷、氣候變遷、水資源管理、時間序列分析、水文模擬、隨機過程

The proposed modified WAVE+ model include consumption to availability ratio (CTA), conditional water depletion index (CWDI), and risk of freshwater deprivation (RFD) to deliver the degree of water deficiency and the vulnerability of the water supply system on a monthly scale. CTA accomplish to evaluate water resource scarcity. Regarding the concept of CTA, the water scarcity information relies on the monthly available water from the streamflow which is highly correlated to the metrological factor, the monthly average water storage, and the regional usage frequency of the water storage

relating to the hydrological-socioeconomic interaction.

The water scarcity, (CTA) could be transformed into the CWDI to represent the water deficiency degree. The RFD is bounded by the effective water consumption considering the return water (vapor or evapotranspiration) via precipitation. Higher vulnerability and water deficiency degree indicate the supply system closer to drought, and the societal damage from the drought would become more server. To diagnosis and to detect the hydrological drought, the comparison of CWDI and RFD to their relative criteria and threshold is the solution in this study. The criteria and threshold of modified WAVE+ model is determined with the historical data. The detail of the comparison and the determination of the criteria and threshold is in my master thesis.

(a) (b)

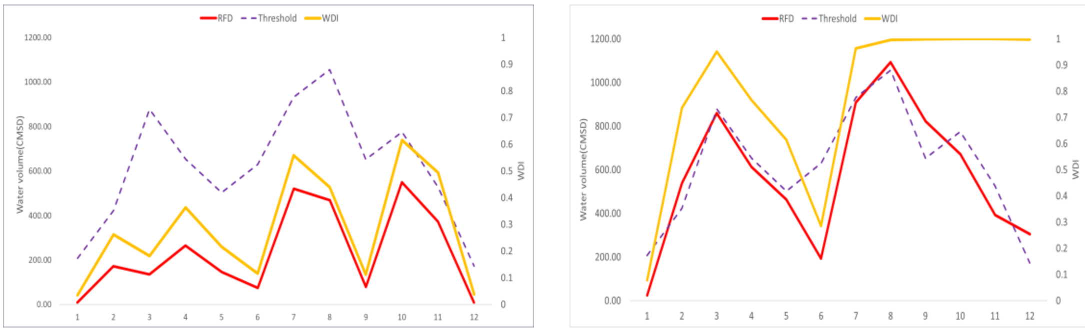
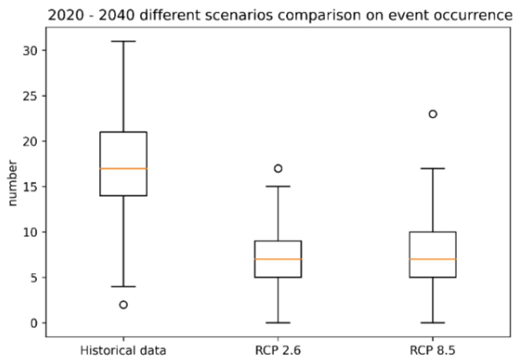


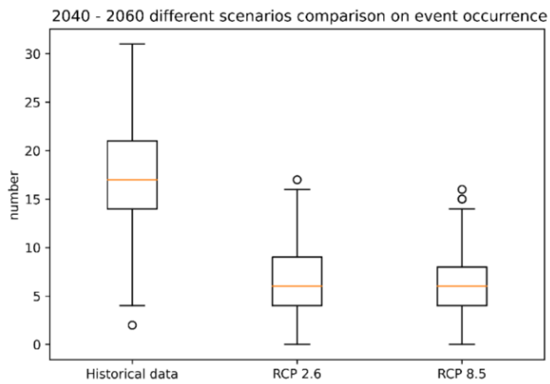
Figure 1 (a) and (b). Yellow, red and purple lines are CWDI, RFD and RFD threshold. (a) and (b) refer to two case, water abounding year (1985) and drought year (1993).

Figure 1 (a) and (b) compares with the water-abundant years, the water consumption in the extreme drought year was low due to two water consumption adjustments: the fallow in March and industrial usage reduction after August. In June, to maintain the economic benefit, the government dropped out the water consumption reduction adjustment since the water consumption authority expected the typhoon to hit after spring. Nevertheless, no typhoon hit Taiwan in the 1993 summer, a severe drought occurred after July 1993.

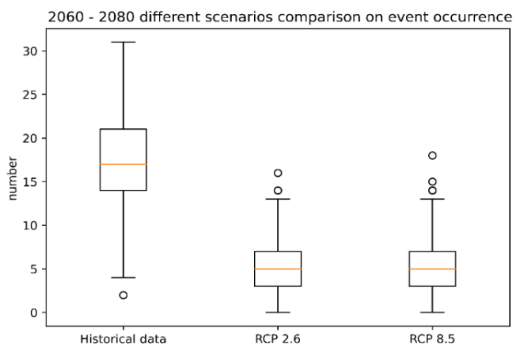
To illustrate how the seasonal RFD threshold relates to hydrological drought detection and diagnosis, this study compared the examples of 1985 and 1993 with the CWDI-based detection method. Figure 1 (a) and (b) demonstrate the reason for introducing two drought determinations, RFD threshold-based detection, and CWDI-based detection method, as the RFD showed a higher sensitivity to water consumption during the dry-period compared to the CWDI. The RFD aligns with the total consumption line but does not exhibit significant changes in the CWDI after August 1993. From a government perspective, when the CWDI closes to one and the RFD is greater than the threshold, it indicates the occurrence of the drought.

(a) (b)





(c) (d)



RFD / IMSRRI	**Drought**	**Normal**	
Predict Drought	**57 / 78**	**27 / 57**	**67% / 57% (Drought prediction accuracy)**
Predict Normal	**36 / 15**	**348 / 318**	**91% / 95% (Normal prediction accuracy)**
	61% / 83% (Drought-hit rate)	**93% / 84% (Normal-hit rate)**	**88% / 85%(Accuracy)**

Figure 2 (a), (b), (c), and (d). (a), (b), and (c) are drought occurrence realization for every twenty years with three climate conditions, based on historical data, RCP2.6, and RCP8.5, from 2020-2040, 2040-2060, and 2060-2080, respectively. (d) is the drought detection performance measured with confusion matrix, compared to IMSRRI.

Initial August water storage (CMSD)																				
2857.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2715	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2572.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2430	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2287.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2145	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2002.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1860	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1717.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1575	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1432.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1290	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1147.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1005	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
862.5	0.00	0.00	0.00	0.00	0.03	0.08	0.13	0.20	0.25	0.29	0.37	0.44	0.49	0.55	0.60	0.63	0.68	0.73	0.77	0.77
720	0.01	0.07	0.13	0.19	0.24	0.30	0.40	0.43	0.49	0.54	0.63	0.66	0.68	0.72	0.75	0.79	0.83	0.83	0.86	0.87
577.5	0.18	0.25	0.32	0.38	0.44	0.49	0.54	0.62	0.65	0.68	0.72	0.77	0.79	0.80	0.83	0.86	0.88	0.89	0.90	0.92
435	0.35	0.39	0.47	0.52	0.60	0.65	0.68	0.73	0.75	0.77	0.81	0.82	0.86	0.88	0.88	0.90	0.93	0.93	0.94	0.95
292.5	0.54	0.55	0.63	0.63	0.70	0.74	0.76	0.80	0.81	0.83	0.85	0.87	0.91	0.91	0.92	0.94	0.95	0.95	0.97	0.96
150	0.64	0.68	0.73	0.74	0.79	0.83	0.84	0.87	0.87	0.89	0.91	0.91	0.92	0.95	0.95	0.95	0.96	0.96	0.97	0.98
0	75	150	225	300	375	450	525	600	675	750	825	900	975	1050	1125	1200	1275	1350	1425	1500
August water consumption(CMSD)																				

Figure 3 represents the conditional probability of drought occurrence in current month, with given initial water storage and planed water consumption in current month. X axis, green part, is the planned water consumption. Y axis, orange part, is the initial water storage in reservoir. The values are the conditional probability from 0 to 1. Yellow part is the transition region.

Initial February water storage (CMSD) / February water consumption(CMSD)

0	75	150	225	300	375	450	525	600	675	750	825	900	975	1050	1125	1200	1275	1350	1425	1500
2857.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2715	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2572.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2430	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2287.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2145	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.21	0.17	0.11	0.03	0.02
2002.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.17	0.08	0.05	0.01	0.01	0.00	0.00	0.00
1860	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.11	0.07	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00
1717.5	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.10	0.00	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1575	0.00	0.00	0.00	0.01	0.08	0.00	0.02	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1432.5	0.00	0.02	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1290	-0.01	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1147.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1005	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
862.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
720	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
577.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
435	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
292.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
150	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(a)

Initial August water storage (CMSD) / August water consumption(CMSD)

0	75	150	225	300	375	450	525	600	675	750	825	900	975	1050	1125	1200	1275	1350	1425	1500
2857.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2715	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2572.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2430	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2287.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2145	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2002.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1860	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1717.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1575	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1432.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1290	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1147.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1005	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
862.5	0.00	0.00	0.00	0.00	-0.02	-0.01	-0.01	-0.05	-0.05	0.00	-0.06	-0.07	-0.02	-0.05	-0.04	-0.02	-0.02	-0.04	-0.04	-0.01
720	-0.01	-0.01	-0.05	-0.01	-0.02	-0.03	-0.06	-0.01	-0.01	-0.02	-0.07	-0.05	-0.01	-0.02	-0.01	-0.04	-0.07	-0.03	-0.02	-0.02
577.5	-0.05	-0.04	-0.02	-0.03	-0.04	-0.05	-0.03	-0.06	-0.04	-0.03	-0.04	-0.03	-0.03	-0.02	-0.03	-0.04	-0.02	-0.04	0.00	-0.02
435	-0.01	-0.01	-0.01	-0.05	-0.04	-0.08	-0.03	-0.06	-0.05	-0.02	-0.05	-0.02	-0.03	-0.05	-0.01	-0.02	-0.02	0.00	-0.01	-0.02
292.5	-0.09	-0.03	-0.05	0.02	-0.01	-0.03	-0.01	-0.03	-0.02	-0.01	-0.01	-0.01	-0.04	-0.03	-0.01	-0.02	-0.02	0.00	-0.02	0.00
150	-0.02	-0.03	-0.03	0.03	-0.02	-0.07	-0.02	-0.04	-0.01	-0.02	-0.02	-0.01	-0.01	-0.03	0.00	0.00	-0.02	0.01	-0.01	-0.01

(b)

Figure 4 (a) and (b) present the conditional probability change under the RCP 8.5.

ABSTRACT

By considering the water stress robustness and the seasonal vulnerability threshold of the water supply system, I developed a modified water accounting and vulnerability evaluation plus (WAVE+) model. Based on the dual system concept, the model effectively assesses and quantifies the multi-causalities of drought from the water supply system point of view. I validated the performance of the modified WAVE+ model in drought detection and diagnosis using the historical data from the Shihmen Reservoir water supply system. This new approach enables the evaluation of drought severity, intensity, and duration, outperforming existing methods such as the SocioEconomic Drought Index (SEDI) and Improved Multivariate Standardized Resilience and Reliability Index (IMSRRI). Additionally, the newly developed Modularized Conditional Data Base Drought Index (MCDBDI) framework, which integrates hydrologic stochastic processes and the modified WAVE+ model, enables the calculation of conditional probability for drought occurrences shown in Figure 3 and Figure 4. The conditional probability could support real-time policy adjustments in water consumption and reservoir operations. Furthermore, I developed a sequential dual system simulation process to evaluate the drought characteristic evolution under climate change and water consumption change scenarios. Figure 2 (a), (b), and (c) indicate a reduction in occurrence numbers and the distribution tail shrinkage on event severity and duration in Northern Taiwan under the projected climate change scenarios (RCP 2.6 and RCP 8.5).

Keywords: Abnormal event detection and diagnosis, Climate change, Water resource management, Time series analysis, Hydrological simulation, Stochastic process