# 應用 WASP8 物理型傳輸機制模組模擬灌溉渠道重金屬傳輸之評估

# Modeling heavy metal transportation in irrigating channels by employing mechanistic solids transport module of WASP8

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## 摘　要

在台灣，由於缺乏適當的土地使用分配規則，臺灣農地與許多工廠和畜牧場並鄰而生，再加上灌溉系統規劃不完善，工業及民生汙水並無獨立排放管道，當汙水排放至灌溉渠道中，再藉由灌溉系統進入農田時，不僅農地遭受汙染，更進一步危害農作物和人體健康。隨著聯合國(United Nations)於 2015 年發布 17 項永續發展目標(Sustainable Development Goals, SDGs)的規範下，水資源的使用與管理亦需符合永續經營的觀念，為使農業水環境邁向永續，藉由水質模式快速掌握灌溉圳路污染物傳輸路徑和污染負荷有其必要性。

WASP(Water Quality Analysis Simulation Program)是一個全球廣泛應用的水體水質模擬模式，其懸浮固體傳輸主要有兩種機制：描述型傳輸(Descriptive Solids Transportation)和物理型傳輸 (Mechanistic Solids Transportation)。在機制差異上，描述型傳輸僅考慮水體與底泥間的作用，而物理型傳輸則多考慮水體與底泥間之沉積層及其黏滯性(cohesive)對各項物理作用的影響；反應在模式的參數設置上，沉降速率和再懸浮速率是描述型傳輸的主要調整參數，而物理型傳輸則以剪應力為主要調整參數，模式隨水理條件和剪應力計算沉降速率、再懸浮速率及其他交互作用，所有作用之速率呈動態變化而非定值，因此物理型傳輸於理論上比描述型更為複雜，使用參數亦比描述型更多。然而，迄今有關 WASP8 的文獻多半著重於描述型傳輸機制的應用，涉及物理型傳輸機制的應用研究相對較少。因此，本研究旨在應用 WASP (Water Quality Analysis Simulation Program)的物理型傳輸機制(Mechanistic Solids Transport)模擬懸浮固體及總鉻(T-Cr)、銅(Cu)、鋅(Zn)、鎳(Ni) 各重金屬的傳輸過程，並深入探討以下標的：1.比較兩種傳輸模組之結果差異。2.建立情境模擬圳路沿線高濃度污染介入和長期底泥未清淤下的污染負荷傳輸情形，以評估圳路的涵容能力。3.分析圳路底泥深度與重金屬濃度的動態變化，以利執行相對應的清淤政策，維護安全的農產環境。

本研究針對彰化洋仔厝溪之新圳進行重金屬模擬的參數檢定與驗證，結果顯示，重金屬銅(Cu)、鋅(Zn)和鎳(Ni)的模擬結果最佳，其檢定與驗證的效率係數(NSE)皆達 0.8 以上，而重金屬總鉻(T-Cr)在驗證的效率係數雖只達 0.6 以上，但平均絕對百分比偏差僅在 9%以內，說明總鉻仍屬於合理的模擬結果，且懸浮固體在檢定驗證的平均絕對百分比偏差(MAPE)均在 30%以內，代表目前的參數設定為合理值。將模擬結果與描述型傳輸模組進行比較，發現物理型傳輸在懸浮固體的模擬結果與描述型傳輸相當接近，檢定略優於描述型傳輸之模擬結果，驗證則反之；重金屬總鉻(T-Cr)在檢定驗證的表現皆比描述型傳輸的模擬結果更優，而重金屬銅(Cu)、鋅(Zn)和鎳(Ni)的模擬結果，無論在檢定還是驗證都與描述型傳輸差異不大。

進一步透過情境模擬，分析水源型汙染和介入型污染的渠道涵容能力；水源型汙染為模擬持續形式的污染，假設取水口發生異常，每日流入標準灌溉水質限值 1 倍和 2 倍的重金屬，結果顯示，當圳路取水口水源不佳時，污染物傳輸至新圳末端的濃度雖漸減，但下降幅度僅在 7%左右，代表取水口水質主控新圳全段的圳路水質；介入型污染為單次極端污染事件模擬，選擇工廠較集中的區域(網格 1、網格 4、網格 7)，於 12 小時內排入濃度為水質標準 200 倍的廢水共 $400m^3$，結果發現，重金屬總鉻、銅、鋅和鎳在整條圳路降至標準濃度以下的時間，網格 1 介入和網格 4 介入均為停止排放後的 2 小時，而網格 7 介入的情境則為停止排放後的 3 小時，說明新圳的圳路型態雖然相對單純，但單次污染事件的發生位置還是會影響水質的恢復時間。

另外，再設置與前期描述型傳輸一樣的介入型污染型態，於網格 6 介入同為水質標準 200 倍的負荷濃度，分別排放 24 小時共 $400m^3$廢水和 12 小時共 $800\ m^3$廢水，物理型傳輸模組的結果顯示，在排放 24 小時的情境中，水質回復標準限值以內的時間，總鉻和鎳為 6 小時，銅和鋅為 5 小時；而在 12 小時的情境中，四種金屬皆為 2 小時。比較與描述型的結果，物理型傳輸在 24 小時的情境下，四種重金屬回復所需時間均比描述型多 3 到 4 小時，但在 12 小時的情境下則一樣，推估此現象與物理型傳輸中計算出的沉降速率，遠比描述型傳輸輸入的沉降速率還小有關。

從以上的結果說明，WASP 物理型傳輸模組於新圳重金屬和懸浮固體的模擬具合理性，能掌握污染物和懸浮固體在時間空間下的變化，且其表現與描述型傳輸模擬之結果相差無幾，適合作為灌溉渠道污染評估之模擬工具。然而，物理型傳輸所選用的參數比描述型更多，在參數的檢定和驗證上相對耗費更多時間，若不考慮模擬底泥動態變化的情況下，可選擇描述型傳輸模組進行模擬即可，但須注意描述型傳輸模組在沉降速率和再懸浮速率的計算上，使用不同公式就有不同數值，因此仍需專業的評估與計算。

關鍵詞：WASP8，物理型傳輸機制，重金屬，懸浮固體，新圳

# Abstract

In Taiwan, due to the lack of proper land use allocation rules, agricultural land is adjacent to many factories and livestock farms. Additionally, the planning of irrigation

systems is inadequate, and there are no independent discharge pipelines for industrial and domestic wastewater. When wastewater is discharged into irrigation channels and then enters farmland through the irrigation system, it not only pollutes the agricultural land but also further endangers crops and human health. With the United Nations issuing 17 Sustainable Development Goals (SDGs) in 2015, the use and management of water resources must also align with sustainable development concepts. To promote sustainability in the agricultural water environment, it is essential to quickly grasp the transport pathways and pollution loads of contaminants in irrigation channels through water quality modeling.

WASP (Water Quality Analysis Simulation Program) is a globally widely used water quality simulation model. Its suspended solids transport primarily involves two mechanisms: Descriptive Solids Transportation and Mechanistic Solids Transportation. In terms of mechanism differences, Descriptive Solids Transportation only considers the interactions between the water body and sediment, while Mechanistic Solids Transportation takes into account the sediment layer and its cohesive properties, affecting various physical interactions. This is reflected in the model parameter settings, where settling rate and resuspension rate are the main adjustable parameters for Descriptive Transportation, while shear stress is the primary adjustable parameter for Mechanistic Transportation. The model calculates settling rates, resuspension rates, and other interactions based on hydrological conditions and shear stress, with all interaction rates being dynamic rather than fixed values. Therefore, Mechanistic Transportation is theoretically more complex than Descriptive Transportation and uses more parameters. However, to date, most literature on WASP8 has focused on the application of the Descriptive Transportation mechanism, with relatively few studies involving the Mechanistic Transportation mechanism. Thus, this study aims to apply the Mechanistic Solids Transport mechanism of WASP to simulate the transport processes of suspended solids and heavy metals such as total chromium (T-Cr), copper (Cu), zinc (Zn), and nickel (Ni). It will further explore the following objectives: 1. Compare the results of the two transport modules. 2. Establish scenario simulations of high-concentration pollution interventions along the irrigation channels and the pollution load transport under long-term sedimentation without dredging, to assess the capacity of the irrigation channels. 3. Analyze the dynamic changes in sediment depth and heavy metal concentrations in the irrigation channels to facilitate the implementation of corresponding dredging policies, ensuring a safe agricultural environment.

This study focuses on the parameter calibration and validation of heavy metal simulation for the Xin irrigation in Changhua. The results indicate that the simulation results for heavy metals copper (Cu), zinc (Zn), and nickel (Ni) are optimal, with the efficiency coefficients (NSE) for both calibration and validation exceeding 0.8. Although the efficiency coefficient for total chromium (T-Cr) in validation only reached above 0.6, the mean absolute percentage error (MAPE) was within 9%, indicating that the simulation results for total chromium are still reasonable. Additionally, the average absolute percentage error for suspended solids in the calibration was below 30%, suggesting that the current parameter settings are reasonable. When comparing the simulation results with the Descriptive Transportation module, it was found that the results from Mechanistic Transportation for suspended solids are quite close to those from Descriptive Transportation, with slightly better validation results for Mechanistic Transportation. Conversely, the performance of total chromium (T-Cr) in both calibration and validation was superior to that of the Descriptive Transportation simulations. For heavy metals copper (Cu), zinc (Zn), and nickel (Ni), the simulation results showed little difference from those of the Descriptive Transportation in both calibration and validation.

Furthermore, through scenario simulations, we analyzed the channel capacity for source-type pollution and intervention-type pollution. Source-type pollution simulates continuous pollution, assuming that the intake point experiences abnormalities, with heavy metals flowing in at 1 and 2 times the standard irrigation water quality limits daily. The results show that when the water source at the irrigation intake is poor, the concentration of pollutants transported to the end of the Xin irrigation gradually decreases, but the reduction is only about 7%, indicating that the water quality at the intake controls the water quality along the entire length of the channel. Intervention-type pollution simulates a single extreme pollution event, selecting areas with concentrated factories (Grid 1, Grid 4, Grid 7), where wastewater with a concentration 200 times the water quality standard is discharged, totaling 400 $m^3$ within 12 hours. The results revealed that the time for total chromium, copper, zinc, and nickel to drop below the standard concentration along the entire channel was 2 hours after discharge cessation for both Grid 1 and Grid 4, while the scenario for Grid 7 was 3 hours after discharge cessation. This indicates that although the channel structure of the Xin irrigation system is relatively simple, the location of a single pollution event still affects the recovery time of water quality.

Additionally, we set up an intervention-type pollution scenario similar to the previous descriptive transportation model, with an intervention in Grid 6 at a load concentration 200 times the water quality standard. We discharged a total of 400 $m^3$ of wastewater over 24 hours and 800 $m^3$ over 12 hours. The results from the mechanistic transportation model indicated that in the 24-hour scenario, the time for water quality to return within standard limits was 6 hours for total chromium and nickel, and 5 hours for copper and zinc. In the 12-hour scenario, all four metals returned to standard levels in 2 hours. Comparing these results with those from the descriptive model, the mechanistic transportation required 3 to 4 hours longer for the recovery of the four heavy metals in the 24-hour scenario, while the recovery times were the same in the 12-hour scenario. This phenomenon is estimated to be related to the sedimentation rates calculated in the mechanistic model, which are significantly lower than the sedimentation rates input into the descriptive model.

The results above indicate that the WASP mechanistic transportation model provides a reasonable simulation of heavy metals and suspended solids in the Xin irrigation. It effectively captures the changes in pollutants and suspended solids over time and space, and its performance is comparable to that of the descriptive transportation simulations, making it suitable as a simulation tool for assessing irrigation channel pollution. However, the parameters selected for the mechanistic model are more numerous than those for the descriptive model, resulting in a relatively greater time expenditure for parameter calibration and validation. If the dynamic changes in sediment are not considered, the descriptive transportation model can be chosen for simulation. However, it is important to note that the descriptive model may yield different values depending on the formulas used for calculating sedimentation and resuspension rates, thus requiring professional evaluation and calculation.

Keywords: WASP8，Mechanistic solids transportation，heavy metal，suspended solids，Xin irrigation