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Flow-Dependent Transport of Glyphosate, Dioxins, and Lead in an Urban River: A Scenario-Based HEC-RAS Numerical Study of Sungai Perai, Malaysia

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Abstract

Municipal waste effluent introduces persistent and toxic contaminants into urban river systems, with their transport and environmental impact strongly influenced by hydrological conditions. This study investigates the flow-dependent transport behavior of three distinct municipal-related pollutants which is glyphosate (first-order decay rate $k = 0.023$ day^{-1}), dioxins ($k = 0.231$ day^{-1}) and lead (Pb, $k = 0.005$ day^{-1}) in the Sungai Perai catchment using numerical modelling. A one-dimensional steady-flow hydraulic model coupled with the General Constituent Simulation Module (GCSM) in HEC-RAS was developed to simulate pollutant transport under three representative flow scenarios: high flow (50 m^3/s), baseflow (36 m^3/s), and low flow (20 m^3/s). Seven effluent-affected locations along the river were modelled using a triangular concentration profile over a 2.5-hour discharge period. Due to the lack of local gauge height data for calibration, the model is applied as an exploratory scenario tool. The results demonstrate that river flow conditions exert a dominant control on pollutant dilution, downstream propagation, and persistence. Low-flow conditions represented the highest water quality risk, yielding peak simulated concentrations that limited the river's inherent dilution capacity. Persistent constituents such as Dioxins and Lead exhibited prolonged downstream residence compared to more weakly reactive constituents, exhibited prolonged downstream residence times compared to highly decaying inputs. Across all scenarios, a consistent pollutant accumulation zone was observed within a mid-reach hotspot between CH4400 and CH4800, driven by local hydraulic channel characteristics. These findings highlight the importance of incorporating flow sensitivity into effluent impact assessments and demonstrate the value of scenario-based modelling for supporting pollution risk evaluation and river basin management in urban catchments.

Keywords: Municipal Effluent, Pollutant Transport, Hec-Ras Gscm, Sungai Perai, Water Quality Modeling, Urban Catchment

1. Introduction

Urban river systems are increasingly exposed to pollution pressures arising from municipal waste effluent, particularly in rapidly urbanising catchments where domestic, commercial, and light industrial activities coexist. Inadequately treated or untreated effluent introduces a range of persistent and potentially toxic contaminants into river systems, posing long-term risks to water quality, aquatic ecosystems, and downstream water uses. The transport and fate of such pollutants are strongly governed by hydrodynamic conditions, as river discharge controls dilution capacity, residence time, and downstream propagation.

Sungai Perai, located in Penang, Malaysia, exemplifies the challenges faced by urban rivers under growing development pressure (Department of Enviroment, 2023). While the river has been identified as a potential supplementary water resource in response to increasing water demand and climate-related uncertainties, its suitability is constrained by ongoing pollution from municipal and urban sources. Previous assessments of water quality in Sungai Perai have largely relied on point-based monitoring, which provides limited insight into the spatial and temporal evolution of pollutants along the river under different flow conditions (Faudzi, 2023). As a result, the influence of hydrological variability on pollutant persistence and accumulation remains insufficiently understood.

Among municipal-related contaminants, glyphosate, dioxins, and lead (Pb) are of particular concern due to their persistence, toxicity, and widespread occurrence in urban environments. Glyphosate is commonly associated with herbicide application and urban runoff, exhibiting slow degradation in aquatic systems (Zhang, et al., 2024). Dioxins are highly persistent organic pollutants with strong resistance to natural attenuation processes (Mathew, et al., 2025), while Lead (Pb) behaves as a conservative or weakly reactive heavy metal in riverine environments (National Research Council, 2013). These characteristics indicate that the transport behavior of such pollutants is predominantly controlled by advection and dispersion processes rather than complex biogeochemical reactions.

Numerical modelling provides an effective framework for investigating pollutant transport dynamics beyond the limitations of field monitoring alone. One-dimensional hydraulic models coupled with constituent transport modules enable scenario-based analysis of how flow variability influences pollutant dilution, downstream migration, and persistence. The General Constituent Simulation Module (GCSM) within HEC-RAS is well suited for this purpose, as it is designed to simulate conservative and weakly reactive constituents using advection–dispersion formulations with simplified decay processes (U.S. Army Corps of Engineers, Hydrologic Engineering Center).

This study applies a scenario-based numerical modelling approach to investigate the flow-dependent transport behavior of glyphosate, dioxins, and lead in Sungai Perai. Steady-flow hydraulic simulations coupled with GCSM-based pollutant transport modelling are used to evaluate pollutant behavior under high-flow, baseflow, and low-flow conditions. The objectives are to assess how different hydrological regimes influence pollutant dilution and persistence, and to identify river reaches that are particularly vulnerable to pollutant accumulation. The findings provide insight into flow-sensitive pollution dynamics and support improved understanding of municipal effluent impacts in urban river systems.

2. Methodology

2.1 Study Area and Model Domain

Sungai Perai (5.395767, 100.384445), shown in Figure 1, is an urban river located in Penang, Malaysia, draining a highly developed catchment dominated by residential, commercial, and light industrial land uses. The modelled river reach extends along the main channel of Sungai Perai, covering multiple effluent-affected locations identified from field observations and secondary monitoring data. The river reach was discretized using surveyed cross-sectional geometry to represent channel morphology and longitudinal variability.

2.2 Hydraulic Model Setup

A one-dimensional steady-flow hydraulic model was developed using the Hydrologic Engineering Center's River Analysis System (HEC-RAS). Steady-flow conditions were selected to isolate the influence of river discharge on pollutant transport while avoiding additional complexity associated with transient hydrodynamics. The governing flow regime along the modelled reach is subcritical. Under the steady-flow condition, the pollutant transport equation (Equation 1) is solved.

$$\frac{dC}{dt} + u\frac{dC}{dx} = D\frac{d^2C}{dx^2} \qquad \text{(Equation 1)}$$

Figure 1. Sungai Perai outline (Google Earth, 2025)

Here, C is the concentration of the substance that being transported, t is time, x is the spatial coordinate, D is the diffusion coefficient (15 m²/s was assumed throughout the river reach due to the absence of tracer calibration data), u is the average velocity of the flow.

River geometry forms the fundamental framework of the HEC-RAS model and directly influences the accuracy of hydraulic and water quality simulations. The geometry was converted into shapefile format using ArcMap and georeferenced before being imported into the RAS Mapper tool (Figure 2). The river reaches and cross-sections were then digitized by tracing over the background layer, with interpolation applied between adjacent sections to ensure spatial continuity and numerical stability. In this study, river cross sectional data were obtained from a licensed surveyor. An example of cross-sectional data is shown in Figure 3. Manning's roughness coefficients were assigned to represent flow resistance in the main channel and overbank areas.

Appropriate values were selected based on channel conditions and land cover characteristics. In this study, the Manning's coefficient of the main channel was selected as 0.040 (clean, winding, some pools, and shoals) and that of floodplains was selected as 0.050 (scattered brush, heavy weeds) (Chow, 1959). From field observation, the flow in the river was found to be subcritical flow; therefore, the downstream boundary condition was set. Downstream boundary conditions were specified using normal depth, as the downstream water level could not be obtained. In addition, model outputs indicate that flow velocities along the river is relatively low, with the maximum Froude number remaining below unity (Fr < 1), confirming subcritical flow conditions throughout the modelled reach. Several assumptions were adopted during hydraulic modelling:

- bridge structures were omitted for simplicity
- contraction and expansion coefficients were assumed as the default values of 0.1 and 0.3 respectively.
- tidal influence and transient flow fluctuations were neglected.

Municipal effluent inputs were incorporated into the HEC-RAS water quality model to represent pollutant discharge into Sungai Perai from urbanized areas along the river corridor. A total of seven effluent discharge points were identified and implemented in the model based on field observations. These points are situated at CH9600, CH8100, CH6700, CH6600, CH4800, CH4400 and CH2800, as shown in Figure 4. These discharge locations represent points where municipal effluent is likely to enter the river system and were treated as lateral inflows within the General Constituent Simulation Module (GCSM). Table 1 lists out the description of each effluent points, and its corresponding additional volumetric discharge. As for pollutant input concentrations, they are defined using triangular concentration profiles, as presented in Figure 5. These profiles represent a gradual increase in pollutant concentration to a peak value followed by a gradual decrease, mimicking the scenarios of municipal effluent discharge pattern. For scenario study, each pollutant was assigned its respective triangular profile, and the discharge duration for all inputs was fixed at 2.5 hours.

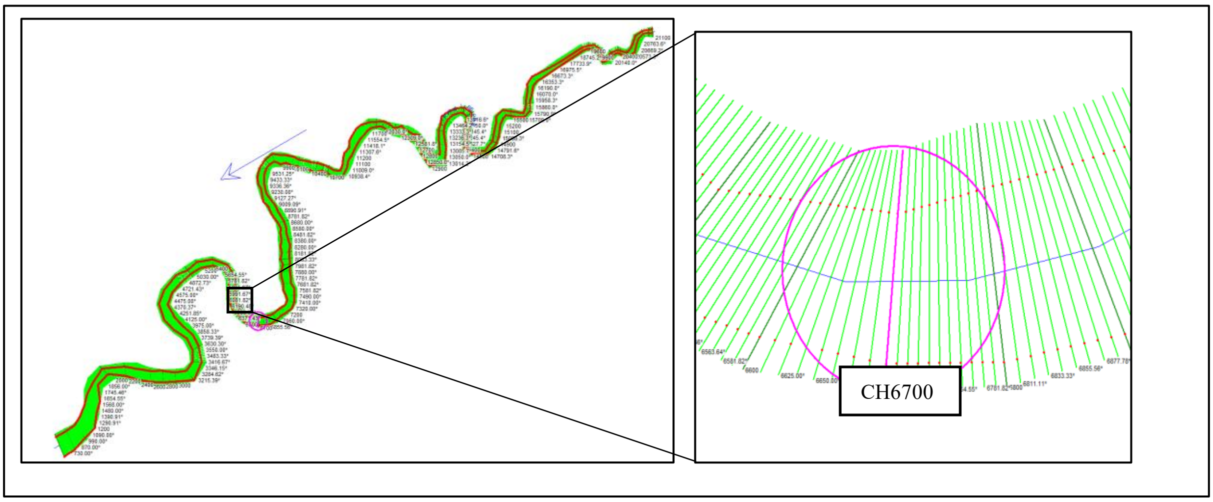
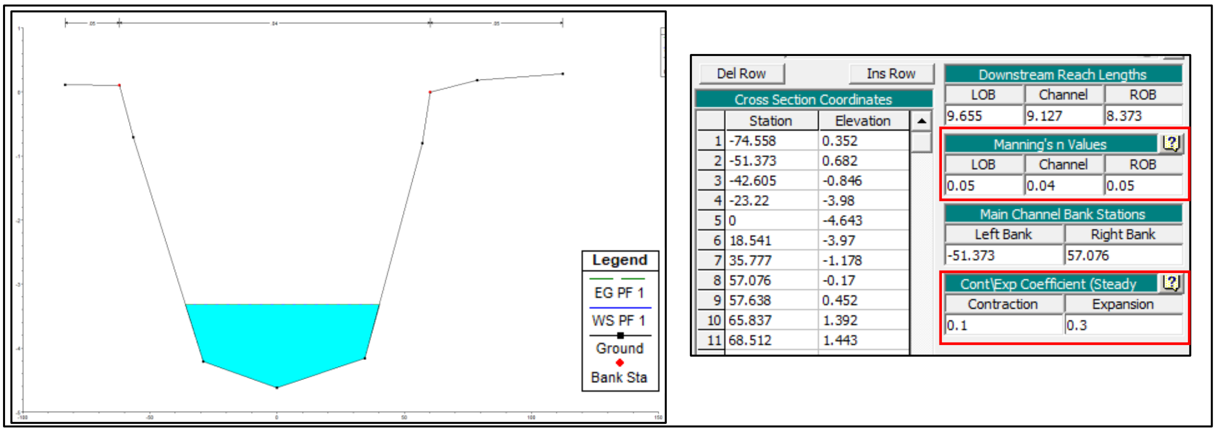


Figure 2. Sungai Perai schematic layout in RAS Mapper tool with a detailed view of chainage 6700



Cross Section Coordinates

	Station	Elevation
1	-74.558	0.352
2	-51.373	0.682
3	-42.605	-0.846
4	-23.22	-3.98
5	0	-4.643
6	18.541	-3.97
7	35.777	-1.178
8	57.076	-0.17
9	57.638	0.452
10	65.837	1.392
11	68.512	1.443

Downstream Reach Lengths

LOB	Channel	ROB
9.655	9.127	8.373

Manning's n Values

LOB	Channel	ROB
0.05	0.04	0.05

Main Channel Bank Stations

Left Bank	Right Bank
-51.373	57.076

Cont\Exp Coefficient (Steady

Contraction	Expansion
0.1	0.3

Figure 3. cross section entry into HEC-RAS for chainage 6700

Figure 4. Effluent points mark as chainage on Sungai Perai (Google Earth, 2025)

Table 1. Effluent point and its corresponding additional discharge

Effluent Point	Description	Discharge (m^3/s)
CH9600	Effluent from municipal area	Negligible additional volumetric discharge
CH8100	Effluent from municipal area	Negligible additional volumetric discharge
CH6700	Effluent from nearby factory	0.1
CH6600	Effluent from nearby factory	0.1
CH4800	Effluent from nearby factory	0.1
CH4400	Effluent from nearby factory	0.1
CH2800	Effluent from municipal area	Negligible additional volumetric discharge

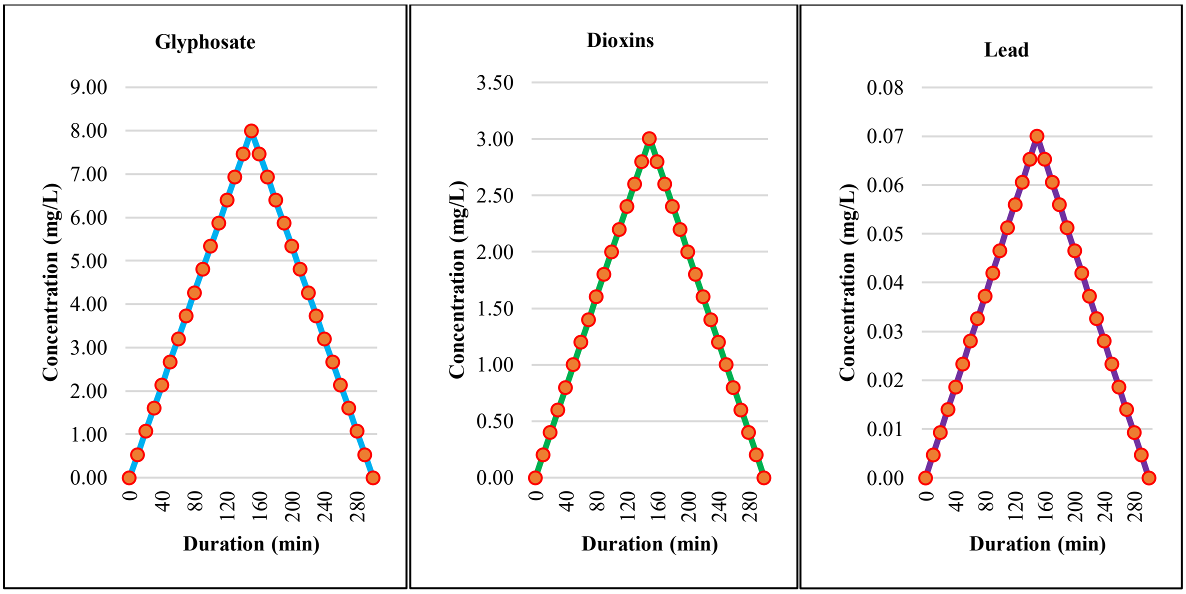


Figure 5. Glyphosate, Dioxins and Lead triangular profile (Concentration against Duration graph) assigned at each effluent point

The properties of each constituent are inserted into HEC-RAS Water Quality Model Configuration. These include the zero-order decay rate and first order decay rate, as shown in Table 3. These inputs allow HEC-RAS to simulate the transport and transformation of constituents within the river system. Three representative flow scenarios were simulated to reflect typical hydrological variability in Sungai Perai.

The high-flow scenario was simulated using a discharge of 50 m³/s to represent wet-season or storm-influenced conditions, during which increased surface runoff contributes to elevated river flows. The high-flow simulation provides insight into the potential for pollutant spreading during extreme hydrological events and the shifting of water quality impacts to downstream reaches. The low-flow scenario was simulated using a discharge of 20 m³/s to represent dry-season or drought conditions, during which reduced inflow significantly limits the river's dilution capacity. The low-flow simulation is critical for identifying pollution hotspots and evaluating the maximum potential risk to the river system. The baseflow scenario was defined using a discharge of 36 m³/s, representing typical river conditions under average hydrometeorological influences. This scenario serves as a reference condition against which the high-flow and low-flow cases are evaluated. The baseflow simulation is particularly important for assessing routine water quality conditions and represents the most commonly occurring flow regime in Sungai Perai.

Table 2. Decay rates of effluent constituents

Constituents	Zero order decay rate (mg/l/day)	First order decay rate (mg/l/day)
Glyphosate	0	0.023
Dioxins	0	0.001
Lead	0	0.005

3. Results and Discussion

Simulation results indicate that effluent transport in Sungai Perai is strongly influenced by river flow conditions. Distinct longitudinal concentration patterns for Glyphosate, Dioxins, and Lead (Pb) were observed under high-flow, baseflow, and low-flow scenarios due to differences in dilution capacity, flow velocity, and pollutant residence time within the river system.

Under high-flow conditions (50 m³/s), illustrated in Figure 6, pollutant transport was characterised by rapid downstream propagation and enhanced dilution capability due to increased discharge and flow velocity. The increased hydraulic energy promoted stronger advective transport, resulting in wider longitudinal pollutant spreading throughout the river reach. Although local concentrations were relatively low, pollutants were transported further downstream, indicating greater downstream propagation potential during wet-season or storm-influenced conditions. This behaviour suggests that high-flow events may redistribute pollutants spatially rather than eliminate their environmental impact entirely.

For Glyphosate (Table 3), the highest concentration during the high-flow simulation was observed at 1200 PM within the midstream section between CH4800 and CH4400, reaching approximately 1.2E−07 mg/L, while downstream concentration at CH2800 remained elevated at approximately 1.1E−07 mg/L. Similarly, Dioxins exhibited a peak concentration of approximately 8.9E−08 mg/L within the same midstream reach, with downstream concentration remaining high at approximately 8.5E−08 mg/L. Lead concentration also reached approximately 5.8E−08 mg/L within the midstream section during the peak simulation period, while downstream concentration remained comparable at approximately 5.7E−08 mg/L. These findings indicate that high-flow conditions improve local dilution but simultaneously increase the spatial extent of downstream pollutant transport due to stronger advective processes. At 0000 AM, all pollutants showed gradual attenuation due to longitudinal dispersion and first-order decay processes. However, residual concentrations remained observable within the downstream reaches, particularly for Dioxins and Lead, indicating persistent transport behaviour within the river system. Similar flow-dependent transport behaviour has been reported in previous urban river water quality studies where elevated discharge conditions enhanced constituent dispersion and downstream migration (Faudzi, 2023).

In contrast, the low-flow scenario shown in Figure 7 produced the most critical water quality condition within Sungai Perai due to reduced dilution capacity and prolonged pollutant residence time. Reduced discharge and lower flow velocities limited pollutant attenuation, resulting in persistent concentrations within the midstream and downstream reaches. For Glyphosate, the highest concentration under low-flow conditions was observed at 1200 PM within the midstream reach, reaching approximately 7.8E−08 mg/L, while downstream concentration remained high at approximately 7.1E−08 mg/L. The relatively small reduction between midstream and downstream concentrations indicates that Glyphosate remained highly mobile even under reduced hydraulic conditions, allowing the pollutant to persist over longer downstream distances.

A similar behaviour was observed for Dioxins (Table 4), where low-flow conditions promoted pollutant retention within the hydraulically stagnant midstream accumulation zone. At 1200 PM, Dioxins concentration reached approximately 6.4E−08 mg/L within the midstream reach and remained elevated downstream at approximately 6.0E−08 mg/L. The persistence of Dioxins throughout the river reach suggests limited natural attenuation under low-flow conditions, potentially increasing the risk of long-term ecological exposure and sediment-associated contamination.

Lead (Pb), however, exhibited a somewhat different transport response under low-flow conditions (Table 5). Although elevated concentrations were still observed within the midstream section, downstream attenuation was more pronounced compared to Glyphosate and Dioxins. At 1200 PM, the Lead concentration within the midstream reach was approximately 9.7E−09 mg/L, decreasing to approximately 5.2E−09 mg/L downstream. This reduction suggests that Lead transport may be more strongly influenced by localized deposition, sediment interaction, or reduced mobility under lower hydraulic energy conditions. Nevertheless, concentrations under low-flow conditions remained consistently higher than those observed during baseflow conditions, indicating that reduced discharge still contributed to prolonged pollutant persistence within the river system. Overall, the low-flow scenario represents the most critical condition for water quality degradation in Sungai Perai, particularly during dry-season periods when the river's self-purification capacity becomes significantly reduced.

The baseflow scenario (Figure 8) exhibited intermediate behaviour between the two extremes. Moderate dilution and transport rates resulted in concentration profiles that were generally lower than those observed under low-flow conditions but more persistent than those simulated during high flow. For example, at 1200 PM, Glyphosate concentration within the midstream reach under baseflow conditions was approximately 5.5E−08 mg/L, compared to 7.8E−08 mg/L under low flow and 1.2E−07 mg/L under high flow. Similar intermediate concentration behaviour was observed for Dioxins and Lead. Baseflow conditions therefore represent typical operational conditions under which cumulative effluent impacts are likely to be most frequently experienced. Although pollutant concentrations were comparatively moderate, continuous discharge during normal river conditions may contribute to gradual long-term water quality deterioration within Sungai Perai.

Across all flow scenarios, a consistent pollutant accumulation zone was identified within the mid-reach of the modelled river section, particularly between CH4800 and CH4400. Reduced flow velocity and local channel geometry within this reach promoted pollutant retention and accumulation. The persistence of this zone under varying discharge conditions indicates that local hydraulic characteristics strongly influence pollutant behaviour independent of flow magnitude. These retention zones may function as long-term contaminant sinks and potential hotspots for sediment-associated pollution and ecological degradation. Overall, the results demonstrate that river hydrodynamics play a critical role in controlling pollutant fate and transport within Sungai Perai, highlighting the importance of incorporating seasonal flow variability and local hydraulic conditions into river water quality management and mitigation strategies

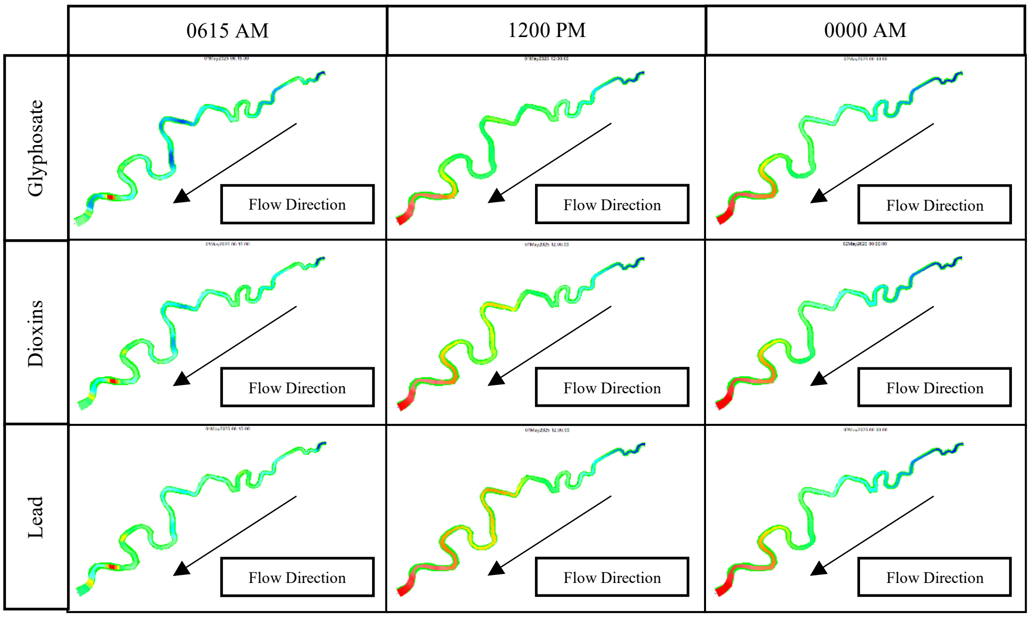


Figure 6. Concentration (mg/L) of Glyphosate, Dioxins and Lead under high flow conditions.

Table 3. Representative Glyphosate Concentration Distribution Along Sungai Perai Under Different Flow Scenarios

Time	Flow Scenario	Upstream Reach (CH9600–CH6700)	Midstream Reach (CH4800–CH4400)	Downstream Reach (CH2800)
0615 AM	High Flow	1.8E-08 mg/L	6.7E-08 mg/L	6.2E-08 mg/L
0615 AM	Low Flow	9.5E-09 mg/L	4.9E-08 mg/L	5.1E-08 mg/L
0615 AM	Baseflow	6.8E-09 mg/L	3.6E-08 mg/L	3.9E-08 mg/L
1200 PM	High Flow	5.4E-08 mg/L	1.2E-07 mg/L	1.1E-07 mg/L
1200 PM	Low Flow	2.6E-08 mg/L	7.8E-08 mg/L	7.1E-08 mg/L
1200 PM	Baseflow	1.9E-08 mg/L	5.5E-08 mg/L	5.0E-08 mg/L
0000 AM	High Flow	2.2E-08 mg/L	5.9E-08 mg/L	6.3E-08 mg/L
0000 AM	Low Flow	1.3E-08 mg/L	4.4E-08 mg/L	4.8E-08 mg/L
0000 AM	Baseflow	9.8E-09 mg/L	3.2E-08 mg/L	3.5E-08 mg/L

Table 4. Representative Dioxins Concentration Distribution Along Sungai Perai Under Different Flow Scenarios

Time	Flow Scenario	Upstream Reach (CH9600–CH6700)	Midstream Reach (CH4800–CH4400)	Downstream Reach (CH2800)
0615 AM	High Flow	1.1E-08 mg/L	4.8E-08 mg/L	4.5E-08 mg/L
0615 AM	Low Flow	5.8E-09 mg/L	3.6E-08 mg/L	3.9E-08 mg/L
0615 AM	Baseflow	4.1E-09 mg/L	2.7E-08 mg/L	3.0E-08 mg/L
1200 PM	High Flow	3.9E-08 mg/L	8.9E-08 mg/L	8.5E-08 mg/L
1200 PM	Low Flow	1.9E-08 mg/L	6.4E-08 mg/L	6.0E-08 mg/L

Time	Flow Scenario	Upstream Reach (CH9600–CH6700)	Midstream Reach (CH4800–CH4400)	Downstream Reach (CH2800)
1200 PM	Baseflow	1.3E-08 mg/L	4.7E-08 mg/L	4.3E-08 mg/L
0000 AM	High Flow	1.6E-08 mg/L	4.2E-08 mg/L	4.8E-08 mg/L
0000 AM	Low Flow	8.9E-09 mg/L	3.1E-08 mg/L	3.6E-08 mg/L
0000 AM	Baseflow	6.4E-09 mg/L	2.4E-08 mg/L	2.8E-08 mg/L

Table 5. Representative Lead (Pb) Concentration Distribution Along Sungai Perai Under Different Flow Scenarios

Time	Flow Scenario	Upstream Reach (CH9600–CH6700)	Midstream Reach (CH4800–CH4400)	Downstream Reach (CH2800)
0615 AM	High Flow	6.9E-09 mg/L	3.4E-08 mg/L	3.2E-08 mg/L
0615 AM	Low Flow	3.2E-09 mg/L	2.3E-08 mg/L	2.5E-08 mg/L
0615 AM	Baseflow	2.1E-09 mg/L	1.4E-08 mg/L	1.9E-08 mg/L
1200 PM	High Flow	2.9E-08 mg/L	5.8E-08 mg/L	5.7E-08 mg/L
1200 PM	Low Flow	1.1E-08 mg/L	9.7E-09 mg/L	5.2E-09 mg/L
1200 PM	Baseflow	6.5E-09 mg/L	6.8E-09 mg/L	3.9E-09 mg/L
0000 AM	High Flow	8.7E-09 mg/L	2.1E-08 mg/L	2.4E-08 mg/L
0000 AM	Low Flow	4.8E-09 mg/L	1.7E-08 mg/L	1.9E-08 mg/L
0000 AM	Baseflow	3.5E-09 mg/L	1.1E-08 mg/L	1.3E-08 mg/L

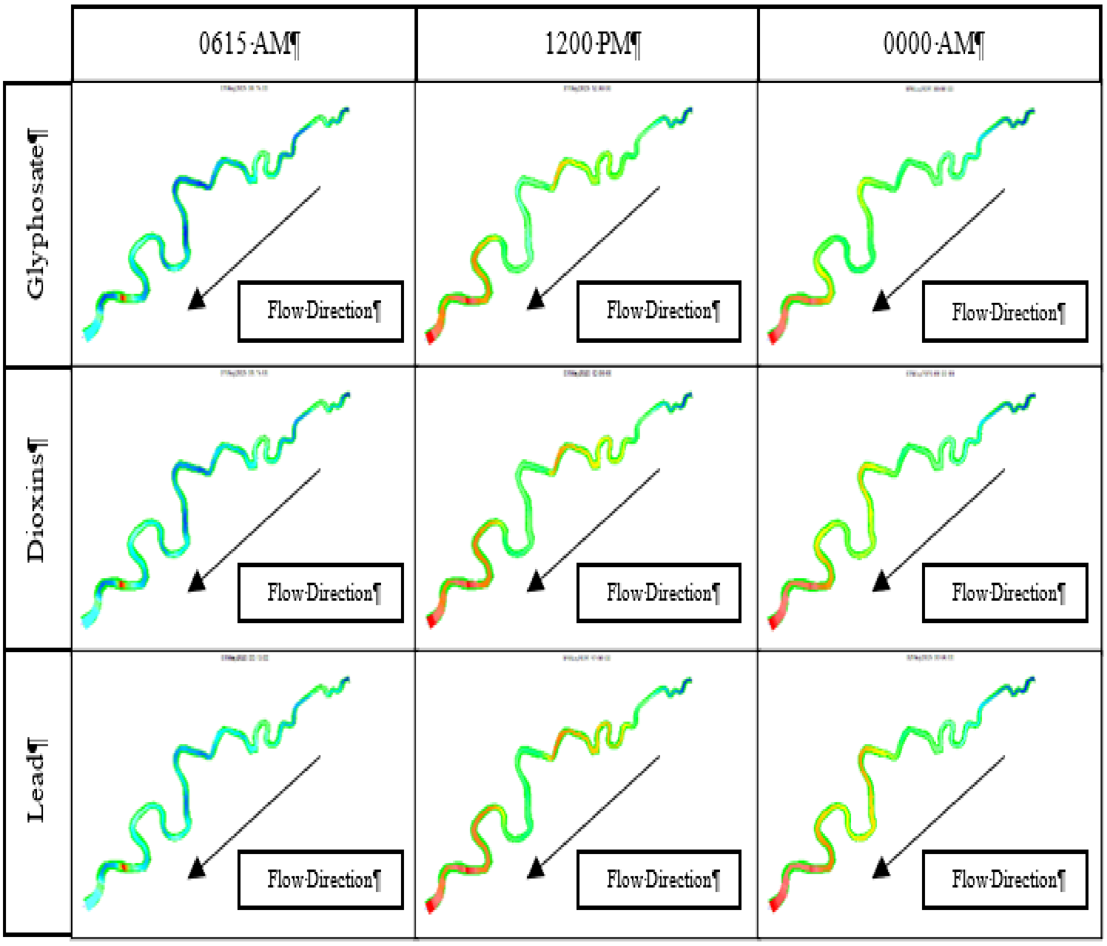


Figure 7. Concentration (mg/L) of Glyphosate, Dioxins and Lead under low flow conditions.

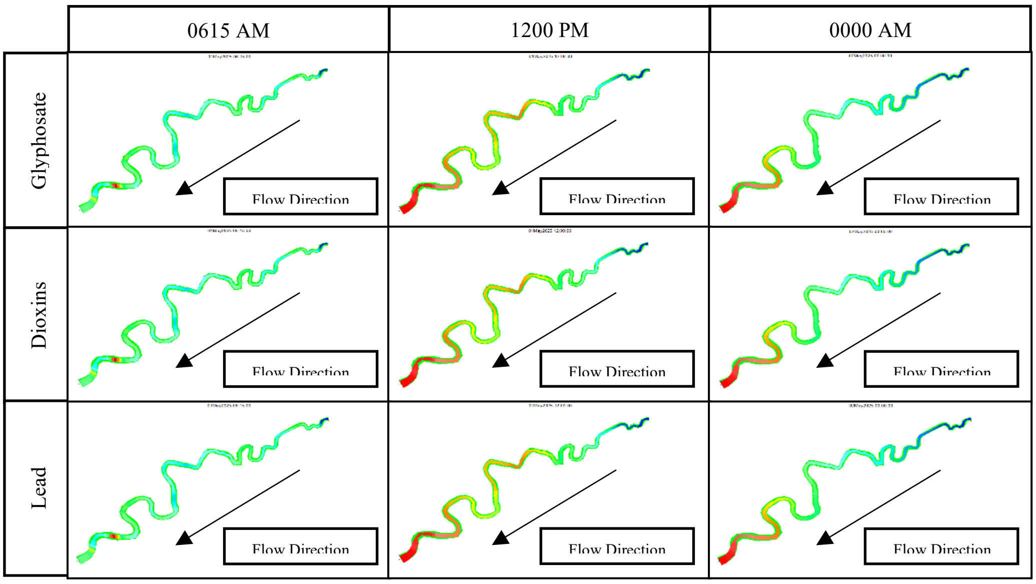


Figure 8. Concentration (mg/L) of Glyphosate, Dioxins and Lead under baseflow conditions.

3.1 Management Implications

The identified accumulation zone between CH4400 and CH4800 should be prioritised for continuous water quality monitoring using automated multi-parameter sondes or real-time monitoring stations. Mitigation measures such as riparian buffer enhancement, constructed wetlands, sediment retention systems, and improved municipal effluent pre-treatment should also be considered to reduce pollutant loading entering Sungai Perai, particularly during low-flow conditions where dilution capacity becomes limited.

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