

Research Article

# Evaluation Of Pesticide Use Towards the Implementation of Pollutant Release and Transfer Registers (PRTRs) In the Upper Citarum Watershed

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## Abstract

*Pollutant Release and Transfer Registers (PRTRs) are publicly based pollutant inventory systems that record the types, quantities, and sources of pollutant releases into the environment. This system promotes transparency and accountability in environmental management, enabling Indonesia to meet international environmental standards, including its accession process to the Organisation for Economic Co-operation and Development (OECD). This study aims to evaluate pesticide use in the Upper Citarum Watershed (DAS Citarum Hulu) as a foundation for implementing PRTRs in Indonesia. The research focuses on identifying the types, distribution, and usage patterns of pesticides in the agricultural sector; estimating pesticide emissions through runoff modelling; and analyzing the readiness of the water quality monitoring system. The methodology involves questionnaire surveys with farmers in West Bandung Regency, supported by secondary data such as rainfall, land area, and soil characteristics. Estimated pesticide residue concentrations are calculated based on factors such as precipitation, land slope, and soil organic carbon content. The findings of this study are expected to provide a foundation for strengthening Indonesia's environmental monitoring system and formulating national PRTRs policies. Additionally, the study highlights the importance of integrating data, public participation, and risk-based approaches in sustainable environmental management*

**Keywords:** agricultural pesticides, Organisation for Economic Co-operation and Development (OECD), Pollutant Release and Transfer Registers (PRTRs), runoff modelling, upper citarum river basin

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## 1. Introduction

Indonesia, as an agrarian country, heavily relies on the agricultural sector, which drives the massive use of pesticides to increase crop yields. Although effective in controlling pests, excessive and uncontrolled pesticide use has caused negative impacts on the environment, particularly on river water quality and human health. Pesticide residues carried by rainwater runoff and groundwater can accumulate in aquatic biota.

The types of pollutant pesticides that are widely used include organochlorines, organophosphates, carbamates (L. Taufik et al., 2017), pyrethroids, triazines, phenoxyacetic acids, chloroacetamides, and triazoles (Székács et al., 2015). Almost all pesticide types released into the environment are non-selective and have a broad spectrum of toxicity, making them potential sources of pollution for water resources and the environment, including rivers (I. Taufik, 2011). Therefore, monitoring systems and policies, such as the Pollutant Release and Transfer Registers (PRTRs), are needed to systematically track and control the release of emerging pollutants, including pesticides, into the environment.

Therefore, in this study, a runoff modelling approach was undertaken utilising pesticide usage data in the Upper Citarum Watershed, coupled with secondary data including land area, rainfall, and soil characteristics, to forecast pesticide concentrations (PEC) in river water. The predicted concentrations were subsequently compared to the Predicted No Effect Concentration (PNEC) standard to assess whether the pesticide levels pose a potential risk of contaminating the surrounding aquatic environment. Based on the pollution potential, the study evaluates the preparedness for the implementation of Pollutant Release and Transfer Register (PRTR) systems for pesticide compounds in Indonesia via the water environmental quality monitoring system in the Upper Citarum Watershed, employing literature and interview data from the West Java Provincial Office of Food Crops and Horticulture. The result of this evaluation constitutes an assessment of the readiness for PRTRs implementation.

## 2. Methodology

This research was conducted in several stages, beginning with a literature review, followed by data analysis, and culminating in the formulation of conclusions and recommendations. It begins with a comprehensive literature study to build a theoretical foundation. This is followed by field observations aimed at identifying key environmental and agricultural issues within the region. Once the context is understood, an appropriate data collection method is selected, along with the determination of a representative number of respondents. A questionnaire survey is then conducted among local farmers to gather information on pesticide use practices. Simultaneously, secondary data on agricultural areas is collected – covering crop types and planting areas, soil conditions, rainfall, and other relevant environmental factors. These data points are crucial in estimating the average pesticide usage by farmers and feeding into a runoff model that predicts the percentage of pesticide emissions entering the watershed flow. The model's outputs are then used to estimate the predicted concentrations of pesticides in the river system. These predicted levels are carefully evaluated to assess their environmental significance. Following this, the study conducts an analysis of how well PRTR mechanisms can be applied to pesticide chemicals in the watershed, evaluating the current level of implementation and identifying any gaps or challenges. Ultimately, the process concludes with a set of recommendations aimed at improving pesticide management and enhancing the effectiveness of PRTR systems in protecting water quality in the Upper Citarum region.

### 2.1 Determining The Number of Samples

The respondents in this pesticide usage survey were farmers selected using the cluster sampling method, referring to the sample size calculation method by Yamane (1967) with a margin of error of 15% (Israel, 2016)

$$n = \frac{N}{N \cdot \alpha^2 + 1} \quad (1)$$

Where:

$n$	=	Sample Size
$N$	=	Population Size
$\alpha$	=	Margin of error

The number of respondents for the Upper Citarum Watershed area, which includes West Bandung Regency, Bandung City, and Cimahi City, was distributed according to the number of farmers in each region, as shown in Table 1.

**Table 1.** Cluster Sampling Distribution by Region

Region	Number of Farmers	Sample Distribution
West Bandung Regency	160,369	42
Bandung City	8,690	2
Cimahi City	2,868	1
Total	171,927	45

### 2.2 Data Collection

Data used in this study consisted of primary data collected through questionnaire surveys administered to farmers in the Upper Citarum Watershed to identify the types and amounts of pesticides used, as well as

secondary data that includes information on crop types and cultivated areas, soil conditions, and rainfall. The secondary data were obtained from agencies such as BPS, the Agricultural Office, BMKG, in addition to satellite imagery, field surveys, and thematic maps. This information was used to estimate pesticide usage and model the potential runoff into river flows

### 2.3 Estimation of Agricultural Pesticide Usage

Based on data on crop types, agricultural land area, types of pesticide active ingredients for each crop, as well as the frequency and quantity of pesticide use obtained from the survey results.

a. The estimated value of pesticide active ingredient usage can be calculated using the following equation.

$$Pa = \frac{C \times V \times F}{A} \quad (2)$$

Where:

$Pa$	=	Estimated use of pesticide active ingredient per hectare per year (ha/year)
$C$	=	Concentration of pesticide active ingredient (g/L)
$V$	=	Total volume of pesticide spraying per application (L/application)
$F$	=	Frequency of pesticide spraying per year (applications/year)
$A$	=	Survey respondents' agricultural area (ha)

$$Pa = \frac{\%w \times W \times F}{A} \quad (3)$$

Where:

$\%w$	=	Percentage of active ingredient by weight in a pesticide mixture (%)
$W$	=	Total weight of pesticide used (g/application)

b. The total estimated use of pesticide active ingredients in the Upper Citarum Watershed can be calculated using the following equation.

$$P_{UCRB} = Pa \times A_{UCRB} \quad (4)$$

Where:

$P_{UCRB}$	=	Total estimated use of pesticide active ingredients (g/year)
$A_{UCRB}$	=	Agricultural land area (ha)

### 2.4 %Runoff Model

In estimating pesticide concentrations in river flow, it is necessary to calculate the percentage of the applied pesticide dose that is dissolved in surface runoff (L%runoff) entering the river, using the following equation (Reus et al., 1999).

$$L\%_{runoff} = \frac{Q}{P} \cdot f \cdot e^{\left(-x \cdot \frac{\ln 2}{DT_{50soil}}\right)} \cdot \frac{100}{1 + K_d} \quad (5)$$

$$K_d = K_{OC} \cdot \%OC \cdot \frac{1}{100} \quad (6)$$

Where:

$L\%_{runoff}$	=	Percentage of the applied pesticide active ingredient dose found in surface runoff as a dissolved substance entering the river (%)
$Q$	=	Amount of runoff (mm)
$P$	=	Precipitation (mm)
$f$	=	Correction factor, with $f = f_1 \cdot f_2 \cdot f_3$
$f_1$	=	Slope factor
$f_2$	=	Plant interception
$f_3$	=	Buffer zone factor
$x$	=	Time between runoff events.

- $DT_{50soil}$  = Half-life of the pesticide active ingredient in soil (days).
- $K_d$  = Ratio of dissolved active ingredient to adsorbed pesticide Concentration.
- $K_{OC}$  = Adsorption coefficient of the pesticide active ingredient to organic Carbon.
- %OC = Organic carbon content in the soil.

### 2.5 Predicted Concentration of Pesticides

The predicted concentration of pesticide active ingredients in river flow can be calculated using the following equation.

$$PEC = L\%_{runoff} \cdot P_{UCRB} \cdot \frac{1}{Q_{stream} \Delta T} \tag{7}$$

Where:

- $PEC$  = Predicted concentration of pesticide active ingredient in river flow ( $\mu\text{g/L}$ )
- $P_{UCRB}$  = Total use of pesticide active ingredients ( $\mu\text{g/year}$ )
- $Q_{stream}$  = Average river flow rate during the sampling period (L/second)
- $\Delta T$  = Annual duration (seconds)

### 2.6 Assessment of PRTR Readiness for Pesticides Compounds in Indonesia

The PRTRs system is built upon 14 fundamental principles that support effective, transparent, and inclusive reporting of pollutant releases and transfers. These principles form the foundation for evaluating a country's institutional, technical, and societal capacity to adopt and operate a PRTR system. The complete list of the 14 PRTR principles as shown in Table 2.

**Table 2.** The Principles of PRTRs

No	Principles
1	Establishment of a legal and institutional framework
2	Clear identification of objectives and goals
3	Designation of responsible institutions and roles
4	Definition of target substances and reporting thresholds
5	Public and private sector participation
6	Reporting system design and implementation
7	Mandatory and voluntary reporting mechanisms
8	Comprehensive data coverage
9	Publicly understandable access to data
10	Regular review and improvement of the system
11	Verification and geolocation of reported data
12	Harmonization with international systems
13	Ensuring the sustainability of the PRTRs system
14	Transparency and objectivity of the reporting process

To assess how well Indonesia aligns with each of the 14 core PRTR principles, a structured scoring approach was utilised. A consistent 3-point scale was applied to each principle, allowing for clear, transparent, and comparable evaluation across all indicators, as shown in Table 3.

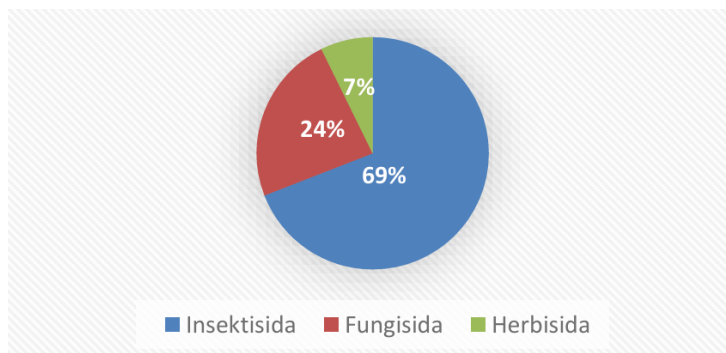
**Table 3.** The Principles of PRTRs

No	Principles of PRTRs
0	Not Implemented
1	Partially Implemented
2	Fully Implemented

## 3. Analysis and Discussion

### 3.1 Types of Agricultural Pesticides Used in The Upper Citarum Watershed

Based on the results of the questionnaire survey conducted in the agricultural areas of the Upper Citarum Watershed, it was found that farmers use nine pesticide active ingredients, which are categorized into three main groups: insecticides (Profenofos, Deltamethrin, Abamectin, Carbofuran, Alpha-cypermethrin), fungicides (Mancozeb, Propineb, Maneb), and herbicides (Metsulfuron-methyl), as shown in Figure 3.



**Figure 1.** Percentage Chart of Pesticide Types Used in the Upper Citarum Watershed

Based on the surveyed area within the Upper Citarum Watershed, specifically in West Bandung Regency, the types and concentrations of pesticides used in the region are presented in Table 4.

**Table 4.** Types and Concentrations of Agricultural Pesticides Use in West Bandung Regency (Lembang District)

Crop Type	Chemical Compound	Pesticide Type	Active Ingredient Content (%)	Active Ingredient Concentration (g/l)
Chilli	Profenofos	I	-	500
	Mancozeb	F	80%	-
	Maneb	F	80%	-
Cucumber	Deltamethrin	I	-	25
Corn	Deltamethrin	I	-	25
	Alpha-cypermethrin	I	-	15
Rice	Mancozeb	F	80%	-
	Carbofuran	I	3%	-
	Propineb	F	70%	-
	Metsulfuron-methyl	H	0.70%	-
Cabbage	Deltamethrin	I	-	25
	Profenofos	I	-	500
Tomato	Profenofos	I	-	500
	Mancozeb	F	80%	-
	Abamectin	I	-	18
Pak choy	Profenofos	I	-	500

The table above indicates that chilli, rice, and tomato are the commodities with the highest pesticide usage. In terms of active ingredients, Profenofos (22 occurrences) and Deltamethrin (9 occurrences) are documented as the most frequently utilised.

### 3.2 Estimation of Pesticide Usage by Farmers in The Upper Citarum Watershed

The average estimated pesticide usage (g/ha/year) was calculated utilising Equations 2, 3, and 4 as previously delineated, yielding the estimated pesticide application values by farmers within the Upper Citarum Watershed, as demonstrated in Table 5.

**Table 5.** Estimated Amount of Pesticide Use in the Upper Citarum Watershed

Crop Type	Chemical Compound	Spraying Volume per Application (L/application)	Pesticide Weight (g/application)	Application Frequency (times/year)	Agricultural Area (ha)	Pesticide Use (g/ha/year)
Chilli	Profenofos	1.2	-	66.84		7,148.66
	Mancozeb	-	1,000	64.08	5.61	9,137.96
	Maneb	-	200	84		2,395.72
Cucumber	Deltamethrin	50	-	12	1.25	12,000
	Deltamethrin	50	-	5.16		5,512.82
Corn	Alpha-cypermethrin	30	-	6	1.17	2,307.69
	Mancozeb	-	1,500	9		1,921.71
	Carbofuran	-	2,000	5.64		60.21
Rice	Propineb	-	1,500	10.2	5.62	1,905.69
	Metsulfuro n-methyl	-	50	6		0.37
	Deltamethrin	50	-	6.96		1,548.04
Cabbage	Profenofos	1.5	-	24	1.67	10,778.44
	Profenofos	1.2	-	78.36		10,154.64
Tomato	Mancozeb	-	1,500	72	4.63	18,660.91
	Abamectin	1	-	102.48		398.41
Pak choy	Profenofos	1	-	36	1.02	17,647.06

Following the determination of the average pesticide usage, the total pesticide pollution load (g/year) emanating from agricultural activities within the Upper Citarum Watershed can be calculated utilising Equation 4. This facilitates the estimation of the aggregate quantity of active pesticide ingredients employed, serving as an initial indicator to evaluate the potential risk of pesticide pollution to the environment by the agricultural sector in the Upper Citarum Watershed, as illustrated in Table 6 below.

**Table 6.** Estimated Total Pesticide Usage in the Upper Citarum Watershed

Crop Type	Chemical Compound	Pesticide Usage (g/ha/year)	Agricultural Area (ha)	Total Estimated Active Ingredient Usage (kg/year)
Chilli	Profenofos	7,148.66	2,610.50	18,661.58
	Mancozeb	9,137.96	2,610.50	23,854.64
	Maneb	2,395.72	2,610.50	6,254.03
Cucumber	Deltamethrin	12,000	50.33	603.96
	Deltamethrin	5,512.82	6,256.31	34,489.91
Corn	Alpha-cypermethrin	2,307.69	6,256.31	14,437.62
	Mancozeb	1,921.71	24,829.85	47,715.77
	Carbofuran	60.21	24,829.85	1,495.01
Rice	Propineb	1,905.69	24,829.85	47,318
	Metsulfuron-methyl	0.37	24,829.85	9.187
	Deltamethrin	1,548.04	24,829.85	38,437.60
Cabbage	Profenofos	10,778.44	3,672.37	39,582.42
	Profenofos	10,154.64	1,018.58	10,343.31
Tomato	Mancozeb	18,660.91	1,018.58	19,007.63
	Abamectin	398.41	1,018.58	405.8125
Pak choy	Profenofos	17,647.06	22.96	405.1765

### 3.3 Model of Agricultural Pesticide Concentration %Runoff in The Upper Citarum Watershed

In estimating the emission concentration from agricultural activities into the river flow in the Upper Citarum Watershed (DAS Citarum Hulu), the initial step is to calculate the percentage of surface runoff (%Runoff). This model, based on references from OECD (1999) and Berenzen et al. (2005), emphasizes that runoff is the primary mechanism for the transfer of active substances from farmland to water bodies. The input parameters required to determine this runoff model are shown in Table 7.

**Table 7.** Input Parameters for Pesticide Concentration Prediction

Parameter	Description	Value	References
P	Average precipitation in the watershed (mm/day)	4.8	BPS, 2024
Q	Runoff volume	0.067	Lutz, 1984 dan Maniak, 1992
Slope	Average slope (%)	14.84	Utami, 2021
$f$	Correction factor	-	(Berenzen et al., 2005; Organisation for Economic Co-operation and Development (OECD), 1999)
$f_1$	Slope factor	0.63	Beinat dan van der Berg 1996
$f_2$	Plant interception factor	0.3 (Insecticides and Fungicides) and 1 (Herbicides)	(Berenzen et al., 2005; Organisation for Economic Co-operation and Development (OECD), 1999)
PI	Plant interception (%)	70 (Insecticides and Fungicides) and 0 (Herbicides)	(Berenzen et al., 2005; Organisation for Economic Co-operation and Development (OECD), 1999)
$f_3$	Buffer zone factor	0.25	(Berenzen et al., 2005; Organisation for Economic Co-operation and Development (OECD), 1999)
WBZ	Width of the buffer zone (m)	7.39	Weatherspark
X	Soil leaching factor (days)	1.05	BPS, 2024
$DT_{50\text{soil}}$	Pesticide half-life in soil (days)	According to the specific pesticide chemical	(University of Hertfordshire, 2025) & USGS, 2025
$K_{oc}$	Pesticide adsorption coefficient to organic carbon (mL/g)	According to the specific pesticide chemical	(University of Hertfordshire, 2025) & USGS, 2025
$f_{oc}$	Fraction of organic carbon in soil	6.926	Hengl, dkk., 2014

Using the input parameter values from the table above, Equations 5 and 6 are applied to determine the L% runoff values for each active pesticide ingredient, as shown in Table 8.

**Table 8.** Percentage of Pesticide Chemical Runoff in the Upper Citarum Watershed

Pesticide Chemical Compound	L% <sub>runoff</sub>
Profenofos	4.571e <sup>-07</sup>
Deltametrin	9.374e <sup>-11</sup>
Alpha-cypermethrin	3.324e <sup>-09</sup>
Carbofuran	9.167e <sup>-06</sup>
Abamectin	1.703e <sup>-07</sup>
Mancozeb	9.618e <sup>-07</sup>
Maneb	4.799e <sup>-07</sup>
Propineb	5.328e <sup>-05</sup>
Metsulfuron-methyl	7.615e <sup>-05</sup>

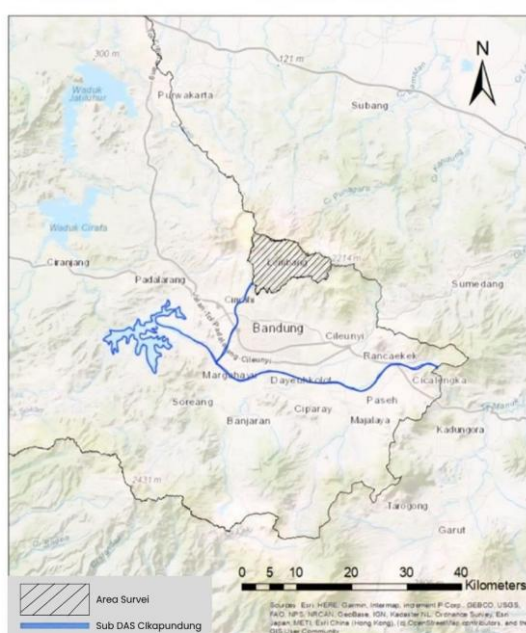
3.4 Predicted Concentration of Agricultural Pesticides in The Upper Citarum Watershed

The calculation of predicted environmental concentrations (PECs) of pesticide use is crucial in estimating the potential concentration of active pesticide ingredients that may enter river systems, which can be determined using Equation 7, as illustrated in Table 9.

**Table 9.** Predicted Environmental Concentration (PECs) Values of Pesticides in the Upper Citarum Watershed

Pesticide Chemical Compound	L% <sub>runoff</sub>
Profenofos	0.00668
Deltametrin	1.46e <sup>-06</sup>
Alpha-cypermethrin	1.017e <sup>-05</sup>
Carbofuran	0.0029
Abamectin	1.463e <sup>-05</sup>
Mancozeb	0.01857
Maneb	0.000636
Propineb	0.534
Metsulfuron-methyl	0.000148

The predicted concentration values of pesticide chemicals are projected to enter the main water body via river flow in the Cikapundung sub-watershed, as illustrated in Figure 2.



**Figure 2.** Sampling Locations and Predicted Entry of Pesticide Chemicals into the Upper Citarum Watershed

The safety assessment of the Predicted Environmental Concentrations (PECs) of pesticides within the aquatic environment is performed by comparing them with the Predicted No Effect Concentration (PNEC) standard. The PNEC represents the threshold concentration of a chemical that does not induce adverse effects on aquatic organisms, utilising data obtained from the Pesticide Properties Database (PPDB), as illustrated in Table 10.

**Table 10.** Comparison of PEC and PNEC Values of Pesticide Chemical Compounds

Chemical Compound	PEC ( $\mu\text{g/L}$ )	PNEC ( $\mu\text{g/L}$ )	Description
Profenofos	0.00668	0.016	Safe
Deltametrin	$1.46\text{e}^{-06}$	0.000034	Safe
Alpha-cypermethrin	$1.017\text{e}^{-05}$	0.00026	Safe
Carbofuran	0.0029	0.22	Safe
Abamectin	$1.463\text{e}^{-05}$	0.001	Safe
Mancozeb	0.01857	0.044	Safe
Maneb	0.000636	0.042	Safe
Propineb	0.534	0.3	Unsafe
Metsulfuron-methyl	0.000148	0.036	Safe

Based on the comparison between PEC (Predicted Environmental Concentration) and PNEC (Predicted No Effect Concentration) values, only one active chemical compound, Propineb, is classified as "Unsafe" because its concentration slightly exceeds the threshold and poses potential risks to aquatic organisms. Although the overall impact on water pollution has not demonstrated significant effects thus far, pesticide utilisation still necessitates meticulous monitoring, particularly for Propineb. Consequently, an integrated monitoring system, such as Pollutant Release and Transfer Registers (PRTRs), is crucial to document, report, and regulate the release of pollutants into the environment.

### 3.5 PRTRs Readiness Assessment In Indonesia

To evaluate Indonesia’s preparedness to implement a national PRTR system, an assessment was carried out across four key areas that reflect the essential technical, institutional, and participatory foundations. This evaluation aims to provide a comprehensive overview of the country’s current strengths and deficiencies, as shown in Table 11.

**Table 11.** PRTRs Implementation Assessment

No	Assessment Aspects	Score Obtained	Maximum Score	Percentage (%)
1	Regulation and Policy	8	18	44.4%
2	Information Flow and Data Management	3	12	25%
3	Industrial Activities	2	10	20%
4	Public Involvement and Transparency	0	8	0%

#### 1. Regulation and Policy

This component assesses the presence of legal and policy frameworks that facilitate the implementation of the Pollutant Release and Transfer Register (PRTR), including pertinent legislation, regulations, and institutional arrangements. Although Indonesia has adopted several relevant policies, such as the PROPER program and its participation in international accords like the Minamata Convention, these frameworks have not yet been fully harmonized with the specific requirements and substance-based reporting structure of a PRTR system.

#### 2. Information Flow and Data Management

This aspect assesses the capacity of existing systems to handle PRTR-related data, covering aspects such as data collection, verification processes, accessibility, and integration across platforms. While certain elements are already embedded in digital platforms like OSS and SIMPEL, the current system

still suffers from limited data coverage, lacks a centralised public portal, and does not yet follow a standardised evaluation cycle.

### 3. Industrial Activities

This section evaluates the extent of industry participation in reporting emissions and hazardous waste, as well as their technical capabilities and readiness. Currently, the majority of industrial involvement takes place through the PROPER initiative, which has not yet incorporated all relevant sectors nor fully adhered to the data standards expected in international PRTR practices.

### 4. Public Involvement and Transparency

This section examines the existence of mechanisms that facilitate public participation, transparency, and access to emission data. The findings reveal that Indonesia currently does not possess formal systems to engage the public, and there is no accessible platform for PRTR data, resulting in a score of zero in this category.

## 4. Conclusion

Based on the analysis results, the types and usage patterns of pesticides in the agricultural sector around the Upper Citarum Watershed (DAS Citarum Hulu), particularly in West Bandung Regency (Lembang District), are quite diverse. Several groups of pesticides with varying chemical compounds were identified, including insecticides (Profenofos, Deltamethrin, Abamectin, Carbofuran, Alpha-cypermethrin), fungicides (Mancozeb, Propineb, Maneb), and herbicides (Metsulfuron-methyl). These findings indicate that pesticide use in the area is relatively intensive and has the potential to become a source of environmental pollution. Runoff modelling and pollutant load concentration estimates (PECs) revealed that the pesticides Propineb, Profenofos, and Mancozeb have the highest PEC values, driven by a combination of high usage volume and substantial surface runoff. Meanwhile, chemicals such as Deltamethrin, Alpha-cypermethrin, and Abamectin showed lower PEC values because they tend to bind with the soil. The chemical properties of each compound play a significant role in determining its pollution potential. Among all active pesticide ingredients used, the PEC values for Propineb have exceeded the PNEC threshold, posing potential risks to aquatic organisms. According to the river flow map, pesticides applied in the region are likely to enter the Cikapundung sub-watershed and subsequently flow into the main Citarum watershed. Although pesticide usage has not yet shown significant pollution impacts overall, stringent monitoring remains essential, especially for chemicals with high-risk potential. Therefore, controlling pesticide use in this area is crucial for preserving water quality in the Upper Citarum Watershed.

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