

Review

Water Pollution of Some Major Rivers in Indonesia: The Status, Institution, Regulation, and Recommendation for Its Mitigation

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Abstract

River water pollution is a significant environmental problem in Indonesia. On the other hand, river water is an important source of drinking water. Therefore, clean and safe water has become a priority program of the Government and is parallel with the international agreement known as the Sustainable Development Goals (SDGs). Rapid population growth and industrialization cause inadequate access to safe water; only 73% of Indonesian people can access safe water. This review paper aims to present a comprehensive discussion concerning water pollution in four big rivers, i.e., Siak, Citarum, Bengawan Solo, and Brantas Rivers, that have experienced pollution and provide alternative solutions to mitigate the pollution. Data were collected from related institutions, governments' regulations, the authors' experiences, and literature studies. Developing a riparian zone with multiple ecological services and introducing Internet of Things (IoT) devices that monitor and provide real-time water quality information is essential for mitigating river water pollution. Law enforcement is an alternative method to reduce point-source pollutants from industries. Non-point source pollutants from domestic and agricultural wastes may be reduced through spreading awareness and implementing personal and environmental hygiene, involving the community in designing, as well as monitoring and evaluating water quality. Those approaches should be accompanied by proper institutions, regulations, and policies.

Keywords: water quality; pollutant; community involvement; riparian zone; IoT

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Introduction

Rapid population growth, particularly in urban areas, accompanied by the increased water demand for industry, irrigation, fisheries, home usage, and other purposes, has led to water supply problems. The lowering of water quality due to water pollution has become a severe global issue [1]. The pollution of water sources can cause a range of health problems, especially waterborne diseases, as well as reproductive problems, cancer, and neurological disorders [2]. This makes the global communities aware of the need for efforts to conserve water resources towards sustainable land use and pollution mitigation [3], as well as the essential public involvement in environmental management [4]. In this regard, the global community set a non-binding international agreement known as the Sustainable Development Goals (SDGs) approved by the United Nations in 2015 [5]. The SDGs target that by 2030, people achieve peace and prosperity through 17 (seventeenth) goals [6]. Eight of 17 SDGs should fulfil the increase in safe and continuous water demand [7]; therefore, the sustainability of clean and safe water has become a priority in the SDGs. In most developing countries, however, the continuity and adequacy of clean and safe water are still a problem.

In Indonesia, river water provides various benefits to human life. Even today, many rivers still serve as transportation routes for communities [8]. Apart from being a transportation route, some rivers, for instance, the Kuin River in Banjarmasin, South Kalimantan, also have an economic function as a floating market with tourism potential. Along this river is Kampong Kuin, a traditional village of Banjar [9]. Many people also use river water for sanitation purposes [10]. These facts show that river water not only meets water needs for daily life, but also supports economic and social activities, and when river water is polluted, the impact is not only on human health but also on economic and social aspects.

Indonesia, a developing country with a population of 275.77 million, faces river water pollution. Several big rivers that flow through urban cities have serious water pollution problems. According to the Central Bureau of Statistics, only 73% of people have access to safe water and around 20 million have difficulty obtaining better sanitation [11].

Among the polluted rivers is the Siak River in Jambi Province, Sumatera Islands [12], while in Java Islands, several rivers also experience pollution, such as Citarum [13], Bengawan Solo [14], and Brantas [15]. All of the polluted rivers mentioned above are located in watersheds categorized as restored watersheds and flow through urban cities. According to the Directorate General of Pollution Control and Environmental Damage (Ditjen PPKL), the percentage of river water in Indonesia classified as heavily, moderately, and slightly polluted are 59%, 26.6%, and 8.87%, respectively, and only 5.3% meets the quality standard [16].

Various legislations concerning water quality management have been issued to prevent further negative

impacts on communities and the environment, but many rivers in the watersheds are still polluted. It is generally because developing countries lack strict law enforcement against those who break the regulations [17]. It can also be caused by a lack of coordination and a holistic approach among related institutions and a lack of community involvement in water quality management [18]. Consequently, the quality of river water tends to decrease.

Although some rivers have been polluted, some people still use them. It is caused by a lack of public awareness of the dangers of using polluted water to human health. For example, invisible pollution due to poor bathing and sanitary activities [19], or the community already knows the dangers of polluted water, but lack of clean water or insufficient of wastewater treatment [20]. Therefore, the social aspects are a concern in mitigating the impacts of river water pollution.

Concerning the pollution impacts, several studies have been undertaken to reduce the pollution problems. However, previous studies have focused only one aspect, particularly on water quality related to the physical condition, and lack of papers discussing water quality from all related aspects comprehensively. This review paper presents a more comprehensive discussion concerning water pollution in some major rivers, from the river pollution status to institutional, policies, regulations, and social aspects. We also offer recommendations for mitigation of river water pollution. The purpose of this paper is to examine the quality of river water pollution in several major rivers and possible mitigation efforts.

Materials and Methods

Materials and data were collected from related institutions, governments' regulations and related documents, experiences of the authors, and literature studies. The analyses and discussions were conducted on the physical aspects of water pollution, institutions, policies, regulations, and social aspects. The results are expected to provide a synopsis and understanding water pollution status of some major rivers.

Regarding the level of water pollution in some major rivers, the study used case studies of selected major rivers in urban watersheds. Several watersheds dominated by urban areas with various activities, including domestic and diverse industries along the river in Sumatra and Java, were chosen. The case study urban watershed includes the Siak watershed in Sumatra and Citarum, Bengawan Solo, and Brantas Watersheds in Java. These watersheds also have a strategic role at the regional/provincial or national level, such as having a vital infrastructure (hydroelectric power plant), sources of water for various needs, and flowing through the provincial capital cities. Figure 1 depicts the geographical position of the case study urban watersheds.

Some of the data were graphed to make it easier for the readers to compare the pollutant content among the rivers. Finally, this study recommended mitigation measures for water pollution toward better water pollution management.

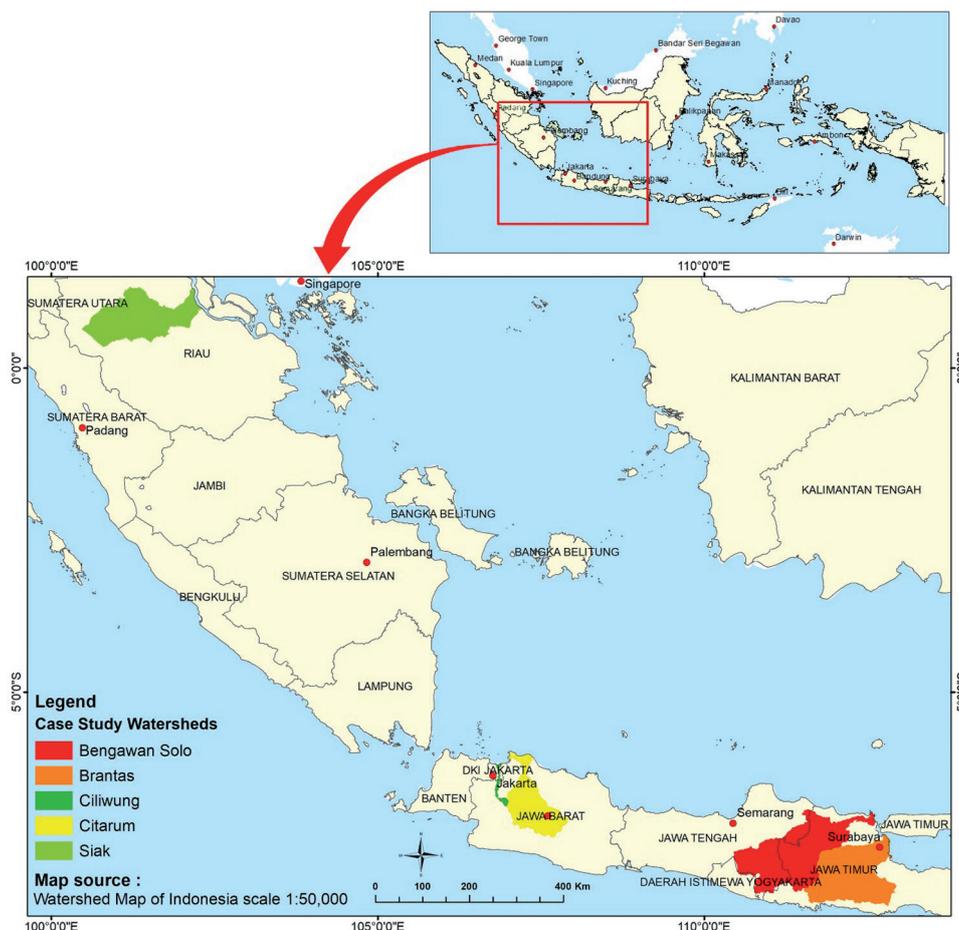


Fig. 1. The geographical position of the case study in the related watersheds

Results and Discussion

Sources of Pollutants

All of the studied rivers flow through urban cities. In this case, the dense urban area will be proportional to the waste generated, whether domestic, industrial, or agricultural. These wastes then flow into rivers and pollute the water. In urban areas, settlements are the highest wastewater contributors compared to offices, industries, or other public places [21].

Water pollution can be categorized as point-source and non-point-source pollution. Point source pollution is usually industrial waste. It is the most manageable source of pollution [22] because the exact location is identified. In contrast, non-point source pollution is characterized by many pollutant sources that mix, making it difficult to trace [23]. In urban areas, most agricultural areas have turned into settlements and industrial areas. The non-point source pollution occurs in agricultural areas that have turned into urban areas [24] because urbanization turns land into an impermeable surface [23]. This impermeable surface disrupts the hydrological processes, including runoff, which turns the point pollutants into non-point ones [23]. Brontowiyono et al. [24] observed that the sources of

pollution in urban areas come from domestic, industrial, and agricultural activities. Domestic waste is primarily produced to meet domestic demands, which frequently rise along with population density [25]. Pollutant elements can be distinguished using the watershed as an observation unit. Temperature, total dissolved solids (TDS), detergent, *Escherichia coli*, and coliform reflect pollution in residential areas. On the other hand, Mn, Cd, Zn, Fe, Pb, Cu, pH, phenol, oil and grease indicate pollution from industrial areas. Nitrate, nitrite, phosphate, ammonia, and dissolved oxygen (DO) parameters are from agricultural areas. Heavy metals pollute the river due to anthropogenic activities [26] such as factories and industry in general. There is uncertainty whether heavy metals like copper and mercury in the Brantas River. Still, they are suspected to have originated from industrial waste or volcanic eruptions [27] because active volcanoes surround the Brantas Watershed. In the Citarum Watershed, heavy metals such as zinc, cadmium, and chromium mostly come from the textile industries [28]. Similar to the Citarum Watershed, Septiono et al. [28] found that pollution in the Bengawan Solo River is also dominated by textile industries, especially garment and batik industries.

Batik manufacturing is one of the industries that use water inefficiently. Its waste disposal pollutes

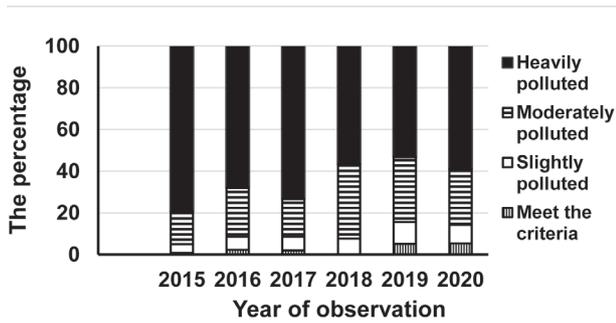


Fig. 2. The status of river water quality from 34 provinces in Indonesia. Source: Based on data of Ditjen PPKL

water sources and causes severe river water pollution. Therefore, water resources management in the batik industry must reduce pollution in the related river [29]. This waste management is specific to each batik industry, depending on the quality of the effluents [30].

Water Pollution in the Studied Rivers

Data on monitoring river water quality status using the Pollution Index from 2015 to 2020 conducted by the Directorate General of Environmental Pollution and Degradation Control (Ditjen PPKL) are graphed in Figure 2. The observation of the water quality came from 563 monitoring places spread out in 34 provinces in Indonesia [16]. Figure 2 demonstrates that no river water in 2018 met the quality criterion, with the highest percentage of river water falling into the extremely polluted category. Although the percentage of water that meets quality standards increased slightly from 0.78% in 2015 to 5.35% in 2020, the percentage of heavily polluted river water is still high, 59% in 2020 [16].

Based on data from Ditjen PPKL [16], the characteristics of water quality of the four studied rivers are provided in Table 1. The pollution level of the Siak River was moderate to heavy in 2018 and 2020; however, it was classified as heavily polluted in 2015, 2016, 2017, and 2019. The Citarum, Bengawan Solo, and Brantas Rivers have been classified as heavily polluted from 2015 to 2020.

Previous studies on river water pollution have been conducted in Siak, Citarum, Bengawan Solo, and Brantas

Rivers. The following sub-sections explain the research findings of each case studied river.

Pollution of Siak River, Riau Province, Sumatra

The Siak River is among the 13 national priority rivers [31]. The length of the Siak River is 300 kilometers with a depth of 20-30 m, and the river flows across Rokan Hulu District, Bengkalis District, Siak District, Kampar Regency, and Pekanbaru City, where the whole of the Siak Watershed takes place in Riau Province [32]. The Siak River is also the largest in Riau Province and flows through Pekanbaru City. The Siak River is utilized for drinking water, bathing and washing, fisheries, agriculture irrigation, industry, and water transportation [33].

Agency for Environmental Impact Control (Bapedal) Riau Province states that the main causes of water pollution in the Siak River are illegal logging in the upstream part of the watershed, domestic waste in the middle area, industrial waste in the downstream area, and settlements [34]. Indeed, water pollution has worsened since the Siak River flows through the urban city of Pekanbaru. It is a consequence of development in all sectors, including settlements, industries, and general economic growth [32].

A study in the headwaters area of the Siak Watershed revealed that among the observed elements, BOD value was the only pollutant above the water quality standard [35]. Another study observed that, on average, the Iron (Fe) content in the Siak River was still below the threshold of 0.06 ppm. In addition, a study conducted in the Siak River around the Sari Residence housing complex in Pekanbaru City showed that the coliform bacteria density ranged from 11,267 - 15,650 units/100mL, above the drinking water quality standard. The effectiveness of reforestation on the water quality of the Siak River was studied by Azmi et al. [36] in areas with high industrial activity, Maredan Village, Tualang District. The research revealed that the Siak River, after reforestation from 2014 to 2016, was relatively stable, in a better condition than the condition before rehabilitation in 2003 to 2005 for the COD, DO, and BOD the Biotic Index of aquatic insects. The findings indicated 15 families of water insects in the Siak River and six bioindicator insects of water pollution.

Table 1. The pollution level of the 4 major studied rivers

Province	River/ Watershed	Pollution status of the river water					
		2015	2016	2017	2018	2019	2020
Sumatera, Riau Province	Siak	Heavy	Heavy	Heavy	Moderate-heavy	Heavy	Moderate-Heavy
West Java	Citarum	Heavy	Heavy	Heavy	Heavy	Heavy	Heavy
Central and East Java	Bengawan Solo	Heavy	Heavy	Heavy	Heavy	Heavy	Heavy
East Java	Brantas	Heavy	Heavy	Heavy	Heavy	Heavy	Heavy

Source: Based on data of Ditjen PPKL [16]

The Chironomidae family (Blood red) found the highest number of bio-indicator insects, with 131 individuals. The Diversity Index varies from 0.10 to 0.72, classified as low [37].

Pollution of Citarum River, West Java Province, Java

Citarum River is a river with the highest pollution around the globe [38]. Resosudarmo [39] compared several rivers in Asia and found that Citarum was one of the rivers that had BOD, COD, and coliform values above the permissible threshold for drinking water, i.e., 12 mg/L, 37 mg/L, and 600,000 units/100 mL, respectively. Another study by Yustiani et al. [40] found that in 2018-2020 the water quality of the Citepus River, the tributaries of the Citarum River, was classified as heavily polluted using the STORET method. Furthermore, it was reported that the major sources of pollution were municipal-domestic activities followed by industrial and agricultural-irrigation activities. Djuwita et al. [41] found that the pollution loads mostly came from non-point sources, i.e., around 85%, dominated by domestic waste (83.5%).

The pollution levels in the rivers of the Citarum Watershed have been a cause of concern for many years. Through the Citarum Harum Program, which started in 2018, there is a remarkable enhancement in the water quality status of the Citarum River. Before the Citarum Harum Program was implemented, Fulazzaky [42] evaluated the water quality of the Citarum River in 11 sites across the river. The result showed that the water quality along the Citarum River was in awful condition, except for a segment that had just left the Jatiluhur dam. According to the 2021 Water Pollution Index analysis of 16 Water Quality Monitoring Stations managed by the Ministry of Environment and Forestry, five stations satisfied the standards, five stations were slightly polluted, five stations were moderately polluted, and 1 station was heavily polluted. Overall, the water quality monitoring results across the Citarum Watershed indicated that the water condition was in a slightly polluted status owing to the success of the water quality improvement program of the Upper Citarum Watershed.

Daily monitoring of water quality status in the Citarum Watershed is operated by the Directorate General of Environmental Pollution and Degradation Control under the Ministry of Environment and Forestry, using 17 water quality monitoring stations [43]. For example, on 26 March 2023, out of 17 stations, 1 station had a water quality status that satisfied the quality standards, 11 were slightly polluted, and 5 were moderately polluted. The BOD was the most significant determining factor of water quality status found in 12 stations. Juwana et al. [13] reported that the implementation of the water quality control programs to refine the Citarum Watershed pollution index significantly affects the cadmium, BOD, and fecal coliform parameters, particularly household waste, agricultural, solid waste, and water resource programs.

Pollution of Bengawan Solo River, Central and East Java Provinces

The Bengawan Solo River is the largest river on Java Island with a length of \pm 600 km, and it flows from Sewu Mountains in the west-south of Surakarta to the Java Sea in the north of Surabaya and across several cities in Central Java and East Java Provinces. The Bengawan Solo River continues to experience decreasing river water quality caused by domestic waste and industrial waste disposal, especially rivers that pass through urban areas such as Surakarta City [44], as well as Lamongan and Gresik Regencies in the downstream area [45]. Economically, industrial developments in the several cities passed by the Bengawan Solo River have many positive impacts; however, based on an ecological point of view, industrial developments directly effluent into rivers [46].

Data from Bengawan Solo River Basin Organization (Balai Besar Wilayah Sungai Bengawan Solo) at 30 observation points in 2022 showed that 11 observation points indicated heavily polluted water. Heavily polluted areas in Central Java are spread over four regions, i.e., Sukoharjo, Surakarta, Karanganyar, and Sragen. Surakarta, an urban city, produced the highest pollution index of 13. Heavily polluted areas in East Java Province are also spread over four regions, i.e., Pacitan, Ngawi, Lamongan, and Gresik. Lamongan Regency, as an urban city, produced the highest pollution index with a value of 9.58. Gresik is a city that often experiences heavy pollution due to industrial developments. More than 1300 companies operate in this regency, such as cement, wood, steel, chemical, and power plants [47].

Research in 2020 on the river branches of the Bengawan Solo River in Surakarta City showed a high total coliform and fecal coliform content that causes diarrhea, conducted by Handayani et al. [29]. The Jenes Hilir River, part of the Bengawan Solo River, has higher total coliform, fecal coliform, than other rivers. This is due to a large amount of domestic waste that enters water bodies, which spurs the growth of coliform bacteria. Similar research was conducted on the water quality of the Bengawan Solo River. The observation found that the concentration of DO and phosphate in the rivers in Surakarta City in 2018 did not fulfill the river water quality guidelines [44].

In another study, phosphate levels in Surakarta City also showed a value of 0.35 mg/L exceeding the threshold based on observational data from January to March 2020 [48]. The pollutants come from domestic and industrial waste, especially textiles. Most of the rivers in Surakarta City show polluted status.

Pollution of Brantas River, East Java Province

Based on the Minister of Public Works and Housing Regulation No. 04/PRT/M/2015 on Criteria and Establishment of River Areas, Brantas River was declared as a national strategic river region. The Brantas Watershed has an area of 11,945.9 km² or 83.8% of the

total Brantas River system, which oversees more than 200 watersheds. The Brantas Watershed is included in the urban watershed category, which passes through the second-biggest city in Indonesia, i.e., Surabaya, and several other cities such as Malang, Batu, Mojokerto, Kediri, and Blitar [49]. As in other large watersheds, the primary sources of water quality problems in the Brantas Watershed include industrial, domestic use, and agriculture. According to the Ministry of Public Works and Housing [49], 483 industries in the Brantas Watershed have the potential to generate a BOD pollution load of 125 tonnes/day. Based on data from Ditjen PPKL [16], the Brantas Watershed is a heavily polluted watershed with indications of total coliform, BOD, DO, and TSS contents that exceed the threshold.

Domestic waste in the Brantas Watershed has the potential to emit 539 kg/day of BOD, and 1032 kg/day of COD [50]. The microplastic content, which is dissolved in water and will be devoured by aquatic species, mainly fish, should be considered when domestic waste is present.

According to Buwono et al. [51], the amount of microplastics in the river is 4,066.7 particles/m³, some of which have been discovered in the digestive system of *Gambusia affinis* fish. Oil and grease, with a concentration of 962.5 mg/L, is another pollutant in the Brantas River that comes from residential waste [15]. Domestic activities produce this oil and grease from soap, vegetable and animal fats, leftover cooking oil, and soap dumped in water bodies. This pollutant is hazardous up to a certain point because, in addition to being toxic, it will prevent other pollutants from self-purification [52].

Fertilizing and using pesticides are two agricultural practices that contribute to water contamination. Eutrophication has been observed in a large reservoir, notably the Sutami reservoir in East Java, because of this activity. Another effect is the occurrence of siltation, which reduces the useful life of the reservoir. Compared

to the intermediate and downstream Brantas Watershed, the Upper Brantas has the highest sedimentation rate at 5.5 mm/year [49]. Because agricultural activity in the upstream Brantas is more extensive than that in the other areas, it is believed that the sedimentation resulted from both the erosion that occurs, as well as the farming there. Even though they contribute to silt, existing agricultural activities are not always a source of water contamination. Hendriarianti et al. [53] state that the average total ammonia content (NH₃ and NH₄⁺), which ranges from 0 to 0.278 mg/L, is still below acceptable limits and can self-purify from ammonia contaminants.

Water quality monitoring is carried out manually by direct observations made at 51 points on the Brantas River, including reservoirs and dams [49]. The agencies involved in monitoring the water quality in the Brantas Watershed are the East Java Province Public Works Office, Bapedal, Ditjen PPKL, and Perum Jasa Tirta I. According to the observation conducted in the upstream Brantas for the four water quality parameters, i.e., pH, DO, COD, and TDS [54, 55], there was a decreasing trend in COD from 2017 to 2019; conversely, the TDS increased. This condition indicates a rise in dissolved solids in the upstream Brantas waters, which may interfere with water use in the Brantas since, at some levels, it will be hazardous to use owing to continuous exposure to chemicals.

Impact of Water Pollution on Human Beings and the Environment

Various impacts of water pollution have been observed in the study areas and the results are provided in Table 2.

By comparing a pollution-affected village and a non-affected village, Reddy and Behera [66] assess the economic consequences of water pollution due to industrial effluent based on losses to agricultural production, human health, and cattle. They concluded

Table 2. Impacts of water pollution on human beings and the environment in the study areas

River	Object	Impacts
Siak	Human beings	Skin disease [56, 57], diarrhea [56], intestinal worm disease [58]
	Environment	Poor aesthetics, poor water appearance [56]
Citarum	Human beings	Cadmium and zinc exceed the threshold standard. In the long term, exposure to zinc will cause anaemia, and other blood diseases, while cadmium will adversely affect bone and kidneys [59].
	Environment	Algal bloom in the reservoirs, rice fields, and fishponds, especially in a stagnant water [60], loss of specific sensitive taxa with adequate diversity downstream of the Jatiluhur Dam [42], cadmium, chromium, and copper are found in catfish and used for duck fodder [28]
Bengawan Solo	Human beings	Diarrheal disease, skin disease, digestive disease [61], hepatitis, yellow fever, typhoid fever, cholera [62]
	Environment	Decreasing in the volume of clean water and disrupting aquatic organisms [63], declining rice quality [46], and sedimentation [64]
Brantas	Human beings	Limited availability of clean water suitable for drinking water [50]
	Environment	Differences in the diversity of fish in the upstream and downstream areas [65]

that water pollution had substantial economic impacts on rural communities. Zhang [67] found that water pollution caused the highest economic loss in the tourism sector, followed by fishery, housing, irrigation, and potable water. Releasing pollution in the upstream watershed can significantly lower the economic growth in the downstream watershed [68].

Several studies reported that water pollution can cause harm to aquatic ecosystems, including fish, plants, and other wildlife. Chemicals and toxins in the water can accumulate in the tissues of these aquatic organisms, leading to diseases, organ damage, deformities, and reduced reproductive success [69]. Another study reported that water pollution caused by heavy metals could cause liver and gill damage, leading to fish death [70].

Polluted water due to excessive N and P compounds causes eutrophication [71]. The adverse impacts of eutrophication in aquatic ecosystems include fish kills due to the reduction of available dissolved oxygen, reduced biodiversity, algae blooms, and damage to habitat, which can lead to declines in populations and even extinction [72].

Institution to Control Water Pollution

Three responsible ministries for river water monitoring and evaluation (MONEV) include (1) the Ministry of Environment and Forestry as stated in Law No. 32/2009, (2) the Ministry of Public Works and Housing as established in Law No. 17/2019, and (3) the Ministry of Home Affairs as stated in Law No. 23/2014 (Table 3).

The Ministry of Public Works and Housing has established the Directorate General of Water Resources through Minister Regulation No. 13/2020. This Directorate

General has the function of compiling norms, standards, procedures, and criteria of water resources management and carry out evaluation and reporting of water resources management. To carry out the technical functions, the Directorate General of Water Resources has the River Engineering Centre. The River Engineering Centre has the duty of carrying out the development, engineering, and implementation of technical services for testing, assessment, inspection, and certification in the field of rivers.

The Minister of Environment and Forestry Regulation No. 15/2021 stipulates that the Directorate General of Pollution Control and Environmental Damage carries out the functions of formulating and implementing policies, compiling norms, standards, procedures, and criteria, as well as evaluating and reporting on the implementation of controlling water pollution, air pollution, land damage, peat ecosystem degradation, and coastal and marine pollution and damage. In carrying out its functions, the Director General of Pollution Control and Environmental Damage is assisted by the Directorate of Water Pollution Control, which technically handles the protection and management of water quality and pollution control.

At the provincial level, the water pollution problem is handled by the Environment and Forestry Office. In contrast, at the district and city levels, it is handled by the District/City Environmental Service as stated in Law No. 23/2014. The duties of the Environmental Service related to water pollution are to develop a management system, manage water quality databases, and implement monitoring and evaluation (MONEV) of river water quality.

In an acute pollution problem, the Government constructs a model for handling river water pollution, such as in the Citarum River. In January 2018, the President instructed to intensively manage the Citarum River,

Table 3. The responsible institutions for monitoring and evaluation of river water

Mandate of	Law No. 32/2009: Protection and Management of the Environment	Law No.17/2019: Water Resources	Law No. 23/2014: Regional Government
Ministries	Environment and Forestry	Public Works and Housing	Home Affairs
Directorate General (Echelon I)	Pollution Control and Environmental Damage	Water Resources	
Directorate (Echelon II)	Water Pollution Control		
Institute (Echelon III)		River Basin Office (BBWS)	
Province			Environment and Forestry Services, Public Works on Water Resources and Spatial Planning Services
District/Regency			Environmental Services

Source:

1. Organizational Structure of the Ministry of Environment and Forestry [73]
2. Organizational Structure of the Ministry of Public Works and Housing [74]
3. Organizational Structure of the Ministry of Home Affairs [75]

namely the Citarum Harum River Program. The Citarum Harum River Program controls related problems on all waste treatments and disposal, law enforcement on waste violations, and educating the public on the importance of maintaining the river environment.

Based on regulations, the management of water resources involves many institutions. To coordinate the management of water resources, a River Basin Water Resources Management Coordination Team (TKPSDA WS) was formed as a coordinating forum at the river basin level representing various cross-sectoral interests (Regulation of the Minister of Public Works and Housing No. 17/PRT/M/2017 concerning Guidelines for Forming Coordination Team for Water Resources Management at River Basin Level). TKPSDA WS membership comes from government and non-government elements. Integrating and coordinating stakeholder interests across sectors, regions, and stakeholders in managing water resources in the river basin is one of the duties of TKPSDA WS. Indeed, more coordination should be emphasized, mainly in establishing the field measurements and data sharing. It is important since the instruments are expensive, and many places should be monitored. In addition, the methods to collect and analyze the data should have a standard to obtain valid information for the Government and public consumption.

State companies also manage the quality of river water. State-owned businesses called *Jasa Tirta I* and *II* manage river water to supply drinking water, agriculture, and industrial water demands. *Perum Jasa Tirta I* and *II* monitor the rivers' water discharge and water quality of the rivers in their working area. As stated in Government Regulation No. 46/2010 concerning *Perusahaan Umum (Perum) Jasa Tirta I, Bengawan Solo and Brantas Watersheds* are under the management of *Jasa Tirta I* and *Citarum Watershed* is managed by *Perum Jasa Tirta II*. Besides MONEV of water quantity and quality, *Perum Jasa Tirta I* and *II* are assigned to disseminate the results of the MONEV to users, communities, and stakeholders as mentioned in Government Regulation No. 25/2022. *Siak Watershed* is outside the working area of *Jasa Tirta I* and *II*; the authority to prepare management plans, MONEV, is handled by the Government of Riau Province.

In addition to those institutions, some NGOs manage river water quality. An NGO concerned with preserving the *Bengawan Solo River* is the *Pusur Institute*. This NGO has activities such as eco-friendly farming, waste banks, research and awareness, and conservation in the upper watershed. Activities in the *Pusur Institute* are also supported by other institutions, i.e., the *Rural Technology Development Institute (LPTP)*, *NGO Gita Pertiwi*, *NGO Lestari*, *NGO Shind*, *NGO SSK*, business entities, and local government [76].

For *Brantas River*, the *University of Technology Delft*, *Makara*, *Tauw*, and the Indonesian environmental group *ECOTON* initiated research called "*Aksi Brantas*". The community's capacity to care more about the health of the *Brantas River* was successfully increased through this activity [77].

Existing Policy, Regulations, and the Implementation

The Government has issued several laws related to water pollution, i.e., (1) Law No. 32/2009 on Protection and Management of the Environment, (2) Law No. 17/2019 on Water Resources, and (3) Law No. 11/2020 on Job Creation. The Law No. 11/2020 was canceled by Constitutional Court (MK) and replaced by the MK through Government Regulations in Lieu of Legislation (PERPU) No. 2/2022, which is valid starting on 30 December 2022. Finally, PERPU No.11/2020 was established as a law on 31 March 2023.

Law No. 11/ 2020 amends several articles in Law No. 32/ 2009 and Law No. 17/2019 to improve the Investment & Business Activity Ecosystem. Law No. 11/2020 states that the entire process of Approval or Licensing Undertakings for the use of Water Resources will be carried out regarding Standard Procedures and Criteria Norms (NSPK) determined by the Central Government to provide Licensing facilities. Many parties suspect this regulation is an effort to centralize permits contrary to regional autonomy.

Regarding the environment, several articles in Law No. 32/2009 have been amended through Law No. 11/2020. Its derivative is Government Regulation No. 22/2021 on implementing Environmental Protection and Management. After the ratification of Government Regulation No. 22/2021, there has been a change in the provisions regarding the Environmental Impact Analysis (AMDAL), mainly related to public participation in preparing the AMDAL. The AMDAL Assessment Commission (KPA), which was previously a forum for the community to participate actively, was disbanded and replaced with the Environmental Feasibility Test Team (TUKLH), which only consisted of the Central Government, Regional governments, and certified experts selected by the Government as stated in Paragraph 3 on Environmental Approval, Article 24 of Law No. 11/2020 and PERPU No. 2/2022. Government Regulation No. 22/2021 also stipulates a change in the terminology related to wastewater disposal from all permits to an agreement that facilitates the flow of permits and is considered prone to permit abuse in some circles.

Unlike Law No. 17/2019, which directly states water quality management and water pollution control, Law No. 11/2020 and the PERPU No. 2/2022 indirectly state the water pollution by: "Determination of environmental pollution is measured through environmental quality standards," thus the statement goes back to Law No. 32/2009. These two laws, Law No. 11/2020 and PERPU No. 2/2022, do not state river water pollution explicitly.

At the ministry level, the Minister of Environment Regulation No. 5/2014 on Wastewater Quality Standards regulates the quality standards of wastewater [78] from various activities, including hotels, hospitals, business, and domestic activities, gold mining, slaughterhouses, fruit and or vegetable processing, fishery processing, meat processing, soybeans processing, processing of traditional medicine/herbs, textile industry, and cigarette

industry. This Ministerial Regulation has undergone two changes through the Minister of Environment and Forestry Regulation No. P.21/MENLHK/SETJEN/KUM.1/7/2018 and the Minister of Environment and Forestry Regulation No. P.16/MENLHK/SETJEN/KUM.1/4/2019. In addition, the Minister of Environment and Forestry also issued Ministerial Regulation No. P.68/Menlhk/Setjen/Kum.1/8/2016 on Domestic Wastewater Quality Standards [79], which regulates wastewater management from businesses that produce domestic wastewater. In this case, the Central Government and Regional Governments must provide and manage facilities and infrastructure for treating domestic wastewater from the household scale.

The implementation of mitigation on the polluted river has been conducted through numerous efforts. The national program, i.e., PROKASIH or Clean River Program was established by the Minister of Environment through Ministry Regulation No. 35/1995. This program aims to increase river water quality and preserve its function. This program has been applied in most regions in Indonesia, especially the regions passed by polluted rivers, including the four case-studied rivers. Another effort conducted by the government was constructing the installation of wastewater treatment (IPAL). In addition, at a research scale, various treatments have been employed to mitigate pollutants, and even using IoT technology for monitoring water quality, such as in Siak River [80]. In Surakarta City, where the Bengawan Solo River flows through, the activities include controlling water pollutants, domestic wastewater treatments, PROKASIH, and Community-Based Sanitation (SANIMAS). The Ministry of Environment and Forestry has installed an Online Monitoring System (OMLINO) in 213 stations to monitor real-time river water quality.

Various programs were conducted to restore the Citarum Watershed and to solve acute pollution of the river water. The Government has established a Citarum Harum Program through Presidential Decree No. 15/2018. Under coordination of the Ministry for Maritime and Fisheries Affairs, numerous parties carry out their respective roles. These integrative teams are the central, provincial, district/city governments, the responsible ministries, the Siliwangi Regional Military Command III (Kodam III), and the West Java Regional Police [81]. The direction of the policy is to prevent watershed pollution and/or watershed damage, to manage watershed pollution and/or watershed damage, and to recover watershed function. Various programs have been established by Task Force for Pollution Control and Damage on Citarum Watershed (Satgas PPK) including management of degraded land; handling of industrial and livestock waste, domestic wastewater, waste management, management of floating net cage; control of the Citarum Watershed spatial utilization; law enforcement; water quality monitoring; management of water resources and tourism; education and community empowerment; data information, and public relations [82]. The Citarum Harum Program is planned to end in 2025, numerous programs have been realized and significant improvement in river water

quality has been achieved [83], although some aspects need improvement and should be conducted continuously. The Citarum Harum program may also be applied to other degraded watersheds.

In addition to technical aspects, various rules and policies regulate community involvement in efforts to control and mitigate water pollution. Community involvement is stated in Law No. 17/2019 and still in the later laws with different versions. Article 63 of Law No. 17/2019 states that community participation in water resources management is carried out through public consultations, deliberations, partnerships, conveying aspirations, and supervision. In the current regulation, Government Regulation No. 22/2021, community participation in environmental assessment is also conducted through public consultation. Based on these regulations, the community has not been encouraged to be self-reliant. In fact, for the sustainability of a program, the communities must be empowered and encouraged to be self-reliant [84].

Law No. 11/2020 and PERPU No. 2/2022 state community involvement concerning the Village Government. In this regard, the Village Government follows the norms, standards, procedures, and criteria determined by the Central Government and has the task of (1) assisting the Central Government or the Local Government in Managing Water Resources in the village area based on the principle of benefit public and concerning interests another village, and (2) encouraging community initiative and participation in water resources management in its territory.

The rights and obligations of everyone in managing water quality and controlling water pollution are regulated in Government Regulation No. 22/2021. Articles 157, 158, and 159 of this regulation determine the rights, obligations, and prohibitions of every person on managing water resources and water quality. Part 7th, on Community Participation, Article 160 on the community participation in protecting and managing water quality states that the communities (1) monitor water bodies independently in their environment; (2) make efforts to reduce water pollutants in their respective environment; (3) convey the correct and accurate monitoring result information; (4) disseminate the water pollutant reduction; (5) establish partnerships with the parties in the framework of water pollutant reduction; (6) undertake an eco-riparian program for the recovery ecosystem of water bodies; and (7) establish partnerships with the parties in the removal of water pollutants. In partnership with business entities, the Central Government and Local Government in accordance with authority can facilitate the formation of partnerships between the community and the business entities in reducing water pollution, as stated in Article 161.

Generally, the rules regarding these obligations can be implemented in the field. However, sometimes there is ambiguity about who is responsible for mitigation [85]. It is not easy, then, to determine which party should be responsible, especially if the source of the pollutant comes from a non-point source such as from agricultural activities.

Thus, in community involvement planning for water pollution control, an important strategic step is to map the sources of pollution and identify the main stakeholders involved. It is related to the interest of law enforcement.

Recommendations for Better Mitigation of River Water Pollution

As discussed previously, the Government of Indonesia has made numerous efforts, both at the level of regulations, policies, and their implementation in the field, but most rivers are still polluted. In addition to the efforts that have been applied, we propose several actions to mitigate river water pollution. The proposed recommendations are not only applicable to the case-studied rivers, but these can also be applied globally outside Indonesia, especially to developing countries. The proposed methods include developing riparian zones, community involvement in water quality management that can be carried out through environmental education, community-based monitoring/voluntary monitoring, and the use of IoT technology.

Developing the Riparian Zone to Prevent and Mitigate River Water Pollution

Water pollution is a significant problem that can have a range of harmful impacts on both humans and the environment. Contaminants such as bacteria, viruses, parasites, and chemicals in polluted water can enter the body through drinking water, swimming, and other activities. In addition, ingesting contaminated fish or shellfish can lead to poisoning by toxic chemicals like mercury or polychlorinated biphenyls (PCBs) [86]. Recently, river water quality improvement has been based on ecological restoration by developing the riparian zone. A riparian buffer is a natural method widely applied to mitigate pollution and improve river health [87]. The riparian wetland is a relatively cost-effective method for (1) treating wastewater resulting from municipal or domestic sewage, industrial processes, and wastewater from over-use of fertilizers and pesticides in agricultural areas, landfill leachate, and filter litter and eroded soil carried by streams during stormwater [88], (2) reducing surface flow velocity or flood control, thus, more opportunities for water infiltration, and (3) maintaining biodiversity [89]. Woody vegetation in the riparian zone interacts with lakes, rivers, and tributaries, strongly affects water quality and protects the entire ecosystem in the watersheds [90]. It also has an essential role in controlling atmospheric moisture content [91].

The riparian zone is an essential ecological transition from rural to urban environment and from river water to terrestrial ecosystem. This ecological zone provides a beneficial relationship between the urban people and the environment that cannot be replaced by structural technologies, and it has various functions in terms of environmental services, social, economic [92], and cultural aspects [93].

Through citizen science projects, the riparian zone can be used as an eco-tourism area and field laboratory of environmental education for students and communities. In addition, the riparian with its vegetation has essential ethical and heritage values [94]. The success of ecological restoration of the riparian zone should consider the socio-ecological context [95] due to the interlink between ecological degradation and human intervention [96]. Besides involving the local communities, improving communication among various parties is crucial to achieving the goal of the restoration [97]. In addition, integrating science and traditional knowledge owned by the local communities is important to realize riparian ecological restoration [98]. In summary, developing a riparian zone can cover mitigation actions of the polluted river for large areas, and all at once has essential ecological, socio-economic, educational, and cultural functions.

Community Involvement in Mitigating Water Pollution

Water pollution can disproportionately impact communities already vulnerable due to poverty, such as rural or slum areas. These communities may have minimal access to safe water [99] and suffer the most from the health and economic impacts of pollution. Children and pregnant women are especially susceptible to the negative impacts of water pollution [2]. Community involvement in mitigating water pollution is generally approached with two activities: environmental education and the establishment of community-based water quality monitoring.

Environmental Education

There is an important role that researchers and academics can play in the development of community-based research and the development of citizen science [4]. Community-based research (CBR) is a collaboration between researchers, academics, and community members who conduct research together to solve urgent community problems or carry out social change arising from the community [100]. Community-based research has significant implications for environmental preservation [101].

Problems from the social aspect are important to be explored as capital for the improvement of river water quality and prevention of its degradation. Some of these problems include (1) Settlements and businesses on the riverbanks; low public awareness to comply with the ban on dumping solid waste and liquid waste into rivers; Micro, Small, and Medium Enterprises (MSMEs) that dispose of liquid waste without going through the Wastewater Management Installation (WWTP) [102]; (2) Inadequate of community involvement in river management on the pretext of the low social and economic status of the people around the river [103]; (3) Weak environmental supervision and law enforcement against industrial waste

[10]; and (4) Water quality monitoring has not been carried out continuously due to limited funds and a lack of human resources in this field [10].

Considering these problems, community participation is one of the keys to its success. Yet, efforts to involve the community in monitoring and mitigating river water pollution still place the community as an object [10]. To foster the community's willingness to participate in preventing river water pollution, the community needs to increase its awareness and be placed as a subject, meaning that the community is positioned as a decision-maker [84]. It is important to involve the community from the planning stage so that the activity matches the community's needs [104]. The government can also use the observed data to formulate river pollution control and mitigation. This activity is a form of community participation in providing data for scientific studies (citizen science). Learning from the existing experience, if the community is the decision maker, their participation will also be high at the implementation stage. It is because the activities are carried out according to their needs, and there is a sense of belonging [84]. Thus, environmental education is the basis for the success in mitigating of river water pollution.

Community-Based Monitoring/ Voluntary Monitoring

Community-based monitoring (CBM) is a process in which concerned citizens, government agencies, industry, academia, community groups, and local agencies work together to monitor, track, and address issues of public concern [105]. The CBM provides opportunities for the community to collect data and use the resulting information through a structured and systematic decision-making process that ultimately promotes sustainability in the community and at a broader level [4].

Governments can gain from CBMs by increasing their monitoring capacity, cutting expenses, encouraging community involvement in achieving government objectives, and offering an early warning system for ecological change [106]. In their research, Ruppen et al. [107] concluded that CBM is a potential method for obtaining high-quality data if appropriate protocols are applied. Monitoring programs considerably improve the collection and understanding of data on water quality in which government entities and industrial participants do not enforce environmental regulations. The results of other studies explain that the difference between formal monitoring and CBM is more toward changing perceptions. However, cost-wisely, CBM is not always cheaper than government data collection [108].

Utilizing the Internet of Things (IoT) for Monitoring River Water Quality

In developing countries, including Indonesia, River Water Quality Monitoring (RWQM) has undergone an evolution in the context of data collection and data analysis techniques. Initially, RWQM was carried out traditionally

based on the results of laboratory analysis [109]. Further, the water quality measurements are developed using sensors placed in the river and locally stored data, which should be downloaded for further analysis [110]. Along with the growing data needs and technology, RWQM has also been developed into Wireless Sensors Network (WSN)-based monitoring. This technology allows data from sensors to be transferred to the main storage remotely for further analysis [111]. Recently, RWQM has begun to use IoT technology which integrates the use of sensors in the river, cloud/digital computing techniques, communication networks, and internet networks [112].

The advantages of applying IoT for RWQM include real-time accessible information on water quality, and low cost since this technology utilizes the available communication infrastructure [113]. The IoT technology increases spatial resolution in transferring information due to the utilization of the internet as the basis for data transmission, with low computational cost and energy requirements, and it can also be integrated with analytical tools to predict future water quality [109]. It makes data collection, analysis, and communication easier by providing an early warning system [114]. In addition, the responsible parties are more efficient and effective in handling the water pollution problem; thus, the negative impact can be minimized [115].

Although IoT technology has many advantages, some aspects should be considered. The use of IoT in RWQM requires various considerations in terms of substance and supporting instruments, such as the selection of parameters, sensors, controller instruments, communication networks, and security aspects of the system being built. Regarding the sensors used in RWQM, the important consideration is the choice of suitable sensors that significantly influence overall system efficiency. Range, reaction time, resolution, sensitivity, and dependability are essential for sensor selection. The use of low-cost sensors with relatively high durability could be considered as well to anticipate the system application on a wider scale [116].

Another consideration is the selection of devices/controllers that communicate with sensors in receiving, recognizing, analyzing, displaying, and sending data to the main device or server (cloud computer). Suppose the task was given to the controllers relatively easily and the most analysis to be done on the server. Commercial IoT cards/controller, such as Arduino Uno, is the best choice. Such cards are inexpensive, power-efficient, lightweight, and readily available. Commercial cards or microcomputers such as Raspberry PI could be a better alternative when a sophisticated analysis conducted locally is needed. The availability of networks is also essential for communication between the controller and server. A GSM/GPRS network should be considered if there is no nearby Wi-Fi network. When the GSM/GPRS module is too expensive or the transmission range is limited, the LoRaWAN technology is the best choice [117].

For security reasons, the use of IoT gateways is

recommended as well. The choice of IoT server is also important and related to the network security and the cost of the RWQM system operation. The server is used for data storage, conducting specific analyses, generating results or early warning, and controlling the whole RWQM system. Many public cloud servers exist with various schemes depending on the capacity and cloud computer specifications. Due to the RWQM system involving a third party [109], customizing the cloud server to minimize the system obstacle and risks is recommended.

Thus, community involvement and the use of recent technologies like IoT are two things that cannot be separated in mitigating river water pollution.

Law Enforcement

From a law enforcement standpoint, one of the obstacles to deterring environmental polluters is that sanctions for environmental pollution due to waste are usually only imposed administratively. As stipulated in Law No. 11/2020 and PERPU No. 2/2022, imprisonment is only imposed if a person or company does not have a business license or approval from the government which causes victims or losses to health, safety, and/or the environment. Civil sanctions can only be imposed if there is a party who sues and there is evidence of violations committed. Administrative sanctions are imposed on a person or company with a business license or approval from the central or regional government but commits negligence, which results in exceeding the quality standards of ambient air, water, and seawater, or environmental damage standard criteria that do not comply with the business license.

In Government Regulation No. 22/2021, the sanctions to the person or company are unclear. It is only stated that criminal law enforcement is the last effort after administrative sanctions are deemed ineffective against business actors who dispose of liquid waste into rivers [118]. The mitigation of river water pollution must be supported by the availability of necessary regulations for law enforcement against offenders, mutual support between institutions, and supervision of polluters by relevant agencies. Imposing sanctions on the actor who destroys the environment, in this case river water pollution, is important to provide a deterrent effect to the actor and the community so that violations do not reoccur in the future.

Conclusions

Data for 2018 shows that there is no water in the main rivers in 34 provinces in Indonesia that meet the quality criteria, and most of it is in the highly polluted category. Of the 4 rivers that we examine in this paper, only the Siak River is at moderate to severe levels in 2018 and 2020; after the previous years were classified as heavily polluted. Meanwhile, the Citarum, Bengawan Solo, and

Brantas Rivers were classified as heavily polluted from 2015 to 2020. Water pollution in these areas causes economic loss in the tourism sector, fisheries, housing, irrigation, and drinking water. Pollution of water sources has resulted in various cases of health problems in various regions. The Government of Indonesia has tried numerous efforts, both at the level of regulations, policies, and their implementation in the field, but most rivers still experience pollution. In this regard, to increase the success of efforts to prevent, control, and mitigate pollution impacts, we recommend four approaches, i.e. (1) development of riparian zones to prevent and mitigate pollution into waters, (2) community involvement through environmental education and development of water quality monitoring, (3) utilization of IoT in monitoring environmental pollution, and (4) law enforcement. These four approaches must be carried out in an integrated and simultaneous manner at various operational levels.

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Conflict of Interest

The authors declare no conflict of interest

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