Pertanika J. Sci. & Technol. 33 (1): 507 - 523 (2025)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Review Article

Integration of Total Maximum Daily Load (TMDL) and Environmental Flow Assessment (EFA) Concepts as an Adaptive Approach to Pollutant Loading Management in Asia: A Review

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ABSTRACT

Water scarcity and pollution are escalating challenges in Asia, impacting ecological systems and human livelihoods. This paper reviews the integration of Total Maximum Daily Load (TMDL) and Environmental Flow Assessment (EFA) in water management to address the dual issues of water quality and quantity. TMDL focuses on regulating the number of pollutants entering water bodies to meet quality standards, while EFA ensures that enough water is available to support aquatic ecosystems. Their independent application, however, often leads to gaps—TMDL can overlook ecological needs, while EFA may neglect pollution control. The integration of these two frameworks offers a more holistic solution, especially in water-stressed regions like Southeast Asia, where moderate water availability is exacerbated by urbanization, industrialization, and agricultural runoff. Case studies from Malaysia, Indonesia, and China reveal the limitations of applying TMDL and EFA separately and underscore the necessity of addressing both ecological flow requirements and pollution limits. This paper identifies key pollutants such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), heavy metals, and total suspended solids (TSS), particularly in urban and semi-urban areas, and highlights the importance of tailoring strategies to the specific needs of different regions. By combining TMDL and EFA, policymakers can better manage pollutant loads, secure ecological

ARTICLE INFO

Article history:
Received: 08 May 2024
Accepted: 04 November 2024
Published: 27 January 2025

DOI: https://doi.org/10.47836/pjst.33.1.23

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ISSN: 0128-7680
e-ISSN: 2231-8526

health, and address Asia's pressing water management issues. This review emphasizes the need for adaptable, integrated water management strategies that account for seasonal fluctuations, competing water demands, and regional water availability and pollution differences.

Keywords: Environmental Flow Assessment (EFA), modeling, pollutant load, Total Maximum Daily Load (TMDL), water quality

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INTRODUCTION

Economic development often takes priority over environmental protection, particularly in regions like Southeast Asia, where water resources are limited. Competition between industries, agriculture, and domestic users complicates pollution control. For instance, reducing water abstraction during high pollution periods is resisted due to economic costs, even though it would help maintain river flow for pollutant dilution (Monfared. et al., 2017). Weak infrastructure, poor regulatory enforcement, and fragmented governance further hinder effective water resource management (Lee et al., 2012).

The integration of Total Maximum Daily Load (TMDL) and Environmental Flow Assessment (EFA) is crucial for comprehensive water resource management, particularly in addressing the interconnected issues of water quality and quantity. TMDL is a regulatory tool that sets limits on the number of pollutants discharged into water bodies to meet water quality standards, primarily targeting human use, such as drinking water and agriculture (Kwon et al., 2023; US Environmental Protection Agency, 2007). It controls both the concentration of pollutants and the volume of discharge, often relying on reservoirs or dams to dilute pollutants while balancing competing water demands (Bello et al., 2024; Setiawan et al., 2018). In certain cases, high pollution levels necessitate the reduction of water abstraction by economic sectors like agriculture and domestic water supply to preserve sufficient river flow for pollutant dilution. However, this may incur significant costs (Monfared et al., 2017). Conversely, EFA ensures that rivers maintain sufficient flow to support ecological health, protecting aquatic species and ecosystem services, but it does not directly address pollutant load reduction (International River Foundation, 2007; King et al., 2019).

In Asia, TMDL and EFA are applied to address growing water management challenges, including pollution and water scarcity. However, the independent application of these frameworks reveals distinct advantages and limitations. TMDL effectively reduces pollutant loads but often overlooks ecological water needs, potentially leading to ecosystem degradation despite improved water quality (Lee et al., 2012). On the other hand, EFA guarantees ecological flow but may leave rivers vulnerable to pollution, as it does not directly tackle contaminant reduction (Liu et al., 2021). These gaps underscore the need for integration, particularly in regions like Southeast Asia, where moderate water availability is compounded by significant pollution (Sedighkia & Abdoli, 2024).

The integration of TMDL and EFA offers a holistic approach, addressing water quality and quantity needs. Both frameworks share common goals, such as regulating water discharge and maintaining flow, albeit for different purposes—TMDL for human and economic needs and EFA for ecological health. Integration ensures that pollutant load limits are set while maintaining environmental flows, balancing socio-economic demands with ecological sustainability (Godinho et al., 2014; Hall et al., 2014). This approach can solve critical issues like reconciling industrial, agricultural, and domestic water demands with the ecological needs of river systems. By combining the strengths of both frameworks, policymakers can ensure the sustainable management of water resources, particularly in water-stressed regions like Asia, where these challenges are becoming increasingly pressing (Theodoropoulos et al., 2018).

WATER QUALITY AND SCARCITY PROBLEMS IN ASIA

Water resource management in Asia faces diverse challenges, with specific regions suffering from water scarcity and pollution. In Central Asia's Aral Sea basin and northern China, severe water scarcity makes pollution control secondary, limiting the applicability of frameworks like TMDL and EFA, which focus on water quality and ecological flows (Satoh et al., 2017). In contrast, Southeast Asia has moderate water availability but struggles with industrial and urban pollution, making the integration of TMDL and EFA highly relevant (Dewata & Adri, 2018; Tang et al., 2020).

This paper focuses on managing pollutants in urban and semi-urban areas in Asia. Industrial, domestic, and agricultural activities significantly degrade water quality in these regions. Pollutants like biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and heavy metals are prevalent due to untreated wastewater and industrial discharges (Dewata & Adri, 2018; Tang et al., 2020). For instance, inadequate sewage treatment in Malaysia has led to high levels of BOD, ammoniacal nitrogen (NH_4-N), and suspended solids in rivers (DOE, 2020). Similarly, Indonesia's Cirarab River receives 80% of untreated wastewater from residential and industrial sources (Indriyani et al., 2020).

Heavy metals, ammonia, BOD, and COD are primary pollutants in Asian rivers. Rivers like the Yamuna in India and the Ganh Hao in Vietnam contain heavy metals exceeding safe limits for drinking water (Akhter et al., 2023; Muoi et al., 2022). Urbanization and industrialization intensify these challenges by increasing water demand and pollution loads (Outlook & Management, 2012). For example, in Indonesia, the TMDL for the Batang Kuranji River was used to estimate pollutant loads of BOD, COD, and TSS, setting targets to meet water quality standards for drinking purposes (Dewata & Adri, 2018).

In the Jiulong River watershed in China, effective non-point source nitrogen reduction strategies have been implemented to improve water quality for drinking and irrigation, focusing on management, mapping, and quantifying these sources (Yan et al., 2018). The increasing industrial and population development in Beijing has worsened pollution in the Beiyun River, where pollution limits are regularly exceeded due to rising sewage discharge (Zhang et al., 2015).

GAPS IN INDEPENDENT TMDL AND EFA APPLICATION

While TMDL originated in the US, many Asian countries have adopted similar frameworks with different terms. Indonesia uses PCC, while Vietnam applies RWEC (Bui & Pham, 2023; Setiawan et al., 2018). In China, RWEC is part of a broader Water Resources Carrying Capacity (WRCC) approach, integrating hydrology, ecology, and economics to assess a river's ability to support human activities and environmental health (Dou et al., 2015). These frameworks ensure that water quality targets are set based on pollutant sources and river conditions. However, these frameworks primarily focus on limiting pollutants without addressing the necessary ecological flows for ecosystem health. In Beijing's Beiyun River, China, while an integrated environmental decision support system (EDSS) for water pollution control is in progress, the water environment problems are complex. More data are needed to verify model calculations under different hydrological flow and pollution conditions and verify water quality simulations(Zhang et al., 2015).

In Korea, the TMDL system has been in place since 2004, with a focus on reducing BOD levels for rivers under low-flow conditions. The Ministry of Environment requires local governments to develop TMDLs for major rivers, and the National Institute of Environmental Research provides guidelines for this process (Kang et al., 2006; Lee et al., 2012). However, the allocation of target water quality somewhat unfairly has faced strong opposition from local governments, which has seriously threatened a plan to add more parameters to be covered in TMDL. On the other hand, efforts in India to maintain environmental flows are progressing but do not fully address pollution issues, as seen in India's Yamuna River, where untreated industrial discharges persist (Asim & Rao, 2021; Godinho et al., 2014).

EFA is progressively accepted in Malaysia within the Integrated River Basin Management (IRBM) framework, focusing on sustainable river management to preserve biodiversity and guide water resource management decisions, as highlighted by Abdullah (2017). The initiative involves various departments and institutes (Ariff et al., 2023), aiming to identify measures for reducing pollutants. However, implementing IRBM frameworks faces challenges as there are many overlapping laws and multiple agencies with fragmented responsibilities. Adopting loading-based standards, such as TMDL, remains a distant goal. Alternatively, the Water Quality Index (WQI) (Table 1), a concentration-based approach, is currently utilized to assess and monitor water quality (DOE, 2020). While it is useful for resource management, this approach is limited in effectively regulating industrial discharges, as it does not account for cumulative pollutant loads, potentially leading to less stringent control over pollution sources. The selected applications of TMDLs across Asia are presented in Table 2.

Table 1
Malaysian Water Quality Index (WQI) Classification (Department of Environment Malaysia, 2020)

PARAMETER	**UNIT**	**CLASS**				
		I	II	III	IV	V
PH	–	> 7	6–7	5–6	< 5	> 5
DISSOLVED OXYGEN (DO)	mg/L	> 7	5–7	3–5	1–3	< 1
BIOCHEMICAL OXYGEN DEMAND (BOD)	mg/L	< 1	1–3	3–6	6–12	> 12
CHEMICAL OXYGEN DEMAND (COD)	mg/L	< 10	10–25	25–50	50–100	> 100
SUSPENDED SOLIDS (SS)	mg/L	< 25	25–50	50–150	150–300	> 300
AMMONIACAL NITROGEN (AN)	mg/L	< 0.1	0.1–0.3	0.3–0.9	0.9–2.7	> 2.7
WATER QUALITY INDEX (WQI)	–	< 92.7	76.5–92.7	51.9–76.5	31.0–51.9	> 31.0

Table 2
TMDLs application in Asia

NO.	**LOCATION**	**METHOD**	**REFERENCES**
1	Yamuna River, Delhi, India	The QUAL2K assessment of organic matter breakdown in terms of BOD, DO, nitrification-denitrification, and phosphate reduction in the composite river water body.	Mangottiri et al., 2011
2	Hongqi River	The QUAL2K model was calibrated by adjusting the input pollution loads through trial and error until the water quality simulation results met the desired objectives	Zhang, 2012
3	Qiantang River Watershed, China	The conventional one-dimensional point discharge model and QUAL2K model were used to examine the BOD assimilative capacity to ensure the sustainable use of water resources.	Fang et al., 2014
4	Karun River Basin, Iran	QUAL2K was the water quality modeling framework employed. BOD and dissolved oxygen were the input parameters used in QUAL2K.	Marzouni et al., 2014
5	Beiyun River, China	Environmental Decision Support Systems (EDSS) development includes hydrological and pollutant load, hydrodynamic, water quality, environmental capacity, and load distribution model.	Zhang et al., 2015
6	Malacca River, Malaysia	TMDL is carried out by conducting water quality monitoring, developing a water quality model using Environmental Fluid Dynamic Codes (EFDC), and implementing a TMDL implementation plan.	Osmi et al., 2016
7	Lake Chini, Malaysia	TMDL was determined by bedload and suspended load sampling in both the dry and rainy months.	Dom et al., 2016

Table 2 *(continue)*

NO.	LOCATION	METHOD	REFERENCES
8	Galing River, Kuantan, Pahang, Malaysia	A numerical model was created using the Environmental Fluid Dynamic Code (EFDC) to determine the optimal action for enhancing the water quality.	Lee et al., 2017
9	Luliao Reservoir Watershed, Taiwan	The EPA's SWMM identifies pollution hotspots and calculates total phosphorus loads. At the same time, the Vollenweider model evaluates water quality in reservoirs under different pollution scenarios, informing TMDL calculations based on target water quality concentrations.	Chen et al., 2016
10	Langat River, Malaysia	Using the application of QUAL2K, the water quality of Sungai Langat is assessed based on the low-flow dry period Q1007.	Abidin et al., 2018
11	Selangor River, Malaysia	The QUAL2K simulation model was used to determine river water quality using the Water Quality Index (WQI). The water quality variables DO, BOD, and NH_3-N were used for modeling.	Chowdhury et al., 2018
12	Dengsha River, China	The export coefficient approach was combined with the QUAL2K water quality model to calculate the loads of NH4-N and total phosphorus from various sources and investigate their individual contributions.	Xin et al., 2019
13	Yeongsan River basin, Korea	A fuzzy model for managing water quality was created to address the satisfaction level related to the cost of reducing pollution and improving river water quality.	Cho & Lee, 2020
14	Skudai River, Malaysia	This study utilized an integrated QUAL2K-GIS application to reduce NH3-N pollution discharge to improve Skudai River's water quality for use as a source of water supply.	Kamal et al., 2020
15	Belik River, Yogyakarta	BOD load reduction using the Water Quality Analysis Simulation Program (WASP) modeling.	Tofani & Hadi, 2020
16	Johor River Basin, Malaysia	The variations in the water quality metrics between base and storm flow events were studied to pinpoint the pollutant sources.	Mohamad et al., 2020
17	Duliujian River, Tianjin, China	Water quality standards are established based on the TMDL and the water's capacity in accordance with the water body's needs.	Liu et al., 2020
18	Tungabhadra River, India	To forecast the water quality in the contaminated areas of the river, use the QUAL2KW water quality model.	Ranjith et al., 2020
19	Tebrau River, Johor	This study used QUAL2K, the modernized version of QUAL2E, to simulate the impact of pollution from industrial areas on the Tebrau River Basin.	Kamal et al., 2020
20	Daejeon City	The study used two methods: the Load Conversion Method (LCM) adjusts discharge loads for rainfall changes, while the Multi-Regression Equation Method (MREM) predicts discharge loads directly.	Park et al., 2021
21	Jing-Mei Creek	The study used HEC-RAS and QUAL2K simulations to determine flow velocities and water depths for different river sections.	Fan et al., 2009

Table 2 *(continue)*

NO.	LOCATION	METHOD	REFERENCES
22	South Korea	The CA-Markov model was used to simulate changes in LULC under the influence of the special countermeasure area (SCA) and TMDL.	Song, 2021
23	Citarum River, Indonesia	To assess pollutant load allocation using the river's TMDL. The pollutant load is BOD, and the model makes use of QUAL2KW.	Djuwita et al., 2021
24	Batu Pahat River, Malaysia	The study measured six parameters: DO, BOD, COD, NH3-N, TSS, and pH. It used them as input in the QUAL2K model to simulate water quality and explore different scenarios for reducing pollutant concentrations.	Adnan et al., 2022
25	Gua Musang, Kelantan, Malaysia	The impacts of mining on water quality during different flow conditions were modeled over time. HEC-RAS and QUAL2K were used for river and stream quality modeling.	Anees et al., 2022
26	Lam Takhong River, Thailand	A one-dimensional steady-flow systems river water quality model, QUAL2KW, was built and simulated to identify the sources of influence on the river's water quality.	Tran et al., 2022
27	Kedah River, Malaysia	Analyzed secondary data to assess TMDL for five water quality parameters, incorporating Risk Quotients analysis. Flow estimation was achieved using remote sensing using Bjerklie's model.	Ariff et al., 2023
28	South Korea Watersheds	The land-based diffused pollutant unit load values are utilized in the Natural Resources Conservation Service (NRCS) technique to compute the diffuse pollutant discharge loads in the TMDL standards.	Kwon et al., 2023
29	Jeneberang River, Indonesia	A geographical methodology and a numerical water quality model are used to calculate TMDL.	Kurniawan et al., 2023
30	Hai Phong City, Vietnam	Contaminants analyzed included BOD5, NH_4, NO_3, DO, and others. The pollutant load production in the water quality model helps forecast pollution trends. This study used MIKE11, a one-dimensional hydrodynamic model.	Hoang et al., 2023

MODELLING TOOLS

Modeling serves as a vital tool in watershed management, offering insights into water system behavior and predicting the effects of management strategies (Wang et al., 2014). Water quality modeling and hydraulic-hydrological models form the basis for determining water environment capacity and calculating pollutant load reductions (Zhao et al., 2012). In recent years, water quality modeling has emerged as a scientifically robust method for understanding the relationship between pollutant reduction and water quality enhancement (Wang & Lin, 2013). It has become a valuable tool for water quality management decision-making (Figure 1).

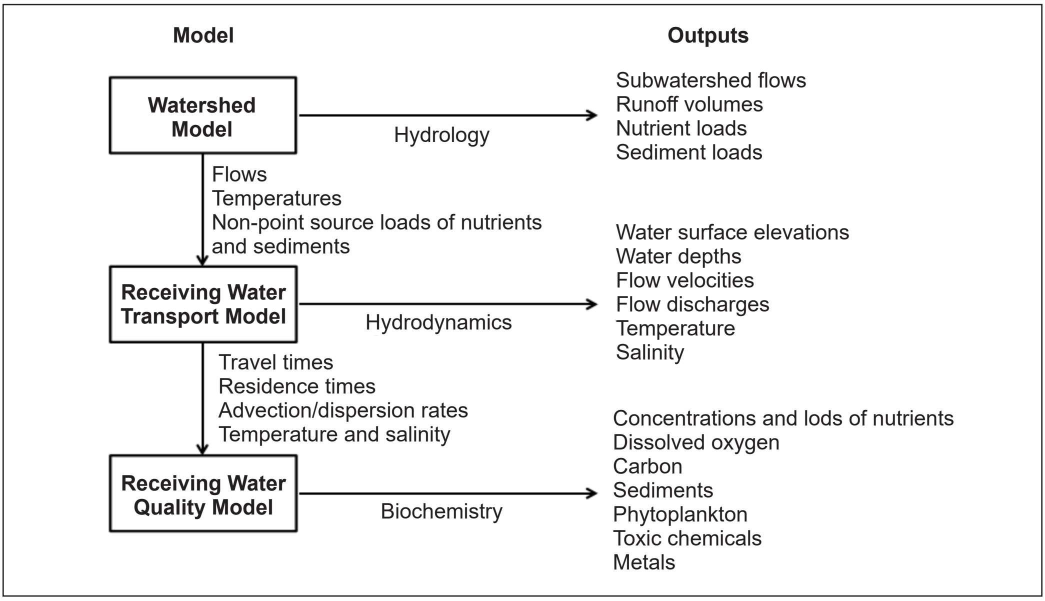

Figure 1. Linkages among watershed, transport, and water quality models (Camacho et al., 2019)

CHALLENGES AND WAYS FORWARD

Water management in a river basin is inherently complex, requiring the reconciliation of multiple, sometimes conflicting needs such as water use, flood control, and ecosystem protection. This challenge becomes more pronounced when considering the integration of Total Maximum Daily Load (TMDL) and Environmental Flow Assessment (EFA) for pollution control. This concept is crucial for addressing river and wetland pollution. However, it remains unclear worldwide, hindering risk assessment, policy formulation, and solutions (Liu et al., 2021). A crucial aspect of this integrated approach is the recognition that different stakeholders, including industries, agricultural users, domestic consumers, and environmental advocates, have diverse needs and priorities (Huang et al., 2023; Jiménez et al., 2020; Saddiqa et al., 2022). The necessity of storing flood runoff and releasing it according to the needs of different water users must be balanced against instream ecosystem needs, which can often conflict with agricultural, industrial, ecosystem needs and domestic water demands (Kennen et al., 2018; Zhang et al., 2023). For instance, opposition from local governments to target water quality allocations complicates matters (Khalid et al., 2018; Lavorel et al., 2020; Lee et al., 2012; Sim et al., 2018), making achieving water quality objectives challenging, even when there is no discharge (Chen et al., 2014).

To succeed, adjustments to target water quality allocations are necessary, considering multiple stakeholders and water resources to ensure sustainability (Novotny, 2004). Each river basin may require tailored policies, reflecting varied priorities such as surface water or groundwater usage (Wang et al., 2019). Several multi-criteria decision-making-model such as the Cobb-Douglas production function (Sun et al., 2023), can be applied to determine the most feasible solution that closely aligns with the subjectively chosen optimal values for each water target objective (Shang, 2008; Wang et al., 2024).

Moreover, the variability in hydrological conditions across seasons poses another challenge (Arthington et al., 2018; Kennen et al., 2018; Liu et al., 2005; Zhang et al., 2020). In regions like northern China, where flow rates fluctuate dramatically, relying on consistent discharge estimates for TMDL and EFA becomes problematic (Li et al., 2018; Li et al., 2010). Seasonal variations necessitate adaptive management strategies that can adjust pollutant load limits and flow requirements in response to changing environmental conditions (Firizqi & Widyastuti, 2020; Ge et al., 2018; Park et al., 2021; Todeschini et al., 2011; Wang & Lin, 2013). This adaptability is crucial for maintaining ecological integrity while meeting human water needs, particularly during low-flow periods when pollutant concentrations can rise significantly (Torrefranca et al., 2021).

Numerous laws have gaps and overlaps; many agencies and departments are also involved in dealing with fragmented sectoral functions (Saddiqa et al., 2022). There is invariably a lack of resources to enforce (Abdullah, 2017; Nurtazin et al., 2019). For instance, Malaysia and most Southeast Asian countries require shifting from concentration-based regulations to load-based pollutant limits, which would necessitate regulatory reforms and the introduction of TMDL frameworks to manage cumulative pollution loads effectively (Firizqi & Widyastuti, 2020). Furthermore, introducing legislation to protect minimum environmental flows is essential, alongside adaptive management strategies that adjust flow requirements based on seasonal and real-time water availability, securing ecosystem health while balancing human and industrial demands (Meynell et al., 2021; Zhang et al., 2020). Adopting an Integrated River Basin Management (IRBM) approach would facilitate collaboration and governance among stakeholders, ensuring that both water quality and quantity are managed holistically to meet the needs of industries, communities, and ecosystems (Burke & Do, 2021; Park et al., 2021; Syahputra et al., 2022).

Furthermore, enhancing data collection and sharing is critical for informed decision-making. Establishing geospatial databases and monitoring systems can provide valuable insights into water quality and flow dynamics, enabling more effective management strategies (Gorgoglione et al., 2020). It is particularly important in regions facing data scarcity, where unreliable information often hinders informed policymaking.

CONCLUSION

In conclusion, while integrating TMDL and EFA presents significant challenges in Asian river basin management, adopting a collaborative, data-driven, and flexible approach can pave the way for more sustainable water resource management practices. A balanced approach that supports both human needs and ecological health can be achieved by addressing the complexities of stakeholder interests, regulatory frameworks, and climate variability.

More research is needed to develop standardized methodologies and guidelines for assessing pollutant loads and environmental flow requirements, considering the unique characteristics and challenges faced by Asian rivers. Additionally, the integration of advanced modeling tools, such as water quality modeling and hydraulic-hydrological models, can enhance the accuracy and effectiveness of TMDL and EFA assessments. These models can provide valuable insights into the behavior of water systems and help predict the impacts of different management strategies. Furthermore, collaboration among countries in the region is crucial to sharing knowledge, experiences, and best practices in implementing TMDL and EFA approaches, as water resources are often shared among multiple countries. By continuously improving and refining these approaches, Asia can better manage and mitigate the impacts of water pollution, ensuring the sustainable use and protection of freshwater resources for future generations.

ACKNOWLEDGEMENT

This research is funded by the Fundamental Research Grant Scheme (FRGS) by the Ministry of High Education Malaysia through FRGS/1/2022/WAB02/02/1.

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