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RESEARCH ARTICLE

Social—environmental analysis of estuary water quality in a populous urban area

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Asia has been experiencing rapid industrialization, urbanization, and economic growth in recent decades. Taiwan was one of the 4 Asian dragons, regions that experienced rapid industrialization and exceptionally high growth rates between the early 1960s and 1990s, but at a high cost to the environment, and thus, it was heavily polluted. Estuaries are highly dynamic and diverse ecosystems that provide multiple ecosystem services that maintain marine ecosystem health and benefit humankind. However, estuaries and the ecosystem services they provide are rapidly degrading due to increasing pressures and changes, especially those in populous, urban areas. Social–environmental analysis integrates scientific information and social activities and thereby provides a comprehensive understanding for the multiparty, joint decision-making processes necessary for successful, sustainable management. In this study, 60 years of economic data and 26 years of water quality data are examined using social–environmental frameworks, the driver-pressure-state-impact-response framework, and the systems approach framework to analyze the management of water quality for an estuary in a populous urban area, the Tamsui River estuary, in Taiwan. Potential societal responses and management measures are identified that can be implemented to reduce human activities, diminish pressure, ameliorate water quality, and enhance the state of the estuarine systems in the Tamsui River and its estuary. The recommended societal responses are increased education, the establishment of community-based river rangers, wetland and mangrove conservation, the development of a circular economy, the implementation of governance measures, and improvements in monitoring and assessments. Improvement of the water quality in the Tamsui River estuary increases the hedonic value of property for people who live near the riverside. Currently, the number of tourists and tourism-based businesses have increased. Nevertheless, improvements in water quality in the Tamsui River estuary bring well-being and benefits that could be further enhanced to increase the cost/benefit relation of the management measures.

Keywords: Ecosystem services, Social–environmental framework, DPSIR, SAF, Tamsui River

1. Introduction

Estuaries are habitats providing unique ecosystem services that benefit humankind and maintain marine ecosystem health (Elliott and McLusky, 2002). However, the coastal environment, including the estuary and the ecosystem services these provide, is facing rapid degradation due to increasing pressures and likely changes in the near future (Schernewski et al., 2019). Estuaries are highly dynamic, unique, and diverse ecosystems. They are naturally stressed areas due to the great variability in the physicochemical characteristics of the water column, such as oxygen, temperature, and salinity (Elliott and Quintino, 2007). Estuaries also show high spatial heterogeneity and complexity and highly fragmented habitats in the freshwater–estuarine–coastal–open marine continuum (Dauvin and Ruellet, 2009). In addition, they are exposed to high degrees of anthropogenic influence, especially estuaries in populous urban areas. The dominant estuarine faunal and floral community adapts to naturally highly stressed areas, and it reflects features very similar to those found in anthropogenically stressed areas (Elliott and Quintino, 2007). Natural and anthropogenic stresses create a variety of conditions, making it difficult to detect human-induced stress in estuaries; this leads to the "estuarine quality paradox" (Dauvin, 2007; Dauvin and Ruellet, 2009). We may be able to restore estuarine/coastal systems by lowering human activities to decrease pressures, even though it is difficult to distinguish between natural and human-induced stress (Jones and Schmitz, 2009; Lotze et al., 2011).

Estuaries and all river-mouth systems are hot spots of vulnerability in coastal zones (Newton et al., 2012;

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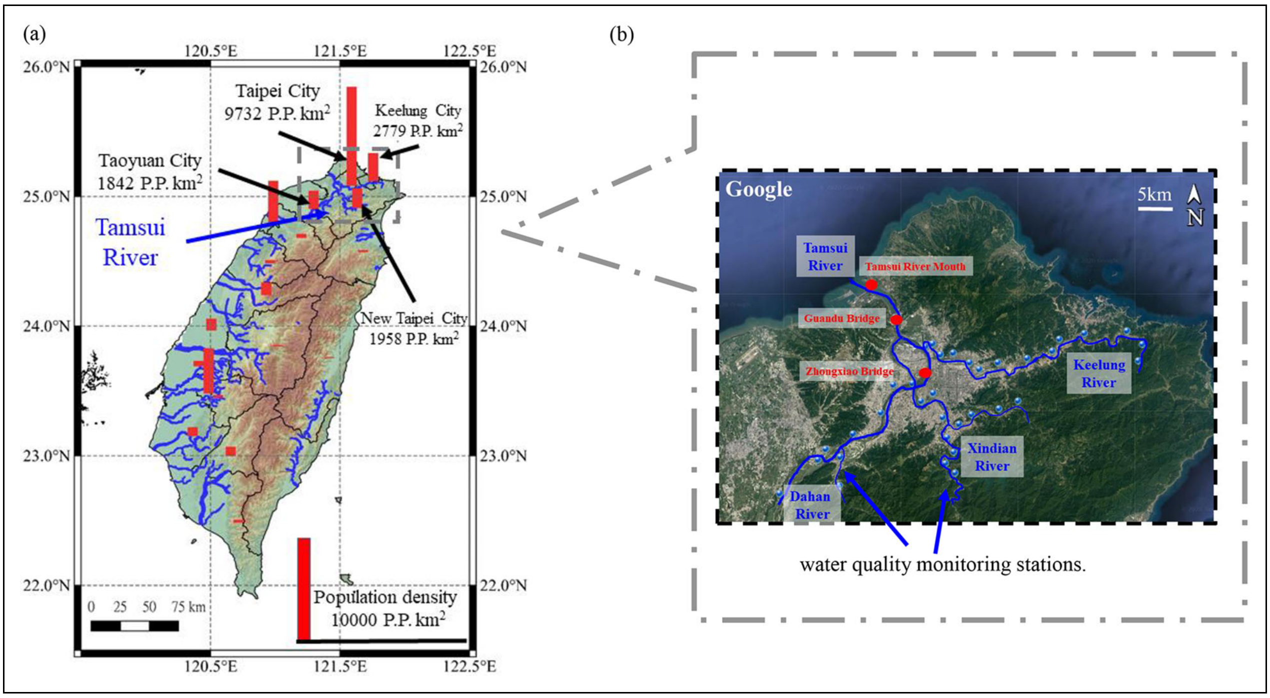


Figure 1. (a) Map of rivers and regional population density in Taiwan. (b) Map of Tamsui River tributaries and water quality monitoring stations. DOI: https://doi.org/10.1525/elementa.2020.00085.f1

Newton and Weichselgartner, 2014). The aquatic environment is a complex system formed by interactions between the ecological structure and functions, physicochemical processes, and socioeconomic systems (Elliott et al., 2017). To better understand the complexity of the system, social–environmental analysis was used to provide a holistic assessment of the causes, consequences, and responses to change. Social–environmental analysis integrates not only scientific information but also social activities, and therefore, it provides a comprehensive understanding that allows multiple parties to make joint decisions to achieve successful sustainable management (Tseng et al., 2018).

The Tamsui River is in northern Taiwan (**Figure 1a**). It has a total length of 159 km and a catchment area of 2,726 km^2. The Xindian River, Dahan River, and Keelung River (**Figure 1b**) are 3 tributaries of the Tamsui River. The main tributary is the Dahan River, and its headwaters are from Pintian Mountain, with an elevation of 3,524 m. The Tamsui River Estuary is a macrotidal estuary, and the extent of saltwater intrusion is strongly affected by the tides (Wang et al., 2004). In addition, it is surrounded by mountains; hence, no significant wind-induced currents occur within the estuary, except during storm surges (Wen et al., 2008). In this study, historical data and information are employed in social–environmental frameworks to analyze the water quality in the estuary most affected by populous urban surroundings, the Tamsui River estuary in Taiwan.

2. Methods of social—environmental analysis

Estuary water quality in a populous urban area is an environmental issue resulting from human activities. Social and environmental data, including historical data and information, were collected to understand the anthropogenic pressures on the water quality in the river and its estuary from different perspectives (social, ecological, economic, and policy). The integrated results were then analyzed by combining features of 2 social–environmental frameworks (the system approach framework [SAF] and an updated driver-pressure-state-impact-response [DPSIR] framework). The SAF (Hopkins et al., 2011; Hopkins et al., 2012; Newton, 2012; Gillgren et al., 2018; Støttrup et al., 2019) is a tool for the transition to sustainable development in coastal zone systems. An updated version of the DPSIR framework (Gari et al., 2015; Patrício et al., 2016; Elliott et al., 2017) involves economic drivers and human activities, pressures from activities, state of the environment, impact on human welfare, and the responses of society and management measures. DPSIR is widely used by international and environmental agencies, such as the United Nations Environment Programme, European Environment Agency (EEA), Food and Agriculture Organization, and Organization for Economic Cooperation and Development. By adopting those social–environmental adaptive management frameworks, we can measure the issue and clarify the key human activities and economic drivers that cause the state of environmental change. Hence, we can estimate the impact on human welfare and then provide the appropriate societal and management responses.

This study integrated both environmental data, such as dissolved oxygen (DO), biochemical oxygen demand (BOD), and ammoniacal nitrogen (NH_3-N), and societal data, such as population, population density, and wastewater treatment rate. The DPSIR analysis (**Figure 2**) addressed the following research questions:

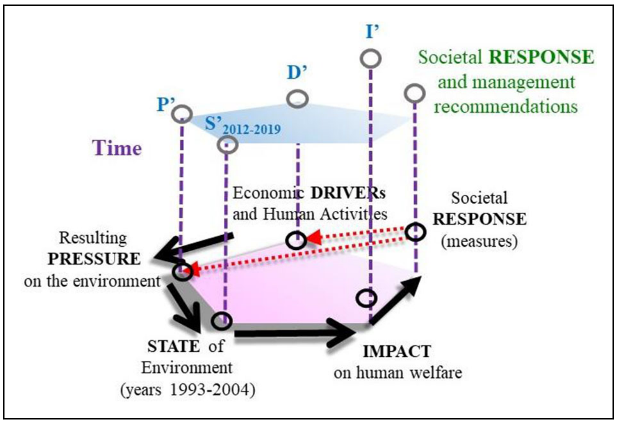


Figure 2. Driver-pressure-state-impact-response framework. DOI: https://doi.org/10.1525/elementa.2020.00085.f2

(i) What drivers and human activities worsened the water quality in the Tamsui River estuary?
(ii) How do those human activities influence (increase pressure on) the water quality?
(iii) What are the consequences for the state of water quality?
(iv) What are the impacts on human welfare?
(v) Which societal responses and management measures can improve the water quality in the Tamsui River estuary?

3. Results of the social—environmental analysis

This section presents the results of the social–environmental analysis under the following headings: issue definition, system definition, and design; drivers, economic sectors, and human activities; resulting pressure on the environment; state change of the water quality of the Tamsui River and its estuary; and impact on human welfare.

3.1. Issue definition

Coasts are at the nexus of the Anthropocene, where land, marginal seas, and atmosphere meet along a thin strip that is inhabited by nearly half the human population globally (Hopkins et al., 2011; Wolanski and Elliott, 2015). Coastal waters and estuaries suffer environmental damage from a wide range of human activities, such as changing land use in watersheds, dams, and irrigation projects (Newton et al., 2016) and environmental contamination from a wide range of industrial activities (Liu et al., 2019; Maher et al., 2020; Wang et al., 2020). Human activities have increased the discharge of organic matter from domestic waste and industry into rivers, estuaries, and coastal areas. Estuaries reflect human disturbance, and prominent impacts on the coastal environment and ecosystem have been observed (Liu et al., 2009). The ongoing increase in human activities has caused severe stress on the estuarine environment. Nevertheless, with adequate management measures and human actions, the situation could be altered and the degraded environment restored. Thus, it is possible to enjoy ecosystem services while maintaining economic development.

3.2. System definition and design

The Tamsui River is the third largest river and the most affected by populous urban surroundings in Taiwan (Hopkins et al., 2011). The Tamsui River catchment covers Taoyuan City, Keelung City, and New Taipei City and includes the capital, Taipei City (**Figure 1a**); there are 7.13 million people living in the catchment. The Tamsui River delivers materials, including suspended particles, nutrients, organic matter, and pollutants, from land before emptying into its estuary and the Taiwan Strait.

3.3. DPSIR framework

This study uses the DPSIR framework to analyze the social environment of the Tamsui River estuary (Patrício et al., 2016). Drivers, economic sectors, and human activities that may influence water quality in the Tamsui River estuary are first identified and then the pressures from human activities on the water quality in the Tamsui River estuary are analyzed. The change in the state of water quality in the Tamsui River and its estuary is characterized, and its possible impacts on human welfare are considered.

3.4. Economic drivers and human activities

The following sections analyze several anthropogenic causes that may worsen the water quality in the Tamsui River estuary, specifically (D1) land use change due to industrial transformation, (D2) urbanization and resulting increases in population density, and (D3) economic growth and resulting increases in municipal solid waste (MSW).

(D1) Land use change due to industrial transformation

The historical period of the Tamsui River catchment began in the 17th century (Chen, 2017), and this area developed quickly in the 18th century because of its role in waterway transportation, fishery, and irrigation. Toward the 19th century, severe sedimentation hindered water transportation, but farming activities thrived on the riparian land. Early in the 20th century, modern industry was first introduced into Taiwan (Liu, 2002).

According to the data from the Statistical Yearbook of Taiwan (2019), the employment structure in the Tamsui River catchment in 1998 was 1.2% in agriculture, 34.6% in the manufacturing industry, and 64.2% in the service industry, and these proportion shifted to 0.5% in agriculture, 28.5% in manufacturing, and 71% in the service industry by 2019. As the primary economic sectors shifted from agriculture and manufacturing to the service industry, land use changed accordingly. In addition, lifestyles changed as direct contact with the natural environment decreased. Modern development creates artificial supply systems to support life that detach humans from fields,

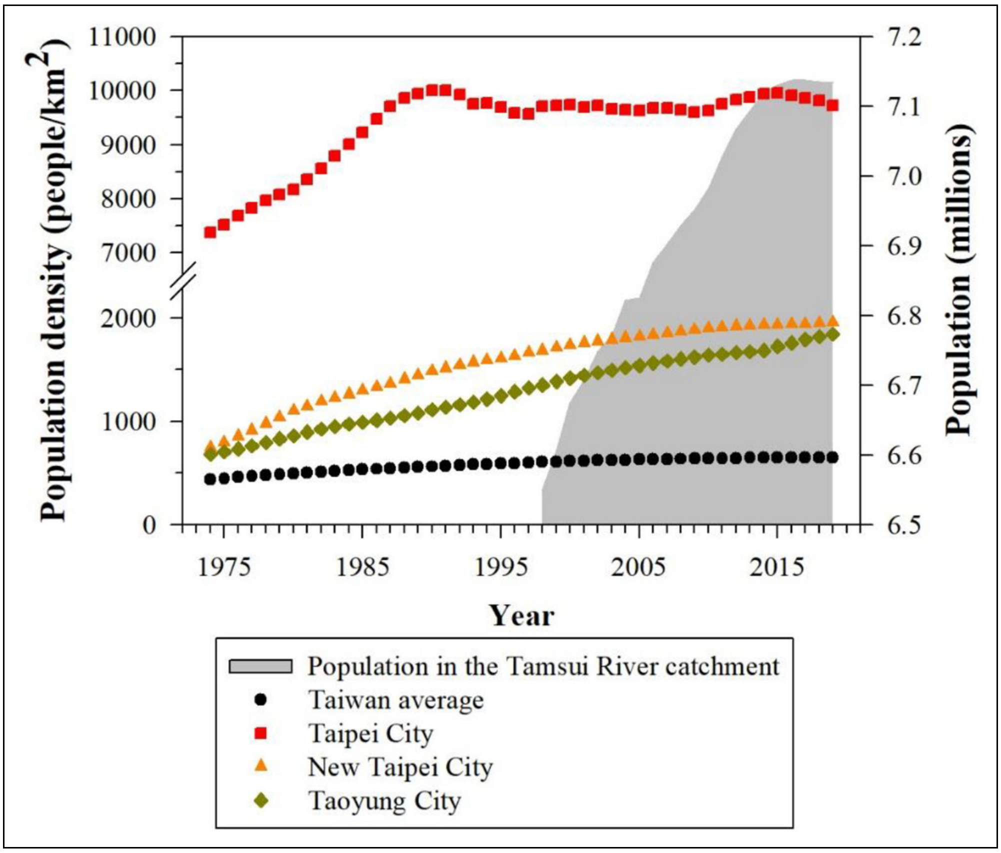


Figure 3. Annual population in the Tamsui River catchment (data between 1998 and 2019) and annual population densities in Taiwan average, Taipei City, New Taipei City, Taoyuan City, and Keelung City (data from 1974 to 2019). DOI: https://doi.org/10.1525/elementa.2020.00085.f3

forests, country lanes, and water courses, replacing them with municipal plumbing, supermarkets, and urban pavements. This detachment also means that the public is unaware of the deterioration of the natural environment.

(D2) Urbanization and the increase in population density

Taiwan is one of the most densely populated regions in the world (Lu et al., 2006). The capital, Taipei City, is located in the Tamsui River catchment; Taipei City is the political and economic center of Taiwan and one of its fastest developing regions. People moved to Taipei City for work during the period of economic growth, swelling the population and increasing its density. According to the Statistical Yearbook of the Ministry of the Interior of Taiwan (2019), the population density in Taipei City was 7,372 people per km^2 in 1974, and it had increased to 9,732 people per km^2 in 2019, compared to Taiwan's national average of 652 people per km^2 (**Figure 3**). Urban sprawl resulted from overspills in the population and created satellite cities. The population densities in New Taipei City and Taoyuan City were 746 and 683 people per km^2 in 1974, respectively, and had more than doubled by 2019 (**Figure 3**).

The population in the Tamsui River catchment was 6.55 million in 1998 and increased to 7.13 million by 2019 (**Figure 3**), representing an 8.91% increase over 20 years. The areas with high population density are mostly distributed near the midstream and downstream of the Tamsui River (**Figure 4**), and the highest regional population density is 38,607 people per km^2 (Yonghe district). The high population density and rapid urbanization result in high pressures and severe stress on the aquatic environment; they also increase domestic water effluents (Putri et al., 2018). The daily discharge of domestic wastewater was 0.47×10^6 m^3 in 2000, but it had doubled by 2015 according to the sewerage systems office in the Taipei City government.

(D3) Economic growth and increase in MSW

In recent decades, Asia has been experiencing rapid urbanization, industrialization, and economic growth. Among Asian regions, Taiwan experienced radical economic and societal conversion during the early 1960s–1990s. According to the Statistical Yearbook of Taiwan (2019), its gross domestic product (GDP) increased from 1,778 million U.S. dollars in 1961 to 611,255 million of U.S. dollars in 2019. The annual gross income per capita in Taiwan also increased from 161 U.S. dollars in 1961 to 26,528 U.S. dollars in 2019, representing a 163-fold increase within 58 years.

Previous research (Sjöström and Östblom, 2010) showed that the quantities of MSW have increased steadily along with the GDP. In general, a positive relationship exists between economic growth and waste generation if waste management and environmental policies are

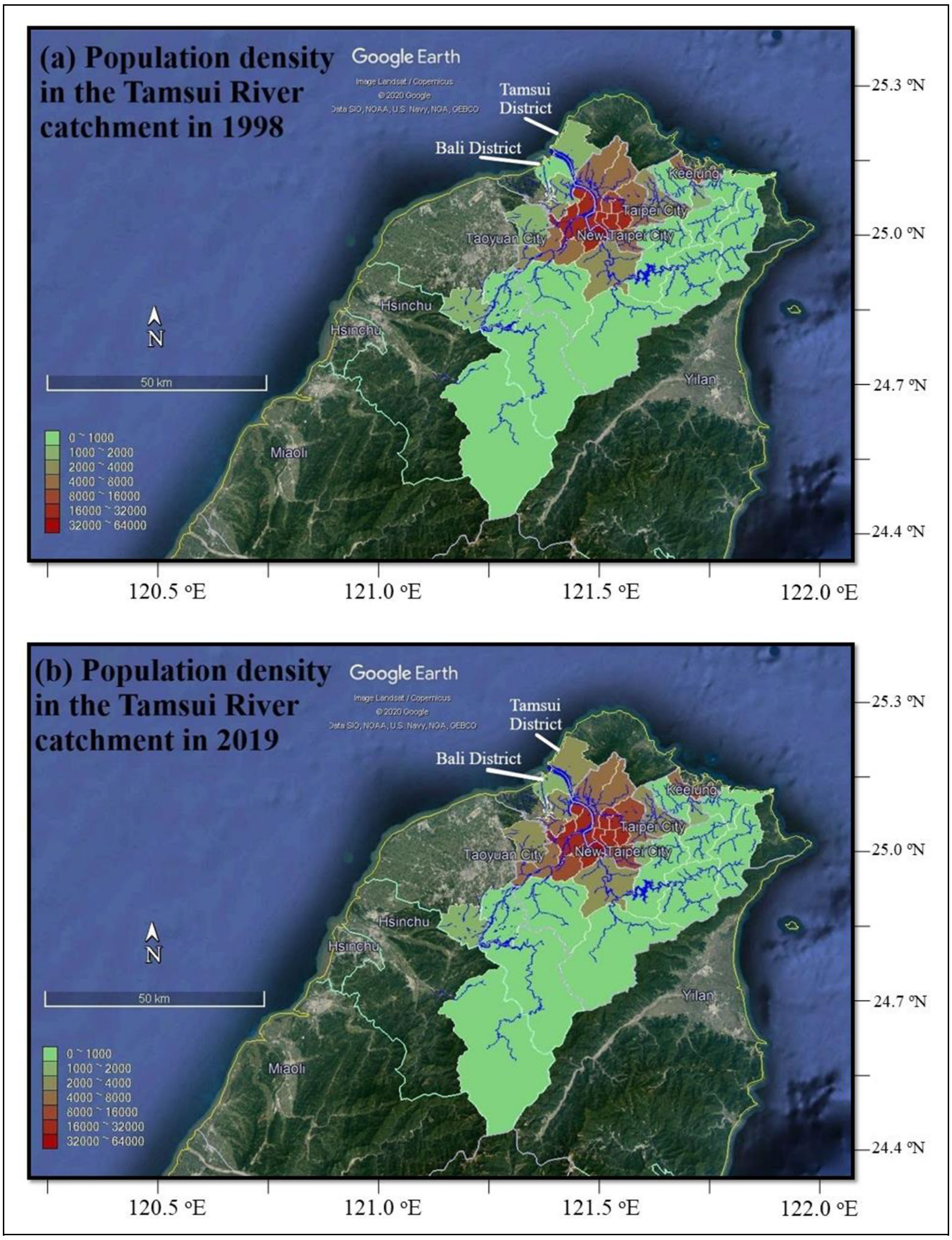


Figure 4. Population density in the Tamsui River catchment in (a) 1998 and (b) 2019. DOI: https://doi.org/10.1525/elementa.2020.00085.f4

lacking (Berglund and Soderholm, 2003; Inglezakis et al., 2012). According to Lu et al. (2006), the average daily per capita weight of MSW in Taiwan was 1.14 kg in 1997. If the average daily weight of MSW per capita remains the same, the total current population in the Tamsui River catchment would result in 8,128 metric tons of MSW daily.

3.5. Resulting pressure on the environment

Economic drivers and human activities create multiple environmental pressures, including (P1) increased organic carbon in the Tamsui River and its estuary and (P2) a decreased DO level for the water in the Tamsui River and its estuary.

(P1) Increased organic carbon in the Tamsui River and its estuary

Riverine organic carbon mainly comes from living and dead biota. Other sources include geological features, pollution, and groundwater (Chen et al., 2012a; Wang et al., 2018). Land-use changes cause the release of organic carbon that has been stored in the soil. Deng et al. (2016) reported that conversion from forest to farmland, grassland, or building site significantly decreases soil carbon stocks. Intense anthropogenic activities on land have generated large amounts of organic pollutants that may be transported by rivers to coastal areas (Ni et al., 2008). In 1997, people in Taiwan generated 1.14 kg MSW per person daily (Lu et al., 2006). According to the World Bank (2012), approximately 50% of MSW is organic matter. If only 1%

of the organic matter from the MSW is transported by the Tamsui River into its estuary, the coastal area will receive approximately 40 metric tons of organic matter daily.

(P2) Decreased DO level in the Tamsui River and its estuary

DO is essential for the survival of fish and other aquatic organisms. Organic matter that consumes DO is thus the ultimate cause of hypoxia under favorable physical settings (Qian et al., 2017; Qian et al., 2018). Hypoxia may not only reduce biodiversity and endanger aquatic and benthic habitats but also alter the redox chemistry in both the water column and the underlying sediments, triggering secondary pollutants in the water body (Breitburg, 2002; Rosenberg et al., 2002). BOD is the amount of DO used by aerobic biological organisms when organic matter in the water is decomposed. The BOD_5 value represents the amount of DO consumed during 5 days of incubation at 20°C. The wastewater generated by inhabitants is often expressed using the unit population equivalent (PE), and the formula is based on a fixed value of daily BOD generated per person (Tseng et al., 2018). According to the Greenhouse Gas Inventory Report (2019), 1 unit of PE in Taiwan generates approximately 40 g BOD daily.

$$1 \text{ PE} = 40 \text{ g BOD}_5/d.$$

However, the person load, which is the actual contribution to the environment of a person who lives in a sewer catchment, varies considerably. As 7.13 million people live in the Tamsui River catchment, the wastewater from these residents contains approximately 285 tons BOD_5 daily. If the wastewater from the Tamsui River catchment was discharged into the river and estuary without any treatment, then the coastal area would receive discharged water annually that had 0.16 million metric tons of BOD_5, which may cause hypoxia in the Tamsui River, its estuary, and nearby coastal areas.

3.6. State of the water quality of the Tamsui River and its estuary

The rapid growth of the economy in Taiwan between the 1960s and the 1990s came at a high environmental cost. In the 1990s, severe pollution degraded the water quality of rivers and estuaries. In 1998, 16% (2,088 km) of the total length of Taiwan's 21 major rivers was ranked as severely polluted, while another 22% was considered lightly or moderately polluted (Putri et al., 2018). The major regulator, the Taiwan Environmental Protection Administration (TEPA, 1998), reported that 13.4% (43.3 km) of the total length of the Tamsui River was severely polluted, while another 22.4% was considered moderately polluted. The Tamsui River is heavily polluted by household sewage, municipal wastewater, and industrial pollution from the manufacturing industry, including illegal discharge. From 1992 to 2005, 16.3% of major public dispute cases were related to water pollution (TEPA, 2006).

3.7. Implementation of management measures by regulatory authorities

The aquatic environments had to be restored to ensure water security and to resolve public disputes. The TEPA worked with the local governments to implement a range of policies and management measures as described in the following.

Measure 1: Reduction in MSW as a source of organic matter

The regulators used a triple approach, including reduction, collection, and recycling programs, by combining the MSW collection system with reduction and recycling. The "extended producer responsibility" policy is the foundation for recycling by producers, retailers, and the public (Lu et al., 2006). This is a "polluter-pays" system and mandates that waste collection fees be paid by citizens. Taipei City and New Taipei City began operating the volume-based collection fee system in 2000 and 2010, respectively. As the government enforced strict MSW management policies, the average daily per capita weight of MSW decreased 70%, from 1.14 kg in 1997 to 0.34 kg in 2014 (Taiwan Council for Economic Planning and Development, 2002, 2015). Assuming that 1% of the organic matter from the MSW is transported by the Tamsui River and into its estuary, the daily pressure of organic matter that the coastal area received has been reduced from 40 to 12 metric tons.

Measure 2: Monitoring water quality

In 2002, TEPA implemented routine water monitoring in rivers, reservoirs, and groundwater to ensure water security and increase public awareness of aquatic environmental protection. Monitoring included the following variables: DO, BOD, NH_3-N, suspended solids (SS), air temperature, water temperature, pH, electrical conductivity, chemical oxygen demand, DO saturation, chloride, and coliforms. The TEPA maintains 38 water monitoring stations (**Figure 1b**) in the Tamsui River to check water quality, and the river pollution index (RPI) is used to assess trends for both long-term planning and day-to-day management of surface water quality.

Measure 3: Increasing and improving wastewater treatment

Untreated domestic wastewater was being directly discharged into the rivers. Wastewater treatment is one of the most common ways to reduce pressure from effluents, and Taiwan built its first wastewater treatment plant (WWTP) in 1979. Although it was designed for only primary wastewater treatment, the treatment system was integrated into the secondary wastewater treatment system in 2003 due to stricter regulations and water standards for effluents. Currently, there are nine WWTPs in the Tamsui River catchment, and their treatment capacity ranges from 60 to 18,433 metric tons daily. Wastewater from households, businesses, and many industries is now collected by sewers and delivered to WWTPs, and both the percentage of households linked to sewers and the sewage treatment rates have increased (**Figure 5**). In 2009,

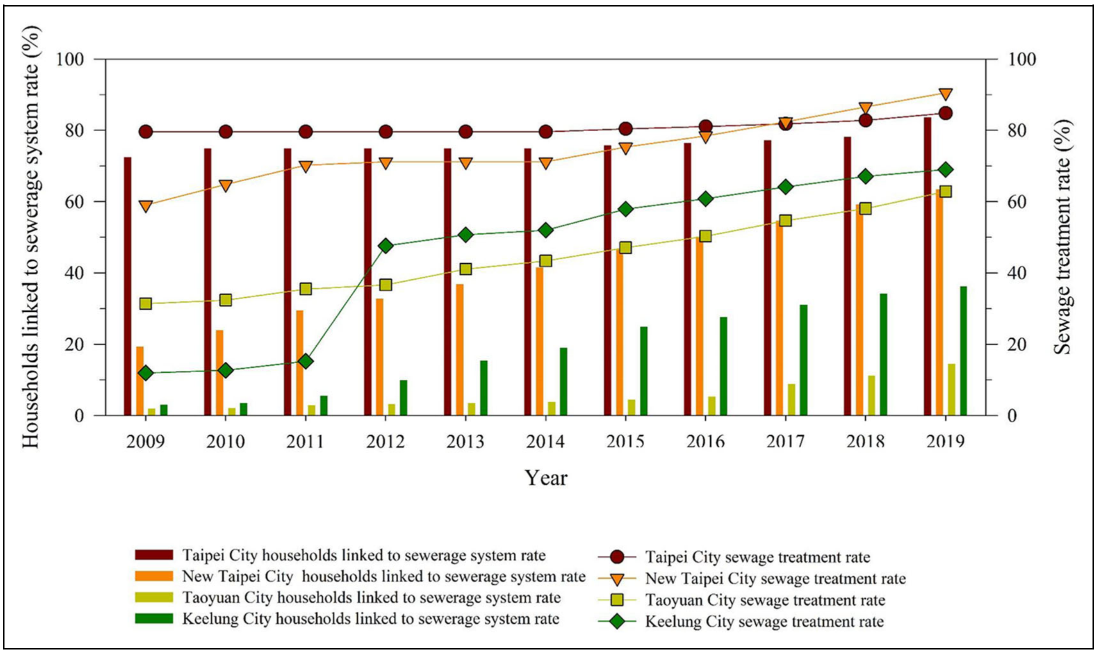


Figure 5. Households linked to sewerage system rate and sewage treatment rate in Taipei City, New Taipei City, Taoyuan City, and Keelung City. DOI: https://doi.org/10.1525/elementa.2020.00085.f5

72.48%, 19.28%, 1.95%, and 3.04% of households were linked to public sewers in Taipei City, New Taipei City, Taoyuan City, and Keelung City, respectively. Ten years later, 83.60%, 63.45%, 14.51%, and 36.23% of households were linked in Taipei City, New Taipei City, Taoyuan City, and Keelung City, respectively. The sewage treatment rates also increased from 79.6% to 84.83% in Taipei City, 59.06% to 90.50% in New Taipei City, 31.36% to 62.84% in Taoyuan City, and 11.95% to 69.02% in Keelung City (**Figure 5**).

Responses as management measures

The regulators implemented multiple management measures in response to the issue of Tamsui River water quality. These measures include the following:

(i) New policies: For example, the strict management policies enforced to reduce MSW also reduced the organic matter inputs to the Tamsui River.
(ii) Monitoring network: Thirty-eight stations provide continual monitoring of 12 environmental variables.
(iii) Assessment: The RPI was implemented for day-to-day management and long-term planning.
(iv) Infrastructure: The construction of a sewer network increased the number of establishments linked to a sewerage system. The construction of WWTPs has increased the volume of effluent treatment. These factors have reduced the organic carbon and BOD from wastewater in the Tamsui River and its estuary.

3.8. Assessing the effectiveness of the measures for improving the state of water quality

The *River and ocean water quality maintenance and improvement plan* was implemented from 2005 to 2011. We analyzed changes in the state of water quality in the Tamsui River and its estuary in the time period before the plan (1993–2004), during the plan (2005–2011), and after the plan (2012–2019) to assess its effectiveness. We analyzed whether the state of water quality in the Tamsui River and its estuary had improved after the measures were applied by the regulators to reduce the pressure from human activities on the environment. Pollution in the main stream generally transmits from upstream to downstream; therefore, the water quality of the midstream, downstream, and estuary at three monitoring stations was examined, specifically, at Zhongxiao Bridge, Guandu Bridge, and Tamsui River mouth (**Figure 1b**). Monthly data for 26 years, from 1993 to 2019, were analyzed.

The changes in the state of the water quality in the Tamsui River and its estuary were assessed with particular consideration for the following:

(S1) increased DO concentrations;
(S2) decreased BOD;
(S3) reduced ammoniacal nitrogen (NH_3-N) concentrations; and
(S4) mitigation of pollution in the Tamsui River and its estuary.

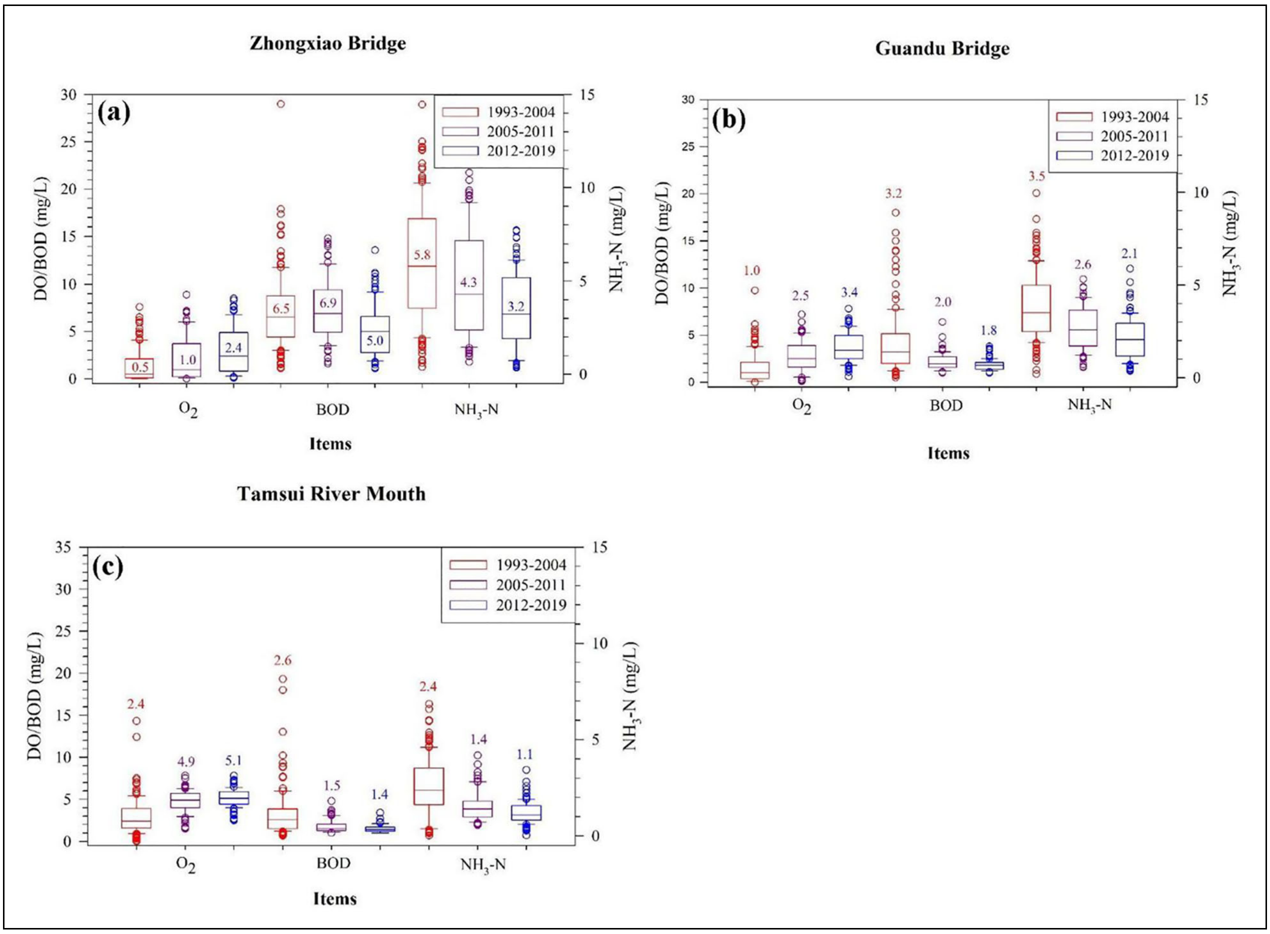


Figure 6. Variations of dissolved oxygen, BOD, and ammoniacal nitrogen between 1993–2004, 2005–2011, and 2012–2019 in (a) Zhongxiao Bridge, (b) Guandu Bridge, and (c) Tamsui River mouth. DOI: https://doi.org/10.1525/elementa.2020.00085.f6

(S1) Increasing DO concentrations in the Tamsui River and its estuary

DO is consumed by aquatic microorganisms during the respiration of organic matter and its decomposition. It is an important indicator of water quality because when DO decreases, hypoxia, and even anoxia, may occur. Although downstream water quality is usually worse because of pollution in the catchment, the estuary of the Tamsui River is tidal, and seawater with high DO concentrations flows into the estuary at high tide. At the Zhongxiao Bridge monitoring station, the median DO concentrations increased from 0.5 mg/L (1993–2004) to 1.0 mg/L (2005–2011) and ultimately reached 2.4 mg/L (2012–2019; **Figure 6a**). At the Guandu Bridge monitoring station, the median DO concentrations increased from 1.0 mg/L (1993–2004) to 2.5 mg/L (2005–2011) and reached 3.4 mg/L (2012–2019; **Figure 6b**). At the Tamsui River mouth monitoring station, the median DO concentrations increased from 2.4 mg/L (1993–2004) to 4.9 mg/L (2005–2011) and reached 5.1 mg/L (2012–2019; **Figure 6c**).

(S2) Decreasing BOD in the Tamsui River and its estuary

At the Zhongxiao Bridge monitoring station, the median BOD was 6.5 mg/L (1993–2004) and 6.9 mg/L (2005–2011) before decreasing to 5.0 mg/L (2012–2019; **Figure 6a**). At the Guandu Bridge monitoring station, the median BOD decreased from 3.2 mg/L (1993–2004) to 2.0 mg/L (2005–2011) and reached 1.8 mg/L (2012–2019; **Figure 6b**). At the Tamsui River mouth monitoring station, the median BOD decreased from 2.6 mg/L (1993–2004) to 1.5 mg/L (2005–2011) and reached 1.4 mg/L (2012–2019; **Figure 6c**).

(S3) Decreased NH_3-N concentrations in the Tamsui River and its estuary

NH_3-N is a severe concern as a contaminant in aquatic systems. It is a toxic pollutant often found in waste products, such as sewage, liquid manure, and other liquid organic waste products. NH_3-N in drinking water causes odor and taste problems (World Health Organization, 2011). One of the main goals of the *River and ocean water quality maintenance and improvement plan* was to reduce NH_3-N concentrations in the water. At the Zhongxiao Bridge monitoring station, the median NH_3-N concentrations decreased from 5.8 mg/L in 1993–2004 to 4.3 mg/L in 2005–2011 and reached 3.2 mg/L in 2012–2019 (**Figure 6a**). At the Guandu Bridge monitoring station, the median NH_3-N concentrations decreased from 3.5 mg/L (1993–2004) to 2.6 mg/L (2005–2011)

Table 1. The calculation and definition of river pollution index. DOI: https://doi.org/10.1525/elementa.2020.00085.t1

	Rank			
Items	Unpolluted	Lightly Polluted	Moderately Polluted	Severely Polluted
DO (mg/L)	$DO \geq 6.5$	$6.5 > DO \geq 4.6$	$4.5 \geq DO \geq 2.0$	$DO < 2.0$
BOD_5 (mg/L)	$BOD_5 \leq 3.0$	$3.0 < BOD_5 \leq 4.9$	$5.0 \leq BOD_5 \leq 15.0$	$BOD_5 > 15.0$
SS (mg/L)	$SS \leq 20.0$	$20.0 < SS \leq 49.9$	$50.0 \leq SS \leq 100$	$SS > 100$
NH_3-N (mg/L)	$NH_3\text{-N} \leq 0.50$	$0.50 < NH_3\text{-N} \leq 0.99$	$1.00 \leq NH_3\text{-N} \leq 3.00$	$NH_3\text{-N} > 3.00$
Index scores (Si)	1	3	6	10
RPI	$RPI \leq 2.0$	$2.0 < RPI \leq 3.0$	$3.1 \leq RPI \leq 6.0$	$RPI > 6.0$

DO = dissolved oxygen; SS = suspended solids; NH_3-N = ammoniacal nitrogen.

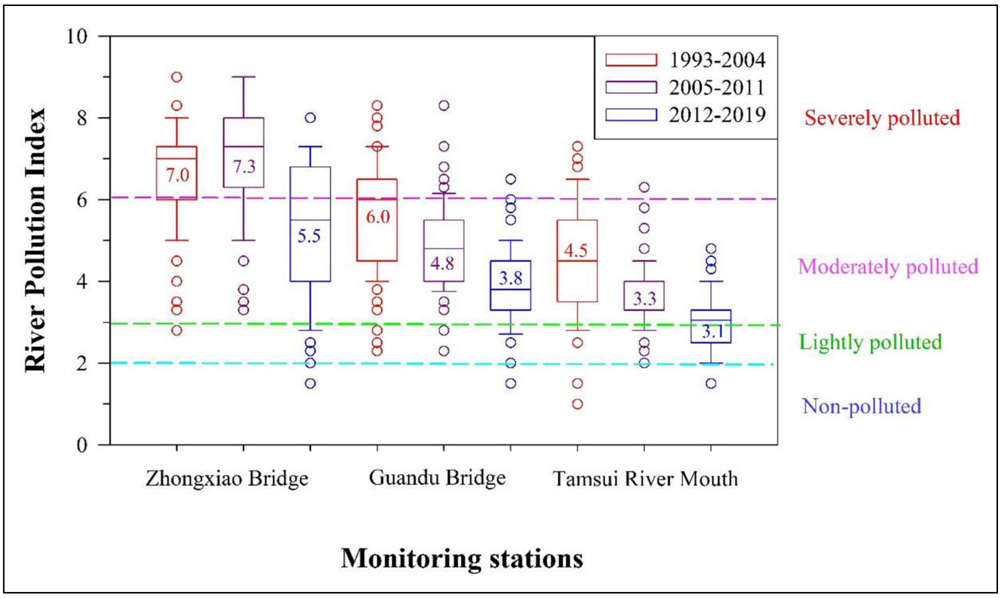


Figure 7. River pollution index variations between 1993–2004, 2005–2011, and 2012–2019 in Zhongxiao Bridge, Guandu Bridge, and Tamsui River mouth. DOI: https://doi.org/10.1525/elementa.2020.00085.f7

and then to 2.1 mg/L (2012–2019; **Figure 6b**). At the Tamsui River mouth monitoring station, the median NH_3-N concentrations decreased from 2.4 mg/L (1993–2004) to 1.4 mg/L (2005–2011) and reached 1.1 mg/L (2012–2019; **Figure 6c**).

(S4) Mitigate pollution in the Tamsui River and its estuary

The RPI includes DO, BOD, NH_3-N, and SS, and each variable of water quality determines RPI:

$$RPI = \frac{1}{4}\sum_{i=1}^{4} Si,$$

where *Si* represents the index scores based on **Table 1**, and the RPI value ranges from 1 to 10. There are four levels of pollution, as follows: nonpolluted ($RPI \leq 2.0$), lightly polluted ($2.0 < RPI \leq 3.0$), moderately polluted ($3.1 < RPI \leq 6.0$), and severely polluted ($RPI > 6.0$; Liou et al., 2004; Chen et al., 2012b).

The water at the Zhongxiao Bridge monitoring station had been severely polluted for 18 years, 1993–2011, but it has improved in recent years (**Figure 7**). The water at the Guandu Bridge and Tamsui River mouth monitoring stations has been moderately polluted since 1993 but has also now improved (**Figure 7**). According to the TEPA data, the overall river pollution was mitigated, with the average RPI decreasing from 4.2 in 1999 to 2.4 in 2019 (**Figure 8**). Although approximately 13.4% of the total length of the Tamsui River was severely polluted in 1999, by 2019, this value had decreased to 2.6%, and approximately 73.2% was considered nonpolluted.

3.9. Impact on human welfare

Economic drivers and human activities cause environmental pressures and result in degradation in the state of water quality. Human welfare was impacted, and several major public disputes occurred due to water pollution. Major impacts on public health from contaminated water and food occurred, threatening both water and food

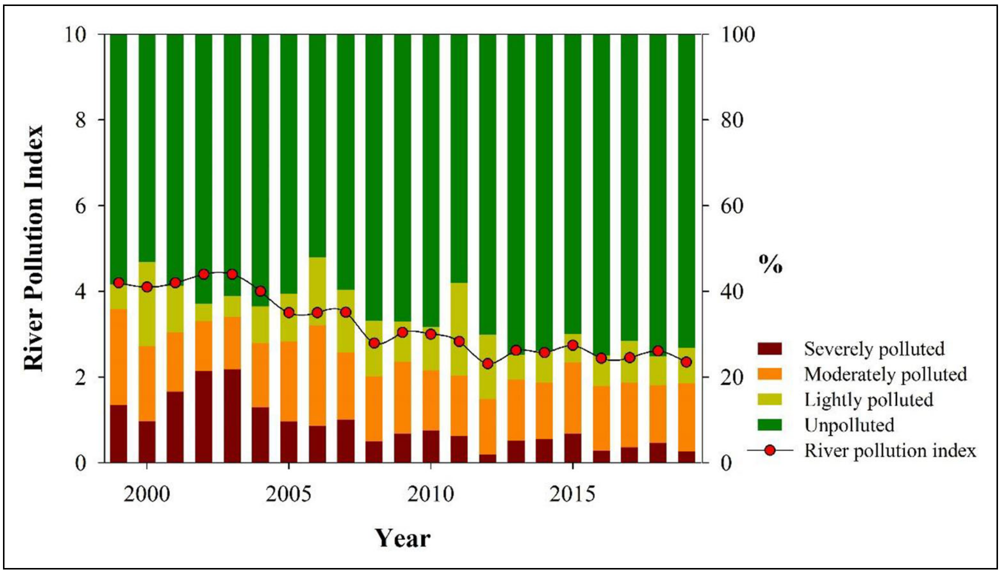


Figure 8. The annual variations of percentage and average of river pollution index in the entire Tamsui River in the recent two decades (data from 1999 to 2019). DOI: https://doi.org/10.1525/elementa.2020.00085.f8

security. This section discusses the improvement in human welfare resulting from management and improvement of the environment. These include (I1) improved quality of the water, aquatic environment, and life; (I2) increased willingness to live by the riverside and thus, hedonic value; (I3) increased tourism and tourism-based businesses; and (I4) flourishing water-based leisure activities.

(I1) Improved quality of the water, aquatic environment and life

The number of households and businesses connected to the sewerage network and WWTPs has increased, as has the volume of wastewater that is now treated. Illegal wastewater discharge from industries has decreased with the strengthening of legal enforcement and the polluter-pays system. The decrease in sewage and effluent discharged into the Tamsui River has increased the quality of riverine water and the aquatic environment. Several riverbank parks have been built, and people are relaxing near the river. Environmental quality is a key factor in people's well-being because quality of life is strongly affected by the health of the physical environment (Kahn, 2002; van Kamp et al., 2003; Holman and Coan, 2008). As a result, the improvement in environmental quality has also improved well-being.

(I2) Willingness to live by the riverside and hedonic value

Environmental qualities contribute to livability and the vision of urban planners (Dantzig and Saaty, 1973). People are more willing to live near the riverside because the water quality in the Tamsui River and its estuary, as well as the nearby environment, has improved. The number of new buildings and housing prices near the riverside are increasing. Poor et al. (2007) showed that ambient water quality can significantly influence residential property values regardless of whether they are on the waterfront. The Tamsui and Bali Districts are on either side of the Tamsui River estuary (**Figure 4**), and the populations in these districts increased more than 50% in 20 years (1998–2019), while population density increased by a multiple of 1.5 (**Figure 4a and b**). Compared to other areas in the Tamsui River catchment, the Tamsui and Bali Districts had a low population density, but people moved from the high to the low population density areas, which helped to balance the development of the city and distribute the environmental pressure.

(I3) Increased tourism and tourism-based business

Tourism is one of the world's largest industries; supporting 284 million jobs and generating 9.8% of global GDP in 2015 (De Urioste-Stone et al., 2016). However, the development of tourism activities is heavily dependent on ecosystem services (Josep, 2018), and ecosystem services can only be provided for tourism when the environmental quality is good. Tourism is one of the most important ecosystem services provided by the environment to the Common International Classification on Ecosystem Services. Thus, tourism is an important expression of the relationship between nature and society (Josep, 2018).

Prior to 2003, there was only 1 tourist attraction near the Tamsui River estuary and fewer than 1 million visitors annually according to the tourism statistics database of the Taiwan Tourism Bureau (https://stat.taiwan.net.tw/). The number of tourist attractions increased to 8 in 2005, and the total number of tourist trips escalated, reaching 13.6 million in 2019. The hospitality sector benefits from tourism along with other businesses, companies, and local communities (World Travel & Tourism Council, 2016).

(I4) Flourishing water-based leisure activities

Historically, the Tamsui River was mainly used for waterway transportation and fishery. However, sedimentation compromised waterway transportation, and pollution compromised the fishery. The recent improvement in the water and environmental quality of the Tamsui River has boosted ecosystem services, especially cultural services. Companies related to water-based leisure activities emerged in 2013, according to business registration data from the Department of Commerce, Ministry of Economic Affairs (https://gcis.nat.gov.tw). Water-based leisure activities include river tracing and creaking upstream, canoeing and dragon boat competitions midstream, and kayaking and water-skiing downstream. Yachting, cruising, and recreational fishing are new leisure activities in the Tamsui River estuary.

4. Discussion and recommendations

The analysis shows that management measures applied by environmental regulators have lowered anthropogenic pressure on the aquatic environment, resulting in improvements in the state of the water and environment and a positive impact on human welfare.

4.1. Further responses and management recommendations

Previous sections analyzed the economic drivers and human activities that have caused environmental pressure, changed the state of the environment, and impacted human welfare. Environmental regulators adopted measures to reduce environmental pressure, which shifted the negative impact to a positive impact on human welfare. This section further discusses societal responses and management recommendations as follows: (R1) increasing education and raising awareness, (R2) establishing community-based river rangers, (R3) restoring wetlands and mangroves, (R4) developing the circular economy, (R5) implementing governance measures, and (R6) improving monitoring and assessment.

(R1) Increasing education and raising awareness

Education plays an important role in our future. Education raises people's awareness of issues and empowers them to make better choices for the environment and themselves. Environmental education should be provided not only by schools but also by environmental organizations, nongovernmental organizations, and nonprofit organizations. When different organizations provide environmental education, it may bring different viewpoints and different perspectives. In particular, involving the public in citizen science makes participants aware of the scientific process in which they are becoming involved (Brossard et al., 2005) and provides teachers with opportunities that are particularly effective for connecting children with nature (Liefländer et al., 2013).

(R2) Establishing community-based river rangers

Community-based management can make a substantial contribution to the sustainability of common-pool natural resources, such as rivers (Gari et al., 2017; van Laerhoven et al., 2020). River rangers actively patrol a river basin, guarding the riverine environment, and supported by other members of the police team when initiating enforcement activities. They have also been trained as environmental educators who provide environmental education and host events that aim to rekindle the relationship between humans and riverine environments. As river rangers are community based, they quickly notice when the riverine environment is abnormal and report it to the authorities. This also raises the local identity and promotes environmentally responsible behaviors (Osbaldiston and Sheldon, 2003).

(R3) Restoring wetlands and mangroves

Wetlands and mangroves provide numerous ecosystem services (Maltby and Acreman, 2011; Locatelli et al., 2014; Owuor et al., 2019) such as water purification, carbon sequestration, and denitrification. They support high biodiversity and represent important breeding, wintering, and stopover sites for migratory birds (Yam et al., 2015). In addition, mangrove swamps protect coastal areas from erosion, storm surges, and tsunamis (Danielsen et al., 2005), and wetlands and mangroves have recreational potential for the general public and visitors by supporting psychological well-being via exposure to nature, especially in stressful urbanized environments (Yam et al., 2015). Thus, wetlands and mangroves can provide supporting, regulating, and culturing ecosystem services. However, global urbanization has caused severe impacts on wetland ecosystems, including habitat deterioration and hydrological alteration (Ehrenfeld, 2000; Yam et al., 2015). The restoration and conservation of wetlands and mangroves ensures that they continue to deliver the abovementioned benefits and valuable ecosystem services.

(R4) Developing the circular economy

A circular economy promotes greater resource productivity, reduces waste, and attenuates pollution (Tukker, 2015), leading to an industrial economy that is restorative and regenerative by design. The concept of the circular economy focuses on bridging production and consumption activities and transforming waste into resources (Witjes and Lozano, 2016). This must achieved by closing different types of loops and achieving the recovery of valuable resources between parties in society (Yuan et al., 2006; Yong, 2007). For instance, food scraps and food waste from households are organic waste. The discharge of organic wastes into rivers or coastal waters without treatment can cause eutrophication and hypoxia in aquatic systems. On the other hand, the reuse of food waste as animal feed or in the production of organic fertilizers reduces the amount of waste and offers benefits.

(R5) Implementing governance measures

Effective governance at all levels, as well as community-based management, is fundamental for sustainability (Ostrom, 2009). Top-down management by a governmental authority or regulator can support various solutions, for example, law enforcement or financial instruments such as taxes, subsidies, and fines. As mentioned previously, government measures, such as MSW reduction, water quality monitoring, and wastewater treatment rate increases, have improved the water quality of the Tamsui River and its estuary. Nevertheless, 8.4 km of the Tamsui River was experiencing severe pollution, and 51.4 km of the Tamsui River was experiencing moderate pollution. In addition, the tourism industry and water-based leisure activities in the Tamsui River catchment are developing and expanding, so water quality has become more important for both the tourism industry and visitors.

Municipal authorities can make decisions on building, expanding, or improving WWTPs to treat domestic sewage and improve water quality (Fonseca et al., 2021). Implementing environmental policy can improve land use and urban planning, linking housing to sanitation facilities. Environmental laws can be used to control and reduce the amount of organic matter and nutrient pollution on land and into waters. Subsidies, taxes, and fines may also be used nationally to encourage environmentally friendly industries.

(R6) Improving monitoring and assessments

Taiwan is not alone in trying to reconcile development and environmental protection. The European Union (EU) has struggled for decades to improve water quality and has issued a series of environmental directives that address water quality from multiple perspectives. These include the use of water, such as drinking water (EU, 1998b), and bathing water (EU, 2006), urban wastewater (EU, 1998a), fertilizers (nitrate; EU, 1991), pollutants that are "priority substances" (EU, 2013), and a general water framework directive (EU, 2000). All of these include specific focused monitoring, for which the member states are responsible, and regular assessments by the EEA (2018).

The U.S. Congress passed the Federal Water Pollution Control Act Amendments in 1972 to respond to declining water quality in surface waters, including estuaries (U.S. Environmental Protection Agency [USEPA], 1972). This was further introduced and amended in 1977 as the Clean Water Act and in 1987 as the Water Quality Act (USEPA, 1977, 1987). These acts emphasize the control of toxic pollutants, the regulation of pollutant discharges into waters, and the maintenance of quality standards for surface waters. The USEPA (1990) began the Environmental Monitoring and Assessment Program in 1990 to monitor the conditions and trends in natural resources in the United States and to develop innovative methods for assessing the environment.

In Taiwan, the Water Pollution Control Act is formulated to control water pollution and ensure the cleanliness of water resources to maintain ecological systems, enhance the living environment, and advance public health. There are water quality standards for drinking, swimming, aquaculture, industry, irrigation, and environmental conservation. According to the Water Pollution Control Act, the competent authority should designate the "water quality standard" for the quality of a water body based on its optimal use. The Taiwan EPA uses the RPI to explore monitoring trends for both long-term planning and the day-to-day management of surface water quality (Putri et al., 2018). The RPI includes few environmental variables and critically misses some important variables, especially in freshwater, such as phosphates, and hazardous substances such as pesticides and toxic metals. Although phosphates and toxic metals such as mercury, copper, cadmium, and so forth are examined seasonally, they are not included in the RPI. A second phase of monitoring and assessment should increase the water monitoring frequency for phosphates and toxic metals and additionally include them in the assessment.

Summary: Societal responses and management recommendations

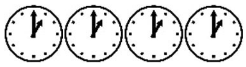
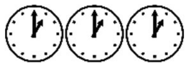
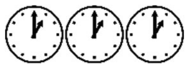
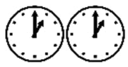
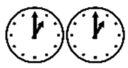
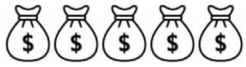
The water quality of the Tamsui River estuary has been improved by the implementation of management measures, such as MSW management policies and the construction of WWTPs and water monitoring systems. This management has been effective in the context of an estuary in a populous urban area that is under direct and indirect anthropogenic pressure while also experiencing ongoing environmental change from the climate.

The improvement of water quality provides a better environment for aquatic life and raises the hedonic value of property for people who live near the riverside. In addition, the number of tourists and tourism-based businesses have increased because water-based leisure activities are flourishing in the Tamsui River estuary. Nevertheless, although the improvement in water quality in the Tamsui River estuary brings well-being and benefits, it could be further enhanced to increase the cost/benefit relation from management measures. The combined (SAF and DPSIR) social–environmental analysis identified societal responses that can reduce anthropogenic pressures and improve the water quality in the Tamsui River estuary. An additional range of societal responses could be implemented across different time scales (from short to long) and relative costs (from low to high) to improve the water quality in the Tamsui River and its estuary. **Table 2** presents the implementation time frame and relative cost of each response as well as the corresponding social actors and implementers.

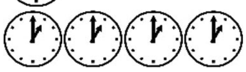
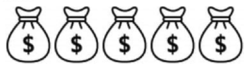
4.2. Future study

The increasing anthropogenic pressures and ongoing environmental alteration, such as climate change and the rising sea level, have degraded the water and environmental quality and reduced the ecosystem services provided by the watershed. Achieving sustainable outcomes that benefit both people and nature is the central challenge for society (Kareiva and Marvier, 2012). According to Leslie et al. (2015), using a social–environmental approach in the generation of knowledge and the formulation of sustainable governance solutions is critical, as it explicitly recognizes the connections and feedback loops linking human and natural systems. Facing human-influenced coastal environments, more social–environmental research is needed to assess the sustainability of current developments. Future studies using social–environmental analysis and a multidisciplinary approach are essential to ensure appropriate recommendations and lower the impact of development (de Alencar et al., 2020).

Table 2. Time frame, relative cost, and corresponding implementers of implementing societal responses. DOI: https://doi.org/10.1525/elementa.2020.00085.t2

Societal Response	Time Frame for Implementation	Relative Cost of Implementation	Corresponding Implementers
(R1) Education and raising awareness			Schools, nongovernmental organizations, and nonprofit organizations
(R2) Setup community-based river rangers			Local communities
(R3) Restore wetlands and mangroves			Local communities and local/national government
(R4) Develop the circular economy			Local/national government
(R5) Governance measures.			National government
(R6) Improve monitoring and assessments			National government

Short term  Low cost 

Long term  High cost 

5. Conclusions

In this study, social–environmental approaches were used to analyze the issue of estuary water quality in a populous urban area, the Tamsui River estuary. The economic drivers and human activities that cause pressure on the environment and worsen the water quality of the Tamsui River estuary were identified and assessed. These economic drivers and human activities are economic growth, land use change, urbanization, population rise, and an increase in population density and MSW production. They impose environmental pressures by increasing organic carbon and decreasing DO in the Tamsui River and its estuary. This research identifies the management measures that have been taken to improve the water quality, and the results also provide information about changes in environmental state based on available scientific data, particularly on increased DO concentrations, decreased BOD concentrations, and reduced NH_3-N concentrations in the Tamsui River and its estuary, as a result of mitigating pollution. Possible future improvements in the environmental state and the positive impacts on human welfare have also been discussed, including benefits such as improved quality of the water, improved aquatic life and environment, increased willingness to live by the riverside, increased tourism and tourism-based businesses, and flourishing water-based leisure activities. Finally, possible societal responses and management measures that can be implemented to ameliorate the water quality in the Tamsui River and its estuary are identified. The responses are increased education, the establishment of community-based river rangers, wetland and mangrove conservation, development of the circular economy, the implementation of governance measures, and improvements in monitoring and assessment.

Data accessibility statement

The following data sets were generated:

- Business registration statistical database of the Department of Commerce, Ministry of Economic Affairs, Republic of China (Taiwan). Available at https://gcis.nat.gov.tw/mainNew/English/ (last access date 5 October 2021)
- European Environment Agency, Common International Classification on Ecosystem Services. https://cices.eu/ (last access date 5 October 2021)
- Statistical Yearbook of Interior, 2019. Ministry of the Interior, Republic of China (Taiwan). Available at https://www.moi.gov.tw/english/ (last access date 5 October 2021)
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- The World Bank. 2012. Urban development and local government unit of the sustainable development network. The Urban Development Series: A Global Review of Solid Waste Management. Available at http://www.worldbank.org/urban (last access date 5 October 2021)
- Tourism Statistic database of the Taiwan Tourism Bureau, Ministry of transportation and communications, Taiwan (R.O.C.). Available at https://stat.taiwan.net.tw/ (last access date 5 October 2021)

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Competing interests

The authors declare no competing interests.

Author contributions

Conceived and designed the experiments: HCT.

Acquired and analyzed the data: HCT, CCL.

Wrote this article: HCT, AN, GCG.

Reviewed this article and approved the submitted version for publication: All authors.

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