Clean Technologies and Environmental Policy (2018) 20:621–638
https://doi.org/10.1007/s10098-018-1492-8

ORIGINAL PAPER

Structural analysis of the interrelationship between economic activities and water pollution in Vietnam in the period of 2000–2011

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Received: 3 September 2017 / Accepted: 15 January 2018 / Published online: 24 January 2018

Abstract
Rapid economic growth and poor waste management have left Vietnam with severe water pollution problems. It is thus important to develop a model to evaluate the relationship between economic activities and water pollution to identify water pollution mitigation strategies within the context of economic development. Recent works have demonstrated the effectiveness of the input–output model in analyzing the interplay between the economy and the environment. To comprehensively understand this relationship, the behavior and trend of water pollution during a specified period should be investigated on. The interaction of different economic sectors and its impacts on water pollution should also be analyzed. For the Vietnamese economy, such aspects have not been fully addressed in previous studies. This work thus examines the state of water pollution in Vietnam as indicated by water quality parameters, total suspended solids and biological oxygen demand, with particular attention to the individual contribution of various economic sectors. The period between the years 2000 and 2011 is taken into account in this work. Environmentally extended input–output analysis coupled with vertical integrated coefficient method is used to analyze the interindustry linkages of sectors and to classify sector role as either key sector or pollution puller or pusher. The pollution trend reveals the tremendous increase in total suspended solids from 345,000 tonnes in 2000 to 1,199,000 tonnes in 2011, while the total biological oxygen demand increased from 43,400 tonnes in 2000 to 123,000 tonnes in 2011. Results show that the basic metals industry was the major contributor of total suspended solids, while the food, beverage and tobacco and agriculture, fishery and forestry sectors contributed most to the biological oxygen demand. The results of sectoral linkage evaluation highlight that food, beverage and tobacco and agriculture, fishery and forestry sectors were key sectors for both water quality parameters. These results provide environmental managers and policy maker insights on how to prioritize economic sectors to achieve emission reduction targets.

Keywords Water pollution · Environmentally extended input–output analysis · Pollution load · Emission components · Water waste management

Introduction

The comprehensive economic reforms from 1986, which have implemented open door policies and transformed Vietnam from a centrally planned economy into a market economy, have contributed significantly to the country's economic development (Que and Thanh 2001). Since the year 2000, the Vietnamese economy has prospered with annual economic growth rate up to above 5% and has been forecasted to be the 20th largest economy in the world by 2050 (PricewaterhouseCoopers 2017). However, this rapid economic development has resulted in the degradation of the ecosystem which also affects the living conditions of humans (The World Bank et al. 2002). Water environmental pollution is considered as the most important concern for Vietnam (Global Environmental Forum 2002). The main reason for this is the huge amount of wastewater coming from household activities and the operation of factories which is discharged into water bodies without treatment. The rapid industrialization and urbanization accompanied with poor wastewater management resulted in the drastic degradation of water quality (WEPA 2011; WSSA 2012). Furthermore, rapid population and economic growth resulted

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in the increase in demand for freshwater use. Tran (2010) reported that the rate of water consumption in industries, households and agriculture is increasing annually by 7, 9 and 3.4%, respectively. Meanwhile, the available freshwater resources are insufficient to meet these increasing demands for water use (WEPA 2011; Hoa et al. 2013). Only 70% of the population is likely to have access to safe water and sanitation (Tran 2010). Traditionally, the rural population uses groundwater pumped from private tube wells. However, there is recent evidence of arsenic contamination in the groundwater in several regions in Vietnam. Arsenic contamination in groundwater is caused by several factors. This includes contamination from the presence of arsenic in geological structures, the use of plant protection drugs containing arsenic and the release of arsenic from chemical factories to name a few (WSSA 2011). This arsenic contamination may cause serious health issues such as cancer or skin problems to people in regions of exposure (Jessen 2009). With such serious issues on water pollution and freshwater resource scarcity, there is thus a need to develop effective strategies to avoid further pollution of freshwater regions and to improve water quality.

To address these problems, the Vietnamese government has employed various strategies, ranging from regulatory to economic tools, but these actions have not seemingly brought positive effect. The reason is that the interrelationship between the economy and the environment has not been well understood (Le et al. 2013). Understanding this relationship is vital in identifying the key sources of pollution and in characterizing wastewater releases. This helps classify sectors as either pollution sellers, pollution purchasers or both. The environmental performance of an economic sector is linked to all other sectors by virtue of its supply chain (Leontief and Ford 1972). Furthermore, studies on the effect of production activities on water quality and water pollution data in Vietnam are limited. Meanwhile, researches on these aspects are carried carefully in developed countries and many developing countries. For example, Wu et al. (2017) proposed a method for quantifying a water pollution ecological compensation standard for China by using emergy theory. An analysis of virtual water pollution transfer embodied in economic activities was employed for Beijing's economy (Li et al. 2017), while Cazcarro et al. (2016) evaluated the relationship between structural production and environmental impact in the consideration of trade among countries. Sanchez-Choliz and Duarte (2005) analyzed the relationship between processes and water pollution for the Spanish economy to identify the roles of economic sector blocks as either generator or consumer of pollutants. Recently, several researchers made numerous efforts in proposing environmental friendly water pollution treatment methods. For example, Kamyab et al. (2015) looked at the efficiency of microalgae in the removal of pollutants from palm oil mill effluents. The wastewater was then investigated for its potential as biofuel substrate (Kamyab et al. 2016) and resource for fertilizer production (Kamyab et al. 2017). Microalgae can help significantly reduce water pollutants in wastewater as it utilizes the pollutants as nutrients for growth. Rezania et al. (2016) emphasized that the use of phytoremediation technology is likely to effectively treat heavy metal-polluted sites with low treatment cost. In Vietnam, there are only a few studies dealing with the interrelationship between economic activities and pollution flows so far. One of the most important references is the ICEM (2007) published by World Bank, which evaluated the national pollution flows by quantifying the different pollutants found in air, land and water media from the manufacturing industries. In addition, Hung et al. (2008) analyzed industrial pollution by focusing on the effect of trade liberalization on the pollution of sectors and subsectors. However, this only considered pollution from manufacturing sectors and did not consider pollution flows from other sectors such as agriculture, mining, services and consumer use. Furthermore, an analysis of the interrelationship among economic sectors and their individual pollution characteristics has not been discussed. A better understanding of these factors is useful in providing and selecting more environmentally friendly production supply chains such as the selection of less pollutive raw materials or inputs and the use of cleaner technologies.

According to Miller and Blair (2009), the best way to describe the interrelationship among economic sectors is to apply input–output (IO) analysis. IO analysis is an analytical framework first proposed by Professor Wassily Leontief in the 1930s and provides a quantitative description of how goods and services of an economy are related. In recognition of his work, he achieved the Nobel Prize in Economics in 1973 (Leontief 1936, 1970). IO analysis shows the interconnectedness of the economy's various sectors by considering the product of each sector both as goods for final demand (i.e., household and government consumption) and as raw materials in the production of commodities in the same sector or in other sectors. The framework captures both direct and indirect effects which may result from an economic shock. The IO model can be extended to capture other characteristics of the economic system. Hoa et al. (2016), for example, utilized the inoperability input–output model (IIM) developed by Haimes and Jiang (2001) and the vulnerability index proposed by Yu et al. (2014) to develop a multicriteria model for disaster vulnerability due to implications of energy policy. The extension of IO analysis to account for environmental impacts is known as environmentally extended input–output (EEIO) analysis, and it has been employed in the accounting of carbon emissions in supply chains for sustainability assessment (Suh 2009; Murray and Wood 2010) and in optimizing multiregional bioethanol supply chains in the presence of multiple objectives (Tan et al. 2008, 2009). Furthermore, IO analysis can be used to study the linkages between economic sectors and to determine their roles (Rasmussen 1956; Yan and Ames 1965). These authors utilized the Leontief inverse or Gosh inverse (Gosh 1958) to categorize sectors as either forward linkage, backward linkage or key sectors (those that act both as forward and as backward linkage sectors) or nonsignificant sectors in relation to purely economic aspects. Then, Sanchez-Choliz and Duarte (2003, 2005) expanded the scope of these models to include resources and emissions through the vertical integration coefficient (VIC) methodology. This facilitated the identification of sector roles in the economy with respect to environmental impacts. The integration of EEIO analysis with VIC may thus create a powerful framework for analyzing the interrelationship between sectors from the point of view of pollution.

In Vietnam, the application of EEIO for environmental–economic impact assessment was performed by Trinh and Nguyen (2013) and Le et al. (2013). Trinh and Nguyen (2013) employed EEIO to develop the framework of an interregional IO model for the years 2000 and 2007. Meanwhile, Le et al. (2013) used the integration of EEIO and VIC for the year 2000 to identify and quantify the sources and causes of water pollution, indirect emissions and direct emissions. Although Le et al. (2013) were successful in quantifying the total pollution load of main sectors, the direct and indirect pollution, they failed to show which sectors are pollution sellers and which are pollution purchasers. Furthermore, both Trinh and Nguyen (2013) and Le et al. (2013) failed to provide a time series analysis of the total pollution load trend induced by economic sectors.

To supplement this research gap, the main objective of this work focuses on looking at the changes in water quality from the year 2000 to 2011. The characterization of economic sectors in relation to water pollution in 2011 is then employed using EEIO coupled with VIC to identify the role of each economic sector as either consumer/purchaser or/and a producer/seller of water pollution. Finally, the combination of water quality trend and characterization of sectoral pollution will give a comprehensive picture on how economic sectors contribute to the main water quality parameters. The rest of paper is organized as follows. "Problem statement" section formalizes the problem that this research intends to address, and the methods are then discussed in "Methods" section. "Data collection" section mentions the database used in this work. Results and discussion are then mentioned in this section. Finally, conclusions and recommendations for future work are discussed.

Problem statement

In this work, the evaluation of how the different economic sectors in an economy contribute toward water pollution relies on results from both the water quality trend and the characteristics of sectors in relation to water pollution. The water quality trend focuses on the annual total pollution load contributed by the different sectors during the observed period. In contrast, the characteristics of sectors are obtained by taking into account water pollution flows and sectoral linkages during a specific year. The formal problem statement can thus be stated as follows:

- Given an economy with n number of economic sectors, an $n \times n$ technical coefficient matrix, **A**, can be obtained for a specific year which describes the interactions between the economic sectors. There is a $nx1$ vector, **x**, which represents the gross domestic output (GDO) of sectors. This is collected from the statistical databases according to the identified time series range.
- There are environmental flows in the production of goods and services from each sector, which are quantified using k number of quality indicators. In this context, only two indicators ($k = 2$) of water quality are considered, biological oxygen demand (BOD) level and total suspended solid (TSS). Thus, a $2 \times n$ vector of pollution intensity, **PI,** is estimated for each year in the observed period.

The problem then is to evaluate how each economic sector contributes to the yearly change in water quality and to identify whether an economic sector is a purchaser (has inputs from high polluting sectors) or seller (is an input to other economic sectors) of water pollution or both. Suggestions for policy makers and manufacturers on how to prioritize sectors to achieve emission reductions are given.

Methods

The framework developed for evaluating environmental quality parameters is shown in Fig. 1:

Generic input–output model The IO framework has been traditionally applied to study the interconnectedness between various economic sectors in an economic system. Its basic formulation includes a system of linear equations in which total output is equal to the amount used internally by the system, as intermediate consumption, plus the amount consumed by final customers (Leontief 1985). For an economy with n sectors, vector $\boldsymbol{x}$ denotes the GDO vector, $\boldsymbol{y}$ is the final demand vector, and **Z** is the $n \times n$ input–output transaction matrix which can be obtained from statistical databases. In matrix notion, the IO model can be stated as follows (Miller and Blair 2009):

$$\boldsymbol{x} = \boldsymbol{E}\boldsymbol{Z} + \boldsymbol{y} \quad (1)$$

where $\boldsymbol{E} = [1, 1, \ldots, 1]$. Let $\boldsymbol{A}$ represent the $n \times n$ technical coefficient matrix with elements, a_{ij} ($a_{ij} = Z_{ij}/x_j$), indicating the amount of product from the ith sector needed to produce

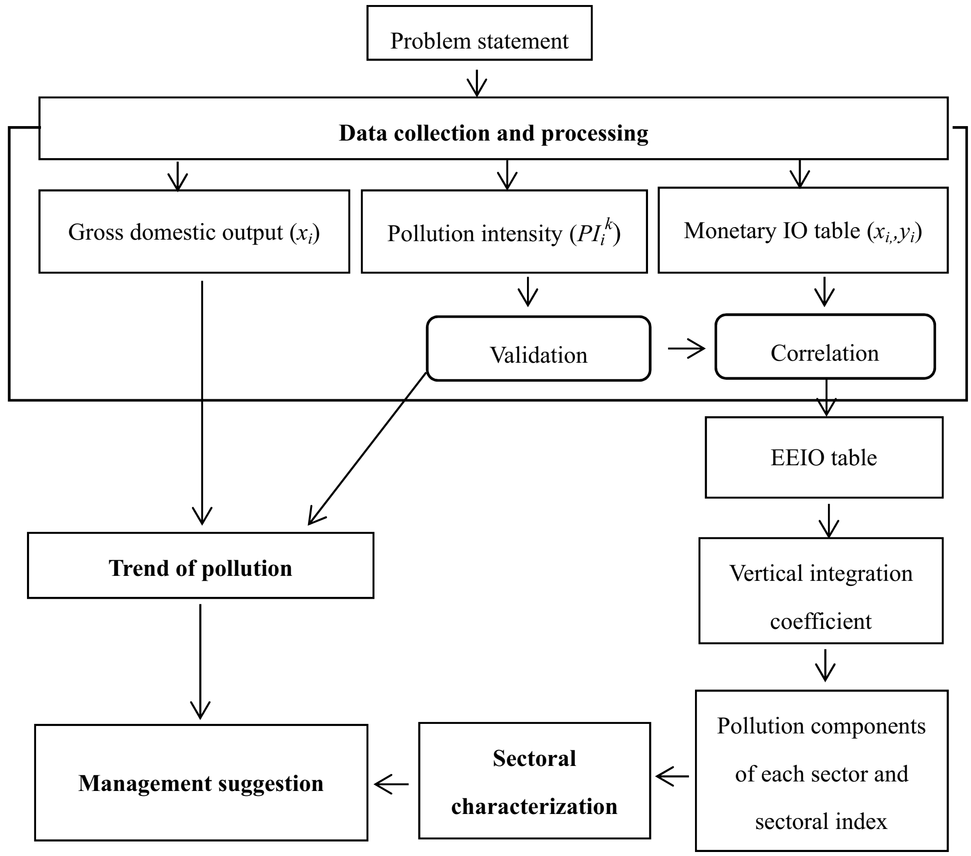

Fig. 1 Framework of water quality parameter assessment

one unit of output from the *jth* sector. Based on this, Eq. (1) can be rewritten as follows:

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} \tag{2}$$

where $\boldsymbol{I}$ denotes an identity matrix and $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ is the Leontief inverse matrix. Let α_{ij} represent the elements of the Leontief matrix. Then, the GDO of sector *i*, x_i, can be expressed as:

$$x_i = \sum_j \alpha_{ij} y_j \tag{3}$$

The detailed discussion of Eqs. (2) and (3) can be found in Miller and Blair (2009).

EEIO model, total pollution load and embedded pollution load

The extension of the IO model known as an environmentally extended input–output (EEIO) model is considered a useful technique for quantifying resource use and emissions resulting from the production activities of each sector (Butnar and Llop 2007). The amount of resource use or emissions from each sector is assumed to be linearly proportional to the size or output of that sector. Let **PI** denote pollution intensity which is the amount of pollution load emitted to produce one unit of monetary output for each sector as indicated by water quality parameters. Its elements, PI_i^k, represent pollution intensity corresponding to the *k*th water quality parameter type for sector *i* in a specific year. The $k \times n$ matrix **PI** is referred to as the pollution intensity matrix. The total pollution load (**PL**) can then be calculated using Eq. (4):

$$\mathbf{PL} = \mathbf{PI}\,\mathbf{x} \tag{4}$$

And the total pollution load for the *k*th parameter for sector *i*, PL_i^k is expressed as:

$$\mathrm{PL}_i^k = \mathrm{PI}_i^k x_i \tag{5}$$

Substituting x_i from Eq. (3) into Eq. (5), an equation for calculating the total pollution load of sector *i* is given as follows:

$$\mathrm{PL}_i^k = \mathrm{PI}_i^k \sum_j \alpha_{ij} y_j \tag{6}$$

The total pollution load of sector *i* provides the total annual pollution that is released to satisfy the whole production of this sector (x_i) which includes intermediate ($\sum_j a_{ij} x_j$) and final demands (y_i). The trend of the water quality parameters shows how the total pollution load varies in each sector during the observed period. Based on the water quality trend, the policy makers can identify which pollution mitigation methods should be implemented by focusing on sectors which contribute greatly toward increasing the BOD or TSS. Alternatively, strategies for managing sectors, which have significantly increasing potential for pollution generation, can be explored.

Besides sectoral total pollution load, there is embedded pollution load which is defined as the pollution load associated with the production of the final demand of a given sector. This is either emitted by the sector itself or attributed to the sector due to the purchase of inputs from other sectors (Sanchez-Choliz and Duarte 2003). It is different from the total pollution load of a sector which is associated with the pollution generated to obtain the GDO of that sector. Let DI_i^k denote the embedded pollution load for the kth parameter resulting from the production of demand y_i of sector i, which is given by:

$$\mathrm{DI}_i^k = \sum_j \mathrm{PI}_j^k \alpha_{ji} y_i \tag{7}$$

The detailed discussion of this formulation was given in Sanchez-Choliz and Duarte (2003). Equation (1) shows that when the final demand of sector i increases, there is a need to increase the production of that sector itself. In addition, there is also a need to increase the productivity of other sectors which are linked to it either directly (i.e., as a supplier) or indirectly (i.e., across the supply chain). As a result, the environmental burden as expressed in Eqs. 4 and 7 also increases. The evaluation of water pollution from economic sectors is clearly visualized when the total pollution load and embedded pollution load are decomposed into different components corresponding to product flows. The next section discusses this in more detail.

Vertical integration coefficient (VIC)

The VIC is employed by disaggregating each embedded pollution load from each sector into four components of pollution including true backward linkage (TB_i^k), semi-own pollution (SE_i^k), own pollution (OW_i^k) and final demand pollution (FI_i^k). The total pollution load of a sector is also decomposed into four components and includes true forward linkage (TF_i^k), SE_i^k, OW_i^k and FI_i^k. These components are related to the flow of goods which are produced to provide for the needs of manufacturing processes required for economic activities (Fig. 2). Table 1 shows the description of pollution components. The detailed discussion of the VIC methodology as introduced by Sanchez-Choliz and Duarte (2003) is given in "Appendix".

After calculating the pollution components, the component indices are given to assess sectoral characterization in relation to pollution flows. Table 2 shows the relative indices for VIC evaluation together with their description, while details for index computation are shown in Appendix. Based on these indices, sectors can be classified as either key sectors, forward linkage, backward linkage or nonsignificant sectors by using the guide in Table 3. It can be said that the values are low when they are close to 0 and high when they are close to 1. Backward linkage sectors are sectors with high pollution amount by virtue of high inputs (purchases) from other sectors; thus, they are called pullers. In contrast, if a sector manufactures goods, then the pollution generated by this sector is virtually sold to other sectors without it finally returning to this sector, in which case this sector is considered as a forward linkage sector and called a pusher (Sanchez-Choliz and Duarte 2003, 2005). Key sectors are those that act both as backward and as forward linkage sectors. According to Shmelev (2010), key sectors have high propensity to cause pollution across the economy in comparison with other sector types. The term "self-polluter by

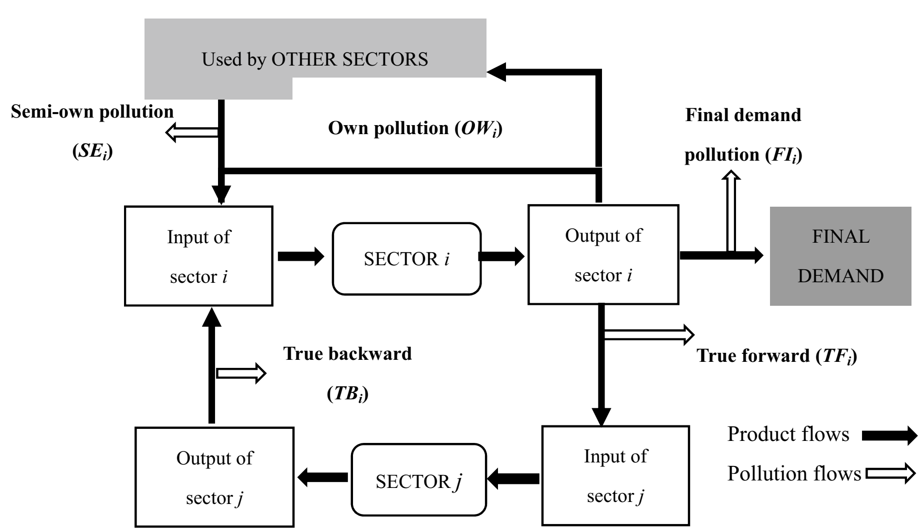

Fig. 2 Pollution components in response to flows of product

Table 1 Description of pollution components

Components of pollution		Descriptions
Name	Abbreviation	
True backward linkage	TB_i^k	kth parameter representing pollution released from other sectors to supply input for sector i
Semi-own pollution	SE_i^k	kth parameter representing pollution emitted by sector i to produce input for other sectors, and then, this input continuously produces other inputs that sector i purchases to produce the final demand
Own pollution	OW_i^k	kth parameter expressing pollution released from sector i to create input which is used by itself
Final demand pollution	FI_i^k	kth parameter representing pollution directly emitted by the production of final demand
True forward linkage	TF_i^k	kth parameter representing pollution directly generated in the production of intermediate demand to supply inputs for other sectors

Table 2 Description of indices for pollution components

Sectoral indices	Description
$\varepsilon_{k,i}^1 = \frac{TB_i^k}{\sum_{j=1}^n TB_j^k}$	Vertically integrated backward linkage index
$\varepsilon_{k,i}^2 = \frac{TF_i^k}{\sum_{j=1}^n TF_j^k}$	Vertically integrated forward linkage index
$\varepsilon_{k,i}^3 = \frac{z_i^k}{\sum_{j=1}^n z_j^k}$, with $z_i^k = SE_i^k + OW_i^k$	Vertically integrated self-pollution by input index
$\varepsilon_{k,i}^4 = \frac{FI_i^k}{\sum_{j=1}^n FI_j^k}$	Vertically integrated self-pollution by demand index

$\varepsilon_{k,i}^1$, $\varepsilon_{k,i}^2$, $\varepsilon_{k,i}^3$, $\varepsilon_{k,i}^4$ corresponding k-pollutant type of sector i

demand" means that pollution is mainly emitted from the production of final demand. In contrast, sectors where most of the pollution is due to own pollution or semi-own pollution are considered as self-polluter by inputs.

Data collection

Water quality parameters

In terms of harmful effects, there are many substances such as pesticides and fertilizers from agricultural activities, heavy metals from mining activities and chemicals from industries, which are considered as major risks to human health and the ecosystem. However, data on these problems are limited and the monitoring of hazardous substances has not been systematically conducted. Thus, recent researches

Table 3 Sectoral characterization based on indices for pollution components

Sector indices				Relevant characteristics
$\varepsilon_{k,i}^1$	$\varepsilon_{k,i}^2$	$\varepsilon_{k,i}^3$	$\varepsilon_{k,i}^4$	
High	High	High	High	Key sector. Self-polluter by inputs and demand
			Low	Key sector. Self-polluter by inputs
		Low	High	Key sector. Self-polluter by demand
			Low	Key sector. Non-self-polluter
	Low and $d_i > 0$	High	High	Backward linkage sector. Self-polluter by inputs and demand
			Low	Backward linkage sector. Self-polluter by inputs
		Low	High	Backward linkage sector. Self-polluter by demand
			Low	Backward linkage sector. Non-self-polluter
Low	High and $d_i < 0$	High	High	Forward linkage sector. Self-polluter by inputs and demand
			Low	Forward linkage sector. Self-polluter by inputs
		Low	High	Forward linkage sector. Self-polluter by demand
			Low	Forward linkage sector. Non-self-polluter
	Low	High	High	Self-polluter by inputs and demand
			Low	Self-polluter by inputs
		Low	High	Self-polluter by demand
			Low	Nonpolluter

d_i is defined in Eq. (23) in "Appendix" have focused on main water quality parameters in Vietnam with available data collected from government databases or obtained from secondary data. Trinh and Nguyen (2013) and Nguyen (2015) indicated that total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD) and ammonia–nitrogen (NH4–N) are important parameters for measuring water quality in Vietnam and are used as indicators of water pollution load. These parameters are used to determine the level of suspended solids, organic substances, nutrition and lubricant. The decomposition processes of these substances may consume dissolved oxygen which is needed for the growth of species and organisms inside bodies of water. As a consequence, when the amount of these substances inside water bodies increases, the amount of dissolved oxygen decreases. This may lead to the death of fish and other aquatic organisms. In other words, at high concentrations, these parameters indicate low water quality. However, data for these indicators for Vietnamese economic sectors are not available from government statistics. Furthermore, global data only allow for the calculation of TSS and BOD load. Thus, these two parameters are chosen for analysis in this paper. The method presented here can easily be augmented once more information becomes available. Details for data collection and data validation are mentioned in "Pollution intensity of water pollution load (PI) and validation process" section.

Gross domestic output (GDO) and IO table

To calculate the annual total pollution load of sectors in the period 2000–2011 using Eq. (4), the GDO of different sectors should be known. These data can be obtained from existing IO tables in the years 2000, 2007 and 2011 (GSO 2003, 2009, 2013). For other years, the GDO of sectors can be achieved from the General Statistics Office (GSO) Web site (GSO 2006, 2011). To analyze the interrelationship between environmental pollution and economic activities, the integration of EEIO and VIC approaches is applied. However, since these methods can be applied for specific years with the condition of IO table availability, the newest IO table of Vietnam in 2011 is employed for this purpose. The 2011 IO table contains 138 columns and rows with 6 final demand columns and 4 value-added rows. The framework of the 2011 IO table is shown in Table 4, while the complete IO table is available from the GSO Web site (GSO 2013).

The Vietnamese IO table was compiled relying on the Provisional Central Product Classification System, while the manufacturing industries in industrial pollution projection system (IPPS) (Hettige et al. 1995) were classified according to International Standard Industrial Classification version 2 (ISIC 2). The manufacturing sectors from the original IO table are thus reallocated to be consistent with IPPS data. The detailed procedure can be found in Le et al. (2013). After reallocating, the IO table with 138 sectors is aggregated and classified into 18 main sectors, which is more convenient for environmental pollution computation. This classification is compatible with the classifications found in the IO table from GSO (2013) and the classification according to the International Standard Industrial Classification version 3 (ISIC 3). The description of the 18 sectors and sectoral GDO in 2000 and 2011 is shown in Table 5. In this table, the proportion of sectoral GDO, which is calculated using the average GDO of years 2000 and 2011, is also mentioned. Based on Table 5, it is shown that sectors which contribute the highest amount of GDO to the economy include Sectors 1 (agriculture, fishery and forestry) (13.4%), Sector 10 (manufacturing of fabricated metal products, machinery and equipment) (12.3%) and Sector 3 (food, beverage and tobacco) (11.6%). Sectors which contribute low GDO include Sector 5 (manufacture of wood and wood products) (0.7%), Sector 6 (manufacture of paper and paper products, printing and publishing) (1.3%) and Sector 17 (government services) (1.9%). However, the total pollution load of sectors may be different from this ranking because they do not only depend on GDO, but also rely on pollution intensity (PI). Sectors with less GDO may have very high total pollution load if they have high PI values. The next part discusses the PI of the different economic sectors.

Pollution intensity of water pollution load (PI) and validation process

To compute the total water pollution load contributed by each sector, there is a need to determine the pollution intensity (PI), which is the amount of pollution load generated in the production of one monetary unit output of each sector (kg/million VND in a specific year). The PI data of economic sectors in terms of water quality parameters in Vietnam are not available from government statistics; thus, secondary data are used to estimate the PI. Trinh and Nguyen (2013) estimated the PI of water quality indicators for the years 2000 and 2007 based on data published by government, survey results in enterprise, information on wastewater calculations employed by the National Environmental Agency and study results obtained by the Institute of Tropical Technology and Environmental Protection. Trinh and Nguyen (2013) used the IO tables of 2000 and 2007 which were disaggregated into 12 economic sectors. This included nine nonmanufacturing sectors (Sectors 1, 2, 12, 13, 14, 15, 16, 17 and 18, as listed in Table 5) and three manufacturing sectors. The classification of nine nonmanufacturing sectors in Trinh and Nguyen (2013) is compatible with the classification of nine nonmanufacturing sectors used in this study; thus, PI data of these nine sectors were obtained from Trinh and Nguyen (2013). However, the classification of

Table 4 Framework of the Vietnamese IO table for 2011

Billion VND	Sector code	Name	Intermediate demand (ID)				Final demand (y)					x
							Final consumption					
			1	2	…	18	HH	G	C	Ex	Im	
Intermediate input	1	Agriculture	150,641	6		722	160,099	0	213,201	178,657	53,106	1,029,583
	2	Mining, quarrying	815	14,410	…	118	5392	0	26,270	235,050	17,971	339,396
	…	…	…	…	…	…	…	…	…	…	…	…
	18	Personal, community…	376	575	…	16,456	196,235	45,329	0	9354	38,428	243,780
Pollution intensity		TSS	0.039	0.045	…	0.001			(Kg/million VND)			
		BOD	0.033	0.020	…	0.002						

Ex export, *Im* import, *HH* household consumption, *G* government consumption, *C* capital and investment

manufacturing sectors in Trinh and Nguyen (2013) is not compatible with the classification used in this work. Therefore, PI of nine manufacturing sectors (Sectors 3, 4, 5, 6, 7, 8, 9, 10 and 11 as listed in Table 5) is obtained from another database—IPPS (Hettige et al. 1995), which was proposed by the Infrastructure and Environment Team of World Bank. IPPS combines the data of industrial activity with data on pollution release. IPPS relates the PI with respect to value added, GDO and employment (Hettige et al. 1995). In this context, PI with respect to GDO is used because of the availability of GDO data. The PI in the IPPS for the year 1997 (pound per million 1987 US dollars) is adjusted to the correlative year in Vietnamese currency (e.g., kg per million 2011 VND) using the deflation factor based on consumer price index (CPI), as outlined by Mani and Jha (2006).

IPPS has been used in many countries such as Nigeria (Oketola 2007; Odesanya et al. 2012), India (Pandey 2005), Lagos (Oketola and Osibanjo 2007), Brazil and Latin American (Aguayo et al. 2001). In Southeast Asia, the estimation of pollution flows for industrial sectors was also applied for Malaysia (Oketola and Osibanjo 2009), Lao PDR (GMS Environmental Operation Center 2014), Cambodia (San et al. 2018) and Thailand (Benoit and Craig 2001). In Vietnam, ICEM (2007) adapted the database from IPPS to compute the total pollution load of several pollutants for specific regions of the country in the year 2004. According to this report, many existing industrial operations in Vietnam now make use of technologies which are over 15–20 years old and are similar to technologies which operated in the USA during the late 1980s. Thus, the existing Vietnamese industrial technologies are well represented by the underlying technologies reflected in IPPS. Furthermore, ICEM (2007) also carried out the validation of IPPS data by comparing it with data from CTC Vietnam. Correlation coefficients were calculated using the pollution load parameters TSS and BOD between CTC data and IPPS data. This was performed at the provincial and sectoral levels. The results were then ranked in increasing order. The purpose of this process was to know whether high values of total pollution load estimated from the IPPS data well corresponded with high values of total pollution load obtained from CTC data. The results of this process are shown in Tables 6 and 7.

Table 6 indicates high positive correlation for both TSS and BOD (0.71 and 0.69) which implies that there is a close match in terms of priority ranking between these two data sets. Table 7 gives the correlation coefficient at the sectoral level which resulted in relatively low values of correlation (TSS: 0.24 and BOD: 0.33). However, ICEM (2007) then performed a statistical test of the level of significance. The results show that differences in total pollution load between sectors of these two data sets are not statistically significant. This means that PI data from IPPS are suitable to use for the Vietnam scenario.

Table 5 Nomenclature of 18 economic sectors and their GDO for the years 2000 and 2011

Sector code	Economic sectors	GDO in 2011 (million VND)	GDO in 2000 (million VND)	% GDO
1	Agriculture, fishery and forestry	1029,582,812	162,539,580	13.4
2	Mining and quarrying	339,396,098	59,382,594	4.4
3	Food, beverage and tobacco	891,436,918	135,436,416	11.6
4	Textile, wearing apparel and leather industries	479,651,951	76,460,656	6.2
5	Manufacture of wood and wood products	54,681,606	10,373,508	0.7
6	Manufacture of paper and paper products, printing and publishing	98,490,343	11,247,212	1.3
7	Manufacture of industrial chemicals	220,750,863	17,637,509	2.9
8	Manufacture of nonmetallic mineral products	199,961,214	25,766,223	2.6
9	Basic metal industries	157,494,854	19,087,004	2.0
10	Manufacturing of fabricated metal products, machinery and equipment	944,851,168	43,058,699	12.3
11	Other manufacturing industries	473,880,422	21,862,409	6.2
12	Electricity, gas and water	175,245,178	20,208,657	2.3
13	Construction	684,211,422	87,649,355	8.9
14	Trade and repairing services	615,591,705	84,381,979	8.0
15	Transportation and communication	542,928,571	28,442,463	7.1
16	Finance, real estate and business services	400,831,479	41,889,501	5.2
17	Government services	145,562,397	22,251,509	1.9
18	Personal, community and household services	243,780,331	80,621,188	3.2

Table 6 Spearman's rank correlation between estimated BOD and TSS at the provincial level

	IPPS BOD	CTC BOD	IPPS TSS	CTC TSS
IPPS BOD	1			
CTC BOD	0.69	1		
IPPS TSS	0.77	0.66	1	
CTC TSS	0.71	0.96	0.71	1

Table 7 Spearman's rank correlation between estimated BOD and TSS at the sectoral level

	IPPS BOD	CTC BOD	IPPS TSS	CTC TSS
IPPS BOD	1			
CTC BOD	0.33	1		
IPPS TSS	0.74	0.2	1	
CTC TSS	0.37	0.95	0.24	1

After the PI of sectors is obtained, the extended IO table is generated and is found in Table 8.

Results and discussion

Total pollution load trend

In the manufacture of goods and services, the products of each sector are distributed into intermediate demand (inputs to other sectors) and final demand (i.e., household and government consumption). Each process has an associated pollution load. Thus, the total pollution load of an economic sector is simply the sum of the pollution associated with the production of goods or services in the sector to serve all requirements needed by the economy to operate as indicated in Eq. (4). The trend of the total water pollution load as indicated by the water quality parameters represents the variations in total pollution load within the period of 2000–2011. This trend is given for two main water quality indicators—TSS and BOD.

Trend of total suspended solids (TSS)

The TSS trend is shown in Fig. 3. In detail, the line "sum" representing the TSS of the entire economy indicates that in the year 2000, TSS was approximately 300,000 tonnes, but this number increased to more than 1,000,000 tonnes by the year 2011. It means the TSS of the whole economy increased 4 times within 11 years. The reason is that the GDO of each sector increased quickly from 2000 to 2011 (except 2002) (Table 3) as a result of rapid economic growth in Vietnam. At the sectoral level, results also indicate the rapid increase

Table 8 Water quality parameter-extended IO table in 2011

	i	*j* 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Y
Economic sector (billion VND)	1	150,642	6	303,083	4,273	11,065	1130	5290	673	1	61	7918	36	521	9117	35,178	872	142	723	498,852
	2	816	14,411	2629	364	91	963	2963	16,426	4292	1969	18,198	13,268	11,876	579	1236	456	1	119	248,742
	3	132,430	21	288,153	81	100	144	3892	58	5	111	110	32	54	7987	47,153	241	208	815	409,842
	4	2148	173	1398	268,130	581	3662	455	896	22	8004	7784	398	1711	6137	947	1243	318	606	175,040
	5	809	55	315	255	16,119	1721	319	527	5	1694	55,039	24	5104	307	345	269	148	244	− 28,616
	6	297	64	16,093	5671	639	44,367	2827	7380	51	3434	6872	266	3807	2371	7455	2899	3360	3560	− 12,923
	7	65,264	10,224	14,349	45,432	2800	5295	95,428	5190	317	23,205	70,890	738	5635	1574	960	2353	525	18,914	− 148,341
	8	1077	416	2168	313	1098	124	4473	59,073	2028	11,832	3208	313	143,531	1429	991	619	184	601	− 33,516
	9	308	9888	3232	721	877	150	1710	2839	120,586	164,154	7291	241	97,213	625	448	864	55	154	− 253,859
	10	4173	3340	9941	4741	613	1527	2849	4408	2438	380,223	16,117	6024	31,847	8241	9725	3692	3311	4431	447,211
	11	42,113	33,725	36,793	16,618	1454	9273	26,320	14,163	3405	104,370	145,229	11,938	40,854	30,714	71,559	8226	5740	8218	− 136,833
	12	7764	3066	10,521	9679	1013	3714	4786	13,014	3063	15,611	8791	26,473	3949	12,379	11,971	7445	2539	5075	24,393
	13	791	1733	414	413	31	30	61	115	44	1143	1837	1055	29,857	1830	5080	967	2937	1638	634,237
	14	28,308	5852	45,229	17,767	1779	4413	11,346	8348	2465	46,821	16,450	2971	20,533	10,152	18,021	2162	2272	3375	367,326
	15	8889	15,681	24,149	7105	1142	2986	9864	3857	1760	19,189	7033	2140	15,783	27,561	44,683	18,310	8585	7692	316,520
	16	2551	2997	8991	4518	469	566	4576	2305	1065	12,106	5862	3609	9540	16,623	17,830	119,507	5773	12,434	169,510
	17	26	27	13	23	10	2	9	6	4	32	29	11	21	4	76	42	4556	162	140,511
	18	376	575	784	295	66	79	252	335	46	616	230	5347	671	984	965	814	2399	16,456	212,491
PI	TSS	0.03945	0.04458	0.04738	0.00851	0.00540	0.53005	0.19988	0.02480	5.34863	0.00243	0.21248	0.01147	0.03610	0.03792	0.00001	0.00062	0.00092	0.00123	Kg/million VND
	BOD	0.03288	0.01950	0.05010	0.00423	0.00118	0.15847	0.02850	0.00064	0.06701	0.00019	0.00287	0.00008	0.00000	0.00004	0.00000	0.00228	0.00226	0.00227	

PI of 3, 4, 5, 6, 7, 8, 9, 10, 11 is from IPPS data, and the remaining is from Trinh and Nguyen (2013)

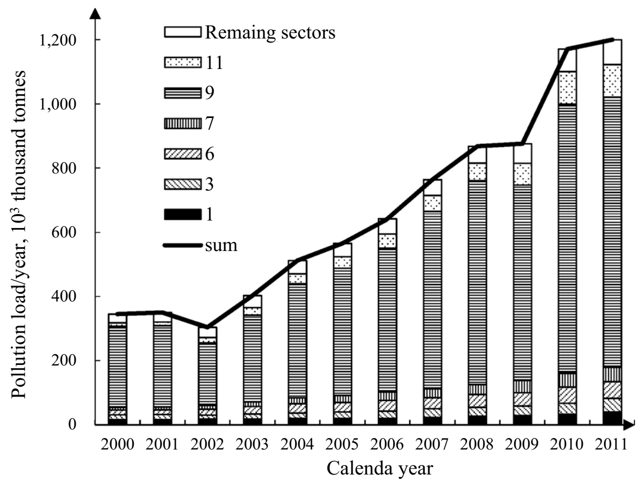

Fig. 3 The trend of TSS pollution load

in TSS of each sector. The variation of TSS among the top 6 most polluting sectors and the remaining sectors in the period is also shown in Fig. 3. It can be seen that Sector 9 (basic metal industries), despite comprising only a small proportion of GDO (2% as shown in Table 5), was a main contributor to TSS, accounting for 71% of TSS within the period of consideration. This results from the high PI of this sector (9.88 kg/million VND on average within the period considered) which was 10 times larger than that of the second highest source (Sector 6 with 0.98 kg/million VND). The second source of TSS was Sector 11 (other manufacturing sectors), accounting for 7% of average TSS load of the whole period. Following these sectors are Sector 6 (manufacture of paper and paper product, printing and publishing) and Sector 7 (manufacturing of industrial chemicals). These sectors had high TSS because many of the processes in these sectors are water intensive. In addition, wastewater treatment from these sectors was not well employed (ICEM 2007). Sector 3 (food, beverage and tobacco) and Sector 1 (agriculture, fishery and forestry) show mid-level of TSS. These sectors had lower TSS per unit of GDO, but they had the highest proportion of GDO contribution (see Table 5). The rest of the sectors had insignificant TSS contribution because they had low PI and low GDO.

From this study, the total amount of TSS due to economic activities in the year 2000 was 344,942 tonnes. The results obtained by other researchers in Vietnam such as Trinh and Nguyen (2013) were 71,391 tonnes of TSS. Trinh and Nguyen (2013) made use of a PI factor which was estimated based on data published by the government as explained in previous section. The results indicate a large difference between the two studies with + 0.79 dissimilarity. The difference is attributed to the large difference in the pollution intensity (PI) of TSS used in these two studies. The average PI of TSS of all manufacturing sectors in this study is 1.7479 kg/million VND. This is almost the same as the result obtained by Le et al. (2013) with 1.8995 kg/million, but it is 28 times higher than in the study of Trinh and Nguyen (2013) which had an average PI of 0.06 kg/million VND. If the PI of Sector 9 (basic metal industries) (13.19 kg/million VND) was replaced by the PI of Sector 6 (manufacture of paper and paper products, printing and publishing) (1.307 kg/million VND), which had the second highest PI, the total TSS in the year 2000 will be 118,154 tonnes. Hence, the dissimilarity can be reduced to only + 0.4. Therefore, it can be said that the high value of PI of TSS in Sector 9 (basic metal industries) obtained from IPPS explains the main difference in TSS between the results obtained here and those obtained by Trinh and Nguyen (2013).

Trend of biological oxygen demand (BOD)

The results of total BOD pollution load indicate that BOD pollution load was 8 times less than TSS. However, the BOD of the entire economy also quickly increased from 42,600 tonnes in 2000 to 121,360 tonnes in 2011 (Fig. 4). Sector 3 (food, beverage and tobacco) was the main contributor of BOD with an average amount of 24,834 tonnes, accounting for 35% of total BOD generation. The next major source of BOD was Sector 1 (agriculture, fishery and forestry) with 19,649 tonnes accounting for 28% of the total average BOD in this period. Two of these sectors show high level of total BOD pollution load because of high sectoral activity as reflected by the high GDO. The mid-level contributor of BOD was Sector 6 (manufacture of paper and paper product, printing and publishing), Sector 9 (basic metal industries), Sector 2 (mining and quarrying) and Sector

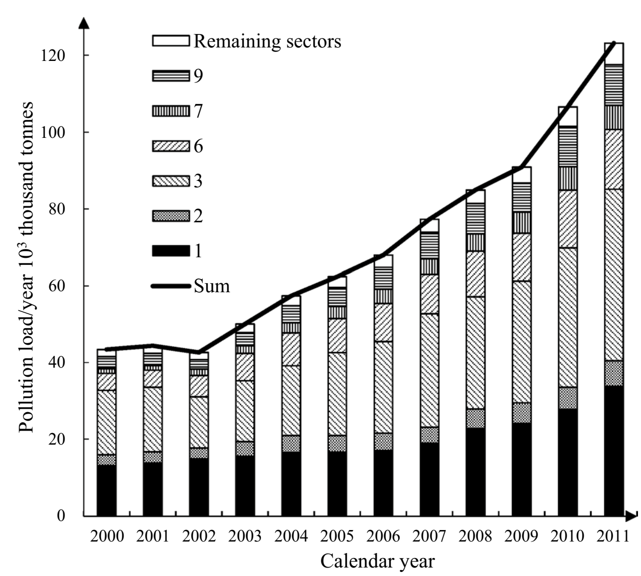

Fig. 4 The trend of BOD pollution load

7 (manufacturing of industrial chemicals). These sectors were water-intensive industries, but their GDO was low. The remaining sectors had low-level BOD because of very low PI values and sectoral GDO; thus, these sectors were considered as insignificant.

The total amount of BOD in the year 2000 for the whole economy was 43,419 tonnes which is − 0.017 dissimilar to the work of Trinh and Nguyen (2013). This points out that there is a slight difference between estimating the PI of BOD obtained from the IPPS and that obtained from the government database. In other words, the IPPS data can be well applied for BOD calculations in Vietnam. The trend in performance of the water quality indicators highlights the variations in total pollution load generated by economic sectors to satisfy the demand for products and services. Meanwhile, these results do not reflect the role of sectors and their sectoral connections in terms of pollution. Thus, there is a need to decompose each water pollutant load and embedded pollution load into different components to characterize sectors according to their contribution to water pollution. This facilitates the classification of each sector as consumer/purchaser or producer/seller of water pollution. The next section explains this in more detail.

Role of sectors in relation to water pollution

This subsection uses formulas which are discussed in detail in Appendix to calculate for the components of TSS and BOD parameters in the year 2011. Table 9 in Appendix shows the total pollution load (PL_i^k), the embedded pollution load (DI_i^k) and pollution components in 2011. In Table 9, it can be seen that Sector 9 (basic metal industries) was responsible for majority of TSS. A total of 95% of TSS from Sector 9 was sold to other sectors of the Vietnamese economy. Thus, Sector 9 is considered a pollution producer or so-called pollution pusher. In contrast, Sector 10 (manufacturing of fabricated metal products, machinery and equipment) and Sector 13 (construction) are of the opposite extreme case and are considered as TSS purchasing sectors and called pollution consumers/pullers. Sector 10 (manufacturing of fabricated metal products, machinery and equipment) required inputs from other sectors which corresponded to purchase 47% of the TSS generated by other sectors of the economy. Similarly, Sector 13 (construction) purchased more than 39%.

The largest purchaser of BOD was Sector 10 (manufacturing of fabricated metal products, machinery and equipment), which purchased 50,500 tonnes (34%) of total BOD from other sectors (Table 9). The second highest purchaser of BOD was Sector 13 (construction) purchasing 45,400 tonnes (31%). These sectors are thus pollution pullers again. Meanwhile, Sector 9 (basic metal industries) was again considered as a pollution pusher and was responsible for contributing the highest BOD, with 58% of its total pollution load distributed to other sectors.

From this result, pollution-pushing sectors and pollution-pulling sectors with respect to TSS and BOD can be identified. In order to identify which sectors should be prioritized when it comes to pollution reduction, the sectoral indices are calculated and characterized (Table 10). These indices are classified as high and low values as indicated in Table 3. The 18 sectors are then classified into 3 groups based on whether the index value score is high, intermediate or low. The top 6 sectors which received the highest index scores are classified as high, while the last 6 sectors with the smallest index scores are classified as low. Based on Table 3, the characteristic of each sector in relation to TSS and BOD for the year 2011 is given in Table 11. Table 3 provides the guideline on how sectors are classified. Sector 1 (agriculture, fishery and forestry) and Sector 3 (food, beverage and tobacco) are considered key sectors for both TSS and BOD. These sectors had the highest propensity to cause water pollution across the economy. Table 12 summarizes the key results on sector classification based on their TSS and BOD contribution.

Pollution reduction priority

Analyzing the total pollution load trend in the period 2000 to 2011 and evaluating the pollution components in the year 2011 provide insights for the development of waste management strategies. Pollution reduction strategies should focus on:

(1) Sectors with high total pollution load during the period. This includes Sector 9 (basic metal industries) for TSS; Sector 1 (agriculture, fishery and forestry) and Sector 3 (food, beverage and tobacco) for BOD.
(2) Sectors having high water pollution impact based on their interrelationship with other economic sectors. Sector 1 (agriculture, fishery and forestry) and Sector 3 (food, beverage and tobacco) have been identified as key sectors in terms of TSS and BOD. Sector 13 (construction) and Sector 10 (manufacturing of fabricated metal products, machinery and equipment) were considered pollution pullers, while Sector 9 (basic metal industries) was considered as pollution pusher.

To decrease water pollution, there are several suggestions to help government, policy makers, household sectors and industrial manufactures in the development and effective implementation of strategies. An example strategy for pollution-pulling sectors is to improve the efficiency of technologies employed in their processes. This can potentially reduce the required inputs of industries and sectors, thereby reducing the pollution associated with sector requirements.

Table 9 Sectoral performance in terms of pollution components in 2011

Parameters	Sector code																		
	Components	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
TSS (thousand tonnes)	TB_i^k	208.5	282.5	320.8	160.5	− 32.7	− 13.1	− 175.9	− 45.1	− 29.5	3364.6	− 222.3	17.1	2813.6	125.6	221.1	61.1	71.0	107.6
	TF_i^k	15.1	3.3	10.6	0.7	0.5	64.9	101.5	6.2	6872.0	0.4	148.8	1.7	0.7	8.9	0.0	0.1	0.0	0.0
	SE_i^k	2.1	0.2	2.0	0.0	0.0	− 0.1	− 2.9	0.0	− 55.2	0.1	− 4.3	0.0	0.1	0.3	0.0	0.0	0.0	0.0
	OW_i^k	3.7	0.5	10.2	1.9	− 0.1	− 5.7	− 24.8	− 0.4	− 4616.5	0.8	− 14.7	0.1	1.0	0.2	0.0	0.0	0.0	0.0
	FI_i^k	19.7	11.1	19.4	1.5	− 0.2	− 6.8	− 29.7	− 0.8	− 1357.8	1.1	− 29.1	0.3	22.9	13.9	0.0	0.1	0.1	0.3
	DI_i^k	234.0	294.3	352.4	163.9	− 32.9	− 25.8	− 233.2	− 46.3	− 6059.1	3366.5	− 270.5	17.4	2837.6	140.1	221.1	61.2	71.1	107.9
	PL_i^k	40.6	15.1	42.2	4.1	0.3	52.2	44.1	5.0	842.4	2.3	100.7	2.0	24.7	23.3	0.0	0.2	0.1	0.3
	d_i	193.4	279.1	310.2	159.9	− 33.2	− 78.0	− 277.4	− 51.3	− 6901.5	3364.2	− 371.1	15.4	2812.9	116.7	221.1	61.0	71.0	107.6
BOD (thousand tonnes)	TB_i^k	13.7	5.5	20.2	7.3	− 1.4	− 0.4	− 5.5	− 1.5	− 3.8	50.5	− 7.6	0.4	45.4	4.6	11.4	2.1	2.7	4.6
	TF_i^k	12.6	1.5	11.3	0.3	0.1	19.4	14.5	0.2	86.1	0.0	2.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0
	SE_i^k	1.7	0.1	2.1	0.0	0.0	0.0	− 0.4	0.0	− 0.7	0.0	− 0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	OW_i^k	3.1	0.2	10.8	0.9	0.0	− 1.7	− 3.5	0.0	− 57.8	0.1	− 0.2	0.0	0.0	0.0	0.0	0.2	0.0	0.0
	FI_i^k	16.4	4.9	20.5	0.7	0.0	− 2.0	− 4.2	0.0	− 17.0	0.1	− 0.4	0.0	0.0	0.0	0.0	0.4	0.3	0.5
	DI_i^k	34.9	10.7	53.6	9.0	− 1.4	− 4.2	− 13.7	− 1.6	− 79.3	50.7	− 8.2	0.4	45.4	4.6	11.4	2.6	3.0	5.1
	PL_i^k	33.9	6.6	44.7	2.0	0.1	15.6	6.3	0.1	10.6	0.2	1.4	0.0	0.0	0.0	0.0	0.9	0.3	0.6
	d_i	1.1	4.1	8.9	7.0	− 1.5	− 19.8	− 20.0	− 1.7	− 89.9	50.5	− 9.6	0.4	45.4	4.6	11.4	1.7	2.7	4.5

d_i is defined in Eq. (23) in "Appendix"

Table 10 Sectoral indices

Water quality parameters	Sectoral indices	Sector code 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
TSS	$\varepsilon^1_{k,i}$	0.0252	0.0341	0.0388	0.0194	0.0040	0.0016	0.0213	0.0055	0.0036	0.4067	0.0269	0.0021	0.3401	0.0152	0.0267	0.0074	0.0086	0.0130
	$\varepsilon^2_{k,i}$	0.0021	0.0005	0.0015	0.0001	0.0001	0.0090	0.0140	0.0009	0.9498	0.0001	0.0206	0.0002	0.0001	0.0012	0.0000	0.0000	0.0000	0.0000
	$\varepsilon^3_{k,i}$	0.0012	0.0002	0.0026	0.0004	0.0000	0.0012	0.0058	0.0001	0.9839	0.0002	0.0040	0.0000	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000
	$\varepsilon^4_{k,i}$	0.0130	0.0073	0.0128	0.0010	0.0001	0.0045	0.0196	0.0005	0.8964	0.0007	0.0192	0.0002	0.0151	0.0092	0.0000	0.0001	0.0001	0.0002
BOD	$\varepsilon^1_{k,i}$	0.0725	0.0294	0.1070	0.0389	0.0073	0.0021	0.0292	0.0082	0.0200	0.2679	0.0401	0.0023	0.2408	0.0245	0.0604	0.0110	0.0142	0.0243
	$\varepsilon^2_{k,i}$	0.0849	0.0098	0.0759	0.0022	0.0008	0.1308	0.0975	0.0011	0.5804	0.0002	0.0135	0.0001	0.0000	0.0001	0.0000	0.0024	0.0000	0.0002
	$\varepsilon^3_{k,i}$	0.0579	0.0038	0.1536	0.0114	0.0002	0.0209	0.0471	0.0001	0.6985	0.0008	0.0031	0.0000	0.0000	0.0000	0.0000	0.0020	0.0001	0.0004
	$\varepsilon^4_{k,i}$	0.2428	0.0718	0.3040	0.0110	0.0005	0.0303	0.0626	0.0003	0.2518	0.0013	0.0058	0.0000	0.0000	0.0002	0.0000	0.0057	0.0047	0.0071

On the side of government and policy makers, they need to devise appropriate regulations for wastewater management especially in sectors contributing to high pollution load and/or having high water pollution impact.

For manufacturers, the best way to reduce pollution is to lower the value of PI. In Sector 9 for example, improvements include strategies which reduce the TSS intensity of processes. This can be obtained by applying cleaner technologies or by improving wastewater treatment systems. In addition, the manufacturers can reduce pollution by shifting from highly pollutive raw materials to less pollutive inputs or by improving process efficiency.

For household sectors, there is a need to manage household consumption by encouraging the use of more environmentally friendly products. Furthermore, the decrease of consumption also helps.

Conclusions and recommendations

This study can be considered as a preliminary investigation of the total water pollution load resulting from economic activities in Vietnam, as indicated by water quality parameters. This can potentially help environmental managers and policy makers in monitoring water pollution in Vietnam. The methodology presented makes use of available IO tables in the years 2000, 2007 and 2011 and other economic data in Vietnam to calculate for two water quality indicators (e.g., TSS and BOD). The results show a tremendous increase in TSS, from 345,000 tonnes in 2000 to 1,199,000 tonnes in 2011, while the total BOD increased from 43,400 tonnes in 2000 to 123,000 tonnes in 2011. For TSS, Sector 9 (basic metal industry) was the main contributor, while Sector 3 (food, beverage and tobacco) and Sector 1 (agriculture, fishery and forestry) were the main contributors for BOD.

In taking account of the linkages among economic sectors and the interrelationship between economic sectors and water pollution, a hybrid approach which utilizes both EEIO and VIC is employed to identify the role of sectors. This is based on an evaluation of pollution component indices proposed by Sanchez-Choliz and Duarte (2003). These indices allow to quantify and disaggregate the pollution that is produced in all sectors. This methodology hence provides a more complete analysis for identifying the role of sectors as either producer/seller or consumer/purchaser of water pollution or both (key sectors). The IO table of 2011 is used for this purpose, and the results highlight that when TSS and BOD are both considered, Sector 1 (agriculture, fishery and forestry) and Sector 3 (food, beverage and tobacco) are identified as key sectors, Sector 9 (basic metal industry) is the highest pollution pusher, while Sector 10 (manufacturing of fabricated metal products, machinery and equipment) and Sector 13

Table 11 Sectoral characteristic/role with respect to TSS and BOD in 2011

Sector indices				Relevant characteristics	Water quality parameters	
$\varepsilon^1_{k,i}$	$\varepsilon^2_{k,i}$	$\varepsilon^3_{k,i}$	$\varepsilon^4_{k,i}$		TSS	BOD
High	High	Low	High	Key sector. Self-polluter by demand		Sector 1 and Sector 3
			Low	Key sector. Non-self-polluter	Sector 1 and Sector 3	
	Low and $d_i > 0$	Low	High	Backward linkage sector. Self-polluter by demand		Sector 4
			Low	Backward linkage sector. Non-self-polluter	Sector 2, Sector 10 and Sector 13	Sector 10 and Sector 13
Low	High and $d_i < 0$	High	High	Forward linkage sector. Self-polluter by inputs and demand	Sector 6, Sector 7, Sector 9 and Sector 11	
			Low	Forward linkage sector. Self-polluter by inputs		Sector 6, Sector 7, Sector 9 and Sector 11
	Low	High	High	Self-polluter by inputs and demand	Sector 5 and Sector 8	
			Low	Self-polluter by inputs		Sector 5 and Sector 8

d_i is defined in Eq.(23) in "Appendix"

Table 12 The role of important sectors in relation to water pollution

Parameters	Key sectors	Highest pushers	Highest pullers
TSS	Sector 1 and Sector 3	Sector 9	Sector 10 and Sector 13
BOD	Sector 1 and Sector 3	Sector 9	Sector 10 and Sector 13

(construction) are the highest pollution pullers. Finally, suggestions for prioritizing sectors to meet pollution reduction targets are presented to help government, policy makers, house hold sectors and industrial manufactures identify the proper water pollution mitigation strategies.

This research focused on the Vietnam case, but it can be easily adapted for use in other nations with existing IO tables and environmental data. This paper is used as another example of applying environmental data from IPPS to calculate environmental pollution. Other developing countries can make use of the methodology presented in this work to track pollution generation in economies of interest and to analyze the interrelationship between economic activities and environmental pollution. The weak point of this research is that the application of global data such as IPPS may result in some uncertainties and the focus has primarily been on the water quality indicators TSS and BOD. Future work can focus on the examination of other pollutants (e.g., chemical oxygen demand, ammonia–nitrogen and hazardous chemicals) or environmental quality indicators and consider different types of environmental media or pathways of pollution release (e.g., water, air and land). In addition, tools for handling data uncertainty can be integrated in the model to result in more robust analysis.

Acknowledgements The authors are grateful for the financial support provided by the Japan International Cooperation Agency (JICA) to study and conduct this research.

Appendix

The method of vertically integrated coefficient

The method of VCI is developed by Sanchez-Choliz and Duarte (2003) which is based on the Leontief equation:

$$\hat{x}_i = A\,\hat{x}_i + \hat{y}_i \tag{8}$$

Eq. (8) can be modified to be new equation:

$$\hat{x}_i = (I - A)^{-1}\,\hat{y}_i \tag{9}$$

where $y_i^{\wedge}$ vector of final demand, $\wedge$ symbol for diagonal matrix, A = (a_{ij}) technical coefficient matrix with $n \times n$ dimension, $\boldsymbol{I}$ identity matrix. From Eqs. 8 and 9, it can be rewritten as:

$$\hat{x}_i = A(I - A)^{-1}\,\hat{y}_i + \hat{y}_i = M\,\hat{y}_i + \hat{y}_i \tag{10}$$

where

$$M = A(I - A)^{-1} = (m_{ij}) \tag{11}$$

$$(\alpha_{ij}) = (I - A)^{-1} \quad \text{(Leontief inverse)} \tag{12}$$

Then, if we multiply pollution intensity PI_j^k, which is the amount of pollution load of an activity j for kth-type environmental quality parameter emitted to produce one unit of monetary output for that activity, with final demand y_i, we obtain the total value of kth parameter:

$$\hat{\mathrm{DI}}_i^k = \sum_{j=1}^{n} \mathrm{PI}_j^k \alpha_{ji} \hat{y}_i \tag{13}$$

is the kth parameter that is associated with the production of the final demand y_i of sector i.

Furthermore, pre-multiplying Eq. (10) by vector $\hat{PI}_j^k$, we obtain:

$$\hat{\mathrm{PI}}_j^k \hat{x}_i = \hat{\mathrm{PI}}_j^k \mathrm{M} \hat{y}_i + \hat{\mathrm{PI}}_j^k \hat{y}_i \tag{14}$$

It can be seen that (14) can be broken down into:

$$\mathrm{PI}_j^k \alpha_{ji} y_i = \mathrm{PI}_j^k m_{ji} y_i \quad \mathit{if}\ i \# j \tag{15}$$

and

$$\mathrm{PI}_i^k \alpha_{ii} y_i = \mathrm{PI}_i^k m_{ii} y_i + \mathrm{PI}_i^k y_i \quad \mathit{if}\ i = j \tag{16}$$

From the combination of three equations (Eq. 13, 15 and 16), it can be written as follows:

$$\begin{aligned}\mathrm{DI}_i^k &= \sum_{j=1, j\# i}^{n} \mathrm{PI}_j^k \alpha_{ji} y_i + \mathrm{PI}_i^k \alpha_{ii} \hat{y}_i = \sum_{j=1, j\# i}^{n} \mathrm{PI}_j^k \alpha_{ji} y_i + \mathrm{PI}_i^k m_{ii} y_i + \mathrm{PI}_i^k y_i \\ &= \sum_{j=1, j\# i}^{n} \mathrm{PI}_j^k \alpha_{ji} y_i + \mathrm{PI}_i^k \left(\sum_{j=1, j\# i}^{n} a_{ij} \alpha_{ij} \right) y_i + \mathrm{PI}_i^k a_{ii} \alpha_{ii} y_i + \mathrm{PI}_i^k y_i\end{aligned} \tag{17}$$

Each term of Eq. (17) is defined as follows:

$$\mathrm{TB}_i^k = \sum_{j=1, j\# i}^{n} \mathrm{PI}_j^k \alpha_{ji} y_i \quad \text{True backward linkage} \tag{18}$$

$$\mathrm{SE}_i^k = \mathrm{PI}_i^k \left(\sum_{j=1, j\# i}^{n} a_{ij} \alpha_{ij} \right) y_i \quad \text{Semi} - \text{own pollution} \tag{19}$$

$$\mathrm{OW}_i^k = \mathrm{PI}_i^k a_{ii} \alpha_{ii} y_i \quad \text{Own pollution} \tag{20}$$

$$\mathrm{FI}_i^k = \mathrm{PI}_i^k y_i \quad \text{Final demand pollution} \tag{21}$$

Forward linkage:$\mathrm{PI}_i^k x_i$ is total pollution load of sector i which consists of TB_i^k, SE_i^k, OW_i^k, FI_i^k and the one emitted to produce inputs for other sectors without returning which is considered as true forward linkage:

$$\mathrm{TF}_i^k = \mathrm{PI}_i^k x_i - \mathrm{FI}_i^k - \mathrm{OW}_i^k - \mathrm{SE}_i^k \tag{22}$$

The difference between true backward linkage and true forward linkage is the following:

$$d_i = \mathrm{TB}_i^k - \mathrm{TF}_i^k \tag{23}$$

d_i tells us whether true backward linkage (buying of pollution from other sectors) or true forward linkage (selling of production to other sectors) is the larger. If $d_i > 0$, then sector i is an overall polluting pullers and other sectors pollute for it. If $d_i < 0$, then sector i is an overall polluting pusher and pollutes for other sectors to obtain their final demands.

References

Aguayo F, Gallagher P, Gohzalez A (2001) Dirt is in the eye of the beholder: the World Bank air pollution intensities for Mexico. Global development and environment institute working paper no. 01–07

Benoit L, Craig M (2001) Estimating conventional industrial water pollution in Thailand. In: Paper presented to the Development Research Group of the World Bank

Butnar I, Llop M (2007) Composition of greenhouse gas emissions in spain: an input-output analysis. Ecol Econ 61:388–395

Cazcarro I, Duarte R, Sanchez-Choliz J (2016) Downscaling the grey water footprints of production and consumption. J Clean Prod 132:171–183

CTC Vietnam. Accessed on 01 May 2016. http://www.ctcgroupe.com/en/locations/ctc_vietnam.php

GMS Environmental Operations Center (2014) Estimating industrial pollution in Lao PDR, Bangkok, Thailand. Accessed on 15 Nov 2017. http://www.gms-eoc.org/uploads/resources/453/attachment/EstimatingIndustrialPollutioninLaoPDR_1.PDF

Ghosh A (1958) Input-output approach to an allocative system. Economica 25(1):58–64

Global Environmental Forum (2002) Overseas environmental measures of Japanese Companies (Vietnam). Accessed on 12 July 2016. http://www.env.go.jp/earth/coop/oemjc/viet/e/contents.html

GSO (General Statistical Office) (2003) Input-Output: IO of Vietnam Year 2000. Statistical Publishing House, Hanoi, pp 142–246

GSO (General Statistical Office) (2006) Statistical Yearbook of Vietnam (2005). Accessed on 05 May 2016. http://www.gso.gov.vn/default_en.aspx?tabid=515&idmid=5&ItemID=5691

GSO (General Statistical Office) (2009) Input–output: IO of Vietnam Year 2007. Statistical Publishing House, Hanoi

GSO (General Statistical Office) (2011) Statistical Yearbook of Vietnam 2010. Accessed on 05 May 2016. http://www.gso.gov.vn/default_en.aspx?tabid=515&idmid=5&ItemID=11974

GSO (General Statistical Office) (2013) Input–output: IO of Vietnam year 2011. Statistical Publishing House, Hanoi

Haimes YY, Jiang P (2001) Leontief-based model of risk in complex interconnected infrastructures. J Infrastruct Syst 7(1):1–12

Hettige H, Martin P, Singh M, Wheeler D (1995) The industrial Pollution Projection System. Work Bank Policy Research Working Paper

Hoa NT, Promentilla MA, Aviso KB (2013) Fuzzy multi-objective optimization of a multi-regional bioethanol supply chain. ASEAN Eng J Part B, 2 (2). Accessed on 05 Feb 2014. http://www.seed-net.org/wp-content/uploads/2015/12/Invited-Paper_FUZZY-MULTI-OBJECTIVE-OPTIMIZATION-OF-A-MULTI-REGIONAL-BIOETHANOL-SUPPLY-CHAIN.pdf

Hoa NT, Dien LQ, Promentilla MAB, Yu KDS, Aviso KB (2016) A model for multi-criteria disaster vulnerability assessment of economic systems: implications for Vietnam's bioethanol policy. Clean Techn Environ Policy 18:1917. https://doi.org/10.1007/s10098-016-1120-4

Hung PT, Tuan BA, Chinh NT (2008) The impact of trade liberalization on industrial pollution: empirical evidence from Vietnam.

Accessed on 29 June 2016. http://www.idrc.ca/uploads/users/12483164701Pham_Hung_Thai_2008_RR5.pdf
ICEM (International Center for Environmental Management) (2007) Analysis of pollution from manufacturing sectors in Vietnam. Indooroopilly, Queensland, Australia
International Standard Industrial Classification of All Economic Activities, Rev.2 (ISIC 2). Accessed on 12 June 2016. https://unstats.un.org/unsd/cr/registry/regcst.asp?Cl=8
International Standard Industrial Classification of All Economic Activities, Rev.3 (ISIC 3). Accessed on 12 June 2016. https://unstats.un.org/unsd/cr/registry/regcst.asp?Cl=2
Jessen S (2009) Groundwater arsenic in the Red River delta, Vietnam: Regional distribution, release, mobility and mitigation options. Accessed on 21 Aug 2017. http://orbit.dtu.dk/fedora/objects/orbit:82605/datastreams/file_5034320/content
Kamyab H, Din MFM, Keyvanfar A, Majid MZA, Talaiekhozani A, Shafaghat A, Lee CT, Shiun LJ, Ismail HH (2015) Efficiency of microalgae chlamydomonas on the removal of pollutants from palm oil mill effluent (POME). Energy Procedia, 75:2400–2408. Accessed on 15 Nov 2017. http://dx.doi.org/10.1016/j.egypro.2015.07.190
Kamyab H, Din MFM, Hosseini SE, Ghoshal SK, Ashokkumar V, Keyvanfar A, Shafaghat A, Lee CT, Bavafa AA, Majid MZA (2016) Optimum lipid production using agro-industrial wastewater treated microalgae as biofuel substrate. Clean Technol Environ Policy 18(8):2513–2523
Kamyab H, Chelliapan S, Din MFM, Shahbazian-Yassar R, Rezania S, Khademi T, Kumar A, Azimi M (2017) Evaluation of lemna minor and chlamydomonas to treat palm oil mill effluent and fertilizer production. J Water Process Eng 17: 229–36. Accessed on 15 Nov 2017. http://dx.doi.org/10.1016/j.jwpe.2017.04.007
Le AH, Tokai A, Yamamoto Y (2013) Structural analysis of relationship between economic activities and water pollution in Vietnam. J. Jpn. Soc. Hydrol. Water Resour. 25(3):139–151
Leontief WW (1936) Quantitative input-output relations in the economic system of the United States. Rev Econ Stat 18:105–125
Leontief WW (1970) Environmental repercussions and the economic structure: an input-output approach. Rev Econ Stat 52(3):262–271
Leontief WW (1985) Input–output analysis. In: Leontief W (ed) Input–output economics. Oxford University Press, NewYork, pp 19–40
Leontief WW, Ford D (1972) Air pollution and the economic structure: empirical results of input-output computations. In: Brody Andrew, Carter Anne P (eds) Input–output techniques. North-Holland Publishing Company, Amsterdam, London, pp 9–30
Li H, Yang Z, Liu G, Casazza M, Yin X (2017) Analyzing virtual water pollution transfer embodied in economic activities based on gray water footprint: a case study. J Clean Prod 161:1064–1073
Mani M, Jha S (2006) Trade liberalization and the environment in Vietnam. Policy Research Working Paper WPS3879; 16-17 and 30. Accessed on 15 May 2016. http://go.worldbank.org/J62ASJBSR0
Miller RE, Blair PD (2009) Input–output analysis: foundation and extensions, 2nd edn. Published in the United States of America by Cambridge University Press, New York
Murray J, Wood R (2010) The sustainability practioners' guide to input–output analysis. Common Ground Publications, Champaign
Nguyen TH (2015) Overview of Water Environmental Pollution in Vietnam Nguyen Thi Hue. Technology, Environmental, Vietnamese Academy, and Hoang Quoc Viet. Accessed on 15 Nov 2017. http://www.wepa-db.net/pdf/0712forum/paper04.pdf
Odesanya BO, Ajayi SO, Shittu M, Oshin O (2012) Use of industrial pollution projection system (IPPS) to estimated pollution load by sector in two industrial estates in Ogun State, Western Nigeria. Int J Sci Eng Res 3(10):11–748
Oketola AA (2007) Industrial pollution assessment in Lagos, Nigeria using Industrial Pollution Projection System and effluent analysis. Ph.D, Thesis, Department of Chemistry, University of Ibadan
Oketola AA, Osibanjo O (2007) Estimating sectoral pollution load in Lagos by industrial pollution projection system (IPPS). Sci Total Environ 377:125–141
Oketola AA, Osibanjo O (2009) Industrial pollution load assessment by industrial pollution projection system (IPPS). Toxicol Environ Chem 91:989–997
Pandey R (2005) Estimating sectoral and geographical industrial pollution Inventories in India: implications for using effluent charge versus regulation. J Dev Stud 41:33–61
PricewaterhouseCoopers (2017). The world in 2050. Accessed on 21 August 2017. https://www.pwc.com/gx/en/world-2050/assets/pwc-the-world-in-2050-full-report-feb-2017.pdf
Que TT, Thanh VA (2001) Vietnam: Achievements and challenges. Soc Watch Poverty Erad Gend Equity Rep 2001:172–173
Rasmussen P (1956) Studies in intersectoral relations. North-Holland, Amsterdam
Rezania S, Taib SM, Din MFM, Dahalan FA, Kamyab H (2016) Comprehensive review on phytotechnology: heavy metals removal by diverse aquatic plants species from wastewater. Journal of Hazardous Materials 318: 587–99. Accessed on 15 May 2017. http://dx.doi.org/10.1016/j.jhazmat.2016.07.053
San V, Vin S, Johannes S (2018) Science of the Total Environment Industrial Pollution Load Assessment in Phnom Penh, Cambodia Using an industrial pollution projection system." Science of the Total Environment 615: 990–99. Accessed on 15 Nov 2017. https://doi.org/10.1016/j.scitotenv.2017.10.006
Sanchez-Choliz J, Duarte R (2003) Analyzing pollution by way of vertically integrated coefficients, with an application to the water sector in Aragon. Camb J Econ 27(3):433–448
Sanchez-Choliz J, Duarte R (2005) Water pollution in the Spanish economy: analysis of sensitivity to production and environmental constraints. Ecol Econ 53:325–338
Shmelev SE (2010) Environmentally extended input-output analysis of the UK economy: key sector analysis. Published in: QEH Working Paper Series No. Working Paper Number 183. Accessed on 08 June 2016. http://www3.qeh.ox.ac.uk/pdf/qehwp/qehwps183.pdf
Suh S (2009) Handbook of input–output economics in industrial ecology. 2nd Printing, Ecology edn. Springer, Berlin
Tan RR, Culaba AB, Aviso KB (2008) A fuzzy linear programming extension of the general matrix-based life cycle model. J Clean Prod 16:1358–1367
Tan RR, Ballacillo JB, Aviso KB, Culaba AB (2009) A fuzzy multiple objectives approach to the optimization of bioenergy system footprints. Chem Eng Res Des 87:1162–1170
The World Bank, the National Environmental Agency, the Danish Agency for international development (2002) Vietnam Environmental Monitor 2002; 20–22. Accessed on 21 May 2016. http://siteresources.worldbank.org/INTEASTASIAPACIFIC/Resources/VN-Monitor-02.pdf
Tran HTH (2010) Water utilization and efficiency in Vietnam, the challenges and solutions. Ministry of natural resources and environment. Vietnam environment administration. Accessed on 21 May 2016. http://www2.gec.jp/gec/en/Activities/ietc/fy2010/wf/wf_s5-1.pdf
Trinh B, Nguyen PV (2013) Economic-environmental impact analysis based on the changes of economic structures of HoChiMinh City (HCMC) and the Rest of Vietnam (ROV) (2000)–(2007). Int J Case Stud 2(3):1–34. Accessed on 28 April 2017. https://ssrn.com/abstract=2868234
Water Environment Partnership in Asia (WEPA) (2011). Accessed on 12 May 2016. http://www.wepa-db.net/policies/state/vietnam/overview.htm
Water and Sanitation Sector Assessment report Vietnam 2011 (WSSA) (2012) Accessed on 05 May 2017. http://www.wpro.who.int/vietnam/topics/water_sanitation/watsan_sector_report_vietnam_2011.pdf

Wu Z, Guo X, Lv C, Wang H, Di D (2017) Study on the quantification method of water pollution ecological compensation standard based on emergy theory. Ecological Indicator. Accessed on 15 Nov 2017. https://doi.org/10.1016/j.ecolind.2017.09.052

Yan C, Ames E (1965) Economic interrelatedness. Review of Economic Studies. Vol. XXIII, no. 4. Accessed on 16 May 2016. http://cje.oxfordjournals.org/

Yu KDS, Tan RR, Aviso KB, Promentilla MAB, Santos JR (2014) A vulnerability index for post-disaster key sector prioritization. Econ Syst Res 26(1):81–97