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Analysis of industrial water–energy–labor nexus zones for economic and resource-based impact assessment

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ABSTRACT

Sustainable Development Goals (SDGs) are the blueprints for achieving a sustainable future, and understanding the interlinkages among social, economic, and environmental fields is a key factor in accomplishing them. The goal of this study was to analyze a framework for sustainable economic growth considering the trade-offs among economic inequality, resource security, and labor requirement through an industrial water, energy, and labor (I-WEL) nexus approach. We analyzed the economic intensity of industrial water, energy, and labor in 47 prefectures in Japan; we found that the more industrialized prefectures showed lower water but higher energy intensities than relatively less industrialized prefectures. We then classified four I-WEL nexus zones—high efficiency, labor-intensive, water-intensive, and water- and energy-intensive zones—based on their economic intensities and by using the K-means clustering method. Finally, we applied economic growth scenarios, weighted by I-WEL nexus zones, and quantified water, energy, and labor requirements by scenario at the local, regional, and national scales. The results show that, by using weighted economic growth in the high-efficiency I-WEL nexus zones and relative to the baseline scenario (which assigns equal ratios of increased economic growth to all prefectures), a potential savings of 337 Mm^3/year of freshwater and 184 PJ/year of energy can be realized. However, as the more industrially developed prefectures were included in the high-efficiency zone, this scenario increased the Gini coefficient, i.e., the economic inequality among prefectures. In summary, this study shows that the application of the I-WEL nexus can be used as a framework for sustainable economic growth considering the trade-offs between efficiency of resource use and economic inequality.

1. Introduction

The 2030 agenda for Sustainable Development Goals (SDGs) attempts to bridge highlighted policies and sectoral gaps (UN ECOSOC, 2016; Al-Riffai et al., 2017; Huber, 2000). The main purpose of the SDGs is to assess the holistic impact of socio-economic and environmental actions through integrated resource management, while considering resource security, distribution, and multiple stakeholders. Accordingly, natural resources such as water, energy, and land have been treated as primary drivers of holistic impact assessment, and the nexus concept is now used to highlight interdependencies between resources and the need for integrated, sustainable governance and the management of those resources (Pahl-Wostl, 2019). In particular, energy and water are crucial resources for economic growth, and the rapidly increasing demand for these resources poses a serious threat to both economic and environmental outcomes (Flörke et al., 2013; Cai et al., 2016).

Generally, water is considered to be essential for humans and food production and to achieve sustainable development. Water demand is a major concern of water management policies, with acute conflicts over allocation in scarcity. However, water resources are also essential to economic development, especially in industrial areas. Thus, it is important to analyze water intensity in industry as a major driving factor

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of economic growth (Dongjing, 2012; Cai et al., 2016; Goodwin et al., 2014; Renzetti, 1992; Rock, 2000). Flörke et al. (2013) calculated manufacturing water withdrawal through structural water intensity, the technological change rate for the manufacturing sector, and gross value added per country in 167 countries using a literature review and a data survey (e.g., national statistics). The study revealed that the significant rise in industrial water use since 2000 can be attributed to the manufacturing sector more than the thermoelectric sector. As industrial water use decreased in most developed countries, the emerging increase is a result of the growing economies of newly industrialized countries. Yue et al. (2017) focused on regional differences in the relationship between industrial water consumption and economic growth, showing that the variation in economic development among regions in China, including technical innovation and industrial structure upgrades, caused different turning points for water intensity. Although a few studies on industrial water use have been published, the value of water for industrial firms has not been assessed in several countries (Reynaud, 2003). Unlike the numerous models for simulating agricultural and residential water use (Chang et al., 1983; Steduto et al., 2009; Wriedt et al., 2009; Cavero et al., 2000; Buchberger and Wells, 1996), a simulation to estimate historical water usage in the industrial sector is still lacking (Flörke et al., 2013).

Energy availability is strongly related to industrial product prices and constitutes one of its main costs. For example, the construction industry, often described as the least sustainable industry, globally consumes nearly half of all non-renewable resources used (Opoku, 2019). Studies on the quantification and decomposition of industrial energy consumption have been conducted to assess energy efficiency (Howarth et al, 1991; Ang, 1994; Worrell et al., 2000). Since 2000, energy efficiency has been a major driver in decoupling energy consumption and economic development; improvements in major economies worldwide have offset more than a third of the rise in energy-intensive activities (International Energy Agency (IEA) 2018). In 2017, global energy demand rose by 2%, the most rapid increase in this decade, driven by economic growth and changes in consumer behavior (International Energy Agency (IEA) 2018). Cornillie and Fankhauser (2004) identified the main factors behind the improvements in energy intensity. They showed that energy prices and progress toward technical efficiency were the most important drivers decreasing energy intensity. Wing (2008) focused on explaining the decline in US energy intensity over the last 40 years of the 20th century by investigating its sources during the 1958−2000 period. Fisher-Vanden et al. (2004) studied China's energy intensity decline and the reasons behind it, namely decreasing coal consumption in the industrial sector.

The key point of the nexus approach for SDGs is the trade-offs among variables; moreover, each variable can act as a threshold for other variables. Accordingly, through nexus thinking, we can promote the important understanding that natural resource availability is limited by other goals associated with economic growth and human well-being (Mohtar, 2011; Hoff, 2011). The innovative aspect of nexus thinking is its more balanced view of the issues linking resources (Al-Saidi and Elagib, 2017). The application of the nexus concept or approach is expected to make the implementation of the SDGs more efficient and robust (Brandi et al., 2014; Yumkella and Yillia, 2015; Terrapon-Pfaff, et al., 2018). In particular, goal 8 (decent work and economic growth) and goal 9 (industrial innovation and infrastructure) are strongly related to economic growth in industrial areas; sustainable development could be achieved via increased efficiency of resource inputs and improved allocation of resources among competitors, thereby increasing socio-economic value and minimizing environmental impact. Early nexus research mostly analyzed conceptual frameworks in the context of the interconnections among water, energy, and food (WEF); however, as its importance as a decision support system grew, diverse nexus tools were developed to assess user scenarios from a holistic perspective (Endo et al., 2020; Rising 2020). For example, the Nexus Assessment 1.0 (Food and Agriculture Organization (FAO) 2014) was a nexus-based policy decision-making platform that assessed the effect of environmental or policy changes through variations in nexus indices developed through discussions and consensus among stakeholders. The Organization for Economic Co-operation and Development (OECD) suggested the land–water–energy nexus as a critical research area, estimating the effects of external environmental changes and their relative economic values for the year 2060 as a standard (OECD, 2017). In 2016, the EU initiated the Sustainable Integrated Management FOR the NEXUS (SIM4NEXUS), which uses various thematic models to evaluate changes in the environment or policies (Sušnik et al., 2018). The Water–Energy–Food Nexus Initiative (WEFNI) at Texas A&M University created a system-wide interdisciplinary group to address the complex resource challenges facing the San Antonio region. It presented a brief overview of the questions and research conducted under thematic foci, including data and modeling, trade-off analysis, water for food, water for energy, and governance (Mohtar and Bassel, 2019).

Recently, diverse research using nexus models has been conducted to develop a platform for SDG implementation (Stephan et al., 2018). Additionally, nexus interactions focused on specialized stakeholders (i.e., those in agriculture, urban areas, manufacturing industries, etc.) have been analyzed. Kucukvar et al. (2016) applied the nexus approach to the manufacturing industry, suggesting new insights into the energy–climate–manufacturing nexus in the context of regional and global manufacturing supply chains. Wang et al. (2019) built a national energy–water nexus scenario analysis framework to evaluate the water-related impacts of energy-related decisions. The nexus approach is widely used in agriculture because food security is one of the main issues, and significant volumes of water are used for irrigation (Zhang and Vesselinov, 2017; Li et al, 2019). Recently, Lee et al. (2020) applied the food-centric WEF nexus approach to assess the holistic impacts of climate change in the context of the interlinkages among food productivity, irrigation water, and energy input in an agricultural area. These studies show that the nexus is an adaptable approach for SDGs, and that nexus challenges present an opportunity for innovation that drives economic development, business expansion, ecosystem health, and social well-being (Stephan et al., 2018).

However, many studies have applied the nexus approach based on existing integrated frameworks, such as in the case of integrated water resource management, which is an oft-cited example of this approach (Benson et al., 2015). In addition, the holistic impacts from the nexus are mainly treated from the resource security perspective; for instance, the impact of food production is evaluated by considering water and energy as inputs. However, from an economic or social perspective, other variables relating to human resources could be primary drivers; for example, labor is a significant variable. Particularly regarding SDGs, labor is one of the key variables relating to the economic and social sectors. Notably, the term labor (labour) appears 11 times in the agenda of SDGs, and Goal 8.2 directly indicates labor-intensive productivity. Accordingly, labor should be included as another circle in nexus diagrams when the nexus approach is employed for holistic impact assessment. Alam et al. (2018) incorporated labor into the nexus approach by assessing the impacts of access to electricity on labor productivity in developing countries. In addition, Fedderke and Bogetic (2006) found a positive association between electricity generation and labor productivity. Asaleye et al. (2017) mentioned that the nexus amongst productivity, employment, and wages has generated debates in the literature. Strauss and Wohar (2004) emphasized the relationship among economic growth, productivity, and wages in manufacturing industries in the US and revealed that increases in productivity were associated with a less-than-unity increase in real wages. However, studies on the incorporation of labor into the nexus approach have mainly focused on the relationship between wages and productivity, and labor has not been adopted as a variable that is equivalent to other variables in the nexus, such as water, energy, food, and land. An inclusive nexus that integrates labor as a primary component could represent holistic impact on nature and human resources, through the interlinkages among water, energy, and labor in an economic area, by including a social perspective.

In this study, we focused on the application of the nexus approach to sustainable economic development from the perspective of industrial stakeholders. Although developing technology to reduce water and energy intensities in industry is important, it is also necessary to understand the relationship between economic growth and local water and energy consumption and the impacts of economic policy from multiple perspectives (e.g., whether intensive economic growth with lower intensities of water and energy use is preferable to greater industrialization). Increasing economic production in industrial areas can be a key driver of national economic development, but intensive industrial development can also steeply increase demand for water and energy, which, in turn, leads to problems of downscaling water or energy security. Accordingly, sustainable economic development must consider the trade-offs between the efficiency of resource use (water, energy, and labor) and economic inequality.

The current study aimed to analyze the industrial water, energy, and labor (I-WEL) nexus in the context of economic development in Japan. A framework for evaluating the impacts of economic growth considering resources and economic inequality at local and national scales was developed. In Japan, traditional economic development has centered around industrial areas: the Japanese government classified 19 prefectures as industrial zones, and the national economy strongly depends on economic growth from the prefectures in these industrial zones, which have highly efficient industrial infrastructure. In 2015, the industrial zones represented 71% of the gross domestic product (GDP) and held 67% of the national population (Ministry of Land 2019) Intensive economic growth in the industrial zones could be more efficient because prefectures in these zones already have infrastructure, but it may also cause more intensive resource use in these zones as well as greater inequality in regional and local incomes. Accordingly, we assessed the impacts of economic growth scenarios considering the I-WEL nexus zones at different spatial scales (local, regional, and national).

2. Methods and data

2.1. Framework for economic and resource-based impact assessment using industrial water–energy–labor (I-WEL) nexus zones

Generally, the water–energy–food nexus is a parameter reflecting resource security based on changes in consumption and capacity in a specific area, such as a water basin or an agricultural area. The nexus approach is considered to be appropriate for sustainable development regarding the interlinkages among various fields and the holistic impacts of externalities. In addition, the holistic impacts of externalities and internal management have been assessed through the nexus approach (e.g., climate change, irrigation method, renewable energy, and urban agriculture), and several studies on the nexus approach reveal the interlinkages among water, energy, food, and land resources. Nie et al (2019) followed a multi-objective optimization strategy for a trade-off analysis using the WEF nexus framework and found that the framework functions effectively to balance multiple objectives of land use. Terrapon-Pfaff et al (2018) identified the complex links that exist between sustainable energy projects and the food and water sectors; further, they highlighted that a systematic WEF nexus approach, which integrates the water and food pillars into energy planning at the local level in the global south, is required to avoid trade-offs and enhance the development outcomes and impacts of energy projects.

The nexus approach has also been used for the integrated management of water basins to optimize the water supply for different water demands such as irrigation, hydropower, public water, and industrial water. Moioli et al (2018) assessed the sustainability of bioenergy production from a nexus perspective through a new efficiency type index. De Vito et al (2017) evaluated the multi-dimensional implications of irrigation practices in a catchment located in Puglia, Italy through the WEF nexus framework, and the results showed that irrigation sustainability depended on water/energy accessibility and costs/benefits. Saladini et al (2018) developed an integrated program of sustainable food production and water provision via the WEF nexus framework. Khalkhali et al (2018) applied the water–energy nexus to water supply for integrated water and energy management; particularly, they focused on water supply–hydropower interactions in an entire urban water cycle. This framework was applied to a water supply system in the Northeastern US to capture its water–energy interactions under a set of future population, climate, and system operation scenarios. In addition, case studies of the application of the nexus approach for assessing policies and strategies relevant to SDGs have also been conducted. Particularly, Wicaksono and Kang (2019) calculated the reliability index of resources based on both the energy policy in South Korea and the capital investment planning of urban water systems in Indonesia using WEF nexus simulations. Nhamo et al (2018) mentioned that the adoption of the nexus approach would be a step forward toward attaining the SDGs on poverty eradication, zero hunger, and providing and energy water to all.

While the WEF nexus approach considers the complex interlinkages accompanying synergy and trade-offs, the approach should depend upon stakeholders or application fields. For example, the nexus specialized in agriculture could include irrigation management as an important linkage between water and food. When considering nexus-wide decision-making approaches, more challenges emerge, including the identification of interactions among the nexus elements and the conflicts between stakeholders' interests and environmental impacts (Mohtar and Bassel, 2019; El Gafy et al., 2017; Dargin et al., 2019).

From an economic perspective, industry is the main stakeholder and industrial resource management is an important variable in the nexus approach; this study analyzed industrial water, energy, and labor nexus zones to suggest sustainable economic growth strategies (Fig. 1). The methodologies employed in current nexus studies to identify unbiased decisions and interactions of nexus elements mainly include data-intensive systematic analyses (Keairns et al., 2016; Albrecht et al., 2018).

Accordingly, we analyzed the economic intensity of industrial water, energy, and labor in local areas and classified four I-WEL nexus zones based on economic intensities using the K-means cluster method. Thereafter, we applied different economic growth scenarios considering the I-WEL nexus zones; lastly, we quantified the water, energy, and labor requirements at different spatial scales.

2.2. Classification of I-WEL nexus zones by K-means clustering and economic intensities

Resource intensity denotes the quantity of resources used for the production and processing of goods, and it is used to analyze the resource efficiency of products or systems. An early indicator of resource intensity is material intensity per service unit (Schmidt-Bleek, 1994; King and Webber, 2008), which is assessed at the micro-level (focused on specific products) or at the macro-level (focused on state or national economies; Metcalf, 2008; Pelletier et al., 2011). For example, energy intensity can be described as a measure of energy consumed per unit of cost (Ma and Stern, 2008), while water intensity implies water productivity, a well-known concept, particularly in terms of agricultural water supply. In agriculture, water intensity is defined as the amount of water required per unit of yield (Vaux and Pruitt, 1983; Alcamo et al., 2003; Brauman et al., 2013) and has been used in crop areas as a measure of crop water productivity. Energy intensity has been discussed with a focus on the impacts of technological changes or the reconstruction of manufacturing structures.

Both water and energy are essential inputs for industry, and products from the industrial sector are the main driver of national and regional economic growth. Relatively high resource intensities indicate a high price or environmental cost for converting a resource into a product (Lorentzen, 2008). Therefore, the role and importance of industrial

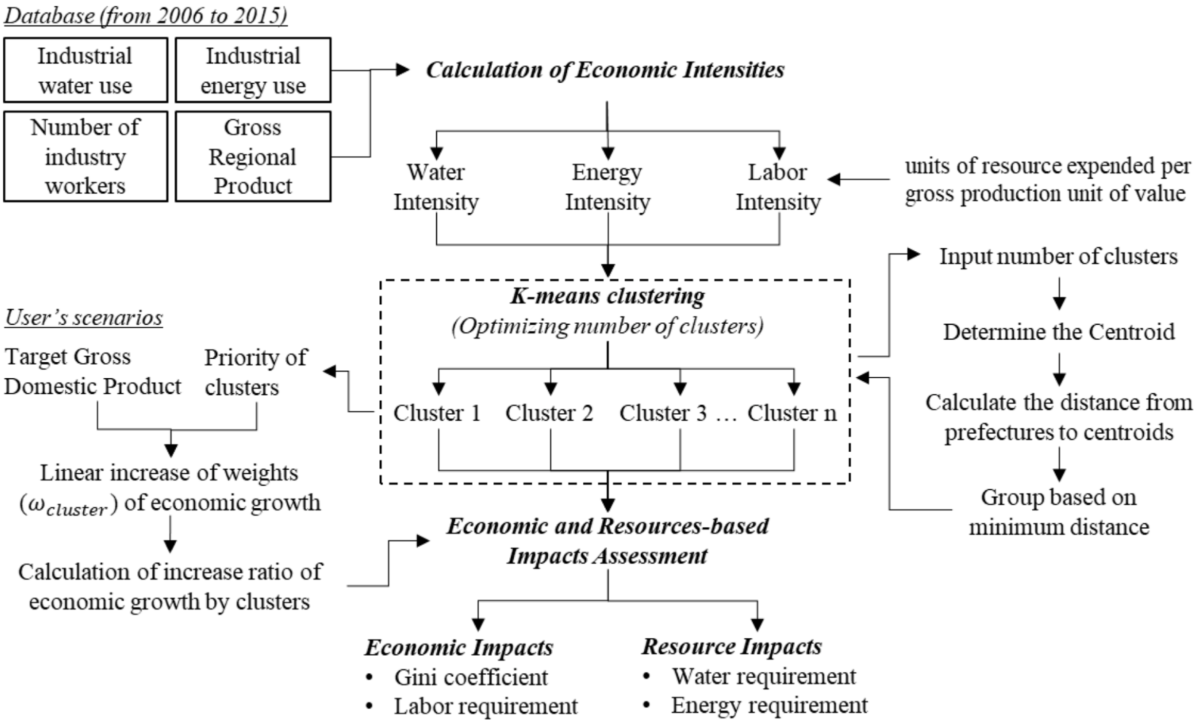


Fig. 1. Framework for economic and resource-based impact assessment considering industrial water–energy–labor nexus zones.

water and energy could rise considering the interlinkages between economic growth and environmental impacts.

In addition, we considered labor to be a main input for economic growth, and the number of workers was used as an indicator of labor intensity. The labor intensity better represents the characteristics of various industrial sectors. For example, the light industrial sector (e.g., garments, shoes, and furniture) is labor-intensive. In contrast, the heavy industry sector (e.g., iron and steel, cement, plastics, and paper) and the mechanical industry sector (e.g., electronic equipment and automobiles) are less labor-dependent but more dependent on conventional capital. Finally, the knowledge industry sector, such as software development and pharmaceutical industries, is labor-intensive, but more dependent on highly skilled labor based on intellectual capability (Powell and Snellman, 2004). By measuring the labor intensity, we can infer the kinds of industrial sectors that exist in each prefecture. This is particularly vital if we want to estimate the historical transitions of the industries in various prefectures. In addition, labor was regarded as the main reason for ecological crises, which entailed a drastic increase in societal metabolism; note that the societal metabolism–labor nexus has been examined (Haas and Andarge, 2017).

The economic intensities of water, energy, and labor are key concepts in sustainability management, in which the trade-offs between resource security and economic growth must be considered while maximizing resource productivity and minimizing resource intensity. In this study, economic output is represented by the gross regional products (GRPs), which can be calculated as the units of resource expended per gross production unit of value (Table 1).

We identified I-WEL nexus zones using measures of economic water, energy, and labor intensity. The K-means cluster method was then used to partition n observations into K clusters, where each observation belongs to the cluster with the nearest mean. Euclidean distance between points was used to measure the similarity between sectors, and each data point was assigned to one of the k groups based on the provided features. The steps involved in the K-means clustering method are as follows (Kanungo et al., 2002): 1) The total number of clusters is determined and various values are applied to identify discrete groups (i.e., each group should be defined by its lack of similarity with other groups). 2) The initial K points are selected using SPSS software to automatically select the farthest K points, producing a good clustering effect. Based on the distance from each cluster to the center, the remaining points are then allocated to the clusters. This is repeated until the changes are insignificant. 3) Points are clustered into different categories with corresponding characteristics; for this study, these categories are water, energy, and labor intensities. Fig. 2 shows that K-means clustering minimizes the within-cluster variances and that data points are clustered based on feature similarity. Each cluster centroid is a collection of feature values that define the resulting groups; feature weights can be examined to qualitatively interpret the type of group each cluster represents.

Table. 1
Definitions of economic intensities of industrial water, energy, and labor.

Economic Intensity	Definition
Economic Water Intensity (EWI, cm^3/Yen)	Amount of freshwater use in industries per GRP in a specific area
Economic Energy Intensity (EEI, KJ/Yen)	Amount of fuel and electricity use in industries per GRP a in specific area
Economic Labor Intensity (ELI, Person/Yen)	Number of industry workers per GRP in a specific area

2.3. Analysis of economic growth using I-WEL nexus zones

A global analysis of the resource system linked to GDP growth is presented by integrating the four sectors into a coherent analysis and modelling framework; moreover, it is demonstrated that increases in GDP are accompanied by increases in water and energy use (Sušnik, 2018). Furthermore, Gasparatos and Gadda (2009) investigated the resource consumption by Japanese society since 1979 and its subsequent effects on the economic output of the nation and on the environment. They revealed a strong the relationship between total energy used and GDP in Japan. Accordingly, it is important to consider economic growth

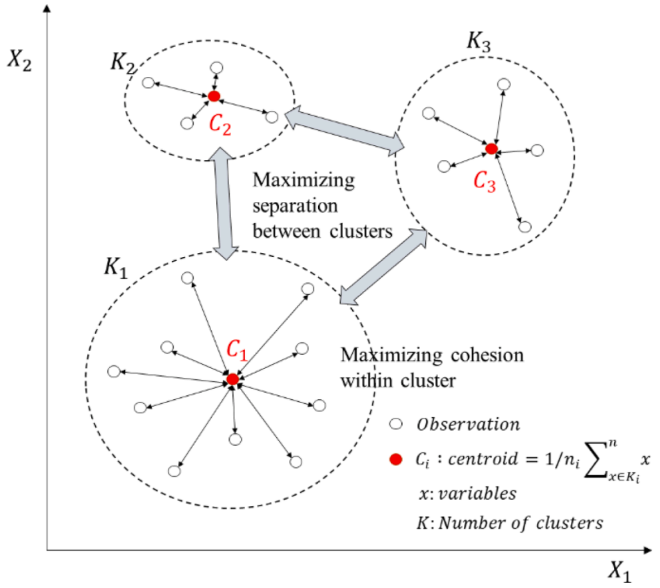


Fig. 2. K-means clustering method.

in combination with resource security. Increases in GDP are accompanied by increases in water and energy use. It is important to consider economic growth in combination with resource security. For example, increases in GRP in prefectures with low levels of economic intensity of water and energy might positively impact water and energy savings. Therefore, we applied different weights to local GRP increases based on economic intensities. To assign the different ratios of GRP increase by prefecture, we classified the 47 prefectures into I-WEL nexus zones. Based on this classification, we assess the manner in which the consideration of I-WEL nexus zones in CDP affects natural resources such as water and energy, in addition to human resources through the labor requirement. To apply the I-WEL nexus zones, we analyze the weight values of local GRP increases consisting of the initial increase (ω_0) and the zone priority. Basically, we assign different weight values to each I-WEL zone within a constant national GDP, and we employ a linear increase of weight values based on the priority (p) of zones (j) to avoid zone-dependent biases. Furthermore, decision makers can apply a different method of assigning weight values in this methodology through surveys or based on detailed data regarding economic situations. In this study, the prefectures in the first priority zone had a greater increase ratio of GRP than prefectures in other zones. The weights of local GRP increase relative to national GDP, as assigned by a user scenario, were calculated using Eqs. (1–(2):

$$Target\ GDP = \sum_{j=1} \sum_{i=1} (\omega_j \times GRP_i) \tag{1}$$

$$\omega_j = (n + 1 - p_j) \times \omega_0 \quad (p_j = 1, 2, 3, \ldots.n) \tag{2}$$

where Target GDP is the national GDP assigned by a user, GRP_i is the GRPs in prefecture (i), ω_j is the weighted increase ratio in zone (j), n is the number of zones, and p_j is the priority of the zone (j). In addition, ω_0 is the initial increase ratio of GRP, and it is calculated by the target GDP assigned as a scenario.

2.4. Gini coefficient for assessing economic inequality

The Gini coefficient is the measure of statistical dispersion commonly used to assess inequality of income or wealth distribution (Gini, 1936). Generally, the Gini coefficient is calculated by the area of the Lorenz curve expressed by cumulative population and cumulative share of income (Fig. 3). For example, if everyone has the same income, a Gini coefficient of zero is calculated, which indicates perfect equality. In contrast, a Gini coefficient of one represents maximal inequality of incomes (Fig. 3 and Eq [3]).

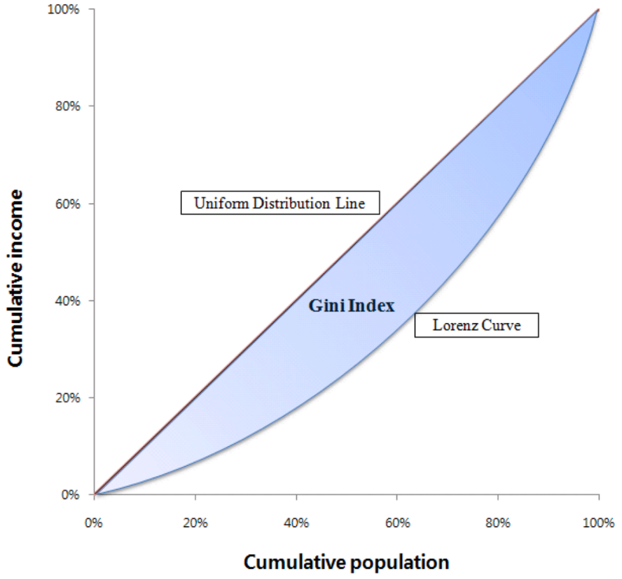


Fig. 3. Lorenz curve and Gini coefficient.

$$Gini\ coefficient = \sum_{i=1}^{n-1} \left| x_i y_{(i+1)} - x_{(i+1)} y_i \right| \tag{3}$$

The measure is not overly sensitive to the specifics of the income distribution but rather only to how incomes vary relative to the other members of a population. Although the Gini coefficient has traditionally been used to assess inequality of incomes (Chen et al., 1982; Bendel et al., 1989; Garner, 1993; Aronson and Lambert, 1994; Alvaredo, 2011), it is basically the methodology to measure statistical dispersion; thus, it could be applied to non-economic fields to measure inequality of adaptable variables (Deltas, 2003; Shkolnikov et al., 2003; Druckman and Jackson, 2008; Vasa et al., 2009, Singh et al., 2010).

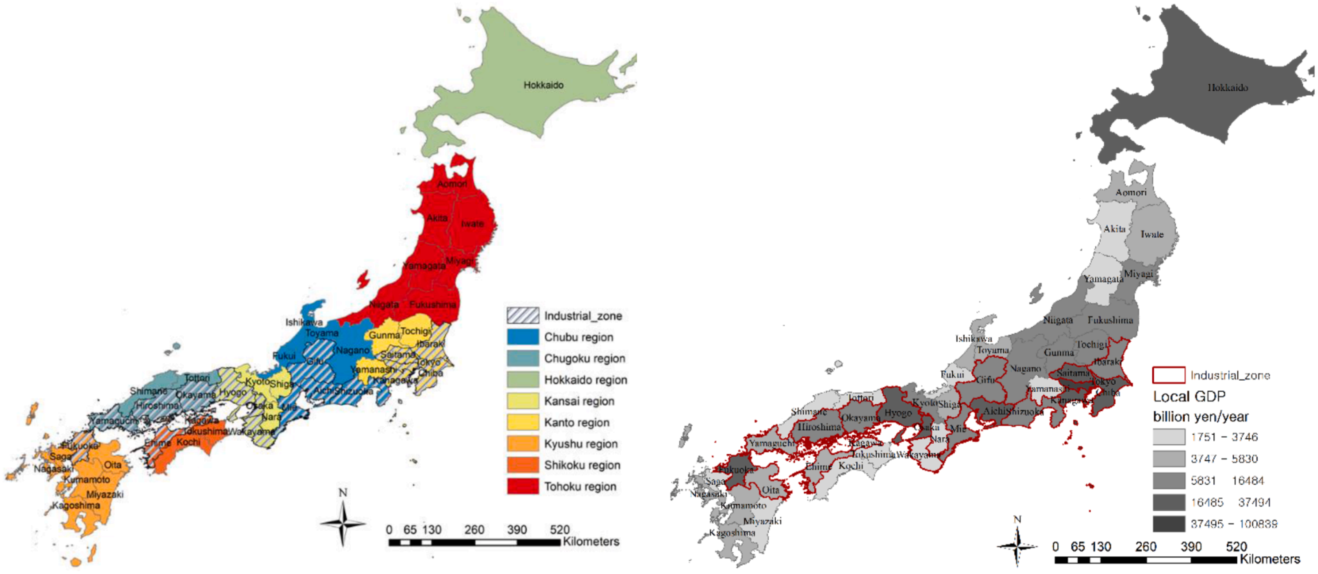
In this study, we analyzed economic inequality in different prefectures using the Gini coefficient. Therefore, cumulative population was replaced by prefectures, and GRPs were used to represent the income of each prefecture on the Lorenz curve. An increase in the Gini coefficient implies that a few prefectures largely contribute to the GDP and that there are disparities in the economic situations of the prefectures.

2.5. Study area and data collection

Japan is a well-developed country with drastic economic growth since 1960. The GDP per capita in 2018 was $39,287 or 82 times greater than that in 1960 (World Bank, 2018). Industrial water and energy used as raw materials or for product processing, cleansing, cooling, heating by boilers, or other uses were essential for Japan's economic growth (Ministry of Land 2019). Industrial water use in Japan sharply increased between 1960 and 1980 but has gradually decreased since 2000. However, 119 million m^3 of freshwater per day (approximately 15% of total water use in Japan) was still being used in manufacturing industrial areas in 2015 (World Bank, 2015). Japan has repeatedly experienced major water shortages over the last century, e.g., at Lake Biwa (1939), the Tokyo Olympics (1964), Nagasaki (1967), Takamatsu (1973), and in Fukuoka (1978) (Wanninayake, 2011). A water shortage event in 1994 affected most of Japan, when approximately 16,000,000 people faced suspended water supply and the cost of the associated loss of agricultural production was estimated at 140 billion yen (Wanninayake, 2011). Thus, industrial energy use could be key to ensuring energy security because Japan's energy self-sufficiency ratio in 2015 was 7.4%, which is low compared to that of other OECD countries (Agency for Natural Resources and Energy (ANRE) 2017). Its dependence on fossil fuels was 81% before the Fukushima accident, but was 89% in 2016 owing to the shutdown of nuclear power plants and the increase in electricity generation from thermal power plants (Agency for Natural Resources and Energy (ANRE) 2017).

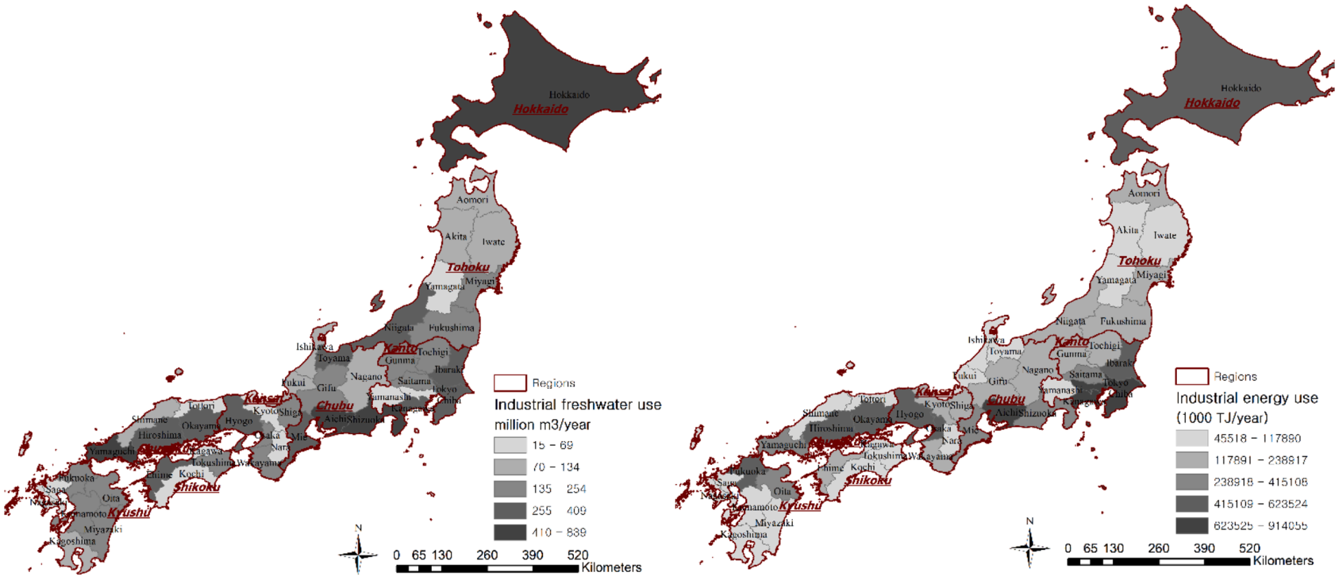
To calculate economic water intensity (EWI) and economic energy intensity (EEI) in the industrial sector, we compiled a database of GRPs, industrial water use, and industrial energy use in 47 prefectures for the period 2006–2015. By analyzing the GRPs in 47 prefectures (Fig. 4), we found that economies in Japan were developed with a focus on the Kanto region and certain other prefectures in each region. For example, the average GDP from 2006 to 2015 was 517,190 billion yen/year, approximately 40% of which came from the Kanto region. The GRP in Tokyo was 100,839 billion yen/year, accounting for 20% of the GDP. Except for the Kanto region, each region has hub-prefectures in terms of economic development. For example, Osaka, Aichi, and Fukuoka prefectures showed the largest GRP contribution in Kansai, Chubu, and Kyushu, respectively. In contrast, the prefectures in the Tohoku and Shikoku region had less than 10,000 billion yen/year in terms of GRP contribution.

However, major industries in each prefecture and region are different. Thus, the regional water and energy use in industry varied by prefecture (Fig. 4). For example, Chubu, Hokkaido, and Tohoku use large amounts of industrial freshwater in their pulp and lumber manufacturing industries. In Tohoku, approximately 44% of the total freshwater used in manufacturing is for these industries. Meanwhile in Kanto, only 8% of the total freshwater used in manufacturing is for pulp and lumber industries, while 33% is suppled for the manufacture of chemical, oil, and coal products and 25% for the iron and steel industry. The prefectures in Tohoku and Chubu have small GRPs but high industrial freshwater use. In Shizuoka (Chubu), where the majority of industries are pulp and lumber, industrial freshwater use reached 762 million m^3 and accounted for 8% of total industrial freshwater use in Japan. In the case of industrial energy, total use in Japan was 9.2 billion TJ/year, with 29% used in the Kanto region. This region used 781 PJ/



(a) Study area

(b) Gross regional products by prefectures



(c) Industrial freshwater use by prefectures

(d) Industrial energy use by prefectures

Fig. 4. Average industrial freshwater and energy use and gross regional product in 47 prefectures from 2006 to 2015. GDP, gross domestic product.

year, accounting for 8% of total industrial energy use in Japan. Aichi (Chubu) had high industrial energy and freshwater use. Meanwhile, the Tohoku region only contributed 7% to the national industrial energy use. Based on these data, this study analyzed EWI and EEI.

3. Results and discussion

3.1. Calculation of economic water, energy, and labor intensities

The economic intensities of water, energy, and labor are related to the efficiency of industries and to the type of processes required for final products. Thus, economic intensities of a local area are determined by which industry leads the local economy. The economic intensities varied by area (Fig. 5), with minimum and maximum EWI found in Tokyo and Yamaguchi (0.5 and 100.5 cm^3/yen), respectively. This is because financial industries lead Tokyo's economic growth, while Yamaguchi is highly dependent on manufacturing. The impact of economic growth on water resources differs among areas. Moreover, EWI and EEI have different relationships in different prefectures, e.g., EWI and EEI were both large in Yamaguchi, but in Kagawa and Fukuoka, water use was more intense than energy for economic growth. Contrastingly, Shizuoka and Shimane had small EEI but large EWI; thus, water resource management could be a more important issue for economic growth in those prefectures.

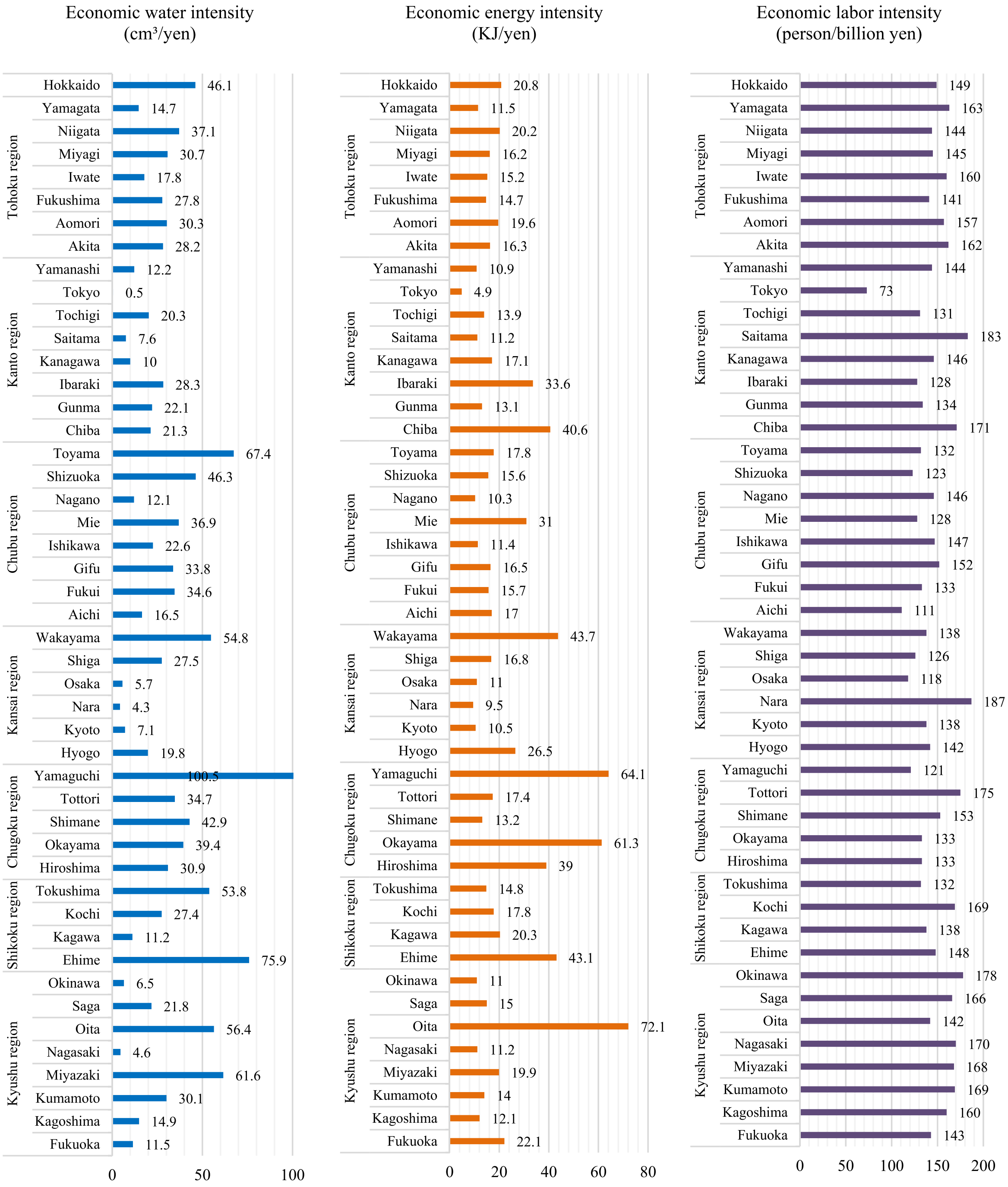
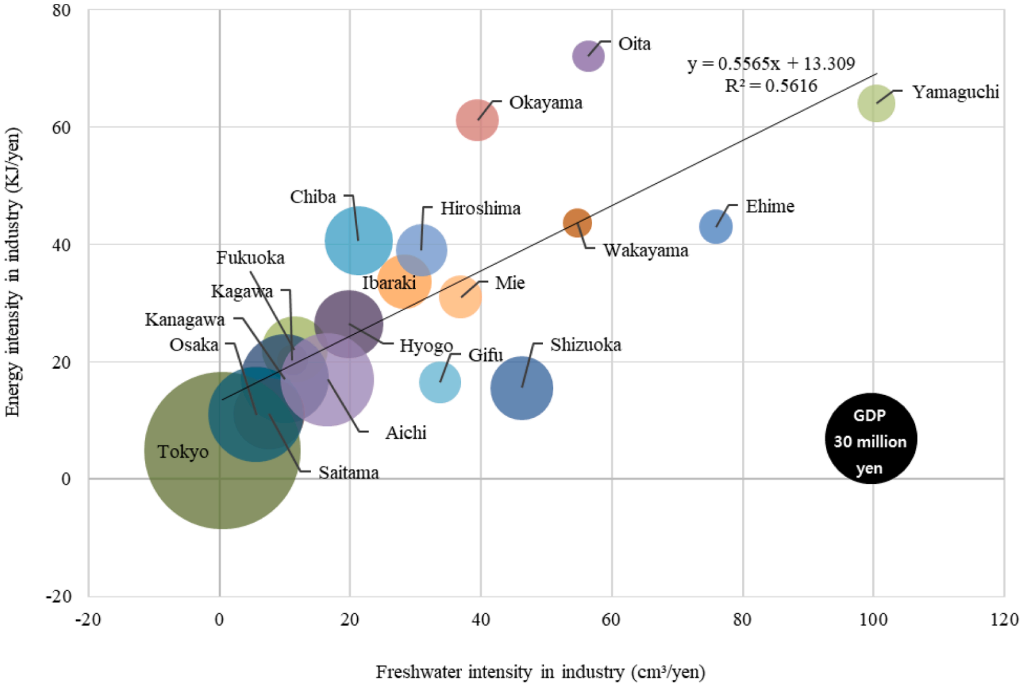


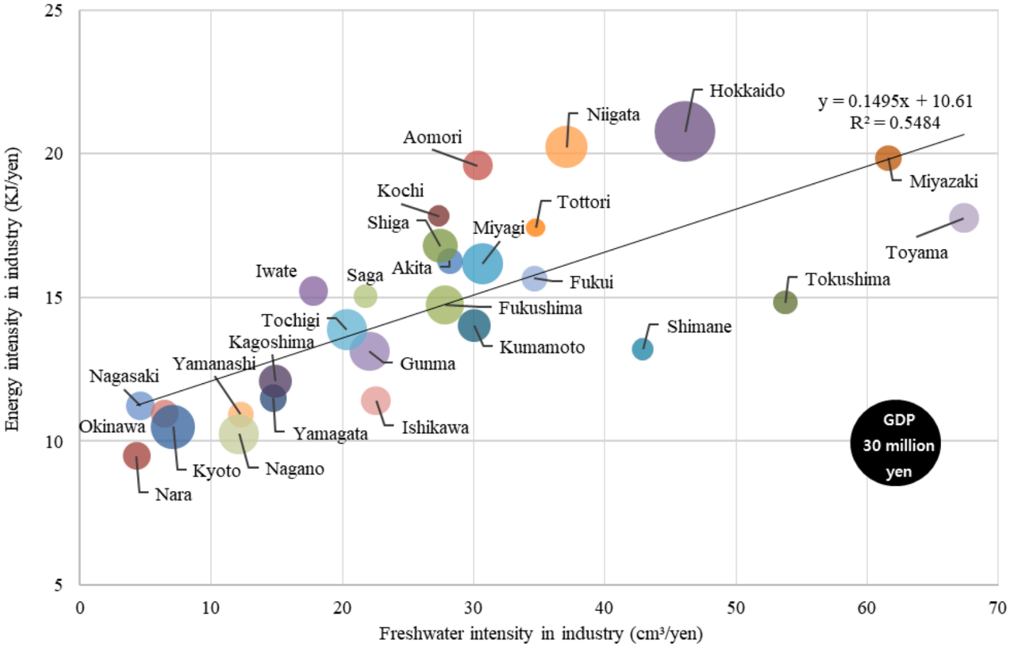
Fig. 5. Economic intensities of water, energy, and labor in 47 prefectures.

In the north and east, prefectures such as Niigata, Aomori, and Miyagi had high EWI. The average EWI in the Tohoku region was 26.6 cm^3/yen, while it was only 15.3 cm^3/yen in the Kanto region. However, EEI in the Kanto region was 1.9 KJ/yen higher than that in the Tohoku region. The main reason for these differences is that Tohoku includes the prefectures with agricultural industries, while the Kanto prefectures depend on financial and manufacturing industries. For example, the EEI of Chiba (Kanto region) was twice as large as the largest EEI in the Tohoku region (40.6 and 20.2 KJ/yen, respectively).

In the middle and western regions, the EWI values of prefectures in Chubu (except for Aichi and Nagano) were larger than the national value. Water security could be the limiting factor for economic growth in Toyama because its EWI was 67.4 cm^3/yen: the second largest value among those of the 47 prefectures. In the Kansai region, Hyogo, Shiga, and Wakayama exhibited EWI values exceeding the national value. Specifically, EWI in Wakayama (54.8 cm^3/yen) was the fifth largest of all 47 prefectures. In terms of water distribution, Shiga, Kyoto, and Osaka share freshwater from the Yodo-Biwa water basin; thus, simultaneous economic growth in these prefectures could cause a water security issue. In Wakayama, EEI was the third largest among the 47



(a) Industrial zones



(b) Non-industrial zones

Fig. 6. Economic water and energy intensities in 47 prefectures of (a) industrial and (b) non-industrial zones in Japan, 2006−2015.

prefectures (43.7 KJ/yen), but GRP (3,555 billion yen/year) was the smallest in Kansai. However, as Hyogo had both a large GRP and EEI, the trade-off between economic growth and energy security could be an issue for future development. In Chubu, most prefectures had a smaller EEI than the national value, except for Mie (31.0 KJ/yen). For example, Nagano's GRP was 7,949 billion yen/year, but its EEI was only 10.3 KJ/yen.

In western regions, including Kyushu, Chugoku, and Shikoku, only the EWI and EEI values of Nagasaki, Kagoshima, and Okinawa were lower than the national values. For example, the EWI in Yamaguchi (100.5 cm^3/yen) and EEI in Oita (56.4 KJ/yen) were the largest among the 47 prefectures. The minimum EWI in Chugoku region was in Hiroshima (30.9 cm^3/yen), 11.3 cm^3/yen higher than the national value. Furthermore, the EEI both in Yamaguchi and Okayama exceeded 60 KJ/yen. Therefore, regional economic growth could be strongly related to both water and energy security in the Chugoku region. In the Shikoku region, Ehime and Tokushima showed the largest EWI values of 75.9 and 53.8 cm^3/yen, respectively; however, the GRPs of the prefectures were lower than those of other regions. In Kyushu, Oita showed the highest values of both EEI (72.1 KJ/yen) and EWI (56.4 cm^3/yen); thus, close cooperation among economy, water, and energy management is more necessary here than in other prefectures. In contrast, in Miyazaki, the EWI was 61.6 cm^3/yen (the third largest EWI in Japan), whereas the EEI was 19.9 KJ/yen; thus, water supply could be a more sensitive factor for economic growth than energy supply.

Economic labor intensity (ELI) variation was smaller than EWI and EEI, ranging from 111 to 187 manpower per billion yen in a year, except for Tokyo. The largest ELIs were observed in Nara and Saitama, and both prefectures need more than 180 manpower for achieving 1 billion yen/year.

3.2. *Assessment of weighted economic growth impacts in industrial zones on resources and economic inequality*

We assessed the impact of intensive GRP increase at prefectures in industrial and non-industrial zones on regional water and energy requirements and economic inequality. First, we analyzed EWI and EEI in industrial and non-industrial zones. Prefectures in the non-industrial zone depended more on water than those in the industrial zone (Fig. 6). In addition, most prefectures in the non-industrial zone had an energy intensity lower than 20 KJ/yen, a low value compared to the average (31 KY/yen) in the industrial zone. In the non-industrial zone, Hokkaido, Niigata, and Aomori depended more on energy than on water, but Shimane, Toyama, and Tokushima exhibited larger EWI values.

Based on EWI and EEI, we quantified industrial freshwater and energy requirements for achieving a target GDP value of 600,000 billion yen/year under two cases, assuming increased GRP in either the industrial or non-industrial zone. Increasing the GRP only in the industrial zone caused 11,475 million m^3/year of industrial freshwater use (Table 2), which was 1,353 million m^3/year more than that under the business as usual (BAU) scenario. In contrast, increasing GRP only in the non-industrial zone resulted in 12,401 million m^3/year of industrial water use, indicating that intensive economic growth in the industrial zone could have a lower impact on national water conservation than that in the non-industrial zone. We also found that economic growth in the industrial zone was accompanied with an energy use of 10,825 PJ/year nationally, which is 325 PJ/year more than that under economic growth in the non-industrial zone. The average energy use in Japan from 2006 to 2015 was 9,250 PJ/year; thus, increasing 325 PJ/year represented a 3.5% increase.

Additionally, we estimated industrial freshwater and energy requirements at regional scales (Fig. 7). The Kanto region had the largest increase in industrial energy use due to more intensive economic growth, while the Chugoku region had the largest increase in industrial freshwater use. The Chugoku region would need 423 million m^3/year of additional freshwater to increase the GRP in the industrial zone. In contrast, as GRP increased in the industrial zone, the Tohoku region showed the largest water and energy savings. Increasing GRPs in non-industrial zones could be a sensitive issue for water management in the Tohoku region. Thus, integrated water and economic management is essential in those regions. Additionally, the impact of intensive economic growth in the Shikoku region was lower than that in other regions.

Industrial energy use was 6,990 PJ/year in BAU, and approximately 75% of total industrial energy was used in the industrial zone. Increasing GRP in the industrial zone increased the industrial energy use in Kanto from 2,719 to 3,276 PJ/year (the largest increase in all regions), while only 662 PJ/year of industrial energy was used in the Tohoku region (in the non-industrial zone). This could be a substantial burden on energy supply-demand in prefectures of the Kanto region. In particular, most of the population lives in the Tokyo prefecture; thus, the energy supply to the public and industrial areas could be managed in terms of the trade-offs between economic growth and public supply.

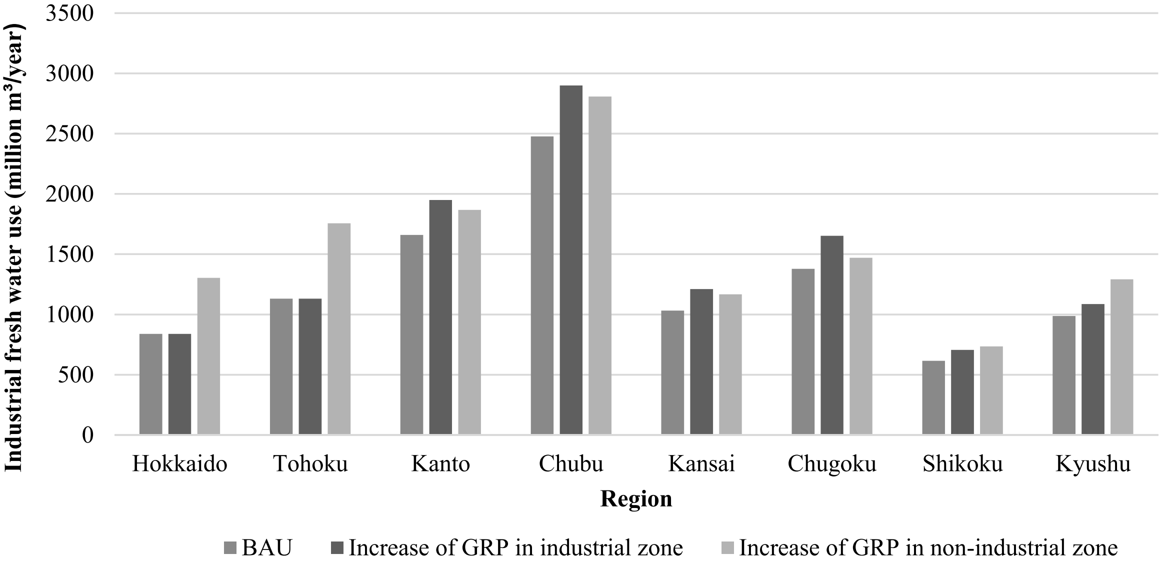
The results showed that intensively increasing GRP in the industrial zone could decrease national water requirements compared to those after increasing GRP in the non-industrial zone. However, it could also increase economic inequality. Increasing GRPs in the industrial zone increased the Gini coefficient to 0.555, which was larger than that in BAU. However, the Gini coefficient decreased to 0.460 (smaller than in BAU) on account of the increasing GRP in the non-industrial zone (Fig. 8 and Table 2). However, as previously shown, increasing GRP in industrial zones decreases freshwater use but increases energy use more than that in non-industrial zones, even though both cases were seen to meet the same national GDP target. Thus, these results reveal the trade-offs among economic, environmental, and social impacts through increases in GRP, water, and energy requirements, and in the inequality of GRPs. Economic growth policies should consider this trade-off. This study highlights the importance of integrating the environmental and social impacts of economic growth through a consideration of water and energy savings as well as economic inequality.

3.3. *Analysis of sustainable economic growth considering water–energy–labor nexus zones*

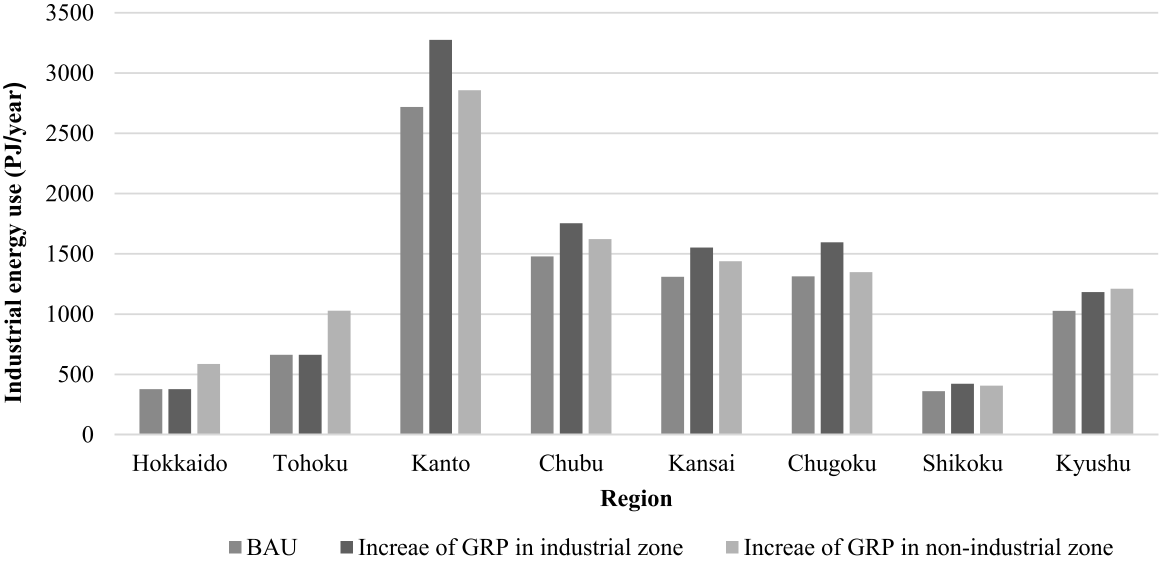
The importance of sustainability has increased along with the SDGs. Thus, we identified a plan to achieve sustainable economic growth with low adverse impacts on environmental, water, and energy resources. Previous results have shown that increasing GRP in industrial zones can result in more efficient economic growth. However, we must also consider the disparity in economic status across zones. Consideration of the social perspective and socio-economic impacts are especially important. Thus, labor was also considered as a major driver of sustainable economic growth. Accordingly, we identified the I-WEL nexus

Table. 2
National Gini coefficient and requirement of industrial water and energy.

Scenarios	Target value of national GDP(billion yen/year)	Industrialfreshwater use(Mm^3/year)	Industrialenergy use(PJ/year)	Ginicoefficient
Mean BAU (2006–2015)	517,190	10,122	9,250	0.523
Increase of GRP in industrial zone	600,000	11,475	10,825	0.555
Increase of GRP in non-industrial zone	600,000	12,401	10,500	0.460



(a) Industrial freshwater requirement



(b) Industrial energy requirement

Fig. 7. Regional water and energy requirements for increasing GRPs in industrial and non-industrial zones.

zones classified by water, energy, and labor intensity and assessed the impacts of economic growth by economic zone on local, regional, and national water, energy, and labor management.

3.3.1. *Classification of I-WEL nexus zones by economic water, energy, and labor intensities*

Sustainability indicates the ability to exist constantly accompanied by low negative impacts on the related area. From this perspective, sustainability in the economy could be defined as economic growth with high efficiency and low impacts on resources.

Each prefecture has different water, energy, and labor intensities; thus, the GRP increase should be applied while considering efficiency and intensity for sustainable economic growth. We set I-WEL nexus zones considering water, energy, and labor intensities in terms of social, economic, and environmental impacts and then assessed various economic growth scenarios based on the zones.

First, we analyzed the correlations among economic intensities (Fig. 9). For EEI and ELI, three clusters were formed, showing a slightly negative correlation. EWI and ELI also showed a negative correlation; thus, the trade-off between water–energy and labor could be considered in economic growth. Contrastingly, water and energy use in economic growth showed a synergistic effect (e.g., low water use could be related to low energy use).

Based on the correlations among economic intensities, we classified the 47 prefectures into multiple I-WEL nexus zones using K-means clustering, as described above. We applied various numbers of clusters and found that four clusters showed discrete classification of prefectures (Fig. 10 and Table 3). However, as Tokyo exhibited water, energy, and labor values significantly lower than those in other prefectures, we regarded Tokyo as an outlier and excluded it from the K-means clustering. Each cluster carried different meanings; we identified four I-WEL nexus zones as Zones 1−4: high-efficiency zones (Cluster 1), labor-

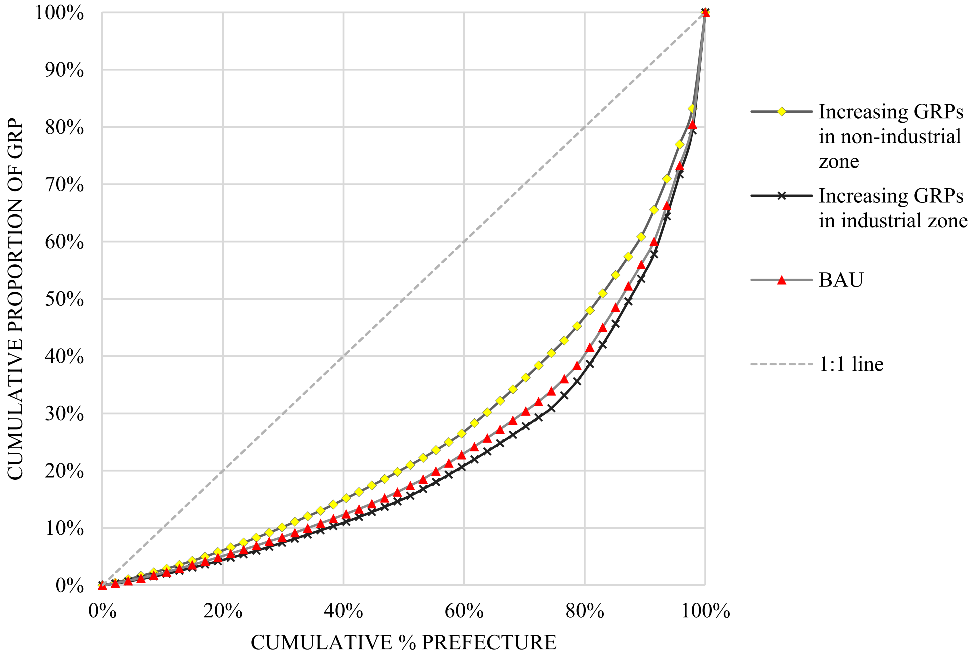
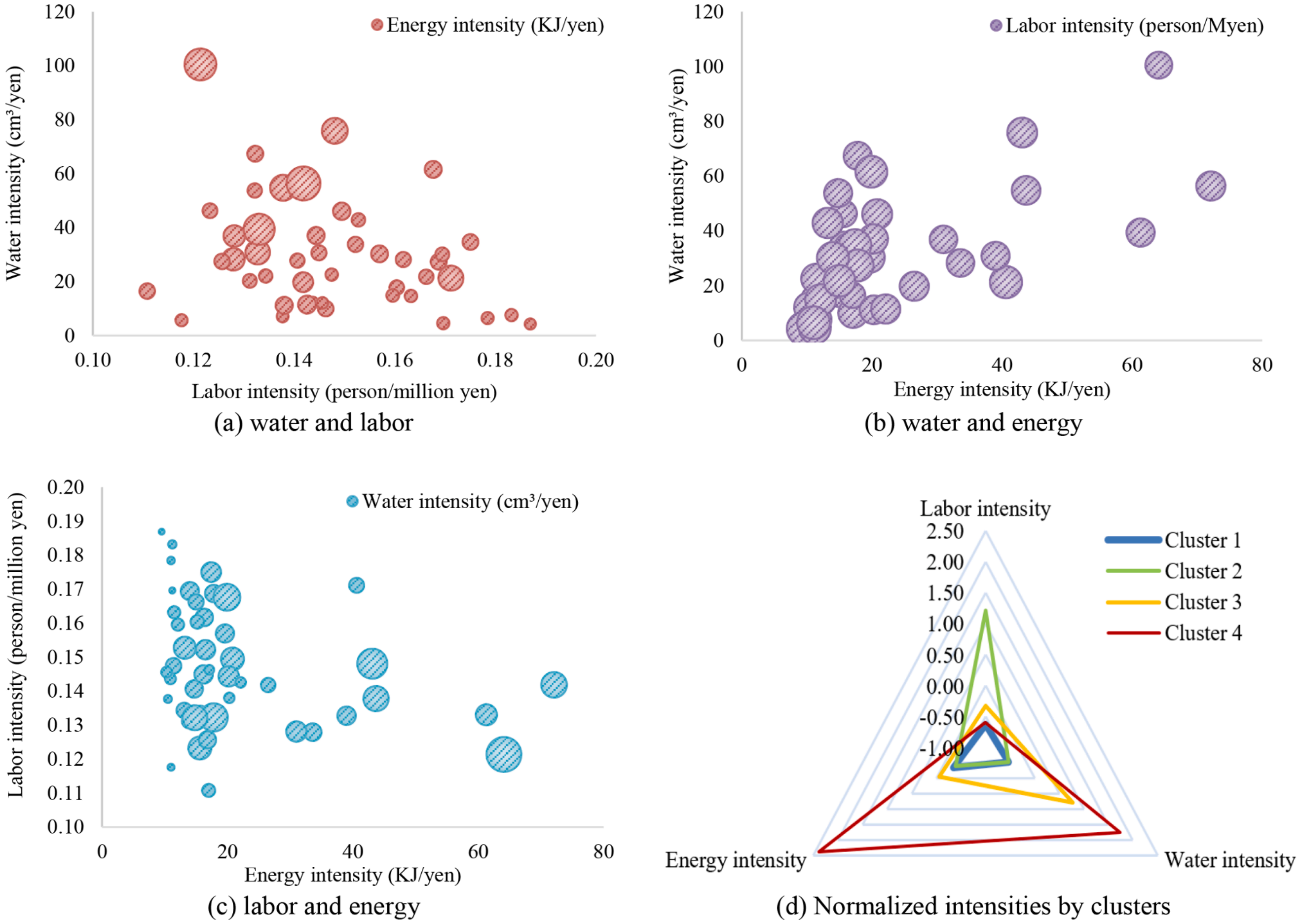


Fig. 8. Lorenz curves under scenarios of intensive increase of GRP in industrial and non-industrial zones.



(a) water and labor

(b) water and energy

(c) labor and energy

(d) Normalized intensities by clusters

Fig. 9. Analysis of economic water, energy, and labor intensities of 47 prefectures. Correlation between (a) water and labor, (b) water and energy, (c) labor and energy, and (d) average values of normalized intensities in each cluster.

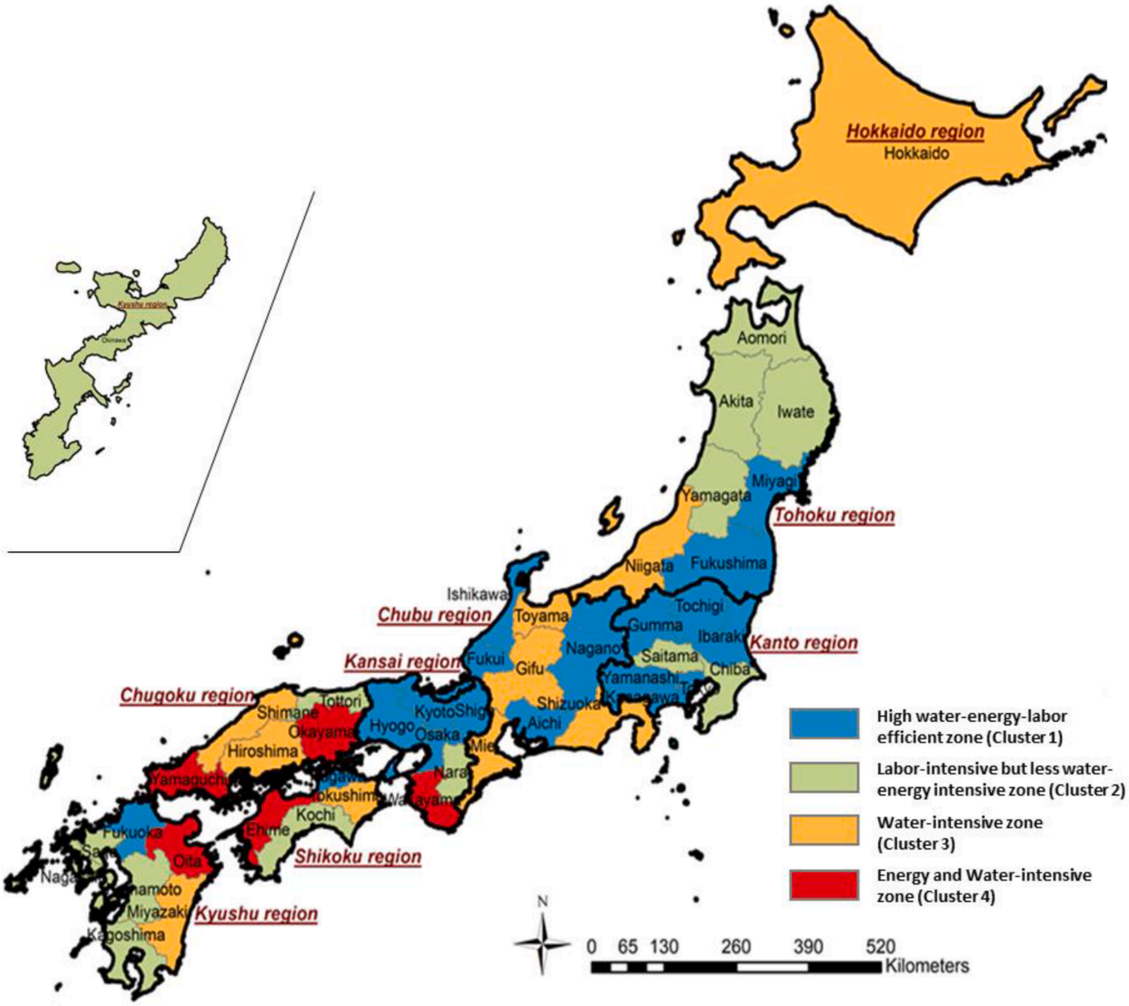


Fig. 10. Classification of I-WEL nexus zones via K-mean clustering.

Table. 3
Normalized values of water, energy, and labor intensities obtained via K-means clustering.

Variables	Normalized values			
	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Labor intensity	-0.626	1.208	-0.326	-0.601
Water intensity	-0.534	-0.532	0.781	1.746
Energy intensity	-0.348	-0.392	-0.053	2.389

intensive zones (Cluster 2), water-intensive zones (Cluster 3), and water- and energy-intensive zones (Cluster 4). As Zone 1 comprised areas with low EWI, EEI, and ELI, intensive economic growth in this zone could lead to large savings of water, energy, and labor, as compared to that in other zones; this could be the optimal choice from an industrial development perspective. In socio-economic terms, additional labor could create positive impacts on job creation and economic growth in Zone 2, making it a more suitable policy for low adverse impacts on water and energy, and it would also create a boost in employment. Zone 3 requires more water use rather than energy and labor for economic growth. Zone 4 showed large inputs of both water and energy use with economic growth; thus, prefectures in Zone 4 need facility improvements to increase their water- and energy-use efficiencies.

From the clustering results, prefectures in the Kanto region, except for Chiba and Saitama, were classified as Zone 1. The Kanto region leads in terms of its contribution to national economic growth, yielding approximately 40% of the GDP. Prefectures in the north (Aomori, Akita, Iwate, and Yamagata, the representative agricultural area) were mainly classified as Zone 2. Accordingly, securing labor could be the main issue in this region rather than energy and water. Prefectures classified as Zone 3 indicate intensive water use in comparison to that of energy. Prefectures classified as Zone 4 are mainly in the southwest and include Okayama and Yamaguchi in the Chugoku region, Ehime in the Shikoku region, and Oita in the Kyushu region.

3.3.2. Analysis of water, energy, and labor requirement for economic growth weighted by I-WEL nexus zones

Intensively increasing economic growth in prefectures with low EWI and EEI could lead to positive environmental impacts in the context of water and energy security. Additionally, as a greater requirement for labor could improve job availability, large labor intensity could be regarded as a positive variable for socio-economic growth; however, from the industry perspective, large labor intensity also results in greater costs and leads to low-efficiency development.

Accordingly, the present study applied the different increase ratios of GRPs by I-WEL nexus zones as different scenarios (Table 4) and assessed the social, environmental, and economic impacts under these scenarios. Scenario 1 considered the high efficiency of water, energy, and labor and the I-WEL nexus zone, with low values of all economic intensities assigned as high-priority economic growth. Accordingly, Zone 1 had the largest GRP increase ratio. In contrast, Zone 4 had the smallest GRP increase ratio. Scenario 2 pursued economic growth with low impact on

Table. 4
Scenarios of economic growth by I-WEL nexus zones considering user priorities.

Scenarios*	Scenario description	Priority of economic growth by I-WEL nexus zones			
		High-efficiency (Zone 1)	Labor-intensive (Zone 2)	Water-intensive (Zone 3)	Water-energy intensive (Zone 4)
Baseline	Equal priority in all zones	-			
Scenario 1	High economic efficiency in water and energy use	1st	2nd	3rd	4th
Scenario 2	Labor-intensive economic growth	3rd	1st	2nd	4th

*All scenarios set target value of national GDP as 600,000 billion yen

water and energy but also considered socio-economic growth through increased labor requirements as a form of employment inducement. Therefore, a high priority of economic growth was assigned to Zone 2. Based on the priority of economic growth, the GRP increase ratio in each zone was assigned to achieve the national GDP target (600,000 billion yen/year). In addition, we applied the equal increase ratio of GRP to all zones as the baseline scenarios.

We quantified the industrial freshwater, energy, and labor requirements in prefectures using EWI, EEI, and ELI (Table 5). As expected, increasing GDP was found to be accompanied by increased resources consumption and labor requirement. If the GDP of Japan increased to 600,000 billion yen, approximately 1,621 million m^3/year and 1,481 PJ/year additional freshwater and energy, respectively, would be required, as compared to the baseline scenario with BAU. In addition, industries would need to employ 10,617 additional employees. When we applied Scenario 1, representing more economic growth in highly efficient prefectures, more GRP was provided by the Kansai and Kanto regions, while the largest GRP decrease (compared with that of the baseline scenario) was observed in the Chugoku region. The impacts of GRP growth under Scenario 1 were quantified as 337 million m^3 freshwater and 184 PJ energy savings nationally. While increasing the labor requirement could be regarded as a driving factor for socio-economic growth in Scenario 2, a freshwater and energy increase of 356 million m^3 and 155 PJ were noted, respectively, compared to those under Scenario 1, and it would employ an additional 820,000 people. This is the trade-off between environmental impact and socio-economic growth.

Although the scenarios lead to national savings of water, energy, or labor, each scenario causes different impacts in different regions (Table 6). For example, compared to other regions, the Kanto and Kansai regions represent areas with high economic growth but low effects of economic growth on water and energy. Additionally, leading agricultural production in the Tohoku region had low impacts on economic growth under Scenarios 1 and 2. In contrast, the Shikoku, Kyushu, and Chugoku regions (western area) increased water and energy productivities through economic growth, considering the low impact of economic growth on water and energy. Thus, this scenario of economic growth is feasible. However, the overall results indicate that economic growth, considering the low impact on national water and energy security, could have different impacts at the regional scale, while achieving water and energy savings at the national scale.

Table. 5
Gini coefficient and requirement of national freshwater, energy, and labor by economic growth scenarios.

Variables	Scenarios of economic growth		
	Baseline	Scenario 1	Scenario 2
Gini coefficient	0.523	0.533	0.517
Fresh water input (million m^3/year)	11,743	11,406	11,761
Energy input (PJ/year)	10,731	10,547	10,702
Labor input (1,000 person/year)	76,923	76,636	77,456

Table. 6
Results of regional freshwater, energy, and labor requirement by economic growth scenarios.

Variables	Regions	Scenarios of economic growth		
		Baseline	Scenario 1	Scenario 2
GRP (billion yen/year)	Hokkaido	21,107	19,922	21,782
	Tohoku	46,211	45,845	47,696
	Kanto	237,267	241,470	236,680
	Chubu	100,926	100,143	100,774
	Kansai	92,040	93,734	90,002
	Chugoku	32,840	30,454	32,274
	Shikoku	15,686	15,037	15,475
	Kyushu	53,924	53,396	55,318
Fresh water input (million m^3/year)	Hokkaido	974	919	1,005
	Tohoku	1,312	1,299	1,348
	Kanto	1,926	1,949	1,953
	Chubu	2,873	2,797	2,906
	Kansai	1,198	1,200	1,157
	Chugoku	1,599	1,471	1,540
	Shikoku	714	664	691
	Kyushu	1,146	1,106	1,161
Energy input (PJ/year)	Hokkaido	439	414	453
	Tohoku	768	760	793
	Kanto	3,154	3,187	3,210
	Chubu	1,716	1,695	1,719
	Kansai	1,520	1,535	1,477
	Chugoku	1,524	1,401	1,467
	Shikoku	418	394	403
	Kyushu	1,191	1,161	1,182
Labor input (1,000 person/year)	Hokkaido	3,155	2,977	3,255
	Tohoku	6,937	6,879	7,178
	Kanto	27,083	27,442	27,350
	Chubu	12,612	12,493	12,608
	Kansai	12,015	12,223	11,774
	Chugoku	4,427	4,113	4,368
	Shikoku	2,281	2,186	2,254
	Kyushu	8,412	8,322	8,670

4. Conclusions

Globally, large quantities of water and energy have been used in industries since the industrial revolution, and the efficiency of the economy of high technology was considered the primary issue in industries. However, currently, “sustainability” has emerged as the key factor, and the consideration of environmental impacts has become important for economic growth. Methods of sustainable development can relate to trade-offs among social, economic, and environmental impacts. Sustainable management may need to consider the governance accompanying transboundary resource management. Considering the influence among prefectures could be key for sustainable resource allocation. Significantly increasing water usage for economic growth in a specific prefecture directly affects other prefectures in the same watershed. However, a few questions regarding sustainable approaches for economic growth still remain, and the impacts of economic growth differ with spatial scales (i.e., national or local scales).

Economic growth generally depends on the areas in Japan’s industrial zones owing to their high efficiency. However, continuous development centered around industrial zones could emphasize resource intakes by industries at the prefecture level and cause economic inequality at the local and regional scales. National policies focus on sustainable development and consider environmental factors such as carbon emissions, energy security, and water quality; however, as national economic growth is derived from local growth, sustainable economic growth must consider the trade-offs between economic and environmental impacts at local, regional, and national scales.

Therefore, as economic growth strategies focus on the trade-offs, synergy is essential. We attempted to understand sustainable economic growth in terms of the interlinkages between resources and products. Thus, we focused on the spatial differences of water, energy, and labor intensities during industrial economic growth, classified the I-WEL nexus zones, and assessed the economic growth scenarios specific to each I-WEL nexus zone.

Nevertheless, this study assessed economic growth without considering changes in population or inflation. Despite this limitation, the study suggests the application of the nexus approach to sustainable economic growth considering the main inputs (water, energy, and labor) and revealed the trade-offs between economic growth and input variables at local, regional, and national scales. While considering the I-WEL nexus zone, increasing GRP could contribute to national water and energy savings; however, resource allocation among prefectures under regional resource security could be a limiting factor for economic growth at the regional scale.

This study used Japanese cases and was highly dependent on data availability, thus we applied the data corresponding to Japan. However, the methodology for assessing economic growth considering the I-WEL nexus could be adapted to other countries for which industrial water, energy, and labor data are available. Depending on the characteristics of each country, various I-WEL nexus zones could be classified; for example, four I-WEL nexus zones were observed in Japan, but this could vary for other countries. In addition, we considered all types of industries; nevertheless, I-WEL nexus zones could be applied to a specific industry, such as the manufacturing industry, and individual zones of specific industries can be obtained through the application of the I-WEL nexus in this study. Therefore, the analysis of the I-WEL nexus by area could provide novel insights regarding economic governance by integrating natural and human resources. Furthermore, we suggested economic growth scenarios considering I-WEL nexus zones. Various areas could adapt the nexus zone concept to increase synergy in strategies regarding integrated governance management. Local governments should proceed with preparing infrastructure for regional governance and sustainable development, while also integrating water and energy supplies with other prefectures and regions through the I-WEL nexus zone approach. Accordingly, this study is expected to provide a useful approach for linking economy and environment, while decreasing the gap between local and national policies.

Data availability: Data results of this study are freely available by contacting the corresponding author.

CRediT authorship contribution statement

Sang-Hyun Lee: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Makoto Taniguchi:** Conceptualization, Methodology. **Naoki Masuhara:** Conceptualization. **Rabi H. Mohtar:** Conceptualization, Writing – review & editing. **Seung-Hwan Yoo:** Conceptualization, Methodology, Formal analysis. **Masahiko Haraguchi:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest regarding this publication. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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