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Article

A Complex Systems Analysis of the Water-Energy Nexus in Malaysia

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Received: 3 May 2020; Accepted: 10 June 2020; Published: 15 June 2020

Abstract: Water security plays a crucial role in maintaining livelihoods, especially emerging economies. In Malaysia, understanding the inter-relationships of water within the water-energy-food (WEF) nexus is at its infancy. This paper investigates the interactions of the water sector with energy sector in Malaysia, through the lenses of WEF nexus, using system dynamics. The first part of the research involves qualitative interviews with key stakeholders in the water sectors, which provides validation for the initial causal loop relationships built and qualitative inputs of the water-energy nexus through the lenses of the water sector. The second part of the research is a quantitative simulation of stock and flow based on four carefully designed scenarios revolving around Malaysian water security. Key findings include an apparent disconnect between the states and federal governments in managing water supply, poor economic sustainability of the water supply and services industry, and significant energy use in the water sector. On the other hand, environmental impacts stemming from the water sector is minimal. Streamlining water governance and revising water tariffs have thus been suggested as policy recommendations, where their implementation could propagate into downstream benefits for the energy sector.

Keywords: water security; water-energy-food; nexus; system dynamics; Malaysia; complex system

1. Introduction

1.1. Global Water Woes and Concept of Water Security

In 2013, UN-Water defined water security as “the capacity of a population to safeguard its sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability” [1]. Despite the many differing definitions of water security that exist [2–7], they usually revolve around elements of availability, acceptability, quantity, quality, and livelihood. The urgency of global water security is magnified by the bursting of “bubbles” in the “water bubble” regions [8] and is emphasized by the facts and figures as illustrated in Table 1.

The concept of water security has been thoroughly discussed by many researchers and organizations alike. One of the earliest discussions on water security, initiated by Falkenmark and Lundqvist [9], discussed water security as closely related to water quality, efficiency, demand management, climate, and food self-sufficiency. Falkenmark furthered this analysis by showing the linkages between land, water, and the ecosystem [6]. Cook and Bakker suggested addressing water security issues using a holistic approach deployed on a paradigmatic level as opposed to an operational level [10].

1.2. Water as the Bloodstream of the Water-Energy-Food Nexus

Whilst water is important, energy and food are also crucial to the survival of humanity alongside their intricate inter-relationships with each other, as discussed in the recently growing research area of water-energy-food (WEF) security nexus [11–34].

Table 1. Facts and figures of global water security.

Source	Facts and Figures
World Economic Forum [35]	Water crises ranked #1 global risk by World Economic Forum.
Gleeson et al. [36]	1.7 billion people living in areas where water use exceeds recharge.
World Health Organization [37]	1 in 10 people lack improved drinking water sources.
World Health Organization [37]	8 in 10 people lack access to improved drinking water and the number is increasing.
Bain et al. [38]	1.8 billion people use fecal-contaminated water.
World Health Organization [37]	Millennium Development Goal (MDG) target for basic sanitation was missed by 700 million people.
World Health Organization [37]	1 in 3 people still lack improved sanitation facilities.
World Health Organization [37]	1 in 8 people practices open defecation.
Hutton [39]	1.5% of GDP of developing countries is loss as a result of lack of access to improved water sanitation.
Danilenko et al. [40]	1 in 3 developing countries unable to cover basic operation and management costs of water utilities.
UN-Water [41]	Freshwater withdrawals for energy production to increase by 20% through 2035.
FAO Aquastat [42]	Agriculture's share of water withdrawals is 70%.
United Nations [43]	4.2 billion people affected by floods, droughts, and storms between 1992 and 2012.
United Nations [43]	USD 1.3 trillion in economic losses from water-related disasters between 1992 and 2012.

The importance of water within the WEF security nexus was first described by Hoff [11] where water resource acts as the central focus, with action fields of society, economy, and environment as inputs to promote the outputs of resource security, equitable and sustainable growth, and resilient productive environment. Ripl described water as the "bloodstream" of the biosphere [44].

Water-Energy Relationships

Water-energy links exist as either water demands for energy or energy demands for water. In water for energy, globally 90% of power generation are water intensive, with the largest proportion of growth occurring in emerging economies [45], such as Malaysia [41] and India [46]. IRENA [15] coined the term 'water-related risks' to energy security, summarizing that the electricity supply chain is extremely sensitive to the quality of water input, such as temperature, flow rates, and density. Points in the electricity supply chain that use water are inclusive of thermo-electric cooling, fuel extraction, mining, processing, transportation, hydropower, etc. [15,41,47–51]. On the other hand, energy for water links exist in the water supply and services industry, as well as in the wastewater treatment industry [15,41,52], such as the energy used for state-wide pumping, treatment of supply water, treatment of sewage water, and electricity usage of water plant operations. Elias-Maxil et al., by considering energy expenditure at various points of the urban water cycle, showed that water heating accounts for 80% of total primary usage of energy in developed nations [53].

1.3. Water in Malaysia—Resource Security and Reform

The Malaysian water sector can largely be divided into two sub-sectors, namely, the water supply and services, and wastewater treatment. In 2006, the federal government restructured a large portion of the responsibilities of water industry respectively into the Ministry of Energy, Green Technology and Water (KeTTHA), the National Water Resource Council (NWRC), and the National Water Services Commission, whilst holding on to the role of overarching policy and national direction setting. This effort coupled with the continuous privatization of water treatment plants resulted in positive outcomes for the community, as observed from the increased coverage and quality of water services provided in the nation. Water withdrawn in Malaysia has almost always equally been distributed among its diverse industries, agriculture, and municipalities [54,55].

From the Eleventh Malaysia Plan, four strategies were put forth in accordance with the sixth strategic thrust, 'Strengthening infrastructure to support economic expansion'; these strategies aimed to raise financial sustainability of the water sector by expanding technologically, optimizing water operations, and consolidating the regulatory framework [56]. The mid-term review of the Eleventh Malaysia Plan shows that there are still gaps to be closed for the water sector, especially in areas of sewerage connected services coverage, population served by clean treated water, as well as non-revenue water [57].

A number of research and investigations have been conducted on and around the water sector for Malaysia and whilst it was acknowledged that key challenges revolve around technology, economy, social, and governance [58,59], the way forward in advancing the water industry should be concerned with implementing actions that are holistic and centralizing [60], to move from Water Supply Management (WSM) mode into Water Demand Management (WDM) mode, as well as to involve inter-ministerial and multi-stakeholder cooperation [58].

1.4. Systems Thinking and System Dynamics for the WEF Nexus

A number of system approaches stemming from the philosophy of systems thinking have been developed and employed both in the industry and academic research. Initially, systems thinking is broadly concerned with thinking holistically about a problem whilst considering various factors together with all stakeholders and eventually co-designing a solution in a participatory manner. However, different methodologies in approaching and performing systems studies emerged and were developed due to the different types of complexity and key stakeholders of the systems.

In 2003, Jackson proposed a comprehensive framework, the system of system's methodology (SOSM). This systems methodology selection is based upon the complexity of the system and the key stakeholders involved [61], as depicted in Table 2. From Table 2, the key stakeholders are being referred to as participants of the system, and they can be divided into three categories, namely unitary, pluralist, and coercive. The WEF security nexus is a complex system consisting of large subsystems, namely the water, energy, and food sectors, interacting with each other in terms of social, economics, and environmental factors. The participant is unitary because the participants, namely key stakeholders from the water, energy, and food sectors, as well as the general public, share a common interest of having best resource use efficiency and performance, improving livelihood, and minimizing environmental damage. Consequently, the WEF security nexus is classified as a unitary complex problem, from which system dynamics stood out as a suitable approach.

Table 2. Jackson's system of system's methodology (SOSM) [61].

Systems	Participants		
	Unitary	*Pluralist*	*Coercive*
Simple	Hard Systems Thinking	Soft Systems Thinking	Emancipatory Systems Thinking
Complex	System Dynamics Organizational Cybernetics Complexity Theory	Soft Systems Thinking	Postmodern Systems Thinking

System dynamics have been employed by other researchers in similar context such as Bahri [62] on Indonesian reservoirs, Bakhshianlamouki et al. [63] on restoration of Umrie Lake, Akhtar et al. [64] on society-biosphere-climate-economy-energy system, Sun et al. [65] on sustainable utilization of water resources in China, Tidwell et al. [66] on community-based water planning in Middle Rio Grande, and Sahin et al. [67] on long-term urban water security.

2. Materials and Methods

2.1. Research Process Flow

This research utilizes a mixed approach of qualitative data acquisition through stakeholder engagement interviews and quantitative simulation using system dynamics modeling. Figure 1 outlines the process flow for the entire research. The qualitative modeling consists of three steps, namely the initial causal loop diagram (CLD) construction, engagement with key stakeholders, and CLD improvement and finalization. Quantitative modeling ensues with stock and flow diagram (SFD) construction, SFD validation, and simulation of scenarios. The research process concludes with the analysis of results, which includes the quantitative assessment of simulated results by comparing the values and behavior of key indicators simulated in different scenarios, before a final conclusion is drawn.

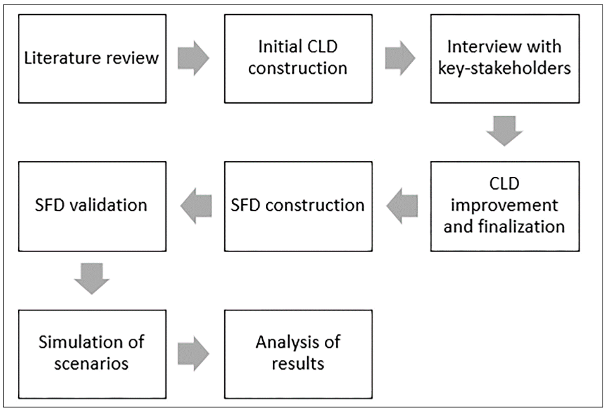

Figure 1. Research process flow.

2.2. System Dynamics Modeling Process

Figure 2 shows the system dynamics modeling process adapted from Sterman [68]. The modeling process starts with defining the systems boundary for the systems model. It is the first step where the problem has to be articulated [68]. Thus, by understanding the definition of water security and setting the approach through the lenses of Malaysian water-energy-food nexus, the boundary of the systems model has been defined.

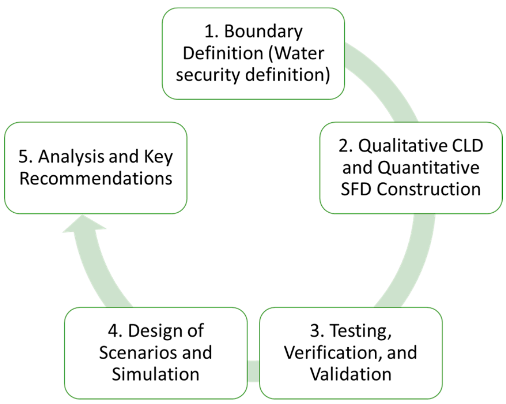

Figure 2. System dynamics modeling process.

Once the boundary is defined, system modeling begins with the construction of CLD and SFD, which describes the interaction of variables within the Malaysian WEF nexus. The models are first constructed using findings from the literature review. In step 3, the models are tested and verified every step along the way by adopting a few tools outlined by Sterman [68], namely, boundary adequacy, dimensional consistency, parameter assessment, extreme conditions, and integration error. Subsequently, validation is performed through true-false questionnaires and broad-based questions conducted in the key stakeholder interview processes. The simulation of designed scenarios take place in step 4, where behavior, over time of key indicators, are generated from the created models. The designs of the scenarios are based upon the inputs provided by key stakeholders from the interviews. The system dynamics process concludes with analyzing the simulated dynamics of behavior over time before key recommendations are put forward.

2.3. Interview Process

The interview process is a key engagement method, conducted to acquire qualitative data to establish a high-level systemic understanding of the complex problem, in this case, the water sector within the WEF nexus. The CLD can be constructed using the insights from this process, which represents the intra-system interactions and is used as a baseline for the SFD modeling.

The interview process is the third step in the research flow, as seen from Figure 1, and is part of the second step of the system dynamics modeling process, as seen from Figure 2. With a clear purpose, the interview questions are designed to invoke the best responses to understanding the roles and responsibilities of the Malaysian water sector and its part within the context of the Malaysian WEF nexus. During the interview, whilst main questions are asked and discussed, follow-up detailed questions are posed to deepen the understanding of the context at hand. Table 3 shows the list of institutions and organizations involved, with the level and position of the interviewees participated.

Table 3. List of interviews conducted.

Institution/Organization	Key Stakeholders Interviewed	Sector
The Ministry of Energy, Green Technology and Water (KeTTHA)	(W1) Director-General	Water
The Ministry of Energy, Green Technology and Water (KeTTHA)	(W2) Director	Water
National Hydraulic Research Institute of Malaysia (NAHRIM)	(W3) Senior Researcher	Water

Each interview session is divided into two parts, namely (1) the validation of each link of constructed CLD models and (2) broad-based question of water security within Malaysian WEF nexus. For the first part, the interviewees are expected to fill in a true-false questionnaire which describes the cause and effect between two variables, as given by the example in Table 4 below. For the second part, a set of broad-based questions were asked, as shown in Table 5 below.

Table 4. True-false questionnaire example.

Cause	Effect	True	False	Don't Know	Remark
Increase in Domestic Usage of Water	Increase in Need for Water Supply System				
Increase in Need for Water Supply System	Increase in Building of Water Supply System				
Increase in Building of Water Supply System	Increase in Size of Water Supply System				

Table 5. Broad-based questions.

No.	Questions
1	How would you define water security?
2	How can we measure water security?
3	What do you think of the water security in Malaysia?
4	What are the strengths and weaknesses of water security in Malaysia?
5	What are the water-energy relationships that you know of?
6	What are the important elements in the water-energy nexus?
7	Do the Causal Loop Diagrams constructed represent the relationships between water and energy security in Malaysia accurately?
8	Are there additional elements which you think should be added to the CLD to show the relationships between water and energy security in Malaysia?
9	What are the water-food relationships that you know of?
10	What are the important elements in the water-food nexus?
11	Do the Causal Loop Diagrams constructed represent the relationships between water and food security in Malaysia accurately?
12	Are there additional elements which you think should be added to the CLD to show the relationships between water and food security in Malaysia?
13	Have you heard of or have any understanding of the Water-Energy-Food Security Nexus before this interview?
14	Do you think that having a holistic understanding on the performance of the WEF Security Nexus in Malaysia is important? Why or why not?
15	If yes, what do you think are important areas to look at when looking into the performance of WEF Security Nexus in Malaysia?

3. System Models

3.1. Interview Inputs and Setting System Boundaries

According to the key stakeholders identified in Table 3, W1 and W2, water security in Malaysia means the ability to supply water of sufficient quality and quantity to consumers from categories of domestic, industry, and commercial. Some vulnerabilities can be seen in Malaysia's water security, namely, extreme flooding in the east coast in 2014 (W3), in alignment with Grey's description [4] of having too much of water may prove destructive. Apart from that, safety of supply sources are paramount (W1).

Quantitative indicators to measure water security for Malaysia are namely water treatment capacities and water supply capacities (W1, W2). Addressing water security is not solely from the supply-side point-of-view, but water demand management is equally important (W2). This is because there is limited amount of space for us to build dams and water facilities and as such, building based upon demand without demand management is unrealistic due to their exponential growth. A few ways to manage water demand are policy implementation, technology control, and tariff setting (W2). For the longer period, education of the public is necessary.

Malaysia's strengths in the water sector lies in having an abundance of water catchment capacities, despite most of which goes to sea (W2). Improved water sector efforts in the past five years (W3), and regulation using acts such as the Water Supply Industrial Act 2006 (WSIA) and the existence of regulatory bodies such as National Water Regulator, are forms of strengths (W1). Centralizing water management is thus seen as a strength of the water sector, in alignment with Kim's research [60], as it represents the current global trend.

The primary weakness of Malaysia's water sector lies in the disconnect of governance where the federal government is in charge of water supply and services whilst the state governments are in charge of water resources (W1, W2, W3). In addition, the extensive water regulatory acts cover only the water supply and services and not the water resources (river, seas, lakes, etc.), which resulted in poor water quality at source. Consequently, this leads to extra efforts and costs in water supply treatment by the federal government (W2). Insufficient revenue or income due to below-cost tariffs [60] have also caused problems for the water sector (W2). A vicious cycle is inherent in the situation—insufficient funding to improve water system because revenue is low—revenue is low because of insufficient justification to raise tariffs to increase revenue to improve the water system (W2).

As such, water security in Malaysia has the following characteristics:

- To supply water of sufficient quality and quantity to consumers from domestic, industry, and commercial areas.
- Quantitative measures are addressed in two ways; namely, from the supply side, where water supply capacities and water treatment capacities are looked at, and from the demand side, where water demand is managed through policies, technologies, tariff setting, and education.
- Disconnect in governance as the state government is in charge of water resources (lakes, river, sea, etc.) while the federal government is in charge of water supply and services.
- Below-cost water tariffs that could not cover the costs of the water sector.

3.2. Causal Loop Diagrams

3.2.1. Resource Demand as a Result of Population

Figure 3 shows that population forms the basic driver for the demand of water. Population is affected by two loops: reinforcing loop of birth and population, and balancing loop of population and death. As such, the demand, or domestic use of water, increases and decreases in tandem with the population.

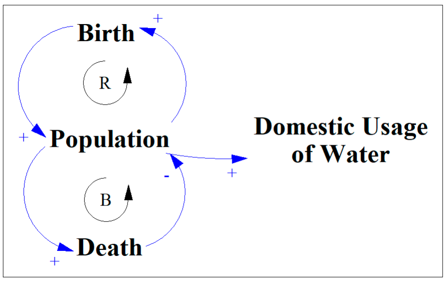

Figure 3. Population as demand of water.

3.2.2. Water Demand Management

Figure 4 shows the CLD for water demand management, which seeks to control the domestic and industrial usage of water. Water demand management is carried out in the form of tariff control and through technological and policy implementation. For example, in the past, water tanks in toilet systems are as large as 12 L (W2). Recent policy changes have compelled the size to reduce to between 3 L and 6 L (W2).

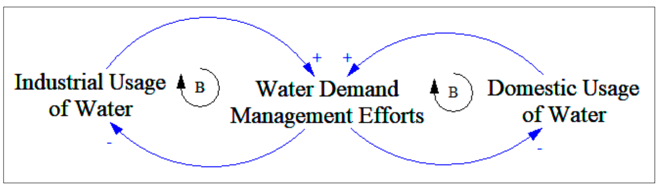

Figure 4. Water demand management loop.

3.2.3. Water Supply, Treatment, Demand, and Tariff Loops

Figure 5 shows the domestic and industrial loops for water supply, treatment, and tariff. This relationship portrays similarities and differences to the energy demand and supply loop in Tan and Yap's model [69]. It is similar, in a sense, that the usage acts as an interface to other sectors, as water usage from other sectors would feed into domestic and industrial usage of water. The difference is shown in the fact that water services in Malaysia are divided into supply and treatment.

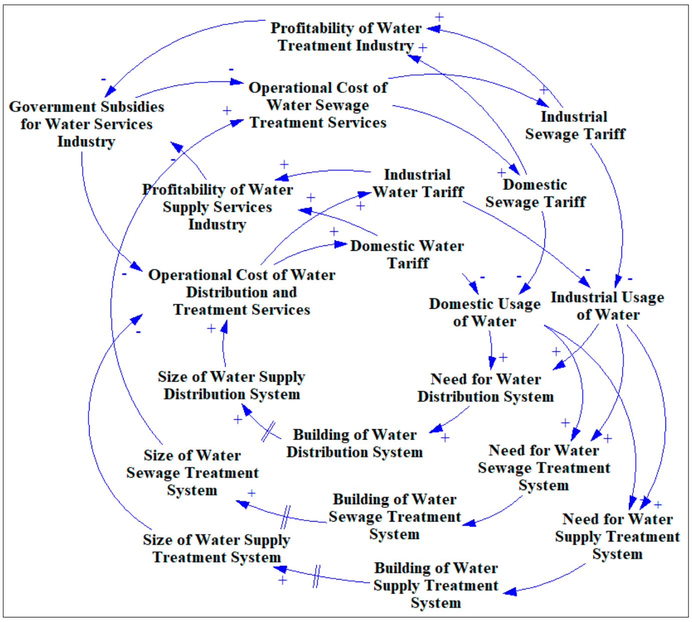

Figure 5. Water supply, treatment, and tariff.

3.2.4. Water-Energy Relationships

Figure 6 describes the links between the water and energy relationships, as adapted from Tan and Yap [69]. The most important loop emphasized here is the mutually reducing closed loop between operational hours of renewable energy (RE) and non-renewable energy (non-RE) power plants. This relationship has been thoroughly discussed in Tan and Yap [69], which is not the focus of this paper.

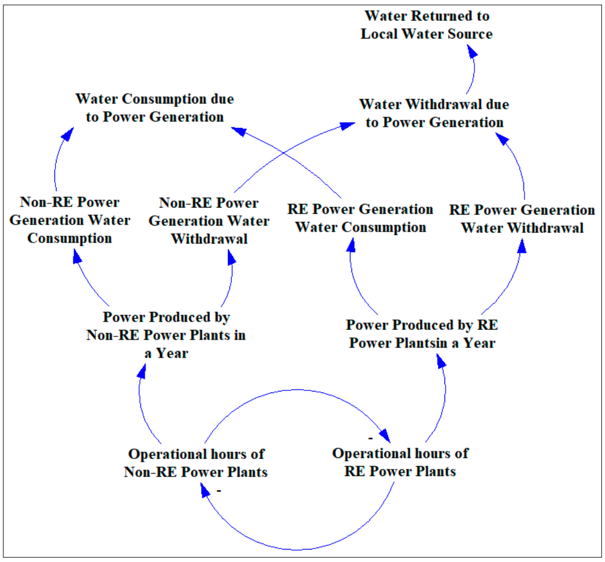

Figure 6. Water-energy relationships.

3.3. *Stock and Flow Diagrams*

3.3.1. Population Growth and Demand

Figure 7 shows the population SFD adopted from Tan and Yap [69], where population is modeled as a stock, which changes according to any instantaneous birth and death rate.

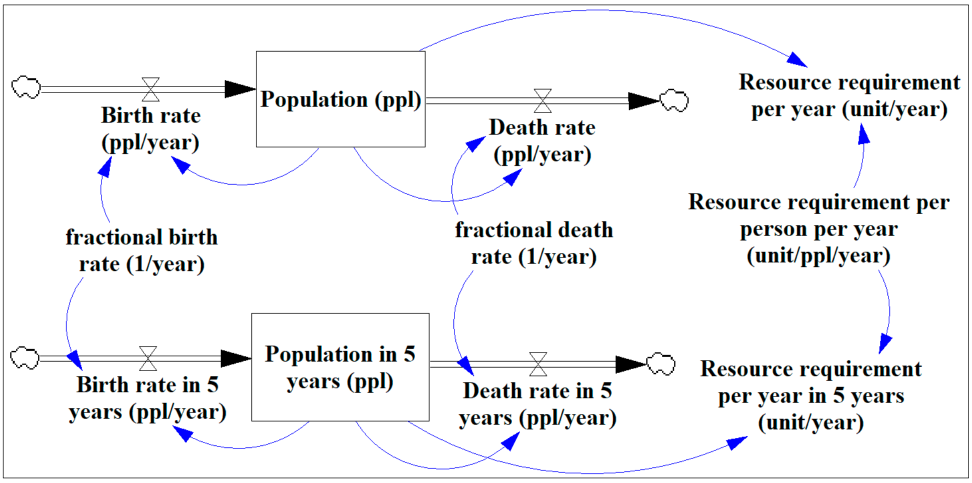

Figure 7. Population SFD (stock and flow diagram).

The population in five years stock is used to project the demand in five years, where the information is used to compute the gap for resources for the next five years. For each type of resource, namely, water, energy, and food respectively, they would have their own units of measure, such as kwh for energy and liter for water. The total resource needs of the country is obtained by multiplying the necessary requirement per person for that resource, with the total population of the year. Whilst there are many factors at play in determining the fractional birth and death rate every year, it is not within the context of this study to consider them, and the assumption that it is constant throughout the year has been made.

3.3.2. Urban Water Cycle

The backbone of the water sector is represented by the urban water cycle [53,70] and is shown in Figure 8. The urban water cycle is then converted into SFD form as depicted by Figure 9. The urban water cycle forms a closed loop starting from natural water resources, to water treatment and supply, usage by end users, disposal by end users, wastewater treatment, and finally, back to natural water resources. As also emphasized by W2, two treatments exist in the urban water cycle, i.e., the water supply treatment before distribution to users and the wastewater treatment after disposal from users.

Natural water resources are natural water bodies such as rivers, aquifers, lakes, etc., and are under the jurisdiction of the state governments. They are represented by the stocks of groundwater and surface water in the SFD. Surface water in Malaysia is much greater than groundwater, 5.6×10^{14} L of surface water as compared to 6.4×10^{13} L of groundwater [71]. Seawater analysis has not been included in this study as desalination of water is non-existent in Malaysia due to prohibitive costs, as understood from interviewees W1 and W2.

Next, the stage of water supply and services is represented by the stock of treated water, and flows of groundwater treatment rate, surface water treatment rate, domestic water supply rate, and industrial/commercial water supply rate. In addition, the rate of supply water treatment is determined by the water supply treatment capacity units that we have in the country.

After treatment, water is supplied and distributed to users from categories of domestic and industrial/commercial. Essentially, treatment and distribution of supply water stems from the same place, and as such, has been considered together in terms of per L water treated/distributed.

Usage and disposal of water have been represented by flows of domestic water expel rate and industrial/commercial water expel rate. These flows determine the rate at which wastewater would accumulate before treatment in the wastewater treatment services stage, where it is represented by the stock of accumulated wastewater. The rate at which wastewater is treated is determined by the number of sewage treatment capacities.

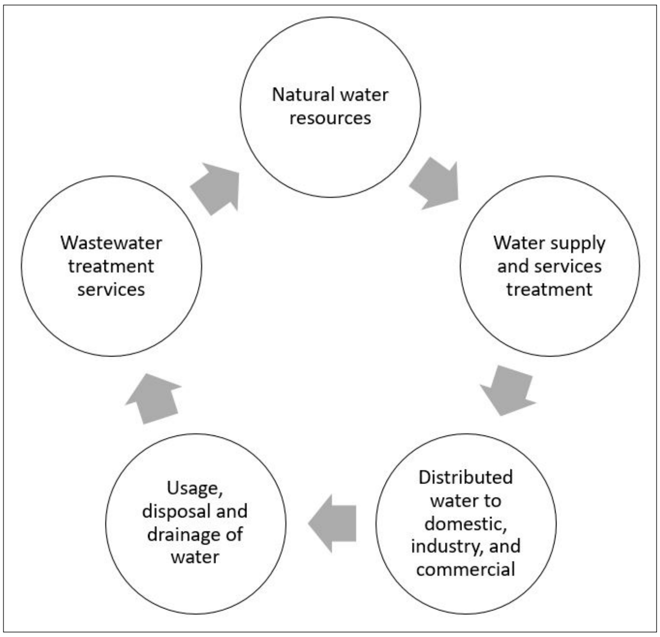

Figure 8. Urban water cycle.

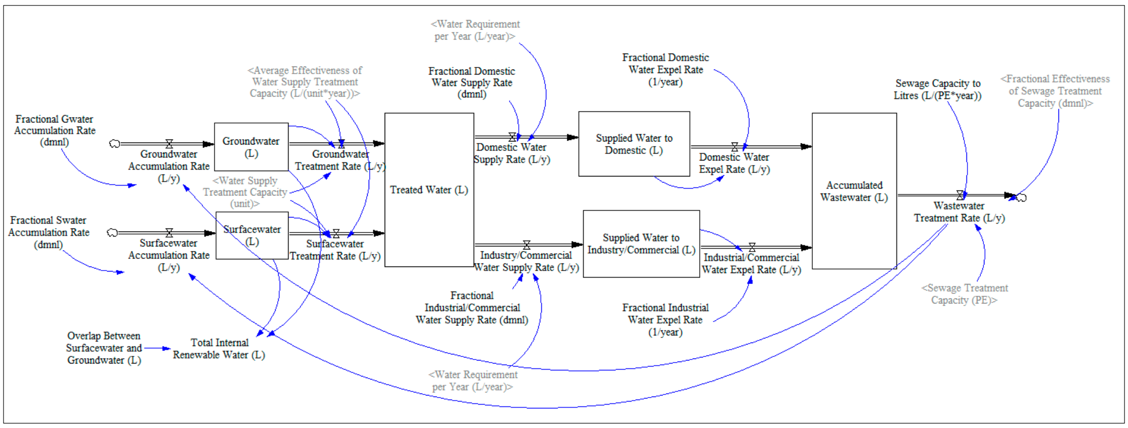

Figure 9. Urban water cycle SFD.

3.3.3. Water Supply and Water Sewage Treatment Capacities

From the urban water cycle as depicted in Figure 8, the water capacities, either water supply treatment or sewage treatment, are represented in this SFD (Figure 10). The water supply treatment is at the stage before distribution to users, where it is under the jurisdiction of federal government. Two main stocks exist in this SFD, namely, the water capacity and the water capacity under construction. Water capacity under construction thus represents the delay for this section due to the long construction time. Based on the data available, the capacities are best measured in units [71] for water supply treatment capacities and population equivalent (PE) for sewage treatment capacities [72]. The number of water supply treatment capacity would then affect the rate at which groundwater and surface water is treated whilst the sewage treatment capacity would only affect the wastewater treatment rate.

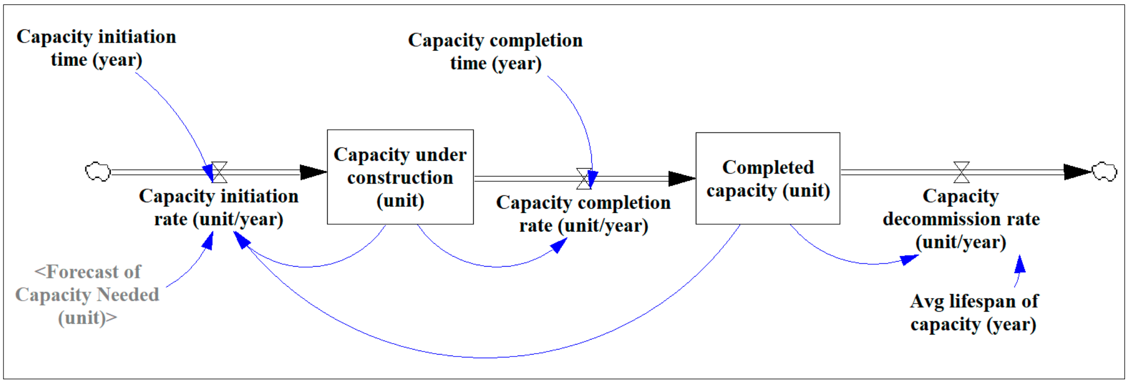

Figure 10. Water capacity SFD.

Water supply and sewage treatment needs are predicted by considering the population number in five years, water requirement in five years, and the effectiveness of both water supply and sewage treatment capacities. These forecasted values are then used to initiate new projects as illustrated in Figure 10, where new capacities can be constructed.

3.3.4. Water Economics

Whilst levelized cost of electricity (LCOE) is well documented, thoroughly used, and practiced in most energy capacity cost projections, the equivalent cost calculation for the water sector is less well documented and information available is scarce. A few methods for calculating the levelized cost of water (LCOW) exist [73,74]. However, to ease comparison with LCOE, Figure 11 shows the SFD used to calculate the LCOW which computes the unit cost of water production:

$$\text{Unit cos t of production}_{\text{supply and services}} = \frac{\sum \text{ Cost of Water Supply \& Services}}{\sum \text{ Supply Water Produced}} \quad (1)$$

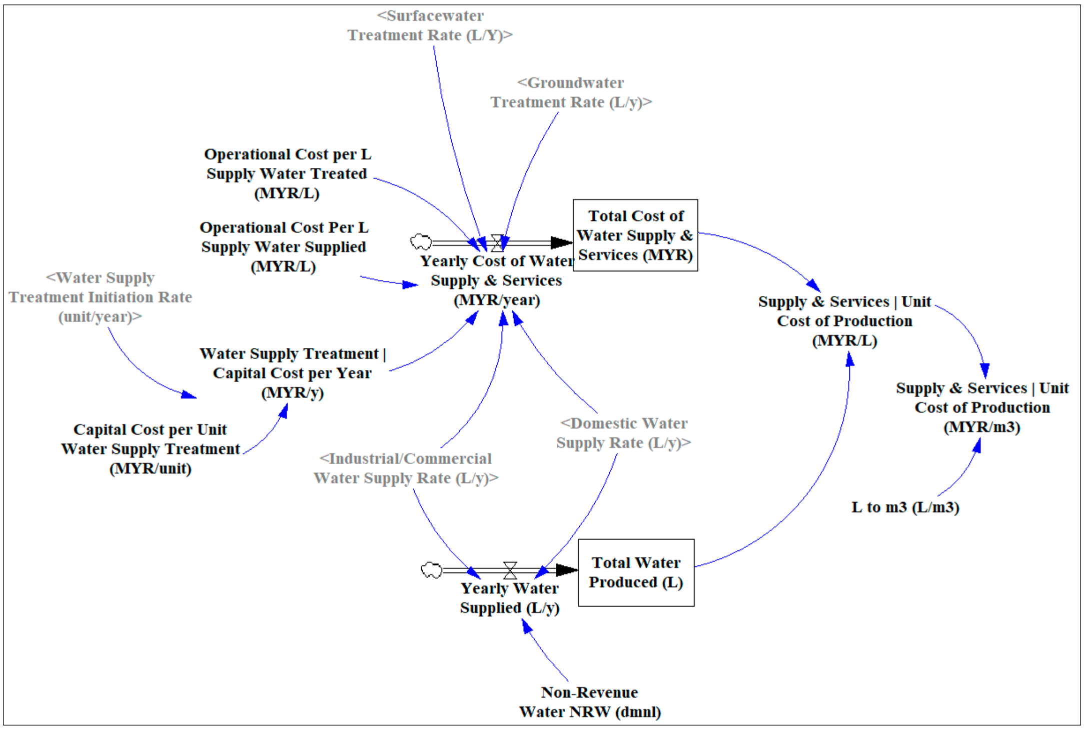

Figure 11. Unit cost of water production.

Similarly, for wastewater treatment, the unit cost of wastewater treated is given as:

$$\text{Unit cost of production}_{\text{wastewater}} = \frac{\sum \text{Cost of Water Sewage}}{\sum \text{Wastewater Treated}} \quad (2)$$

3.3.5. Water Emissions

Figure 12 shows the CO_2e emissions from the water supply and services sector and the sewage (wastewater) sector. CO_2e emissions for water supply and services sector is calculated by considering emissions from both unit treatment of groundwater and surface water while wastewater emissions consider unit treatment of wastewater as expelled by the end users.

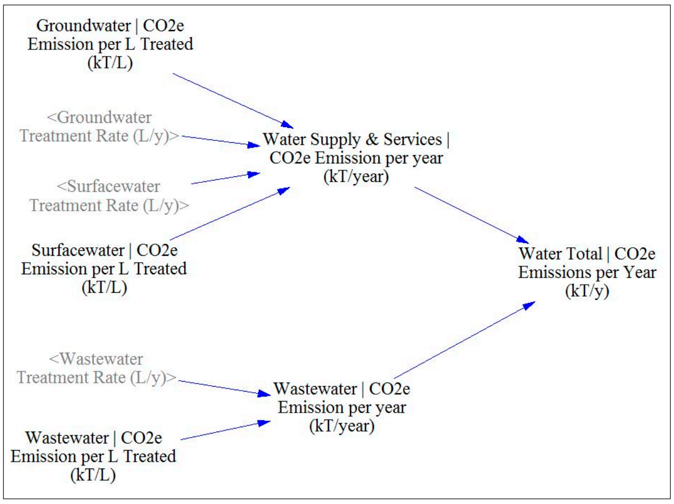

Figure 12. Water sector emissions.

4. Scenario Design

The water sector in Malaysia revolves around the economic sustenance of water services, supply, and wastewater treatment. On top of that, the disconnect in governance between state and federal governments contributes to one of the several problems of the water sector—the overly low water tariff. As pointed out by key stakeholders from the water sector, there are two main ways to control water demand management: setting water tariffs and public education.

This scenario is concerned with two crucial variables, namely "water tariff" and "water requirement per capita". Water tariff is important because it determines water affordability for the people and the economic viability of the water service provider (e.g., water supply treatment and distribution, wastewater treatment). Water tariff can be divided into two, namely the domestic water tariff and industrial water tariff. Whilst the water tariff rates (both domestic and industrial) are different in every state, this study uses an average as national presentation. The domestic tariff rate starts at 0.0007 MYR/L for domestic and 0.0017 MYR/L for industrial/commercial [60]. Additionally, the current water consumption per capita per year for Malaysians is estimated at 120,000 L/(ppl/year).

There are different ways to control water demand (W2). One example is technological policy implementation where the maximum capacity of toilet flush is reduced from 12L to 3L (W2). The multiple ways to control water demand can be reflected in the "water consumption per capita per year" variable.

Since this study is a continuation and extension of an earlier work in Tan and Yap [69], this can be considered the third scenario in the project scope and is assigned as Scenario 3 (S3) shown in Table 7. Key indicators for this scenario revolve around the sustenance of the water sector, namely, financial indicators such as LCOW, water supply sector revenue, and yearly cost of water supply and services. On top of that, the energy-for-water indicator in this case is "total electricity used per year for water sector", which forms an important W-E link in the WEF security nexus. S3A provides a control for this scenario analysis, using current values of "water supply tariffs" and "water consumption per capita per year". S3B and S3C looks into doubling the water tariffs, and implementation of water demand management by reducing "water consumption per capita per year" by approximately 16.6% respectively. S3D looks into the combination of S3B and S3C. Table 6 provides the list of relevant constants. Table 7 provides the list of scenario values and Table 8 provides the list of key indicators.

Table 6. Relevant constants for Scenario: Water Demand Management (S3).

Relevant Constants	Value	Units	Source
Average Effectiveness of Water Supply Treatment Capacity	0.85	L/(unit × year)	[75]
Fractional Effectiveness of Sewage Treatment Capacity	0.85	dmnl	[75]
Operational Cost per L Supply Water Treated	3.00×10^{-4}	MYR/L	[60]
Operational Cost per L Supply Water Supplied	3.00×10^{-4}	MYR/L	[60]
Capital Cost per Unit Water Supply Treatment	0.01	MYR/unit	[60]
Operational Cost per L Sewerage Water Treated	6.00×10^{-4}	MYR/L	[60]
Capital Cost per Unit Water Sewerage Treatment	1.00×10^{-9}	MYR/PE	[60]
Energy Used per Supply Water Treated	5.86×10^{-4}	kWh/L	[76]
Energy Used per Sewerage Water Treated	6.34×10^{-4}	kWh/L	[76]
Groundwater | CO2e Emission per L Treated	2.90×10^{-10}	kT/L	[76]
Surface water | CO2e Emission per L Treated	2.90×10^{-10}	kT/L	[76]
Wastewater | CO2e Emission per L Treated	4.10×10^{-10}	kT/L	[76]

Table 7. Scenario S3.

Scenario: Water Demand Management (S3)	A	B	C	D	
Variable	**Values**				**Units**
Domestic | Effective Water Supply Tariff	7.00×10^{-4}	1.40×10^{-3}	7.00×10^{-4}	1.40×10^{-3}	MYR/L
Industrial | Effective Water Supply Tariff	1.70×10^{-3}	3.40×10^{-3}	1.70×10^{-3}	3.40×10^{-3}	MYR/L
Water Consumption per Capita per Year	1.20×10^{5}	1.20×10^{5}	1.00×10^{5}	1.00×10^{5}	L/(ppl/year)

Table 8. Key indicators for S3.

Key Indicators	Units
Supply and Services | Unit Cost of Production	MYR/m^3
Sewage | Unit Cost of Production	MYR/m^3
Total Electricity Use per Year for Water Sector	kWh/year
Water Supply Sector Revenue per Year	MYR/year
Yearly Cost of Water Supply and Services	MYR/year
Yearly Cost of Water Sewage Treatment	MYR/year

5. Results and Discussion

This section presents and discusses the simulated results of four scenarios from inputting the values as designed, as shown in Table 7. The behavior of identified key indicators, as laid out in Table 8, are shown from Figures 13–17. Each figure includes results from all four sub-scenarios, where their behaviors could be compared and discussed.

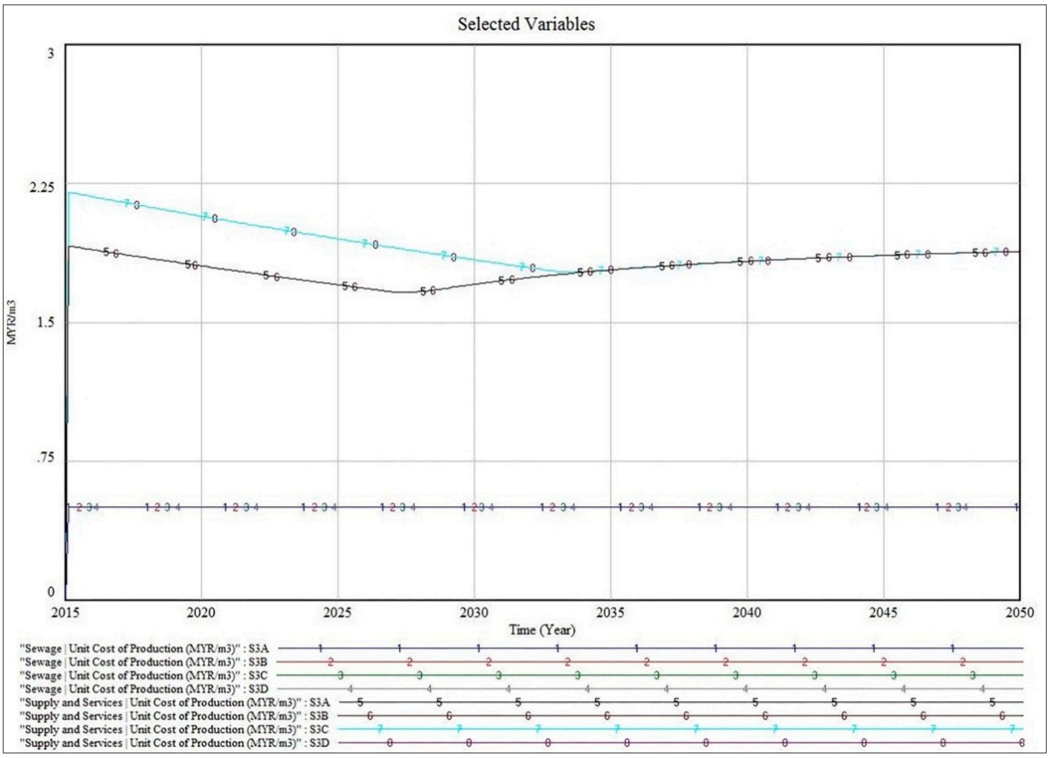

Figure 13. S3—Unit cost of production.

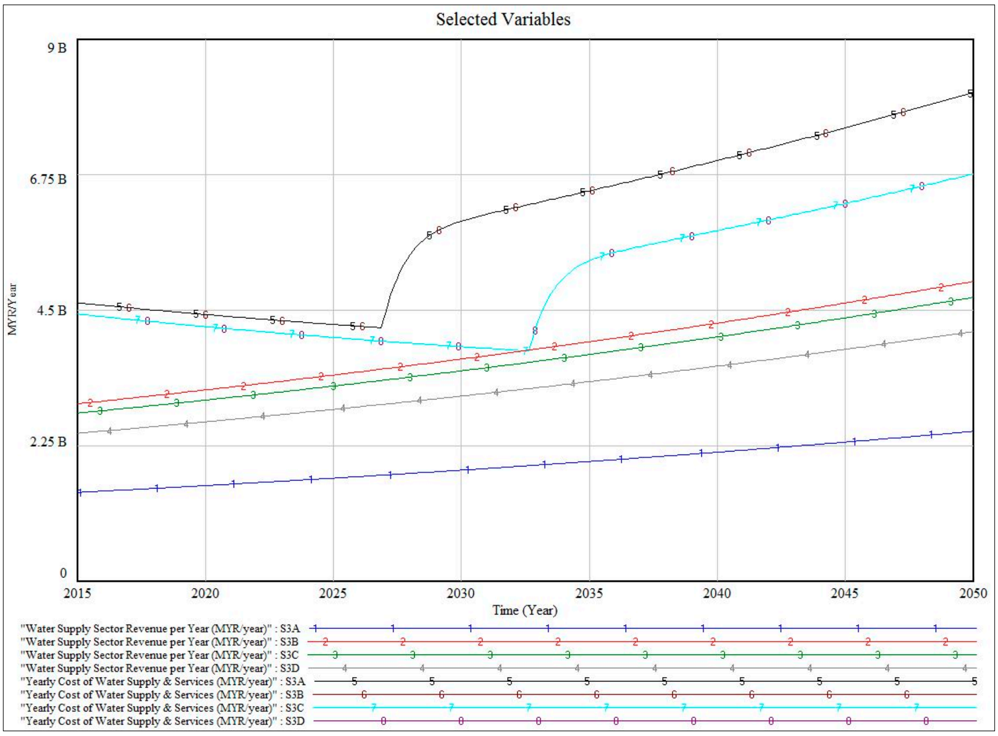

Figure 14. S3—Water supply and services cost and revenue.

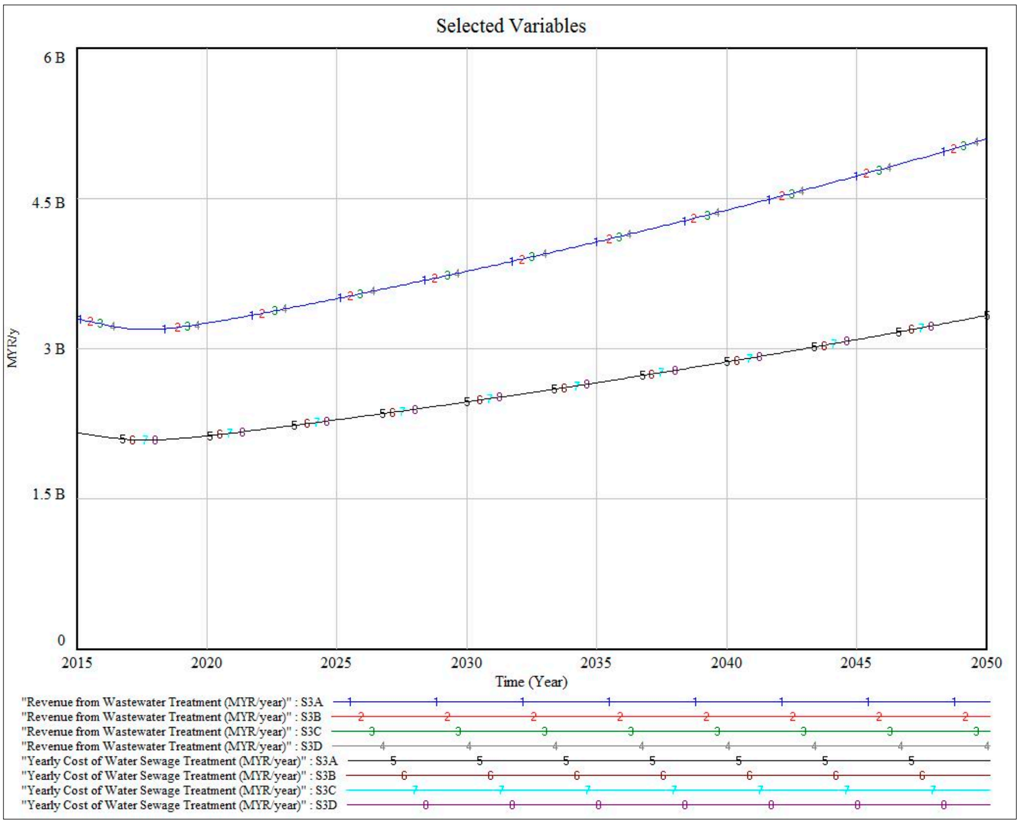

Figure 15. Sewage cost and revenue.

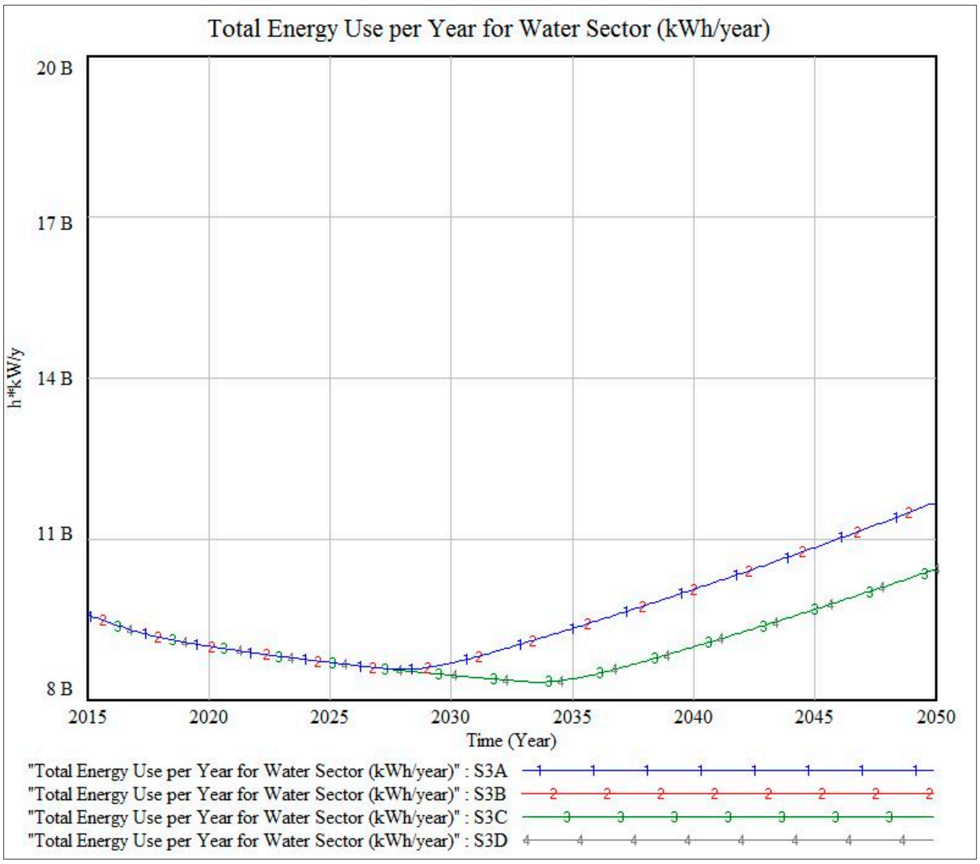

Figure 16. S3—Energy use per year for water sector.

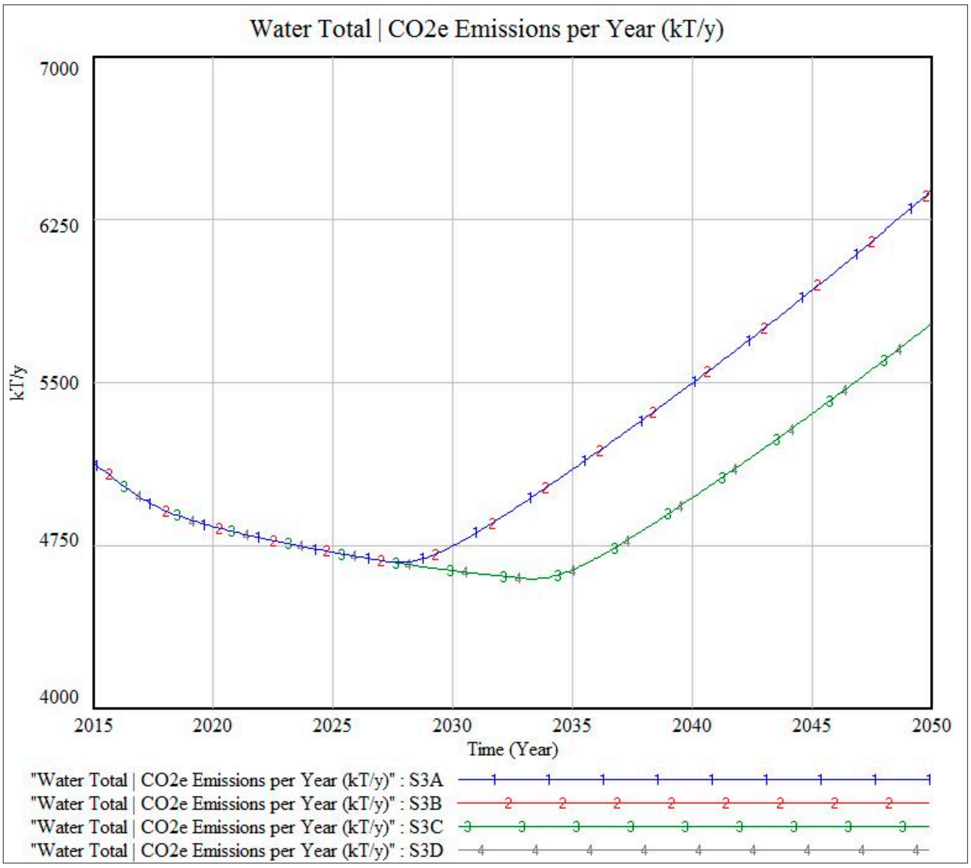

Figure 17. S3—CO2e emissions per year.

Figure 13 shows the graph for unit cost of production for water supply and services, and sewage. Considering the available data on Malaysian water facilities, and reserve margin, Malaysia has sufficient facilities to cater for the projected demand. As such, the number of water facilities is seen to decrease through normal rate of retirement/decommission. However, as the population grows, new facilities would need to be constructed at around 2027, if water demand is left at 120,000 L/(ppl/year), and to be constructed at 2033 if demand is controlled to 100,000 L/(ppl/year). Despite that, the unit cost of production would stabilize towards 2050 at MYR 1.80 for water supply and services, and MYR 0.50 for sewage services.

Figure 14 shows the graph on cost and revenue for the water services and supply sector. From the graph, it can be seen that the annual cost for the sector remains above the revenue received from tariff for all four sub-scenarios. The hike in annual cost in 2027 and 2033 is due to new facilities initiated where fresh capital costs are incurred. New facilities are initiated when the number of water treatment facilities can no longer meet the demand. As such, it can be deduced that the water supply and services sector is not economically sustainable. On the other hand, Figure 15 shows the cost is below the revenue for the water sewage sector.

Energy used per year from treating and distributing water is shown in Figure 16. For all four sub-scenarios, their energy use is similar, increasing towards 12 B kWh/year for S3A and S3B, and 11 B kWh/year for S3C and S3D. These values are approximately 12% from the total power generation projection of 175 B kWh/year at 2050. These values are accurate concerning surface water in Malaysia because surface water forms the primary water source for Malaysia. Should Malaysia attempt to tap into groundwater or adopt desalination, the numbers may increase significantly because processing these types of water are more challenging compared to surface water [77]. Desalination and groundwater tapping are potential water supply alternatives with the benefits of being unaffected by weather and sea water in abundance. However, the drawbacks are technological challenges as well as higher economical and energy cost.

Figure 17 shows CO_2e emissions per year for the water sector is within the order of 6300 kT/year for S3A and S3B, and 5700 kT/year for S3C and S3D. This is approximately one order lower than that of the electricity production sector. As such, it is safe to say that the water sector plays a minimal role in environmental degradation in the context of this water-energy-food nexus in Malaysia. However, one must consider the energy use of water processing and production, where electricity use translates into energy production and, consequently, CO_2e emissions. The illusion of water sector's impact on the environment is thus enhanced if energy intensive water producing technologies are utilized, such as the desalination of seawater and tapping of groundwater.

6. Conclusions

Whilst the WEF nexus is a web of complex interactions, the water sector plays a central role, especially in the Malaysian WEF nexus. As shown by Tan and Yap [69], the electricity production sector is water thirsty. Simulated results in this paper show that water treatment and distribution use a substantial amount of energy as well—approximately 12% of total electricity generated. At the same time, it may not be straightforward to optimize water efficiency for electricity production and energy efficiency for water services, as governance of the water industry is divided between state and federal governments, ascertained from the qualitative interviews. This contributes to the low water revenue, as seen from the simulated results, where agreement between state and federal governments on water tariff setting is pivotal. Additionally, the cost of water industry operations is above the revenue received from water tariffs. This simulation is consistent with findings from the qualitative interviews, where government continually underwrites the water sector in order to sustain the industry. The stalemate of not increasing the water tariffs has led to the vicious loop of dwindling revenue where quality of services remained unchanged, which, consequently, led to the absence of justification for increasing water tariffs.

Whilst water supply and services tariffs are separate from the sewage tariff, the main disconnect in the ownership, governance, and management of the water sector in Malaysia lies between the states and federal governments. As highlighted by stakeholder W2, policy implementation and decision making becomes problematic when collective approval is required from both governments. To further complicate the matter, state and federal governments' interests and incentives when managing their water sector may not always align. For example, increasing water tariffs to better reflect the costs of water production is almost impossible because state governments are not always agreeable (W2). As such, it is imperative to revamp the governance structure of the water sector in Malaysia, to enable seamless and effective decision-making, cooperation, management, and monitoring at state and federal levels. This can be achieved by centralizing the governance and authority of the water sector with a unified oversight by state and federal governments.

The second policy recommendation is the socio-economic improvement of water economics. This policy should be implemented in close relation with the centralizing and streamlining of water management, as the latter would allow for smoother implementation of the former. Two important actions should be carried out under this recommendation: (1) revising water tariffs to appropriate levels such that the water sector can be financially self-sufficient and (2) ramping up strategies and methods to reduce average water consumption per capita. As illustrated from the results from the water demand management scenario, water supply and services revenue are well below the water supply treatment costs. This has caused poor awareness amongst members of the public that water is a scarce and precious resource. Given the fact that the total internal renewable water resources is a constant, whilst population and per capita usage are not, it is thus necessary to pay attention to the demand side of water management, i.e., revise tariffs and reduce per capita usage.

By implementing these two policies, the revenue, and thus, the economic well-being of the water sector should be improved. Once this is achieved, the energy expenditure of the water industry would be better justified, which could consequently allow for alternative energy scenarios to be considered, as concluded in Tan and Yap [69], where further socio-environmental advantages can be realized.

Furthermore, improving the economics of the water sector relieves the government from continually underwriting the water sector from other sources of revenue.

Author Contributions: A.H.P.T. performed the literature review, designed the embodiment and detailed research framework, refined the research questions, employed the methodology, engaged key stakeholders, constructed the systems model, analyzed the simulation results, and wrote the original draft. E.H.Y., as the principal investigator, designed the initial conceptual framework, conducted the initial background research and framing, liaised with key stakeholders, provided the tools and resources, secured the funding, and reviewed the manuscript. Y.A.A. provided input and ongoing advice in the broad spectrum of the research especially on sustainability and, contextually, in the energy sector. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by UCL Engineering and UCL Australia.

Acknowledgments: The authors wish to thank all interviewees and participants for their keen participation in this research.

Conflicts of Interest: The authors declare no conflict of interest.

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