

**THE UNIVERSITY OF DANANG
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**DEVELOPMENT OF AN INTEGRATED WATER
STRESS INDEX (WSI) – LIFE CYCLE ASSESSMENT
(LCA) MODEL FOR SUPPORTING THE
SUSTAINABLE MANAGEMENT OF THE WATER
SUPPLY SYSTEM IN DA NANG CITY**

Major: Environmental Engineering

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SUMMARY OF DOCTORAL THESIS

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INTRODUCTION

1. Urgency of the thesis

Water production and supply activities typically consume energy, chemicals, and resources, and generate significant environmental impacts. In the global context of applying environmental assessment tools, the LCA method helps quantify impacts throughout the life cycle of water supply systems, while the WSI reflects the level of water stress in each basin. However, in Vietnam, the integration of LCA and WSI in water supply planning remains limited.

Coastal cities like Da Nang are under great pressure from urbanization, climate change, pollution and saltwater intrusion, which are reducing raw water resources and increasing operational risks. Rapidly increasing water demand is also making the supply-demand balance increasingly difficult.

On that basis, the thesis “***Development of an integrated Water Stress Index (WSI)–Life Cycle Assessment (LCA) model for supporting the sustainable management of the water supply system in Da Nang City***” develops a combined WSI-LCA methodology framework for the urban water supply system in Da Nang, providing a comprehensive approach to environmental impact assessment and supporting the selection of optimal water supply scenarios.

2. Objectives of the thesis

General objective: To establish an integrated framework combining the Water Stress Index and Life Cycle Assessment (WSI–LCA integrated model) to comprehensively evaluate environmental impacts and water scarcity levels during the extraction and production of potable water for urban supply systems. The findings of this dissertation serve as a scientific foundation for optimizing water extraction and production scenarios under the impacts of climate change.

Specific objectives:

a) To develop the integrated WSI–LCA model as a scientific basis for basin-specific urban water supply system analysis, ensuring rigorous scientific validity and reproducibility.

b) To quantify the comprehensive landscape of water stress levels and environmental pressures within the urban water supply system of Da Nang City through the application of the integrated WSI–LCA model.

c) To simulate water extraction and production scenarios in alignment with urban water supply planning through 2045: conducting a quantitative analysis of the trade-offs between water resource security and environmental burdens to identify sustainable planning alternatives that are resilient to climate change.

3. Objects and Scope of Research

Research Subjects: The methodology of the WSI–LCA integrated model, raw water extraction, transportation, and clean water production.

Spatial scope of research : The research focuses on the exploitation, transmission of raw water and water treatment at Cau Do Water Treatment Plant.

Temporal scope: For streamflow, data are taken from historical data series at stations from 1987-2023. Plant operational data are collected from the 2023 operational log. Water supply scenarios are based on planning.

4. Research contents

a) Development of the integrated WSI–LCA model: To construct an integrated framework for evaluating water scarcity levels and the environmental impacts associated with the extraction and treatment processes of potable water within urban water supply systems.

b) Application of the integrated WSI–LCA model for baseline assessment: To conduct a quantitative empirical assessment of current water scarcity levels and environmental burdens of Da Nang City's urban water supply system during the contemporary period.

c) Formulation of water extraction and production scenarios for Da Nang through 2045: To develop future scenarios based on urban development planning orientations, taking into account the complex dynamics of climate change and saltwater intrusion.

d) Quantitative comparative analysis for optimal scenario identification: To utilize the integrated WSI–LCA model to compare and identify the optimal scenario that simultaneously satisfies the criteria for water resource security and low-emission performance for the urban water supply system of Da Nang.

5. Scientific and practical significance of the thesis

a) Scientific significance:

Refining the methodology by developing the integrated WSI–LCA model; Strengthening the scientific foundation for water resource assessment in Vietnam; and contributing to the advancement of interdisciplinary science, thereby opening new research directions for urban infrastructure systems resilient to climate change.

b) Practical significance

Evidence-based decision making. Scalability and practical application for coastal cities and downstream river basins in Vietnam, which are also affected by saline intrusion and climate change.

6. New contributions of the thesis

The dissertation contributes a novel methodological approach to the LCA of urban water supply systems by integrating the WSI. This integration allows for the simultaneous reflection of environmental impacts and water resource stress, tailored to the specific geographical and socio-economic conditions of each locality.

The dissertation is the first to develop and validate an integrated model between the WSI and LCA specifically designed for urban water supply systems under conditions of water source fluctuation and saltwater intrusion. This approach possesses a high degree of generalizability and can be scaled for application in other municipalities across Vietnam.

The dissertation applies the integrated WSI–LCA model to quantify water scarcity levels and site-specific environmental impacts for the Da Nang water supply system. The research findings facilitate the identification of an optimal water supply scenario for the 2030–2045 period by addressing the equilibrium between surface water extraction from the Vu Gia – Thu Bon river system and the diversification of reserve water sources, thereby ensuring the dual objectives of water resource security and greenhouse gas (GHG) emission mitigation for the city.

7. Thesis layout

The main content of the thesis includes the following parts: Introduction; 4 chapters; Conclusion, recommendations.

CHAPTER 1. OVERVIEW OF RESEARCH ISSUES

1.1. Overview of water resources

Water resources are unevenly distributed over space and time, resulting in large disparities in water access across regions and countries. In the context of climate change and increasing water demand, the imbalance between supply and demand is becoming an urgent challenge. This requires the use of quantitative assessment tools to support equitable and efficient water allocation, while protecting ecosystems and ensuring access to clean water for communities.

The rapid increase in water demand due to urbanization, industrialization and population growth has caused many basins to fall into a state of supply-demand imbalance, especially in the dry season. In Vietnam, water resource security depends largely on resolving water stress, water quality degradation and related natural disaster risks. In the Vu Gia - Thu Bon basin, drought and saltwater intrusion often occur in the dry season, causing water shortages for the Da Nang water supply system. To ensure sustainable water supply, it is necessary to manage surface and groundwater exploitation reasonably, reduce losses, improve efficiency of use, and apply quantitative assessment tools to forecast water scarcity and analyze environmental impacts.

1.2. Fundamental Concepts of Urban Water Supply Systems and Life Cycle Assessment System Boundaries

Fundamental concepts regarding water supply systems and their associated components are standardized in accordance with current applicable standards:

a) *Water Supply System*: A water supply system is an integrated complex of closely interrelated engineering structures designed to abstract water from raw sources, treat it to comply with quality standards, equalize, convey, and distribute water to end-users.

b) *Water Supply Facilities*:

- **Water Intake Structures**: Responsible for extracting water from raw sources. For the Cau Do Water Treatment Plant (WTP): the raw water intake structure at Cau Do WTP and the An Trach pumping station.

- **Raw Water Pumping Station:** Transports raw water from the intake structures to the water treatment plant.

- **Water Treatment Facilities:** An ensemble of engineering structures aimed at purifying raw water to meet prescribed quality standards.

- **Treated Water Pumping Station:** Conveys treated water from storage reservoirs into the distribution system and pipeline network.

- **Balancing/Regulating Structures:** Elevated water tanks (water towers) and intermediate reservoirs designed to equalize the operating regime between the WTP and the fluctuating consumption patterns of consumers.

c) *Water Distribution System:* The water distribution system comprises secondary pumping stations, balancing reservoirs, primary transmission mains, and ancillary equipment tasked with conveying water from the WTP to end-users.

d) *Water Supply Network:* The water supply network is an assembly of multi-tier pipelines and pipe appurtenances configured in looped or branched layouts to deliver water directly to points of consumption.

1.3. Current status of Da Nang city's water supply system

1.3.1. Raw water source

Da Nang's water supply system currently relies mainly on surface water from the Vu Gia river system, Cu De river and Hoa Trung lake .

Main surface water sources:

Vu Gia river (main source for Cau Do Water Supply and San Bay Water Supply): The city's main water supply is currently from Cau Do river, which is showing signs of decline in reserves and increasing salinity intrusion in both intensity and time of year.

In the dry season, increased saline intrusion and reduced upstream flow pose risks to raw resources at Cau Do and Cu De intake gates. The city's water supply depends on the operation of reservoirs, saltwater pumping stations and inter-reservoir management to maintain supply.

1.3.2. Clean water plants

Da Nang urban water supply system with total design capacity of 463,500 m³/day.

Cau Do Water Treatment Plant: Design capacity is 290.000 m³/day.

Raw water is taken from river Vu Gia next to plant; Airport plant: Raw water source from Cau Do intake gate, designed capacity is 30.000 m³/day; Hoa Lien plant: Water source from Cu De river, designed capacity phase I: 120.000 m³/day; Son Tra 1 & 2 plant: Raw water source from Da stream. Total designed capacity: 7.000 m³/day; Hai Van plant: Raw water source from Luong stream, capacity 5.000 m³/day (unstable operation); Hoa Trung Lake plant: Raw water source from Hoa Trung lake, capacity phase 1: 10.000 m³/day.

1.3.3. Water supply network

The network is about 3.310 km long, with a connection rate of nearly 100% in urban areas. The average water consumption standard is 150 l/person/day. The loss rate is 14–16%.

Overall rating:

Advantage:

- Infrastructure and raw materials are continuously expanded and invested, with reserves.
- Reasonable zoning network, convenient for pressure management and troubleshooting.
- High connection rate, stable urban water supply service.

Limitations and risks:

The urban water supply system in Da Nang depends heavily on surface water sources and the risk of saline intrusion. The frequency, duration, and amplitude of salinity are increasing at the water exploitation point of Cau Do Water Supply Plant. The salinity period forces the An Trach pumping station, 8km from the plant, to operate at a higher capacity, increasing operating costs (pumping) and energy dependence, while also causing greater environmental impacts.

Urbanization and tourism recovery after the pandemic have caused a spike in water demand. Water demand increases precisely during the peak months.

1.4. Tools and methods for assessing water scarcity and environmental impacts of water systems.

1.4.1. Water stress index

Several water stress indices have been developed, reflecting different aspects of the water supply–demand relationship: The Falkenmark index (1986) is based on average water availability, based on per capita water availability, providing a rapid assessment at the national level; The WTA index measures the ratio of water extraction to total renewable resources; The WSI index takes into account Ohlsson's social capacity (2000) and adds the HDI index to reflect the adaptive capacity of each country; Recent models (Asheesh, 2015; McNulty, 2016) calculate WSI based on aggregate water demand; The approach of Smakhtin et al. (2005) is an important step forward, when environmental flows (EWR) are incorporated into the formula:

$$WSI = \frac{WU}{WR - EWR}$$

In which:

WU: Total amount of water exploited and used; WR: Total amount of renewable water; EWR: Environmental flow.

Indices such as Falkenmark or WTA are suitable at the national scale but lack the granularity for basin or urban scales. In contrast, WSI takes into account environmental requirements suitable for integration with LCA in the assessment of urban water supply systems, especially in the context of climate change and salinity intrusion.

1.4.2. Some methods to support decision making related to the water industry

Many tools are applied in the water industry, including: EIA – environmental impact assessment at project scale; SEA – assessment at strategic scale; MCA (Multi-Criteria Analysis) – comparison of options according to economic, social, environmental criteria; LCA is a tool that looks at environmental impacts throughout a product's life cycle, from resource extraction to disposal.

Among them, LCA is considered the most powerful tool to quantify the environmental impact of water supply systems .

1.4.3. LCA on water systems and research results on urban water systems.

The LCA structure in water systems consists of four main stages:

(1) Define goals and scope – defining system boundaries, functional units, and proposed scenarios.

(2) Life Cycle Inventory (LCI): collect and quantify input data electricity, chemicals, transportation and emissions.

(3) (4) Impact Assessment and Interpretation (LCIA) – calculating impact indicators and impacts on ecosystems, human health and natural resources.

Commonly applied LCIA methods include ReCiPe, CML-IA, Eco-Indicator 99, EDIP, depending on the scope and objectives of the research.

International research overview shows:

- The first phase (1995–2005) focused on wastewater treatment and drinking water production. Since 2005, LCA has been extended to the entire urban water system .

- Scenarios are divided into three groups: (i) change in technology or chemicals; (ii) change in raw water source or receiving water body; (iii) change in user behavior or energy structure.

- Most studies show that wastewater treatment (WWT) and clean water production (DWP) are environmental hotspots .

Some key points of the research:

LCA studies on water supply systems show that: (1) Climate change and eutrophication are the two most commonly assessed impacts; (2) Energy consumption ranges from 0,58–2,11 kWh/m³; (3) Emissions mainly include CO₂, CH₄, NO_x and eutrophic substances; (4) SimaPro is a widely used analysis tool. However, most studies focus on Europe, lacking data for Southeast Asia and Vietnam. LCA has quantitative assessments but cannot reflect the specific water scarcity of each locality.

1.5. Gaps in research

In Vietnam, LCA is still limited, especially in the water supply system. Meanwhile, the WSI index allows to assess the level of water exploitation compared to the renewable supply capacity of the basin. WSI and LCA are often applied independently; there is no combined research for the water supply system in the context of saline intrusion and climate change, leading to: Lack of connection between water resource stress and life cycle impacts; Limitations in supporting decision making; Gap in localization: WSI provides regional information but has not been incorporated into life cycle analysis to reflect geographical characteristics in product assessment.

Recently, Pfister et al. (Ridoutt & Pfister, 2014) proposed a new approach in life cycle assessment. This index is called Water Scarcity Footprint (WSF) and is calculated by the formula:

$$\text{WSF} = \text{WC} \times \text{WSI} \text{ (Ridoutt \& Pfister, 2014)}$$

In which:

WSF: Water scarcity footprint; WC: Water Consumption (amount of water consumed, unit: m³); WSI (water stress index)

The WSF calculation formula is derived from modern LCA method, the higher the WSF value, the greater the impact on water security.

1.6. Summary of Chapter 1

Current indicators such as WSI or water exploitation ratio are mainly based on average annual flow, so they do not reflect seasonal fluctuations and often ignore environmental flows. Therefore, water scarcity assessment needs to be carried out in more detail in space and time, taking into account seasonal characteristics and ecological needs to reflect the current status and sustainable exploitation capacity. The trend of integrating WSI into LCA, in line with ISO 14046 recommendation, is a modern approach that links emissions, resource use and scarcity pressures in a unified assessment system. From the overview of studies, this thesis proposes to develop a combined WSI–LCA assessment framework to comprehensively quantify the environmental impacts of urban water supply systems, especially in the context of climate change and saltwater intrusion. The research framework consists of three main components:

- Water stress assessment (WSI) taking into account environmental flows (Smakhtin, 2005);
- Environmental impact assessment using LCA, in which water consumption is adjusted according to the level of scarcity (WSI) at each exploitation location;

This approach allows for simultaneous reflection of resource and environmental aspects, creating a foundation for a decision support system in urban water planning and management towards sustainability and climate change adaptation.

CHAPTER 2. RESEARCH SUBJECTS AND THEORETICAL BASIS OF RESEARCH METHODS

2.1. Research objects and scope

Subjects: The methodology of the integrated WSI–LCA model, raw water extraction and transportation processes, and clean water production.

The study was conducted at Cau Do Water Treatment Plant with 03 treatment lines: line with capacity of 50.000 m³/ day (2002); line with capacity of 120.000 m³/day (2008); 3rd line with capacity of 120.000 m³/day (July 2021) .

2.2. Research methods

2.2.1. Statistical and inheritance methods

Statistical, inheritance and retrospective methods are used throughout the thesis to synthesize published research results and identify gaps in research. The thesis conducts:

- Systematic review of domestic and foreign studies on LCA for water supply systems with the same functional units and similar scope.
- Synthesizing and comparing models and methods of calculating WSI.
- Inheriting secondary data on electricity consumption, chemicals, emissions and exploitation flow from reports of DaNang water industry and Eco invent database.

2.2.2. MIKE-SHE hydrological model

The thesis uses the MIKE-SHE distributed hydrological model to determine the natural flow in the Vu Gia - Thu Bon basin. The simulation results provide input data for calculating the water stress index (WSI) and building water supply scenarios.

2.2.3. Life cycle model using SimaPro

Environmental impact assessment was performed using SimaPro software with Ecoinvent 3 database and ReCiPe 2016 method. The functional unit is 1 m³ of clean water.

2.2.4. Field survey, data collection and processing

Data: Topographic maps, rainfall, flow, river cross-section, land distribution and geological characteristics, groundwater level; Water demand:

Forecast based on Da Nang City Master Plan; Environmental Flow (EWR).

LCA data: Primary: Raw water flow, electricity consumption, chemicals and emissions at Cau Do NMN; Background: Ecoinvent 3.11 database integrated in SimaPro, covering the electricity, chemicals and materials supply chain.

2.2.5. Method of assessing the impact of water exploitation

The WSI index was chosen because it reflects the level of water exploitation associated with ecological carrying capacity and environmental flow (EWR) integration. The study applied the formula of Smakhtin (2005), in accordance with the recommendations of UNEP (2016) and ISO 14046. The WSI results were used as an adjustment factor in the Water Scarcity Footprint (WSF), converting water consumption to local scarcity levels, accurately reflecting the impact of exploitation in the context of climate change, salinity intrusion and dry season in Da Nang.

2.2.6. Life cycle assessment method

LCA consists of four steps: (1) defining the objective and scope, (2) life cycle inventory, (3) impact assessment, (4) interpretation of results. The functional unit is 1 m³ of clean water, the boundary from raw water extraction to treatment.

In LCIA, ReCiPe 2016 was selected because it covers 18 impact categories, combines detailed analysis and impact endpoints, allows simulation, comparison and standardization of results, suitable for urban water supply system research.

2.3. Summary of Chapter 2

Chapter 2 present The research object, scope, characteristics of the water supply system in Da Nang city, along with data sources and research methods used. The methods include the MIKE - SHE hydrological model to calculate available flow, inventory method and life cycle assessment using SimaPro software with the ReCiPe 2016 assessment method, combined with the WSI index to reflect the level of water stress in the context of saline intrusion and climate change. At the same time, this chapter also outlines how to determine water demand, environmental flow and how to incorporate WSI into LCA results to quantify environmental impacts at the local scale.

CHAPTER 3. DEVELOPMENT AND VALIDATION OF THE INTEGRATED WATER STRESS INDEX AND LIFE CYCLE ASSESSMENT MODEL

3.1. Development of the integrated water stress index and life cycle assessment model

In practice, this model helps to simultaneously assess global-level energy-emissions and local-level water scarcity, supporting the comparison and selection of sustainable water supply scenarios.

Scientifically, LCA according to ISO 14040/14044 provides the foundation for life cycle assessment, while WSI based on the correlation between the demand for water and the amount of water recharged after subtracting environmental flows. When integrated into LCA, WSI is used as a characteristic factor to convert water consumption according to the level of scarcity. The assessment framework consists of 5 main steps.

The assessment framework uses a WSI that is graded from light to severe depletion to reflect the carrying capacity of the basin. In the life cycle inventory (LCI) step, data on electricity, chemicals, emissions and extraction flows are collected from the study area and the Ecoinvent 3.11 database. Impact assessment step performed using ReCiPe 2016 in SimaPro software, where WSI is integrated to calculate the WSF Water Scarcity Footprint, Adjust water consumption according to local scarcity levels. After the interpretation phase, the results are analyzed to compare scenarios, identify environmental hotspots, and propose solutions.

3.2. Application of the integrated WSI - LCA model in assessing the current state of water extraction and clean water production in Da Nang city.

3.2.1. Objectives and scope

The study applied the integrated WSI - LCA model to comprehensively assess the environmental impacts and water scarcity levels in water exploitation and treatment activities at Cau Do Water Plant (WTP).

Functional unit: 1 m³ of clean water meeting QCVN 01-1:2024/BYT standards. Boundaries: (1) raw water exploitation and supply; (2) water

treatment; (3) internal treatment .

3.2.2. WSI Calculation

Based on a 37-years data series (1987–2023), it shows many water shortage periods lasting from May to the end of the dry season.

Dry season flows tend to decrease due to climate change, upstream forest degradation and reservoir regulation, leading to the risk of deep saltwater intrusion, lack of domestic water and ecosystem degradation. In the estuary, from February to July, low water levels cause prolonged saltwater intrusion, directly affecting the water exploitation of the Cau Do plant, as shown by the amount of water exploited at Cau Do and An Trach in 2023.

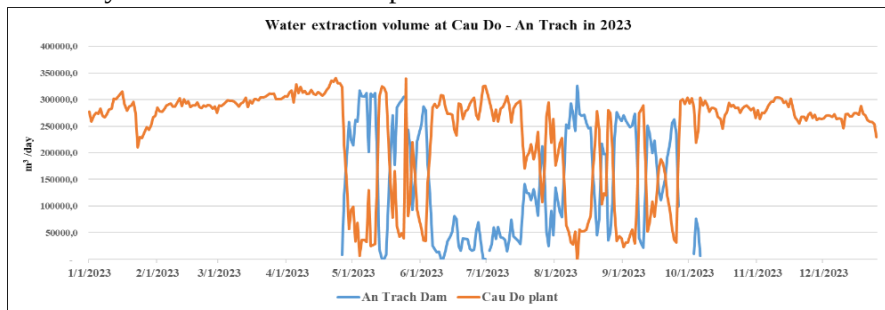


Figure 3.1. Water volume exploited at the intake gate of Cau Do factory and An Trach dam in 2023

In the first 4 months of 2023, the Cau Do intake gate operated stably at 250.000–320.000 m³/day. From May to September, due to increased salinity intrusion, the station had to stop operating many times, forcing An Trach to increase its capacity to 300.000–350.000 m³/day, increasing electricity costs and increasing water resource security risks. Compared to 2020 – the driest year in the 1987–2023 period – the water volume in April only reached 17,5 m³/s, much lower than the downstream water supply demand.

According to Decision No. 359/QD-TTg on Adjusting the Master Plan of Da Nang City, the frequency of ensuring water supply for domestic use, services and industry $P = 95\%$. The total amount of water that can be used at An Trach dam and Cau Do intake gate in the period of 1987–2023

corresponding to the frequency of 95% is 58,92 m³/s and 70,08 m³/s.

Figure 3.4 depicts the fluctuations of the water stress index (WSI) at Cau Do intake gate by month in 2020, clearly reflecting the level of water exploitation pressure at the main supply point of the Da Nang water supply system corresponding to the water supply frequency of 95%.

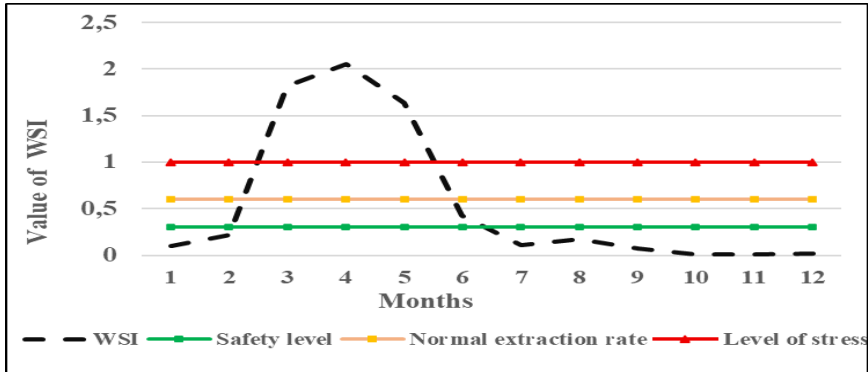


Figure 3.2. WSI value at Cau Do water intake

The chart shows that water resources at Cau Do are always tense during the dry season, especially from March to August. when the average WSI reached 1.035. April was the most serious time, forcing the majority of water to be taken from An Trach due to the salinity of Cau Do. This basin mainly supplies the domestic and industrial needs of Da Nang, while the water volume is low and is strongly affected by salinity intrusion, increasing the risk of scarcity.

3.2.3. Life cycle inventory

The study uses two groups of data: (a) Specific data from Cau Do NMN, including raw water flow - clean water, electricity and chemicals in 2023, ensuring reliability for system simulation; (b) Background data from Ecoinvent v3.11 in SimaPro 10, used to inventory and calculate environmental impacts according to international LCIA methods.

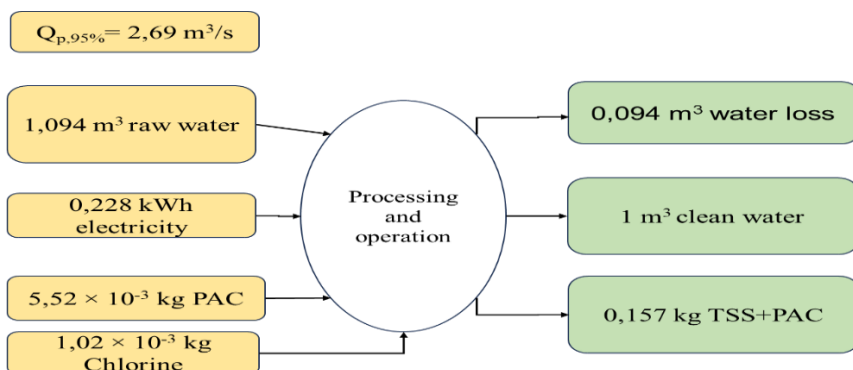


Figure 3.3. Data diagram at Cau Do factory

Factors used in the SimaPro calculation model :

Table 3.1. Emission factors of sources

Source	Emission factor (EF)	Source
Electricity used	0.6592 tCO ₂ eq/MWh	(Climate Change Agency, 2024)
PAC	1.71 kg CO ₂ eq/kg	Ecoinvent v3.11
Chlorine gas	0.995kgCO ₂ eq/kg Chlorinegas	Ecoinvent v3.11
BOD	0.48 kg CH ₄ /kg BOD	IPCC, 2006
COD	0.25 kg CH ₄ /kg COD	IPCC, 2006

Factors are updated according to the announcement of the Department of Climate Change (2024). PAC data is used at GLO level because Ecoinvent does not have separate data for Vietnam and this chemical is mainly supplied internationally. Chlorine disinfection is simulated using production data using membrane technology in Ecoinvent v3.11, suitable for Vietnam conditions.

3.2.4. Life cycle impact assessment and interpretation of results

LCI results show that electricity consumption increases in the dry season due to pumping water from An Trach; The two old lines consume more electricity (0.241–0.245 kWh/m³). 6 main environmental impact groups: climate change, acidification, eutrophication and freshwater ecotoxicity, fossil fuel scarcity, water resource consumption . The results show that the new 120,000 m³/day line has a high impact level.

significantly lower environmental impacts than the two older lines. GHG emissions are reduced by about 11.5%, and acidification and fossil resscarcity impacts are reduced by 11–13%.

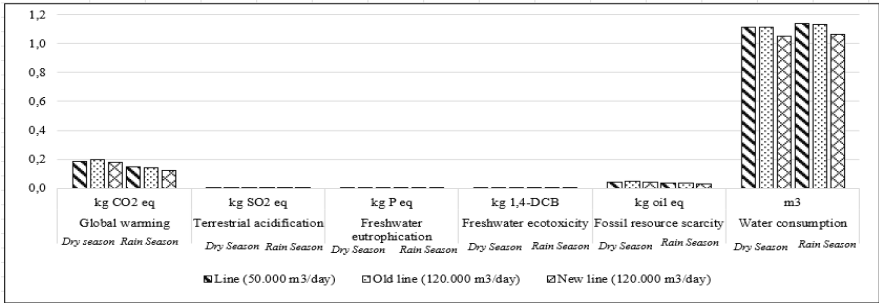


Figure 3.4. Impact of the operation of Cau Do NMN on the environment

Electricity 0.17–0.33 kWh/m³ and emissions 0.1767–0.1997 kg CO₂ eq/m³, lower in Türkiye, similar to Scotland, Indonesia and China. This result confirms the operational efficiency and sustainability of the plant. Expansion and standardization to the new line will reduce CO₂ emissions, save energy and chemicals and move towards a climate-resilient urban water supply system.

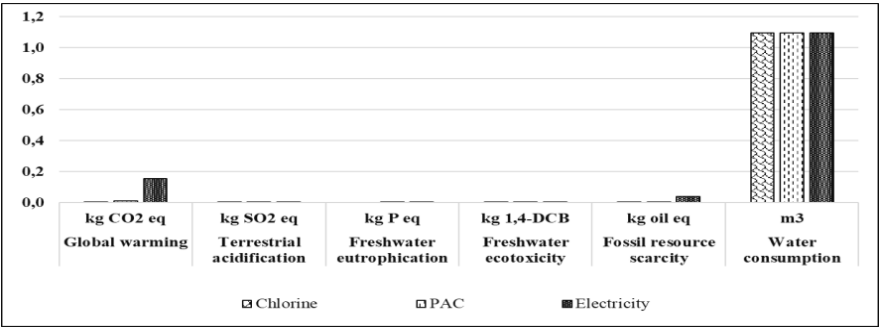


Figure 3.5. Impacts related to chemical and energy use

Electricity is the main contributor to environmental impacts at NMN, dominating GHG emissions, fossil resource scarcity and other impacts. Water use is relatively uniform across inputs. Impact reduction solutions focus on optimizing pumping, treatment and transmission efficiencies, increasing the share of renewable electricity and chemical control, especially in the dry season, to reduce GHG, save costs and improve sustainability, for Da Nang

water supply system. Results of 06 impacts of each processing cluster above the old 120.000 m³ line is shown in the following figure:

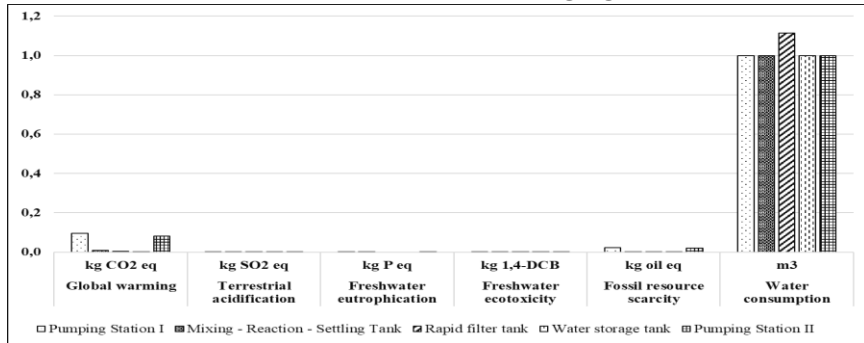


Figure 3.6. Impact of each processing cluster

Impacts at Cau Do NMN are unevenly distributed: pumping stations 1 and 2 account for 93% of GHG emissions. and fossil energy scarcity, which is also the main source of acidification. The dry season increases electricity and chemical use, leading to a peak GHG emission of 0.2474 kg CO₂ t/m³, fossil energy scarcity is twice as high as the wet season, and raw water pressure, WSI > 1.

To quantify the water scarcity impact in the LCA framework, the study used the WSI = 1.035 as the Characterization Factor (CF), according to Ridoult & Pfister (2010, 2014). Apply the formula:

$$\begin{aligned} \text{WSF} &= \text{WC} \times \text{WSI} = 1.133 \times 1.035 \\ &= 1.17 \text{ m}^3 \text{ water t/d/m}^3 \text{ clean water} \end{aligned}$$

In which: WC: amount of raw water consumed to produce 1 m³ of clean water (1,133 m³/m³); WSI: water scarcity index at Cau Do in the dry season (1,035).

Every 1 m³ of clean water produced at Cau Do Water Supply Plant in the dry season is equivalent to 1,17 m³ of water according to the scarcity level (WSF > 1), showing that the water resources downstream of Vu Gia River are being exploited beyond their regeneration capacity, with high risks.

3.3. Testing the reliability of the water supply system performance assessment framework using a combination of WSI and LCA indices

3.3.1. Assessment of input data quality of the WSI–LCA framework

The WSI–LCA framework was tested for reliability using the Pedigree Matrix, evaluating the criteria: accuracy, representation of time, space, technology and completeness. The results: electricity, water extraction and

electricity emission factors were of very high quality (5/5), updated in 2023; PAC and Chlorine were of medium-high quality due to data from Ecoinvent v3.11. Thus, the dataset was reliable enough to perform quantitative WSI–LCA analysis.

3.3.2. Data uncertainty analysis (Monte Carlo model)

To verify the stability, the study performed Monte Carlo simulations of 10,000 iterations on dry season data of the old 120,000 m³/day line at Cau Do Water Supply Plant. The WSI–LCA framework is stable and reasonably reflects the relationship between emissions – energy consumption – water scarcity.

3.3.3. Sensitivity analysis of inputs: The sensitivity analysis revealed that electricity was the most important variable influencing the LCA; a $\pm 10\%$ change in electricity resulted in a change of almost $\pm 12\%$ in CO₂ emissions, identifying electricity as an “environmental hotspot” that should be prioritized for savings and renewable energy use.

3.4. Summary of Chapter 3

Chapter 3 presented the development and validation of the integrated WSI - LCA model, aimed at comprehensively quantifying environmental impacts and water stress levels within the water extraction and production system. In this model, the WSI is directly integrated into the LCIA phase as a characterization factor. This integration allows for the conversion of water consumption into “m³ world equivalents,” accurately reflecting the water scarcity context of specific basins over time. Incorporating WSI into the LCIA stage via this approach represents a novel contribution of this thesis, addressing the limitations of traditional LCA studies that often overlook local hydrological conditions in water scarcity calculations.

The findings of this chapter establish a crucial scientific and practical foundation for Chapter 4, where the integrated model will be employed to analyze and select the optimal scenario for Da Nang City's water supply system under the mounting pressures of water scarcity and climate change

CHAPTER 4. ASSESSING THE EFFECTIVENESS OF CLEAN WATER EXPLOITATION AND TREATMENT SCENARIO IN DA NANG VIA AN INTEGRATED WSI - LCA MODEL

4.1. Developing water supply scenarios for Da Nang city

Scenarios are built based on water resource allocation, water treatment and reuse technology and energy sources used:

- Scenario S1 (Base): Mainly exploited at Cau Do intake, supplemented from An Trach in the dry season; using conventional grid electricity.
- Scenario S2: Add RO desalination (brackish water), ensuring raw water source but very high energy consumption.
- Scenario S3: Combining wastewater reuse (Hoa Xuan), reducing some pressure on fresh water resources.
- Scenario S4: Add a plant at An Trach dam .
- Scenario S5: Keep the same source as S1 but improve technology and use rooftop solar energy .

4.2. Applying the integrated WSI - LCA model to compare the impacts of clean water exploitation and treatment scenarios in Da Nang city

This section presents the LCA and water impact (WSF) results for 05 proposed scenarios for the urban water supply system in Da Nang City. The results are analyzed by each group of impact indicators (impact type and impact end point), water impact with WSI and comparison, synthesis, and selection between scenarios.

4.2.1. Objectives and scope

The objective is to compare the environmental performance of five urban water supply scenarios for Da Nang until 2045, in the context of climate change and saltwater intrusion.

The analysis includes: Calculating WSI for each dry season resource to assess water stress; Life cycle inventory (LCI) including electricity, chemicals, internal water and GHG emissions; Impact assessment (LCIA) according to ReCiPe 2016.

System boundary: from raw water extraction to clean water supply to the network, including treatment, operations, energy and chemicals. Functional

unit: 1 m³ of clean water, ensuring consistent comparison between scenarios.

4.2.2. WSI with water supply scenarios for Da Nang city under climate change conditions

WSI is calculated for each water source in the five water supply scenarios for Da Nang, focusing on the dry season (March–August) when flow is low and demand is high. The analysis is based on the extreme climate change scenario RCP8.5, with input data including: water flow at Cau Do and An Trach (95% frequency), raw water exploitation demand according to the scenario, and a forecast population of 2,5 million people with a water supply level of 160 l/person/day by 2045. The climate change scenario considers changes in temperature, rainfall and extreme climate phenomena in the 21st century.

Both RCP4.5 and RCP8.5 scenarios project a sharp decrease in water flow at Cau Do inlet from February to August, with RCP8.5 seeing a more severe decrease, especially from May to July. Meanwhile, summer water demand increases due to high temperatures and the tourist season, making water shortages more severe.

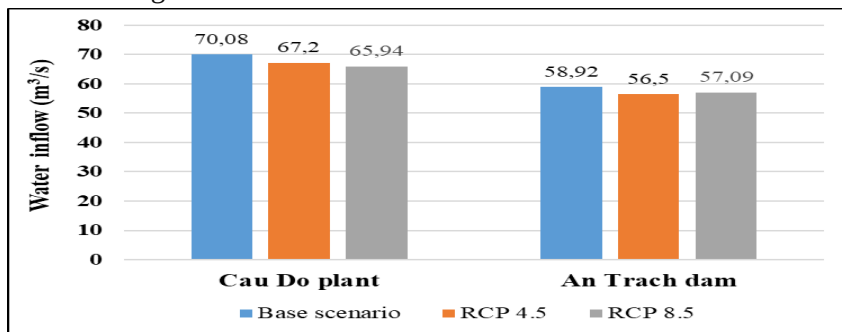


Figure 4.1. Water flow corresponding to 95% frequency corresponding to climate change scenarios

With a 95% frequency, the RCP8.5 scenario shows extreme flows and lower water inflows than RCP4.5, reflecting the strong impact of climate change and the risk of severe water shortages in the dry season. According to the plan, Da Nang's water demand in 2045 is 920.000 m³/day, while exploitation at Cau Do and An Trach is 420.000 m³/day. On this basis, WSI is calculated for each water supply scenario of the city.

The WSI index is determined by the formula of Smakhtin . Each scenario is built corresponding to different water resource combinations, so the WSI value of each scenario will directly reflect the level of water stress of the city's water supply system under different conditions. The WSI results of the five input scenarios are shown in Table 4.1.

Table 4.1. Summary of WSI values in the dry season of 5 water supply scenarios

Scenarios	S1	S2	S3	S4	S5
WSI	2,69	1,56	1,60	0,58	2,69

4.2.3. Life cycle inventory.

A life cycle inventory (LCI) was conducted for five water supply scenarios (S1–S5) in Da Nang, collecting data on raw water sources, extraction capacity, electricity, treatment chemicals, internal water and grid electricity emission factors. The results showed that:

Electricity: S2 (RO desalination) consumes the highest (2,6 kWh/m³), S1 and S5 are lower.

Chemicals: Using advanced desalination technology (S2, S5) requires additional chemicals, affecting toxicity and eutrophication.

Energy source: S5 integrates 30% solar energy, reducing GHG emissions compared to using only grid electricity.

4.2.4. Life cycle impact assessment and interpretation of scenario results

WSI–LCA assessment for 5 urban water supply scenarios shows that:

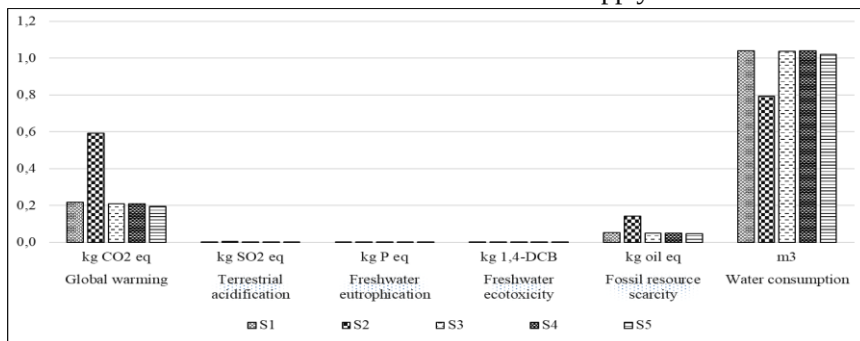


Figure 4.2. Results of the 6 impacts of the 5 water supply scenarios developed.

Intermediate impacts: Climate change and fossil resource exploitation account for a large proportion. S2 has the highest impact due to high energy consumption, S5 has the lowest.

Impact endpoint: S2 has the highest total impact ($7,10 \times 10^{-5}$), more than twice that of S5 ($3,04 \times 10^{-5}$). S3 and S4 are intermediate, balancing water supply benefits and environmental costs.

WSF index (water stress): S1: $2,80 \text{ m}^3$ – high pressure at Cau Do; S2: $1,24 \text{ m}^3$ – reduced stress due to brackish water, but high energy costs ; S3: $1,66 \text{ m}^3$; S4: $0,60 \text{ m}^3$ – significantly reduced water pressure; S5: $2,74 \text{ m}^3$ – maintained high pressure.

S2 is only suitable as a backup plan in extreme situations. S1 and S5 are not sustainable in the long term due to their dependence on Cau Do water source. S3 and S4 balance energy, emissions and water resource protection; S4 (combined with An Trach) is the optimal plan for 2030–2045, ensuring safe water supply in the dry season, reducing exploitation pressure and maintaining reasonable emission levels, energy and costs.

4.3. Summary of Chapter 4

Chapter 4 focuses on simulating, comparing, and quantifying five water supply scenarios for Da Nang City during the 2030–2045 period using the integrated WSI–LCA model. The key findings are as follows: While the desalination scenario (S2) reduces water source pressure by over 40% (WSI index), it imposes the heaviest environmental burden, with carbon emissions 2.7 times higher than the baseline scenario. Conversely, the infrastructure expansion at the An Trach diversion dam demonstrates superior efficiency, reducing the dry season water resource burden at Cau Do by up to 78% (with the WSI index dropping to 0.6

m^3 water equivalent). Notably, this scenario does not increase carbon emissions, even performing better than the baseline scenario (S1).

This study serves as empirical evidence of the applicability of the integrated WSI–LCA model in providing scientific justifications for decision-making in sustainable water supply planning for unique urban areas like Da Nang

CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

The research results successfully established the integrated WSI–LCA model, marking the first time that 'local water resource pressure' and 'global environmental impacts' have been quantified simultaneously. The model demonstrates high reliability and applicability for similar river basins.

Assessment of the current state of Da Nang's water supply system reveals that: The environmental hotspot is located in the operational phase, where emissions from electricity consumption account for over 90% of the total carbon footprint. Modern production lines reduce emissions by 11–13% compared to older ones. During the dry season (March to August), the Water Stress Index (WSI) reaches a critical level (1.035). Due to the combined effects of saltwater intrusion and the requirement for pumping from An Trach, greenhouse gas (GHG) emissions in May are 70% higher than in December.

Scenario simulations for 2045 indicate that the optimal scenario (S4)—shifting the source structure upstream toward the An Trach diversion dam—is the most sustainable option. This is because it reduces the water resource burden by 78% without increasing carbon emissions (performing better than the baseline). Conversely, while desalination technology addresses water resource security, it imposes an extreme environmental burden, with carbon emissions 2.7 times higher.

2. Recommendations

Integrating new assessment tools into the appraisal and selection process for urban water supply options. This is particularly crucial for coastal cities facing the dual challenges of saltwater intrusion and low-flow fluctuations during the dry season (similar to the context of Da Nang).

Enhancing monitoring systems to collect long-term, synchronized data on hydrology (streamflow, salinity) and operations (electricity consumption, chemical usage, sludge emissions). This will improve the accuracy of the Life Cycle Inventory (LCI) and the reliability of predictive

models.

Expanding the research scope: Moving beyond water production to a comprehensive evaluation of the entire Urban Water Cycle, including distribution, consumption, and wastewater treatment.

Adapting the model to incorporate emerging variables in urban planning, water demand trends, and updated climate change scenarios.

Applying the model to other municipalities (such as Hue, Quy Nhon, Hai Phong, etc.) to validate the flexibility and adaptability of the established methodological framework.

LIST OF PUBLICATIONS

1. INTERNATIONAL PUBLICATIONS

- [1]. “ *Water Stress Index application to assess water scarcity of Lower Vu Gia - Thu Bon River Basin in Vietnam* ”. Authors: Mai Thi Thuy Duong , Vo Ngoc Duong, Tran Thi Viet Nga. IOP Conference Series: Earth and Environmental Science, **1143** , 2023. <https://doi.org/10.1088/1755-1315/1143/1/012004>
- [2]. “ *Sustainability evaluation of freshwater withdrawal on the Vu Gia Thu Bon basin river in Vietnam* ” . Authors: Duong Thi Thuy Mai, Duong Ngoc Vo, Nga Thi Viet Tran . IOP Conference Series: Earth and Environmental Science, **1226(1)**, 2023. <https://doi.org/10.1088/1755-1315/1226/1/012007> .
- [3]. “ *Life cycle assessment on water treatment: Case study in Cau Do water treatment plant – Da Nang city – VietNam* ” . Author: Duong Thi Thuy Mai, Duong Ngoc Vo, Nga Thi Viet Tran . IOP Conference Series: Earth and Environmental Science . **1391**, 2024. doi:10.1088/1755-1315/1391/1/012015.
- [4]. “ *Comparative Life Cycle Assessment of Urban Water Supply Strategies under Salinity Intrusion in a Coastal City*”. Author: Duong Thi Thuy Mai, Duong Ngoc Vo , Nga Thi Viet Tran, Doan Thuy Kim Phuong, Hua Manh Thinh. River Journal. Under review.

2. NATIONAL PUBLICATIONS

- [1]. “ *Water scarcity assessment index: Overview and calculation method* ” . Authors: Mai Thi Thuy Duong , Vo Ngoc Duong, Tran Thi Viet Nga, Le Thi Hoang Dieu. Journal of Science and Technology - University of Danang, Vol. 19, No. 9, 2021.
- [2]. “ *Status of salinity at raw water exploitation points for Da Nang city in the period 2005 - 2016. Trends to 2030* ”. Authors: Mai Thi Thuy

Duong , Phan Thi Ha Giang , Huynh Van Tai , Dang Thi Huyen Ny , Vo Ngoc Duong, Tran Thi Viet Nga. Construction & Urban Magazine. No. 84. 2022. Pages: 78-82. [Year 2022.](#)

[3]. “*Overview study on life cycle assessment method on urban water system*”. Authors: Mai Thi Thuy Duong , Vo Ngoc Duong, Tran Thi Viet Nga, Ho Diu Ny. Journal of Science and Technology - Danang University. Vol. 22, No. 7, 2024.

3. REPORT AT THE 28TH HYDRAULIC MECHANICS SCIENCE CONFERENCE:

[1]. Application of Simapro software in life cycle assessment of water use in Da Nang City.

[2]. An approach in assessing the level of water stress under the influence of climate change and increasing water demand. Applied to Cau Do Water Plant, Da Nang.