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Life Cycle Impact Assessment (LCIA) of Potable Water Production in Malaysia: A Comparison among Different Technology Used in Water Treatment Plant

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Abstract

LCA is a systematic procedure which assesses the lifecycle of a product to analyze the extent of its environmental impact contribution. In this LCA study comparison between three different water treatment plants in Malaysia have been conducted. Conventional Plant (using Dissolved Air Floatation (DAF) and Pulsatube ® Clarifier Technology) must undergo treatment process uses a standard system of screening, coagulation and flocculation, sedimentation, filtration and disinfection processes. While nonconventional plant using Ultrafiltration (UF) not does go through processes like conventional plant. In reviewing the water treatment process by using LCA procedures, detailed information of every process involved is needed, including acquiring the energy information and materials consumed during the entire treatment process. The LCA procedure applied in this research uses the ISO 14040 series. Data inventory from selected month will be analyzed to gauge the impact to the environment using Eco-indicator 99 method. The high consumption of electricity in UF and DAF technologies is the contributing factors to the depletion of natural resources. Even though the electricity consumption in pulsatube ® clarifier technology is seen as efficient, but its PAC chemical usage is seen as the major contributor to the reduction of environmental quality and human health.

Keyword: life cycle assessment (LCA); life cycle impact assessment (LCIA): potable water; dissolved air floatation (DAF): pulsatube ® clarifier; ultrafiltration (UF)

1. Introduction

Generally, there are two methods used in water treatment; the conventional and non-conventional. Conventional method (Fig. 1) is water treatment which undergoes processes such as coagulation, flocculation, sedimentation, and filtration. While non-conventional method are much simpler compared to conventional method. The non-conventional method however uses more sophisticated equipment if compared to conventional. Selection of the technology to be used depends on the quality of the water source. The non-conventional method will only be used if the conventional method is no longer viable for use due to factors such as severe water contamination or alternative water source other than fresh water is used. Malaysia uses both conventional and non-conventional methods. Among the latest conventional technology in use is Dissolved Air Flotation (DAF), Pulsatube Clarifier and Actiflo. There is only one water treatment plant that uses Actiflo technology in Malaysia and it is the only plant of its kind in Southeast Asia. DAF technology was said to be recently established in Malaysia during the 90s eventhough this technology was already in use since the 60s. There are only 11 water treatment plant using DAF in operation throughout Malaysia (Lin, 2008).

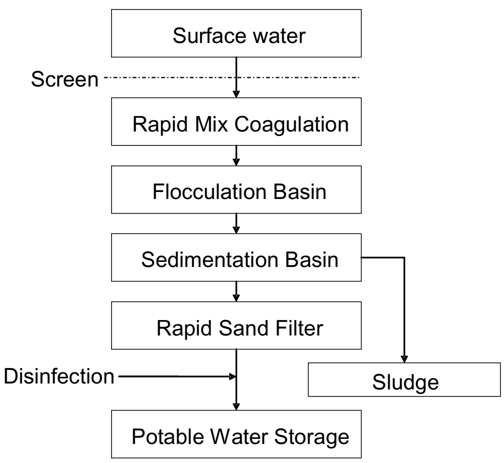

Figure 1. Flow diagram of a conventional potable water treatment plant

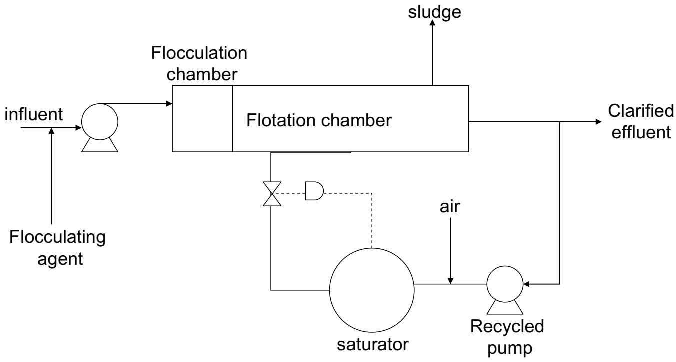

Figure 2. Schematic diagram of water treatment plant with DAF technology (Lin, 2008)

In DAF process, air is dissolved under pressure in a clean liquid, usually recycled effluent from the DAF unit, and injected into the raw feed stream. Upon entering the DAF unit, the air pressure is released and combined with the liquid, which become supersaturated with micron-sized air bubbles. Suspended materials attached to the anionically-charged air bubbles producing a lower specific gravity for the agglomerate to less than that of water, thus effectively raising the suspended particles to the liquid surface, forming a floating sludge layer that is removed by skimmers. Generally, a water treatment plant that uses DAF technology can be illustrated in Fig. 2.

The second conventional technology is the plant that uses the Pulsatube®Clarifier technology. This technology is developed by combining the processes of flocculation and clarification in one area. Pulsatube® clarifier technology is the second generation technology after Pulsator®Clarifier. Pulsator®Clarifier was used sometime in the 50s. Until now there are two other new generation that is superpulsator®Clarifier (Fig. 3) and Superpulsator® Type U clarifier. The difference between generation to generation are from the aspects of space, design and lamella tubes installed on top of the settling plates. These technologies also designed to be easily operated with minimal maintenance (Dyson, 2000).

Membrane technology is the only non-conventional method used in Malaysia. To date, there is only 3 water treatment plant operating with this method throughout Malaysia. The first plant with membrane technology in Malaysia using ultra-filtration process started operation in 2006 in Bukit Panchor, Pulau Pinang (PBA, 2006). Then 2 other plants were built and started operation early 2008 in Selangor (Ibrahim, 2008). Ultrafiltration process uses membrane modules (Fig. 5) as filtration media as compared to conventional plant which uses sand. Usually, a water treatment that uses ultrafiltration technology goes through simpler phases compared to conventional as shown in Fig. 4. Among the advantages of using the UF technology is, it could produce clean water of high quality, lower operation cost, easily upgradeable system and space reducing compact system.

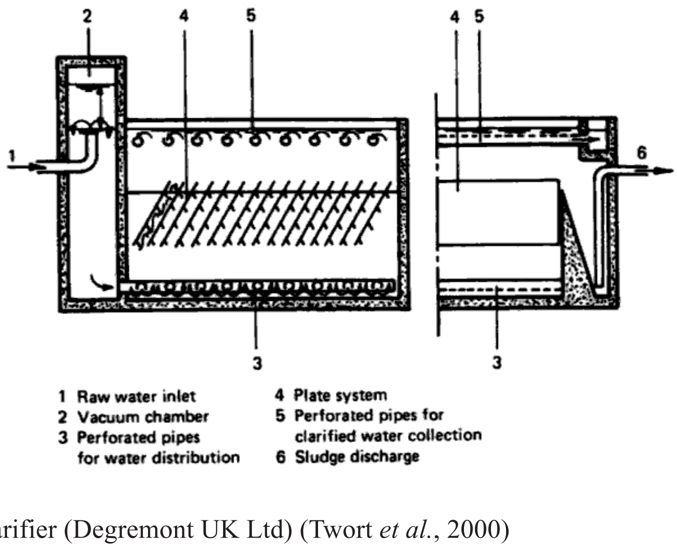

Figure 3. Superpulsator Clarifier (Degremont UK Ltd) (Twort *et al.*, 2000)

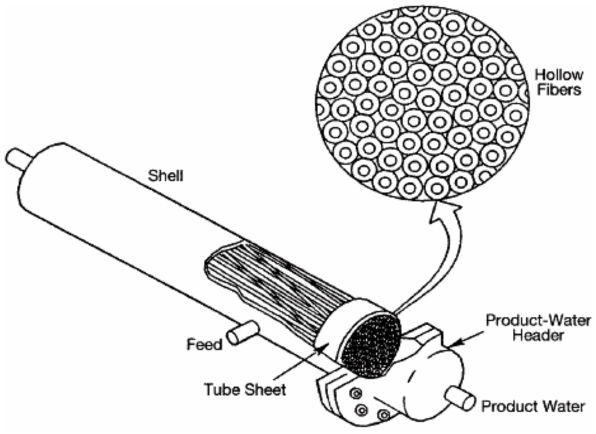

Figure 4. Cutaway view of hollow-fiber membrane module (Chen *et al*., 2006)

All three technologies mentioned above show progression and development in water treatment technology. The advancement and development of this technology are based on current water needs and the decreasing water source quality over time resulted from human activities. The development in water treatment technology, undeniably provide more advantages from the aspects of minimal space usage, cost effective, higher yield of production, safe drinking water and reduced labor. In another hand, assessment needed to be done to ensure that this technology will not cause any adverse effect to the environment throughout its life cycle. Thus a tool that could be used for this purpose is Life Cycle Assessment (LCA). By evaluating the life cycle of the technology used in the water treatment plant, improvements could be implemented to improve on all identified flaws.

There are several LCA methods developed, but LCA methodology refined by the International Organization of Standardization (ISO) under ISO14040 series is seen to be more robust and have higher credibility. ISO 14040 series (ISO 14040 and ISO 14044) (Finkbeiner *et al*., 2006) is under the oversight of the ISO 14000 environmental management. This shows that LCA is a tool which has an important role in ensuring sustainability development. According to ISO 14040 and ISO 14044 standards, a Life Cycle Assessment is carried out in four distinct phases as shown in Fig. 6. Explanation on the four phases will detail in the next subtopic.

2. Goal and Scope of the Study

Malaysia is a fast developing country and this situation fire up the population growth, especially in the vicinity of major cities. Settlement and industrial areas expansion forces new water treatment plants to be built to cater to consumer needs. It is fitting situation for a LCA study to be conducted seeing more and more water treatment plants that could adapt environmental friendly technology will be built. The result of this LCA evaluation can be used by water treatment technology engineers, water operator, the government and parties of interest to make the right decision to build a treatment plant that would benefit all parties and would preserve the environment from LCA's perspective.
To achieve these goals, three types of water treatment plant are chosen:
Water treatment plant using Dissolved Air Flotation (DAF) technology,
Water treatment plant using ultrafiltration (UF) technology, and
Water treatment plant using Pulsatube®Clarifier technology.

To ensure that the study is conducted systematically, the life cycle of the water treatment

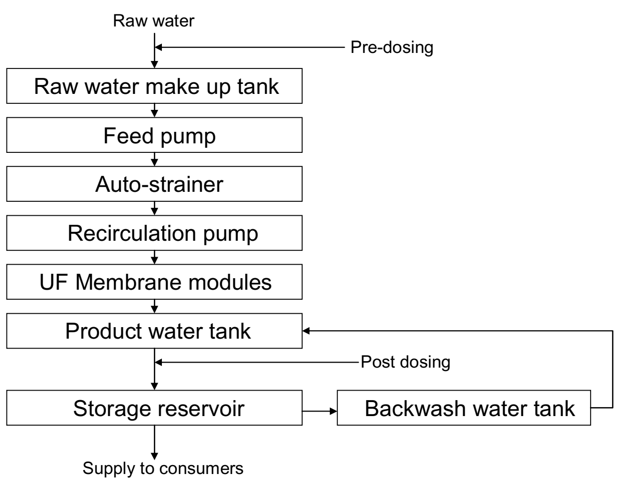

Figure 5. Water treatment process using UF technology (PBA, 2006)

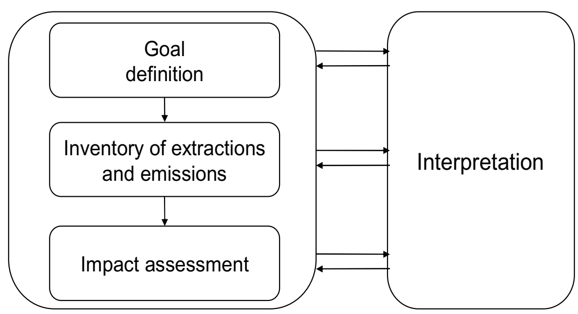

Figure 6. Framework of Life Cycle Assessment (LCA) (Guinee, 2002)

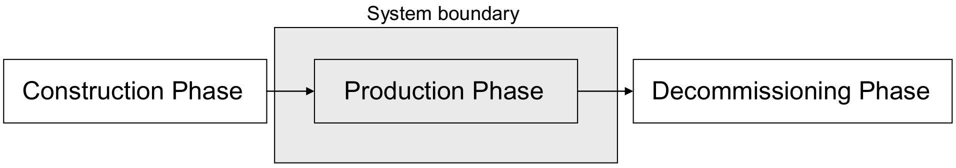

Figure 7. System Boundary in Life Cycle Assessment in Potable Water Production

plants is identified. Generally, a water treatment plant's life cycle consists of 3 stages i.e., construction stage, operation stage and finally the decommissioning stage. This LCA study is a gate-to-gate study that focused on one stage of the life cycle. The chosen stage is the production stage, taking into consideration the chemical usage and electricity consumption at this stage to produce treated water. Life cycle for all chemicals and electricity generation process begins from raw material acquisition until the disposal stage is considered as the system boundary for this study. Fig. 7 shows the simplified system boundary for this study.

To differentiate between the three types of treatment plants, a constant functional unit is chosen for use in this study. The functional unit chosen is the production of 1000 m^3 treated water which passes the standard set by Ministry of Health, Malaysia and the water source extracted for treatment is at class II (only uses normal water treatment).

3. Life Cycle Inventory (LCI)

Foreground data on chemical substances such as Polyaluminium Chloride (PAC), Aluminium Sulphate (Alum), Chlorine, Calcium Hydroxide (Lime) and electricity utilize on the selected month are collected and analyzed (see Table 1). Criteria for mass inclusion are:

Include all unit processes up to 95% of the cumulative weight of the total product weight (cut off 5%).

If the unit process, however, is considered environmentally significant (e.g. toxic chemicals), the process is included in the product system.

This LCA study is a streamlined LCA study where the background data for the listed materials are obtained from secondary data i.e., Simapro and Jemaipro software.

4. Results (Life Cycle Impact Assessment (LCIA))

Generally, there are 3 steps in LCIA: Classification and characterization, Normalization, and Weighting. Classification and characterization are mandatory elements while normalization and weighting are optional elements (ISO14000, 2000). But normalization and weighting is done as a reference only as both uses the standards for depicting population of European countries and would not be able to depict the population of Malaysia. In this working paper, the

Table 1. List of Inventory

Inventory	Water treatment technology		
	Pulsatube	DAF	UF
Chlorine (kg)	3.65	14.13	NA
Alum (kg)	22.55	132.49	NA
PAC (kg)	16.85	NA	NA
Lime (kg)	11.12	116.04	NA
Electricity (kWH)	397.28	1580.85	2585.81
Emissions (cut off 0.01%)			
Carbon dioxide (kg)	327	1.38E3	1.98E3
Metals (g)	0.788	3.68	3.18
Methane (kg)	0.732	3	3.85
Nitrogen oxides (kg)	152	2.69	3.85
Sulphur oxides (kg)	152	2.6	0.685
Arsenic, Ion (mg)	81.9	363	460
Particulates (g)	45.2	191	169

Table 2. Damage Assessment and Impact According to Eco-Indicator 99 Evaluation Method

Damage Assessment	Unit	Impact
Human Health	DALY	Carcinogen, radiation, respiratory organic and inorganic, climate change and ozone layer
Ecosystem Quality	PDF*m2yr	Land use and acidification/eutrophication, Ecotoxicity
Resources	MJ surplus	Minerals and fossil fuels

(Goedkoop and Spriensma, 2001)
DALY Disability Adjusted Life Years (Years of disabled living or years of life lost due to the impacts)
PAF Potentially Affected Fraction (Animals affected by the impacts)
PDF Potentially Disappeared Fraction (Plant species disappeared as result of the impacts)
SE Surplus Energy (MJ) (Extra energy that future generations must use to excavate scarce resources)

classification element is not shown. LCIA for this study uses the Eco-Indicator 99 evaluation method where it listed 11 impacts classified into 3 damage assessment (refer Table 2):

4.1. Characterization

In the classification step, all substances are sorted into classes according to the effect they have on the environment (Weidema, 1997). Steps in performing classification are not included in this explanation. While characterization are steps where the substances are aggregated within each class to produce an effect score (Wenzel *et al*., 1997). This is divided into two sections: 1) Characterization to damage category, 2) Characterization to impact category.

4.1.1. Characterization to Damage Category

Based on Fig. 8, it is found that Pulsatube contributes higher than UF and DAF in the category of human health destruction i.e., Pulsatube contributes 0.021899 DALY compared to 0.000736 DALY and 0.00087 DALY for DAF and UF. Three substances that are identified to contribute to this are carbon dioxide, nitrogen oxides and sulphur oxides.

For the destruction of Ecosystem Quality, pulsatube contributes much higher impact compared to the other two technologies. DAF and UF only contribute less than 5%. The value of contribution by Pulsatube, DAF and UF are 1030.349, 26.45355 and 33.00491 respectively in PDF*m2yr unit. The main substances that contribute to destruction of ecosystem quality are nitrogen oxides and nickel.

In the category of destruction to natural resources however, it is found that UF technology (100% that is 3303.64 MJ surplus) contributes higher in comparison to DAF (around 65% or 2110.815 MJ surplus) and Pulsatube (around 15% or 521.421 MJ surplus). Electricity generation is found to contribute to the natural resources reduction on all three technologies used such as natural gas, coal and crude oil.

4.1.2. Characterization to Impact Category

As explained earlier, destruction is categorized into several sections of impact categories. (refer Table 2). From Fig. 9, it is found that impacts from the category of carcinogen, respiratory organics, climate change, ecotoxicity and fossil fuels are contributed higher by UF technology. While DAF technology contributes higher in the impact to radiation, ozone layer, land use

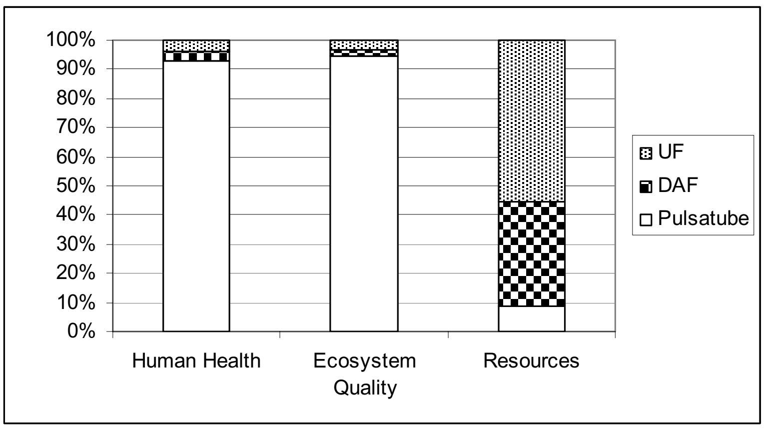

Figure 8. Graph shows the difference between all three type of technology (Pulsatube, DAF and UF) in damage category (human health, Ecosystem quality and Resources) (in percent)

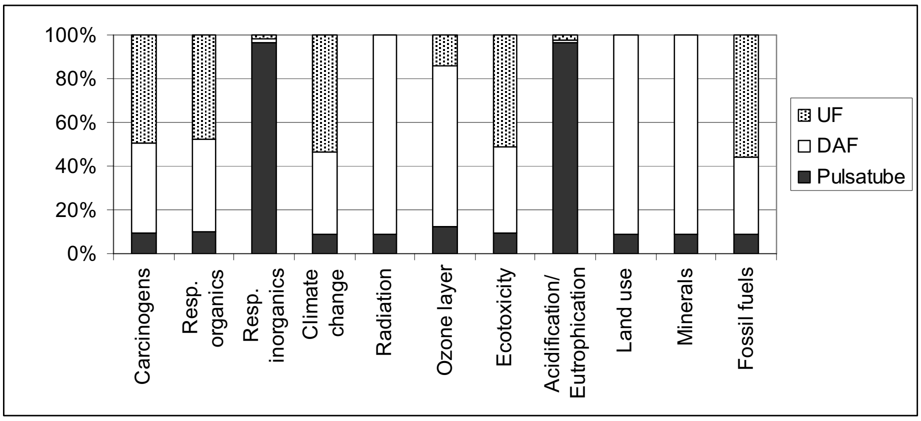

Figure 9. Comparison among Pulsatube, DAF and UF in impact category (in percent)

and mineral. The high usage of lime in DAF compared to other technologies was identified as the cause in higher impact in radiation. Emission from lime production process generates carbon-14, iodine-129, krypton-85, radon-222, cesium-134, cobalt-60 and other radioactive substances. The impact on land use and mineral is also caused by the lime production process. Ozone depletion problem is caused by Methane, Bromotrifluoro and Halon 1301 released during lime production. Pulsatube technology contributes higher in the impact category of respiratory inorganic and acidification (refer Table 3 to obtain the comparison value between the three types of technologies according to their respective units). Both impact categories is identified to be caused by PAC chemical production process which releases several chemicals such as Nitrogen oxides and Sulphur oxides.

4.2. Normalisation

Many methods allow the impact category indicator result to be compared by a reference (or Normal) value. This means the impact category is divided by the reference. The reference may be chosen, often the yearly average environmental load in a country or continent, divided by the number of inhabitants, is used as the reference. For Eco-indicator 99, the European country population is the guidance for the impact that might occur from malfunction of the studied life cycle of product or services. After normalization, the impact category indicators all get the same unit (usually 1/yr), which makes it easier to compare them.

From the results, figure 10 shows the destruction to human health is the main contributor to the destruction. In this category, pulsatube technology is the main contributor (1.43), while DAF only contributes 0.048 and UF 0.057. The dominating impact in this category is respiratory inorganics. The main substance that contributes to respiratory inorganics impact is nitrogen oxides (61.9%) compared to sulfur oxides (38.1%) and others. Both substances are produced during the production of PAC.

The same goes for destruction of ecosystem quality. Contributors to this category still remains with

Table 3. Comparison among technology in impact category

Impact category	Unit	Pulsatube	DAF	UF
Carcinogens	DALY	6.4E-06	2.87E-05	3.45E-05
Resp. organics	DALY	1.01E-07	4.31E-07	4.82E-07
Resp. inorganics	DALY	0.02182	0.000402	0.000398
Climate change	DALY	7.2E-05	0.000304	0.000438
Radiation	DALY	1.17E-08	1.22E-07	0
Ozone layer	DALY	4.2E-09	2.51E-08	4.82E-09
Ecotoxicity	PAF*m2yr	18.51406	80.23568	102.7239
Acidification/ Eutrophication	PDF*m2yr	1028.461	18.05059	22.73252
Land use	PDF*m2yr	0.036363	0.379393	0
Minerals	MJ surplus	0.008192	0.085029	0
Fossil fuels	MJ surplus	521.4128	2110.73	3303.64

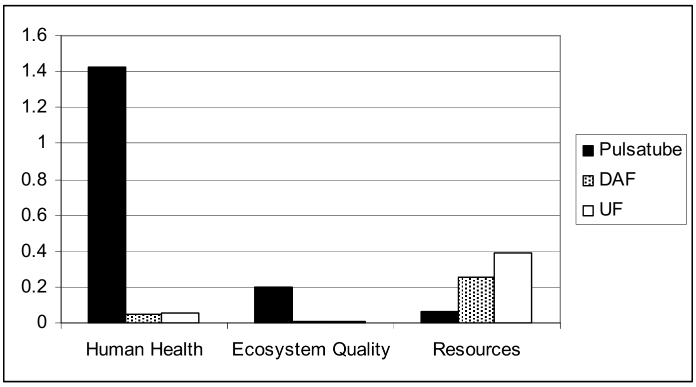

Figure 10. Graph for normalization in damage category

pulsatube (0.2) compared to DAF (0.005) and UF (0.006). The main chemicals that contributes to this category are nitrogen oxides (84.45%) and sulphur oxides (15.37%) which could have affected the impact category of acidification/eutrophication. Nitrogen oxides and sulphur oxides are also the by-product of PAC production.

Lastly the destruction of natural resources, UF (0.393) contributes higher than DAF (0.251) and pulsatube (0.062). Fossil fuels is a significant impact category after normalisation where natural gas was the substance that is most affected (99% - UF, 96.6% - DAF and 97% - Pulsatube). Natural gas is used in the generation of electricity.

4.3. Weighting

Weighting stresses on and bring forth the impact section that has most potential. This is also closely related to the voices garnered from the local community. In other words, it might be different from one location to the other and from one country to another. Fig. 11 shows a comparison graph between the three types of technology for weighting. The ranking is the same such as normalization being the most in human health, followed by resources and finally ecosytem quality.

5. Discussion (Life Cycle Assessment Interpretation)

Based on the weighting result, human health destruction caused by PAC may be relieved by replacing it with Alum. The result of Alum replacement can be seen in Fig. 12. The use of Alum is twice the quantity of PAC in producing 1000m3 treated water has shown a very positive result where the value drops from 428Pt to 3.69Pt for existing Pulsatube and it is the corrective measure in the destruction to human health. Destruction to ecosystem quality is also positive with drastic reduction from the original value of 80.4Pt to 0.528Pt.

For the category of destruction to natural resources it is probably caused by the generation of electricity using natural gas. Full reliance on it should be reduced as other alternative can be used. Among others are the mixed usage mode which may be used to avoid complete reliance to natural gas. The use of hydropower which may be generated by the fast water current flowing into the water treatment plan and the use of solar cells can be put in place seeing that water treatment plants are exposed to the sunlight. These alternatives if used in combination with natural gas would definitely preserve the earth's priceless natural resources while conserving the environment at the same time.

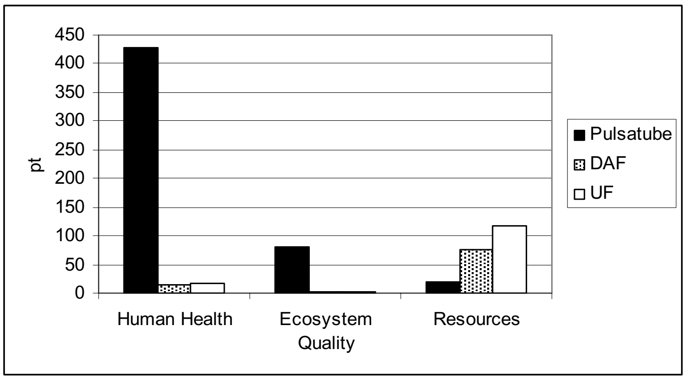

Figure 11. Graph for weighting in damage category

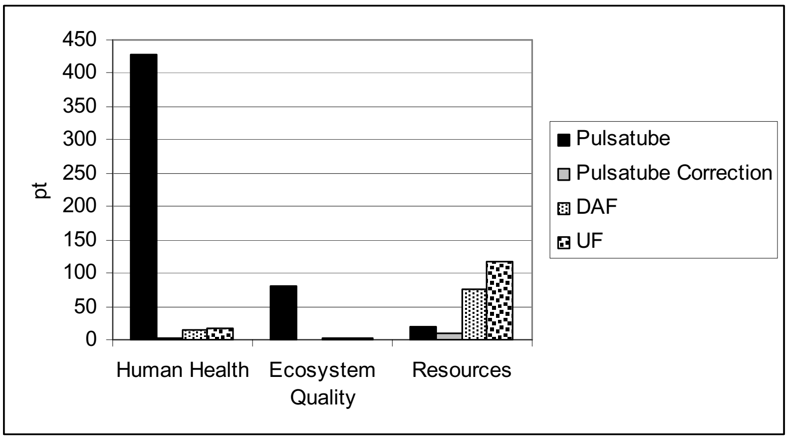

Figure 12. Graph for weighting shows noticeable change to Human Health and Ecosystem Quality when PAC replace fully with Alum

6. Conclusion

This study is a gate-to-gate study which only focuses on part of the phases in a life cycle. However, this study shows that generation of electricity and chemical use during water treatment has resulted negatively to the environment. The PAC substance, as an example, is found to be non-environmental friendly and negatively affects the human health and destruction of ecosystem quality. Complete reliance on electricity in the UF technology is seen as a barrier to its usage, even though it is the best alternative of the existing technologies. If this technology is to be developed further, it has to opt for other natural resources which are much cheaper, safer and more environmental friendly.

Acknowledgement

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