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Life cycle assessment of filtration systems of reverse osmosis units: a case study of a university campus

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Abstract

Environmental concerns are gaining importance in ground water resource management. Reverse osmosis (RO) systems are commonly used for filtration of surface and ground water for domestic and commercial purposes. This study aims to analyze the environmental impacts of electricity, fresh water and material consumption in various types of RO systems. The evaluation tool used for this study is life cycle assessment (LCA) and for this purpose Umberto NXT Universal software with Eco-invent version 3.0 database has been utilized. The inventory analysis has been done for RO systems of four different capacities, viz 25, 50, 250, and 500 liters per hour (LPH). This research also provides comparison of quantitative impacts of different capacity RO systems. All inclusive, the study presents an insight into the environmental impacts of various RO systems used in India and also discuss the alternative technologies for filtration of surface and ground water.

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Keywords: Reverse osmosis; Life cycle assessment; Environmental impacts; Water resource;

1. Introduction

Water is a crucial element for maintaining environment and ecosystem conducive to sustain all forms of life. It plays a vital role in fulfilling basic human needs for life and health as well as in socio-economic development. The demand for drinking, domestic activities, livestock, agriculture, industries, power generation, and other uses are all increasing to meet the requirements of increasing population and also to cater for the enhanced per capita requirement due to rise in living standard [1]. The available surface and ground water resources, which are the part of a larger ecological system, are renewable but limited and India has 16% of the world population where as the water resources are only 4% [1]. The arid regions are solely dependent on ground water for their domestic usage. Hence the quality of ground water is important, especially for drinking purposes. The ground water contains impurities such as suspended solids, dissolved solids, and other impurities [2] Hence, water needs to be treated before it reaches to the households. One such well known treatment methodology is reverse osmosis (RO). Reverse osmosis uses a membrane for the removal of contaminants from polluted water [3]. The process takes place when a pressure is applied to the concentrated side of the membrane forcing purified water into the dilute side. The rejected impurities from the concentrated side are being washed away in the reject water. This rejected water is one of the major wastage and hence this gives a scope for estimating the amount of water which gets treated using RO system and also for estimating the reject water. It is a social obligation to provide the population with the sufficient quantity of drinkable water and at the same time it is also necessary to prevent environment impact by reducing wastage and recycling the water [4].

The drinking water requirement of university campus is also fulfilled by RO systems. The aim of this study is to analyze and visualize the environmental impacts of electricity, fresh water and material consumption in RO systems of various capacities to produce potable drinking water.

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2. Case study

At university campus the main source of water is ground water. However, for irrigation purpose a small amount of harvested rainwater is used. The groundwater is extracted, using submersible electric pumps, from nine tube-wells providing 2,010 Kiloliters of water per day. The depth of these wells varies between 310 to 800 feet. Rainwater harvesting is implemented in newly constructed buildings to collect water. In 2013, the total amount of water harvested is estimated to be approximately 2,396,284 litres [4]. The groundwater is tested and it is found that the deep tube-well water is within the desirable limit of the Indian Standards and hence distributed without treatment. However, for drinking purposes the university has installed reverse osmosis (RO) treatment devices in the campus.

However the water supply system is a combination of gravity and pumping system. First the water extracted from the wells is stored at the reservoirs near to wells. Afterwards, the water in the reservoirs is transported with booster pumps through the pipeline system to tanks on the rooftops or inside the buildings. They are refilled automatically in all buildings for a 24 hours continuous supply. The staff quarters of campus are exceptions with an intermittent supply. The tanks in the buildings are only filled in the morning and evening. In addition, there is a refilling time in the night for the staff houses with two floors to provide sufficient water pressure to reach the tanks on the roof top.

The tap water is treated for drinking purpose using RO (reverse osmosis) systems installed at different locations in the campus. Anyhow; tap water can also be consumed without treatment due to good groundwater quality as described earlier.

A total of 6191 residents live on the campus including students, research scholars, faculty, staff and family members, guests and workers [5]. In the university campus the capacity of RO systems employed is approx. 33000 litres of ultrapure water, which is sufficient to meet the drinking water requirement for the residents. It is assumed that an average person needs 5 liters/day (The Hindu, 2013)of water for drinking purpose.

Table 1. Overview over water demand [4]

Consumer	Water demand in l/d
Domestic	829,980
Businesses	39,650
Institutional	198,270
Public	544,602
Losses in distribution	302,400
Wastage	123,820
Total water demand	2,038,722
Water demand per capita	329

3. Materials and method

LCA is an evaluation technique used for analyzing the energy and material flow throughout the life cycle of a product or a process. LCA has been widely used nowadays in various treatment processes [7] [8]in process industries as well as in manufacturing industries [9],[10]. In this study material and energy flow of drinking water, its purification and rejected water treatment was included. In this study a simple LCA has been performed using ISO 14040/44 (ISO, 2006), which comprises of four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation. For this the collected data of water supply, demand and energy consumed was evaluated and visualized. The outputs were allocated to impact categories which resulted in a more vivid presentation. As a consequence, the awareness for negative effects has been increased.

To carry out this assessment, the whole life cycle of the product (including groundwater catchment, storage, distribution, purification, consumption, disposal, and recycling), the required energy, and material production is taken into account. In this study one important point to be mentioned is that during the purification process approximately 75% of the supplied water is wasted and 25% of the supplied water is purified. This waste water is directly supplied to the sewage treatment plant for further treatment and re-distribution. The energy and material required for sewage treatment of both used and wastewater is also considered. This provides better understanding of the environmental impacts of the drinking water supply system.

The inventory analysis and the impact assessment of both models were conducted in the Umberto NXT LCA software. The used assessment method was ReCiPe 2008 which combines midpoint and endpoint approaches.

In this study two models have been considered to find out the most efficient RO system for the institutional purpose. The results of both models were analysed to determine the intensity of the reduction of environmental impacts due to the related optimization ideas. The scope of this method is to find a base for developing efficient optimization methods.

3.1. Goal and scope definition

The main objective of the study was to identify most environmentally efficient RO systems used in the campus for drinking water supply. According to the data provided by RO system distributors, most commonly used RO systems for institutional purpose are 25 LPH, 50 LPH, 250 LPH and 500 LPH. Thus these four RO systems were chosen for analysis. The energy and material requirement for all these RO systems were significantly different from each either and resulted in different environmental impacts. Thus for conducting LCA of these RO system including all pre-chain of water supply

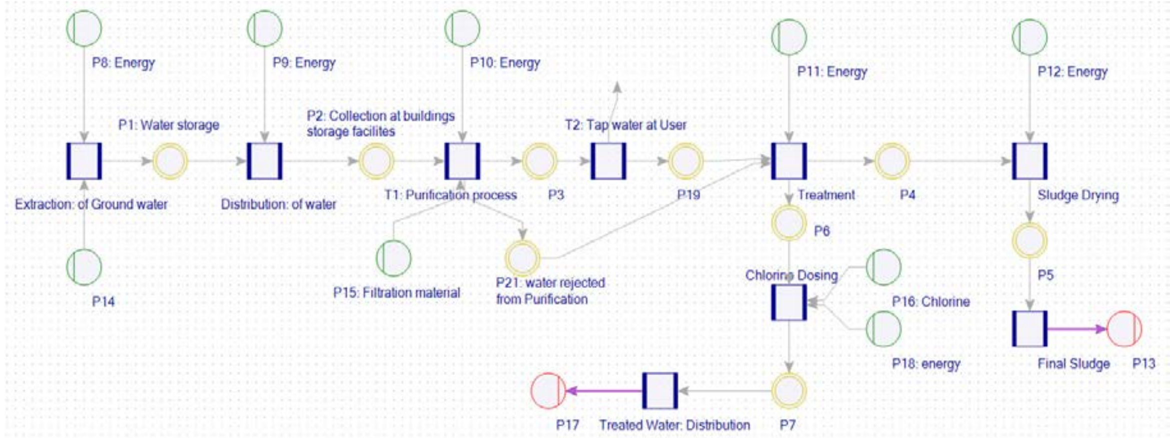

Fig. 1. Basic LCA model of the study

system, the functional unit chosen for first LCA model was "1875m3 of ultrapure water"(first model) from each of the above mentioned RO system in a duration three year. It is assumed that the RO systems were used five hours per day for 250 days per year for duration of three years. Further, in this study second model of LCA was prepared for all of the various RO systems equipped in the campus. The functional unit of this model was chosen as "ultrapure water consumed in one day by campus inhabitants"(second model). It was assumed that all RO systems are working for five hours per day for purification process. According to US Department of Energy [12] the functional unit should be defined in quantified measure of performance to create a common basis for conducting LCA[13].

The service life and the quantity of material required for maintenance for all RO systems (25LPH, 50 LPH, 250 LPH and 500 LPH) are different. Hence, for the first model maximum service life and maximum ultrapure water delivered by 500 LPH RO systems was taken as a functional unit. Further the other RO systems have less service life and deliver less ultrapure water, so, they were multiplied to a number to achieve same output of ultrapure water. In the university campus 6 RO systems of 500 LPH, 7 RO systems of 250 LPH, 32 RO systems of 50 LPH, and 9 RO systems of 25 LPH capacity are installed. The second LCA with one day capacity functional unit is designed by considering the same number of systems.

3.2. System boundary

A cradle to grave approach has been taken for performing the LCA analysis in the study. It included the extraction of raw water from underground sources, collection, distribution, purification, maintenance and services, public use, waste water treatment, and treated water distribution. In this study distribution loss of approximately 14% had been incorporated in water distribution, waste water to sewage treatment plant, and re-distribution of treated water. The impact due to the setup of infrastructure (pipeline, pumps manufacturing etc.) involved in the whole water supply system and maintenance of the same was not considered in the study. Use of manpower and other local transportation was also kept out of the system boundary. It is necessary to mention that maintenance/service of the RO systems was included in the study.

3.3. Inventory analysis

The primary data was collected by conducting semi structure interview with the authorities of water supply systems in the campus. Estimation of quantitative data was done either by actual or measurement wherever possible. The inventory analysis of the RO systems was done using the manual/brochures available and information provided by the manufacturer/distributor. Possible and feasible, average or typical process-specific data were collected, by performing time study of the systems. To develop the LCA model for both functional units (full capacity 1875 m3 and one day ultrapure water consumption), the data collected from the primary and secondary sources was complied together.

3.4. Impact Assessment

For the impact assessment, the well-known ReCiPe midpoint and endpoint methodology was used with a top down approach to provide a single score of environmental impact (Sangwan et al., 2014). The various damage categories selected under the mid-point assessment method were climate change(CC) (kgCO2-Eq), fossil depletion (FP) (kg oil Eq), freshwater eco-toxicity (FET) (kg1,4-DCB-Eq), freshwater eutrophication (Ep) (kg P Eq), human toxicity (HT) (kg1,4-DCB-Eq), ozone depletion (ODP) (kg CFC11 Eq), terrestrial acidification potential (TETP)(kgSO2-Eq), and water depletion (WDP) (m3). For endpoint assessment the damage categories selected were ecosystem quality, human health, and resources/fossil depletion. Some environmental impact subcategories are available to measure the harm in end-point assessment with single score. In this study freshwater eutrophication and freshwater eco-toxicity, human toxicity, and fossil depletion were analysed under the label of ecosystem quality, human health, and resources respectively.

4. Results and discussion

The Umberto results of the life cycle assessment for the various RO systems are shown below in table 2 and 3. Table 2 presents the results of RO systems of both models – 1875 m3 ultrapure water and one day consumption of ultrapure water in mid-point impact assessment scores. Whereas table 3 presents the results of RO systems in endpoint impact assessment scores for both full capacity and one day consumption of ultrapure water in endpoint impact assessment scores.

Table 2.Results of mid-point impact assessment using ReCiPe method

Midpoint impact for full capacity					
Impact categories	**25 LPH**	**50 LPH**	**250 LPH**	**500 LPH**	**Unit**
Climate change	29193.73	31241.78	41019.16	35367.67	kg eq CO2
Fossil Depletion	6242.04	7057.1	10375.31	8120.23	kg oil eq
Freshwater eco-toxicity	1091.5	1098.26	1155.99	1126.99	kg 1,4 DCB eq
Freshwater Eutrophication	18.28	18.52	22.32	20.61	kg P eq
Human Toxicity	12981.25	13303.7	15751.82	14550.16	kg 1,4 DCB eq
Ozone Depletion	0.000257	0.00031	0.000352	0.0003	kg CFC 11 eq
Terrestrial Acidification	158.2	166.33	224.44	194.43	KG SO2 eq
Water Depletion	9077.72	9081.55	9108.29	9094.84	m3
Midpoint impact for one day consumption of ultrapure water					
Climate change	1.96	4.16	29.43	47.15	kg eq CO2
Fossil Depletion	0.42	0.94	7.38	10.83	kg oil eq
Freshwater eco-toxicity	0.07	0.15	0.86	1.54	kg 1,4 DCB eq
Freshwater Eutrophication	0.00	0.00	0.02	0.03	kg P eq
Human Toxicity	0.87	1.81	11.73	19.74	kg 1,4 DCB eq
Ozone Depletion	0.00	0.00	0.00	0.00	kg CFC 11 eq
Terrestrial Acidification	0.01	0.02	0.16	0.26	KG SO2 eq
Water Depletion	0.61	1.21	7.08	12.13	m3

As shown in table 2, the value of climate change is showing an increasing trend with the increase in capacity of RO systems. In the first model (1875 m3 of ultrapure water) this trend is changed due to the 250 LPH RO systems. However, the 250 LPH RO system is following the increasing trend for second model. Thus it is found that in long term it is better to employ small capacity RO systems then the 250 LPH RO systems. Although the service life of the 250 LPH RO system is same as of the 500 LPH RO system but it generates more environmental impacts to deliver the same quantity of ultrapure water.

As shown in table 3, in the endpoint impact assessment the 250 LPH RO system is found to be the most environmental impacting RO system for first model and 500 LPH RO system is found to be most impacting RO system in second model. It is interesting to know that the number of units employed for 50 LPH RO systems are almost 3.5 times the 25 LPH RO systems, but the environmental impact of 50 LPH RO system in second model is slightly more than the 25 LPH RO system. Thus it is showing that the shear environmental impact of 50 LPH RO system is found to be least and the 250 LPH RO system is most. When the environmental impact of two RO system 50 LPH and 25 LPH are compared for second model 50 LPH is found the best RO systems in terms of ultrapure water delivery and environmental impacts.

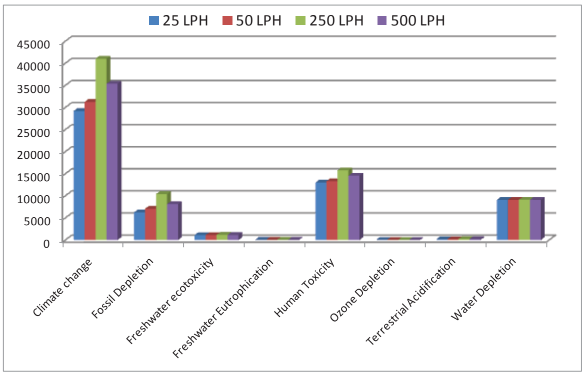

Fig. 2. Mid-point assessment of full capacity model

In the results of mid-point assessment for first model as shown in figure 2, it was found that the 250 LPH RO system was generating more environmental impact in climate change, fossil depletion, freshwater eco-toxicity, and human toxicity categories.

Table 3.Results of endpoint impact assessment using ReCiPe method

End Point Impact for full capacity					
Damage categories	25 LPH	50 LPH	250 LPH	500 LPH	Unit
EQ (freshwater eco-toxicity)	2.02	2.03	2.14	2.09	Points
EQ (freshwater eutrophication)	1.78	1.8	2.17	2	Points
HH(human toxicity)	27.33	29.56	35.05	30.06	Points
Resources (fossil depletion)	789.94	894.6	1314.54	1027.8	Points

End Point Impact for one day consumption of ultrapure water					
EQ (freshwater eco-toxicity)	0.00013	0.00027	0.001590	0.00285	Points
EQ (freshwater eutrophication)	0.00011	0.00024	0.001530	0.00267	Points
HH(human toxicity)	0.00184	0.00439	0.030000	0.04000	Points
Resources (fossil depletion)	0.05000	0.12000	0.940000	1.37000	Points

Further, the climate change category was analyses for 250 LPH RO system for first model and the results are shown in

figure 3. It was observed that the energy consumed in purification was the most contributing factor to climate change potential followed by water extraction and re-

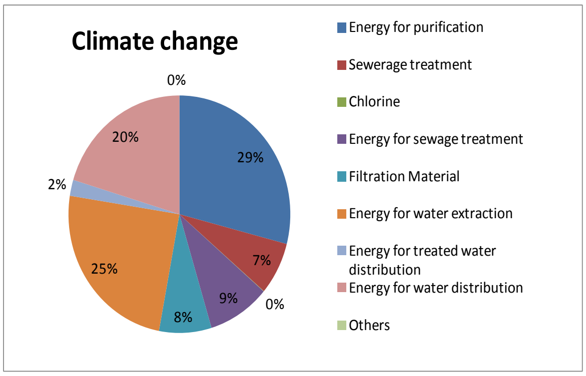

Fig. 3. Climate change potential of first model LCA

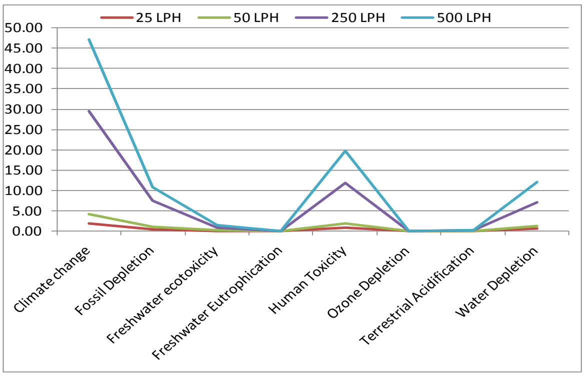

Fig. 4. Midpoint assessment of all type of RO systems

distribution. As shown in figure 3, filtration material and sewage treatment were contributing 7.63% and 7.17% respectively.

In the mid-point assessment of second model, the impact was more in climate change and human toxicity potential for all type of RO systems and an increasing trend is found to be followed by all as shown in figure 4. Also in the second model it was observed that the environmental impact generated due to one 50 LPH RO system was significantly less as compared to other four systems. This resulted in the least total environmental impact generated due to 50 LPH RO system despite of its higher number of units installed.

In all the impact assessment method energy used for extraction, purification, and re-distribution of treated water is found to be more significant than other materials and processes. It is also found that the water rejected during purification processes is also increasing the water depletion potential.

5. Conclusions

LCA is valuable tool to analyze and visualize the environmental impact in quantitative terms and also to identify the life cycle stages for these emissions. Adding life cycle assessment to the decision-making process provides an understanding of the human health and environmental impacts that traditionally is not considered when selecting a product or process. In this study the 50 LPH and 500 LPH RO system employed in the campus are found least environmental impacting with reference to their service life and quantity of ultrapure water produced.

It is concluded that the research should be directed toward increasing the efficiency of RO system and reducing the quantity of waste water during filtration process.

Combined with a little vigilance would contribute to substantially not considered when selecting a product or process. This valuable information provides a way to account for the full impacts of decisions, especially those that occur outside the scope of model and are directly influenced by the selection of a part/product or process. It should be remembered that LCA is a tool to better inform decision-makers and should be included with other decision criteria such as cost and performance to make a well-balanced decision in product design and waste management. This model can easily be extended for the industrial application by providing the appropriate inventory and process information.

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