

Technical Report of Milestone 3

Application of Capacitive Deionisation in Inland Brackish Water Desalination

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Abstract

In this work, the performance of a portable commercialized CDI unit developed by AQUA EWP, USA (supplied by LT Green Energy) has been assessed at Wilora, a remote community in Northern Territory, Australia. The tested CDI unit has demonstrated sufficient salinity and hardness removal ability at the remote brackish water source. It has been found that increased flow rate tend to decrease the overall TDS removal efficiency. However, in terms of energy efficiency, higher flow rate tend to be favourable. At the current CDI unit configuration and local water conditions, 7L/min is recommended as the optimal operational parameter with an energy consumption of around 1.89kWh/m³ treated water. The total water recovery rate is between 75% and 80%. The current portable CDI technique offers a viable alternative solution to brackish water treatment especially in remote area communities where building large treatment plant is not practical. The data and results shown in this work can be used as guidance for the onsite operation using the current technique.

Keyword desalination, CDI, commercialization, inland, brackish water

1. Introduction

In many remote areas of central Australia, total dissolved solids (TDS) level of the local brackish water is no more than 2000mg/L, which render the large scale treatment plant (i.e. RO) economically unpractical. In this work, a portable CDI unit has been tested as an alternative desalination technique at Wilora, a remote community in Northern Territory,

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Australia (see Figure 1). The overall salinity removal efficiency and energy efficiency has been assessed and reported. Some of its ions selectivity has also been studied.

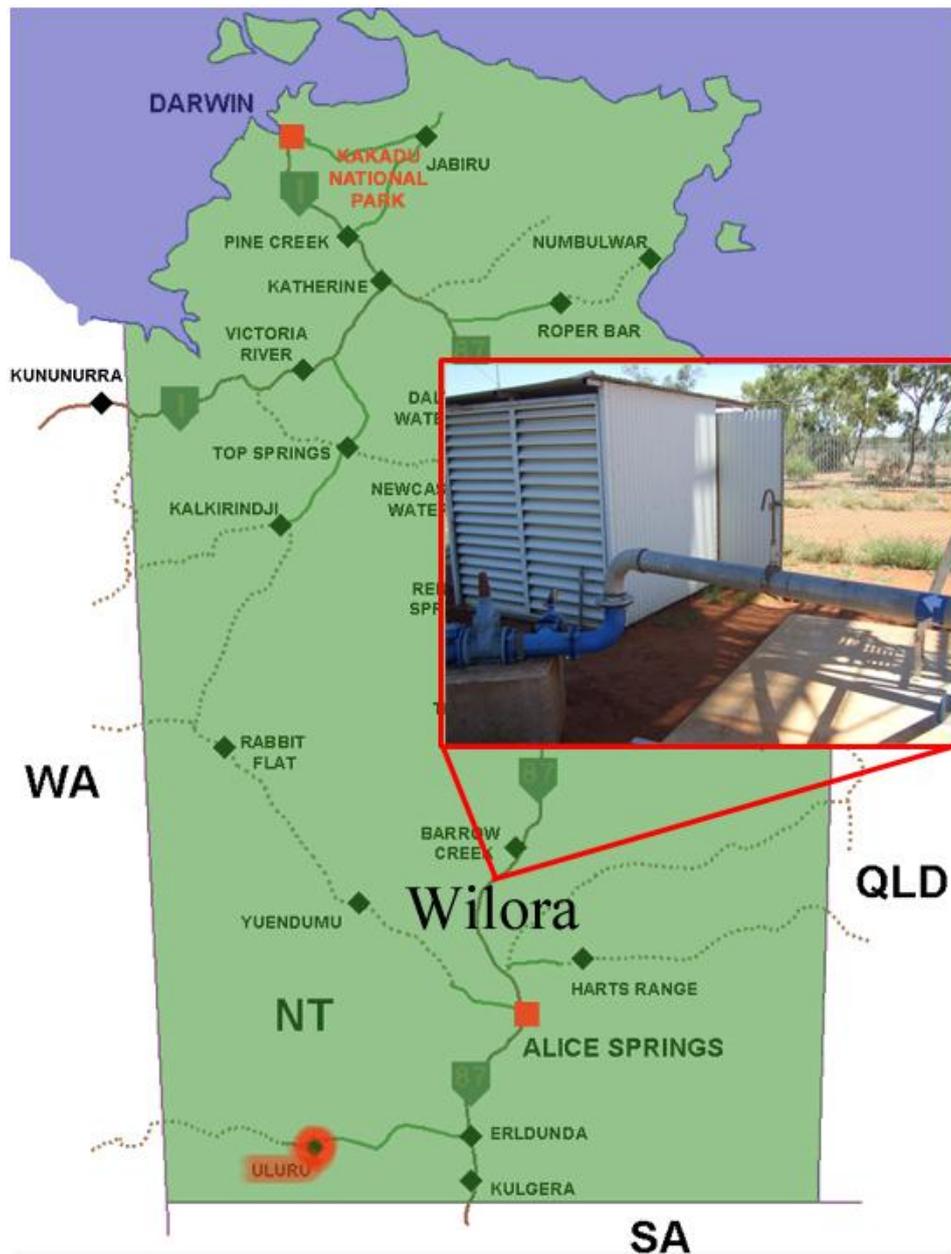


Figure 1 The location of Wilora community in Northern Territory, Australia, where the inset is a photo of local water pipeline connection.

2. Experimental

1. Description of the commercial CDI unit

The commercial CDI unit used in this work is shown in Fig. 2, which was developed by AQUA EWP, USA. Fig. 3 illustrates a schematic diagram of the working CDI unit. The

influent water is pumped from the main pipeline of Wilora water station through a sand filter for pre-treatment and passes over a flow weir to measure the influent flow into four carbon electrode cells, of which double-cells parallel groups are connected in series. The electrodes within the cell are chargeable by an applied DC potential in the range of 1 to 1.5 VDC. The whole operational cycle of CDI takes 2.5 minutes. The cycle consists of two main steps, the regeneration mode step and the purification mode step. The regeneration step commences with 30 seconds when the effluent solenoid valve (SV2) and the influent solenoid valve (SV1) are closed and the power supply is off, followed by another 30 seconds when the effluent waste solenoid valve (SV3) and the influent solenoid valve (SV1) are opened and the power is turned on with the opposite polarity of 1.5 VDC. The regeneration step finishes after 60 seconds. The purification step is started immediately following this and it takes 90 seconds to purify the feed solution. Here the influent solenoid valve (SV1) and the effluent solenoid valve (SV2) are opened. The CDI also contains a citric acid cleaning tank for the periodic cleaning of the electrodes.

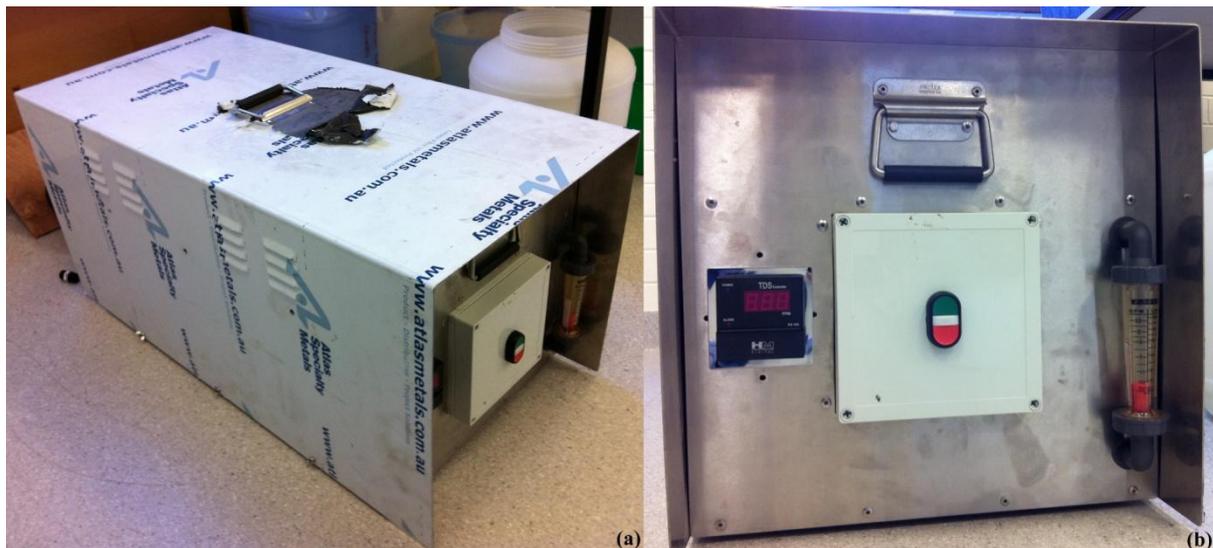


Figure 2 (a) side view and (b) front view of the commercial CDI unit developed by AQUA EWP.

Fig. 4 shows a schematic diagram of the CDI cell construction. The CDI cell mainly consists of graphite current collectors and porous activated carbon electrodes derived from coconut shell with a specific area of 800 m^2 per gram. The graphite current collectors were alternatively positively or negatively biased. Each activated carbon electrode pair was separated by a non-conductive polymeric membrane to prevent short circuiting. The activated carbon electrodes were coated with anion exchanging moulded bodies, which were manufactured from the combination of the reactive halogen containing polyether and the inert

polymer with the amine component. These electrodes are connected to the two sides of the DC power supply by using connecting leads. Each cell assembly contains 200 sheets of activated carbon (100 cathodes and 100 anodes) with dimensions of $158 \times 174 \times 0.3 \text{ mm}^3$ and a total mass of 1354 grams of activated carbon.

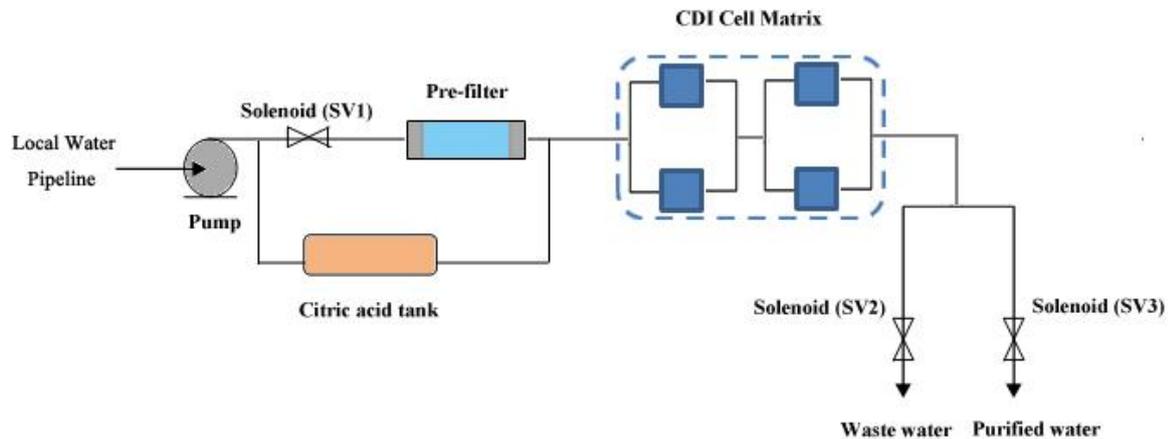


Figure 3 CDI schematic diagram.

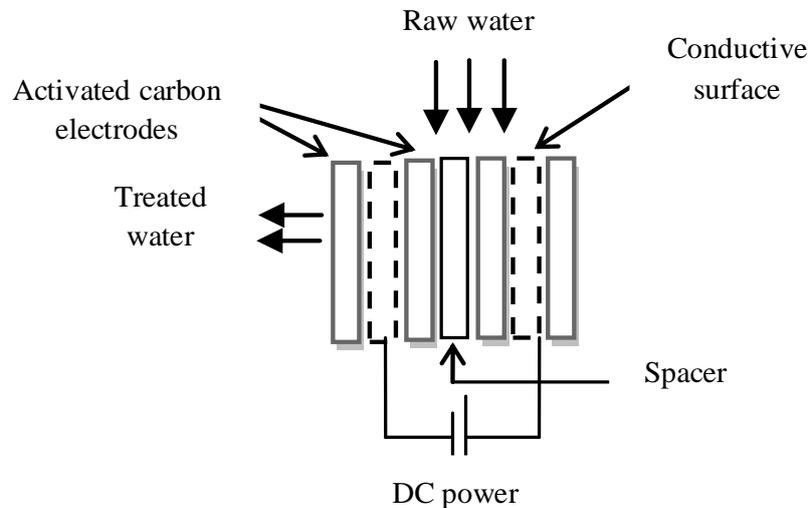


Figure 4 CDI cell construction schematic diagram

2. Process parameters investigation

TDS removal efficiency will be assessed by a conductivity monitoring meter (Hach HQ 40d) at a 10s interval continuously, which is connected to the purification stream at the outlet. The TDS removal efficiency R is defined as $(C-C_0)/C_0$, where C_0 is the initial concentration and C

is that at a given time, t . Flow rate will be varied from 1 to 9L/min at a step of 2L increment in order to observe the optimal working condition.

Ion selectivity study was carried out by investigating the removal efficiency of different metal (i.e. sodium, calcium and magnesium) and non-metal (i.e. nitrate, arsenic and fluoride) ions. For each tested flow rate, a certain amount of water sample (around 100ml) at a given time, t , will be extracted from the treated water and sent for off-site analysis. The extraction time was determined by monitoring the TDS level of treated water at its lowest point. Before the sample extraction, the CDI unit will be run for at least one hour or 24 working cycles to ensure that the content (i.e. different metal and non-metal ions) in the treated water stream is stabilized. Calcium, magnesium and sodium were measured using Inductively Coupled Plasma Optical Emission Spectroscopy (ICPOES). Arsenic ion was measured using Inductively Coupled Plasma Mass Spectroscopy (ICPMS). Nitrate and fluoride ions were measured using the flow injection analysis (APHA 4500NO₃-I) and ion selective electro analysis (APHA 4500F-C), respectively.

Energy consumption efficiency at each flow rate was assessed as kWh/m³ treated water. A portable power-meter (Power-Mate 15A) was attached to the CDI unit to monitor the energy consumption over 3 hours at each flow rate. Water collected from both waste and purification tanks will be measured for at least 10 working cycles to find out the water recovery rate of the CDI unit. The water recovery rate is defined as $V_p/(V_p+V_w)$, where V_p is the purified water volume and V_w is that of the waste water.

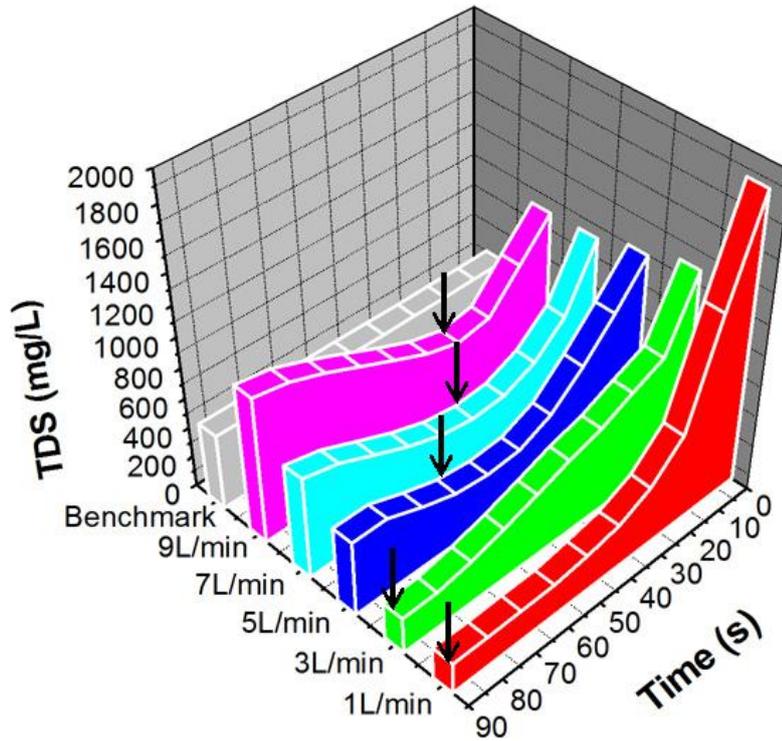
3. Results and discussion

3.1 TDS removal investigation

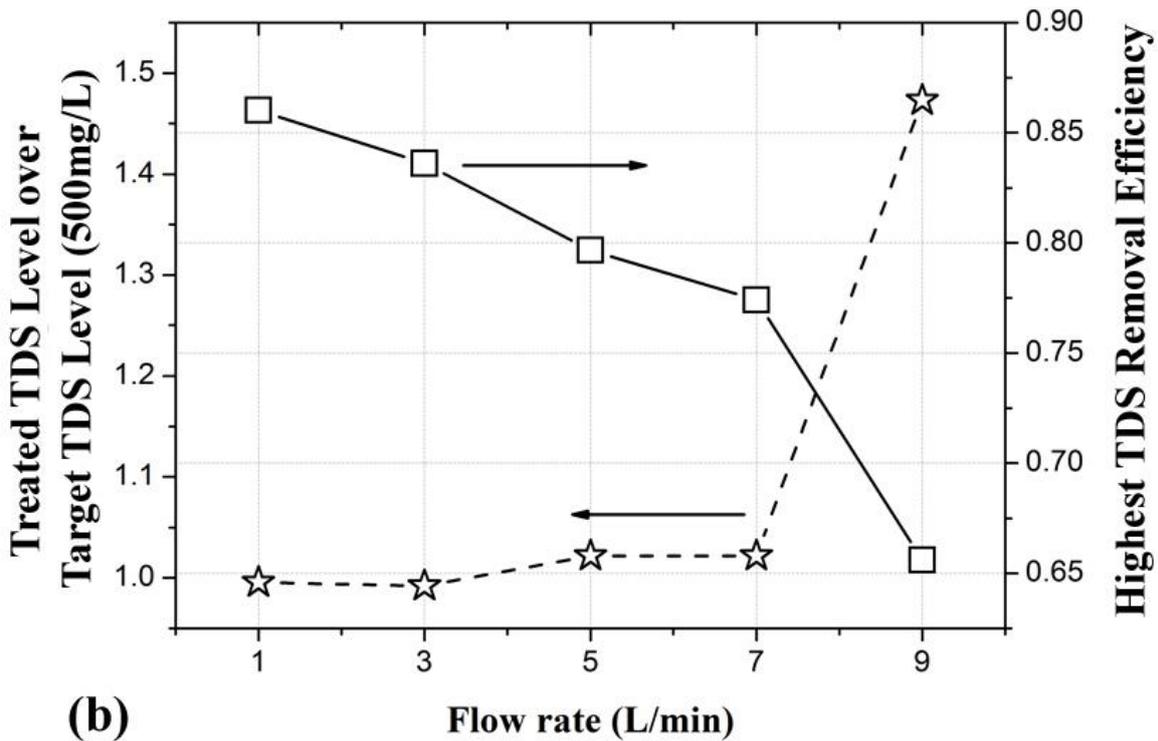
As a secondary standard, TDS level is widely benchmarked at drinking water standard of 500mg/L. The initial feed TDS in Wilora community, Northern Territory is determined by averaging ten days measurement of the feed water, which is levelled at 1500mg/L and around three times of the drinking water standard. Figure 5(a) shows a typical TDS variation level of treated water stream over the 90s unit purification cycle for each flow rate. The typical TDS curves of Figure 5(a) at each flow rate were plotted after the CDI unit was stabilized for at least one hour. The each coloured area under the line times its designated flow rate could be interpreted as the total TDS amount (mg) of the collected treated water within one 90s working cycle.

In Figure 5(b), total TDS ratio is defined as the total TDS during the 90s desalination cycle divided by that of equivalent 500mg/L benchmark level at each flow rate. The total TDS during 90s desalination cycle is calculated by integration of the total coloured area in Figure 5(a) for each flow rate, respectively. It can be seen that any flow rate lower than 7L/min in this location could maintain around the benchmark (500mg/l) level or below using the current CDI unit, whereas higher flow rate (i.e. 9L/min) can result in a TDS level exceeding the 500mg/L benchmark. This is most likely due to the fact that lower flow rate could result in longer retention time of the water stream within each CDI cell and thus better ions mass transfer to electrodes. Interestingly, the lowest flow rate (i.e. 1L/min) of the tested unit tend to make the purification cycle start at very high TDS level. At the current configuration, the flow rate of regeneration and purification stream is set as identical. As a result, the most likely reason is that extreme low flow rate could also enable a better regeneration during the regeneration cycle and thus more discharged ions are left over in the system before the next purification cycle.

The peak TDS removal efficiency during one 90s purification cycle of each flow rate is shown in Figure 5(b). Slightly different to the overall TDS level within 90s at different flow rate, the highest TDS removal efficiency seem to follow a more distinctive drop as the flow rate increases. Another interesting observation is the onset time of peak TDS removal rate (i.e. the lowest TDS points at each flow rate marked by arrows in Figure 5(a)) appears later during the 90s purification cycle as the flow rate decreases. For the flow rate set at 9L/min, the peak was obtained around 30s after the purification cycle started. As the flow rate went down to 3L/min, the peak TDS removal rate started to disappear and the decrease of the TDS followed a smooth curve, which is an apparent sign of unsaturated AC cells after a full 90s working cycle. This can be rationalized as the total salt content passing through the CDI cells per minute is higher when the flow rate is set higher, which could potentially overwhelm the capacity of the activated carbon within shorter time.



(a)



(b)

Figure 5 (a) a plot of TDS level as function of time during 90s purification cycle for each flow rate, where the arrows indicate the appearance of lowest TDS level or peak TDS removal rate; (b) highest TDS removal rate and treated TDS level over the target TDS level (500mg/L) as function of flow rate

3.2 Ions selectivity studies

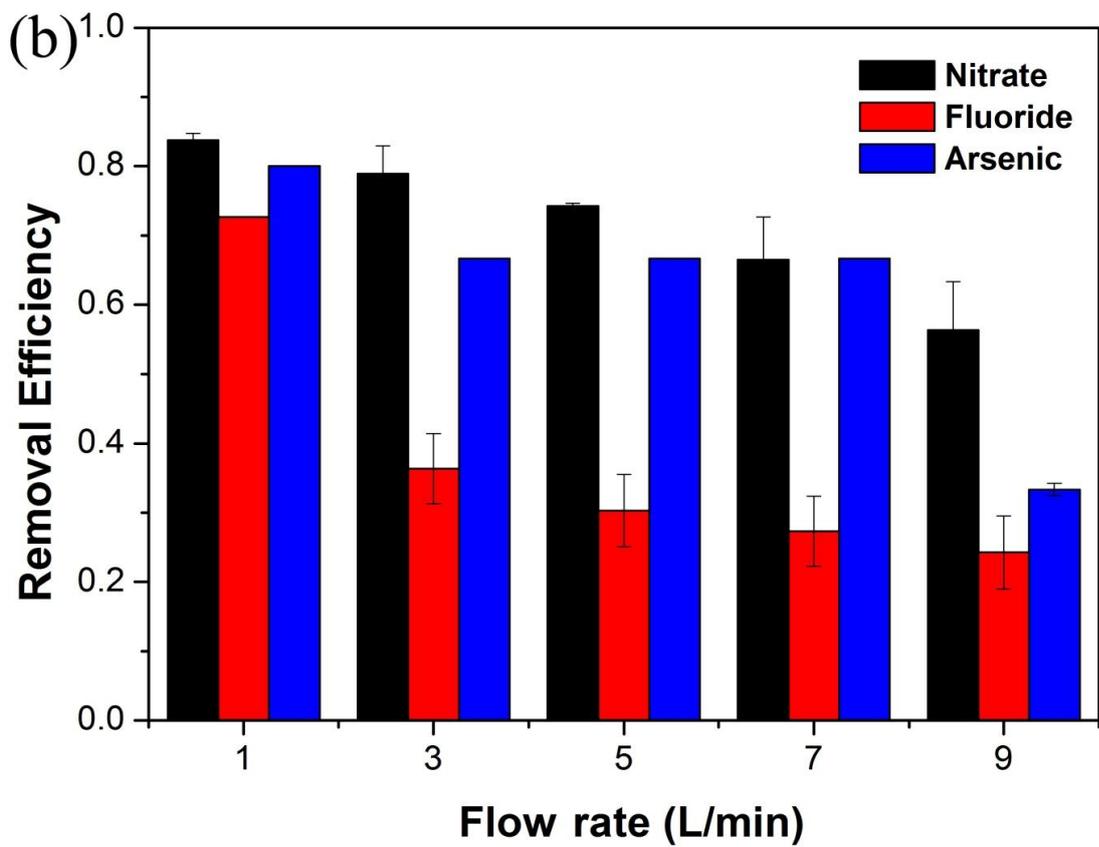
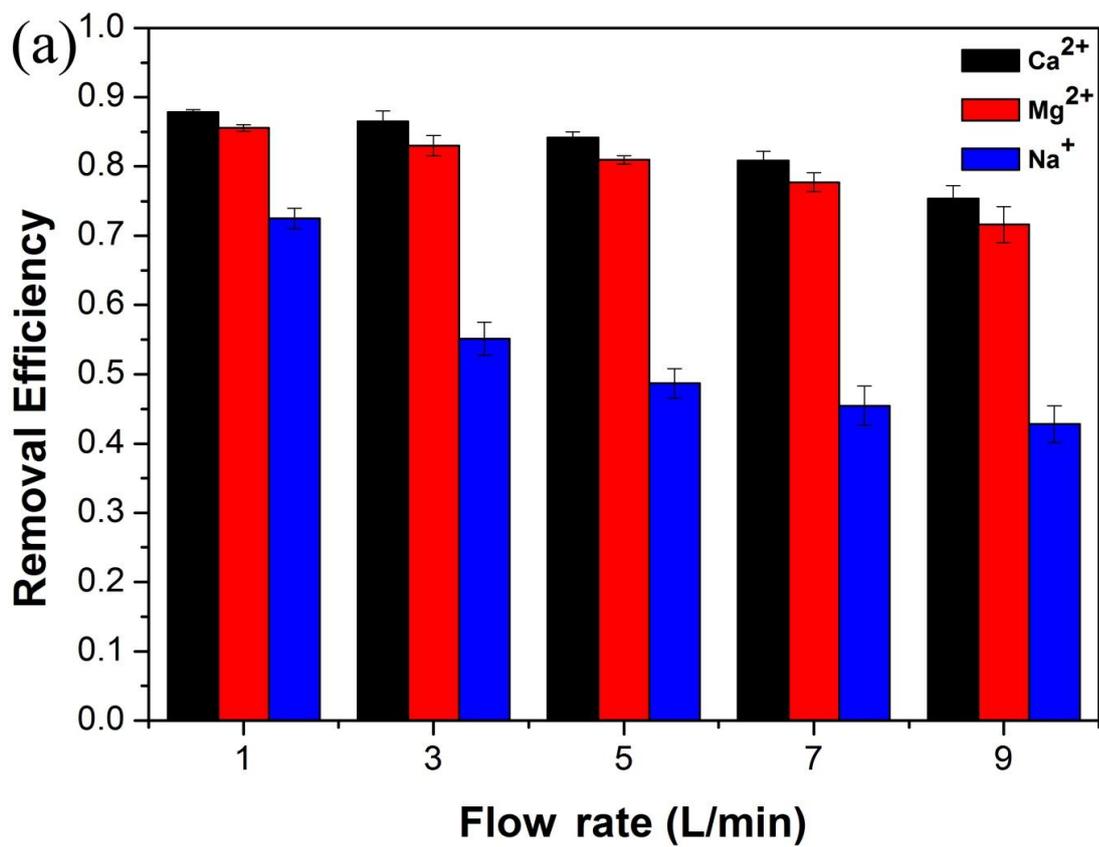


Figure 6 (a) different metal ions removal efficiency and (b) different non-metal ions removal efficiency for each flow rate. The error bars represent the 3 runs of different days under the same condition.

Table 1 Initial composition of the feed water at Wilora, Northern Territory.

	Calcium	Magnesium	Sodium	Nitrate	Fluoride	Arsenic
Feed concentration (mg/L)	106.3	96.6	341	4.06	1.1	0.0015

Different levels of inorganic ions in the drinking water could have the deepest implications in people's general health. Therefore, monitoring their presence in the drinking water is of great importance. The initial feed concentrations of different ions studied at Wilora, Northern Territory, are shown in Table 1. As seen from the Table 1, the hardness (Ca^{2+} and Mg^{2+}) of the local water source is particularly high considering World Health Organization (WHO) standards (40-80mg/L for calcium and 20-30mg/L for magnesium). For non-metal ions, nitrate, fluoride and arsenic in the local feed water are all way below the standards set by WHO (10, 1 and 0.01mg/L for nitrate, fluoride and arsenic, respectively) even without further treatment.

Removal efficiency of different ions at each flow rate is shown in Figure 6, of which each is the average of three measurements under the same conditions. As the flow rate increased, all removal efficiency of ions drop, which is consistent with their peak TDS removal efficiency. For metal ions in Figure 6(a), calcium and magnesium ion achieved the higher removal efficiency than sodium ion, which probably resulted from their higher charge. It has been reported that ions with greater charge are more easily adsorbed onto the electrode surface under the effect of electric field applied at the activated carbon electrodes. Between calcium and magnesium ions of comparable feed concentrations, higher removal efficiency of calcium is most likely due to the fact that ions with smaller hydrated radii are more easily adsorbed onto the electrodes. Previous studies reported that for ions having similar feed solution concentrations and the same charge, the hydrated radius might dictate their selectivity on carbon-aerogel electrodes [1,2,3]. Charge, mass and hydrated radius of tested ions is summarized in Table 2 [4]. The current CDI set-up has demonstrated a satisfactory overall hardness removal at Wilora community, as the calcium and magnesium level could be kept

well below the WHO standard at all flow rate. It is also noteworthy that consistent hardness removal (i.e. calcium and magnesium ions) is also beneficial to the scaling prevention of the CDI electrodes in long-term operation. For all non-metal ions in Figure 6(b), satisfactory removal efficiency has also been obtained, of which the fluoride is lowest probably due to its largest hydrated radius.

Table 2 Charge, mass and hydrated radius of the studied ions

Ion	Charge	Mass (amu)	Hydrated radius (pm)
Sodium	+1	22.99	358
Magnesium	+2	24.31	428
Calcium	+2	40.08	412
Nitrate	-1	62.01	335
Fluoride	-1	19	352

3.3 Energy consumption assessment

Figure 7(a) shows the energy consumption as the function of the feed flow rate. It can be seen that energy consumption as kWh/m³ treated water (right side of Figure 7a) drop significantly as the flow rate increases. At the 9L/min, the energy consumption can reach as low as 1.52kWh/m³ treated water, which is about half of the typical RO treatment (2.9 to 3.7 kWh/m³ treated water). Plus, the energy consumption in terms of kWh per gram of salt removed (the left side of Figure 7a) also decreases greatly by increasing the flow rate. It can be rationalized as follows: In Figure 7(b), multi-fold increases of both electrosorptive loading (mg removed salt per gram AC) and treated water volume within one working cycle are observed with the increase of flow rate. However, the absolute energy consumption of one working cycle (90 seconds) only increased slightly when flow rate changed from 1L/min to 9L/min. These together resulted in the improved energy efficiency in terms of both kWh/m³

treated water and Wh per gram salt removed. Meanwhile, as we discussed the total TDS concentration of the treated water stream within one working cycle (90s) increases as the flow rate increases. In terms of highest energy efficiency and meeting health standards (~500mg/L TDS), the optimal flow rate is found to be set at around 7L/min with energy efficiency of 1.89kWh/m³ treated water at the Wilora community. The water recovery rate at different feed flow rate was found to vary between 75% and 80%, which is comparable to other desalination technology reported.

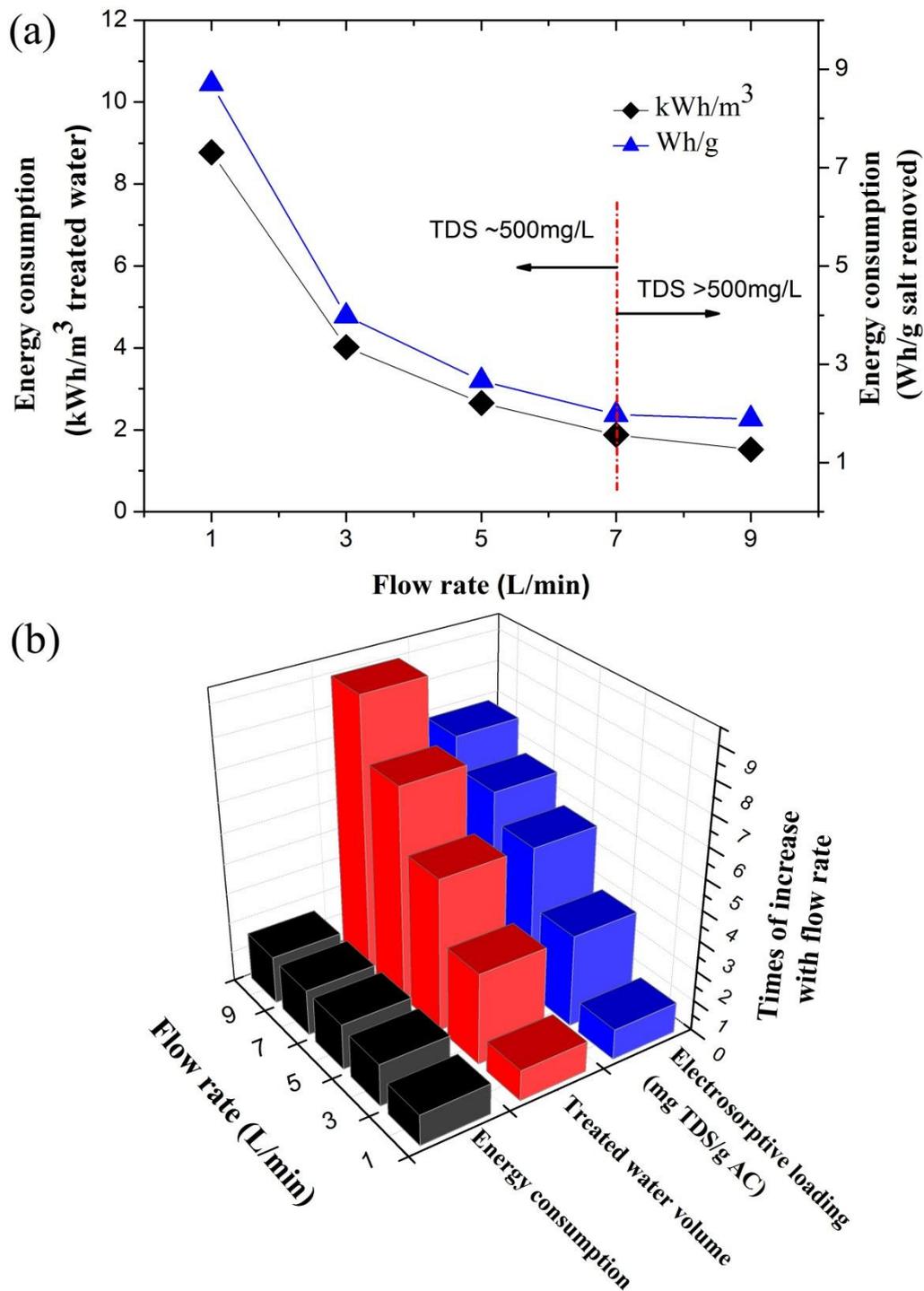


Figure 7 (a) Energy consumption (kWh/m³ treated water) and (Wh/g salt removed) as function of feed flow rate; (b) times of increase of one working cycle absolute energy consumption, treated water volume and eletrosorptive loading of each flow rate over that of starting point (i.e. 1L/min).

4. Conclusion

For the commercial CDI unit tested in this study, the performance of the salinity reduction was consistent without any electrode deterioration observed at the remote brackish water

source of Wilora, Northern Territory, Australia. Increasing the feed flow rate tend to decrease the overall TDS removal efficiency. However, in terms of energy efficiency, higher flow rate tend to be favourable. Both the TDS removal efficiency and energy need to be considered when choosing the optimum operational flow rate. At the current configuration and local water conditions, 7L/min is recommended as the optimal operational parameter with an energy consumption of around 1.89kWh/m³ treated water. In addition, the current CDI set-up has demonstrated a satisfactory overall hardness removal at Wilora community at all flow rates, which was found to be a major problem affecting the local water sources. For the non-metal ions tested, good removal efficiency has also been achieved although the initial levels of those at the local water source are readily lower than WHO standards. The current CDI technique offers a viable alternative solution to brackish water treatment especially in remote area communities where building large treatment plant is not practical. The data and results shown in this work can be used as guidance for the onsite operation using the current technique.

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