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Case study and LCA of coastal utility experiencing saltwater intrusion

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Abstract

A case study was conducted on a saltwater intrusion event that affected a coastal water utility in Florida. The conductivity of the groundwater increased from approximately 500 to 4000 µS/cm. The possible causes of the saltwater intrusion event were explored and the steps taken by the water utility to manage the saltwater intrusion were documented. To understand the environmental impact of the saltwater intrusion event on drinking water treatment, the life cycle assessment (LCA) method was used to compare the original water treatment plant with virtual treatment trains that could treat source waters ranging from freshwater to seawater. Specifically, the LCA results showed the change in environmental impacts between chemical intensive and electricity intensive processes. As such, an LCA toolbox is proposed that could be used by water utilities as part of the decision-making process when confronting major changes in water quality and treatment.

Keywords: Saltwater intrusion; Extreme event; Case study; Life cycle assessment.

1. Introduction

Changes in source water quality present a challenge for water utilities because treatment trains are typically designed for a relatively constant source water quality. Factors that can influence source water quality include changing weather patterns or physical changes to the landscape, such as floods, droughts, algal blooms, and saltwater intrusion (Villacorte et al, 2015; Hrdinka et al, 2012). These types of changes may become more common in the future under a variety of climate change forecasts and rising sea-levels (Berry et al, 2011; Delpla et al, 2011). Changes in source water quality cause water utilities to alter their operations in one of two ways: (1) Proactive water treatment changes and preparation in anticipation of future water quality issues, or (2) reactive water treatment changes in response to water quality changes in real-time.

In both situations, knowledge from other water utilities that have dealt with similar problems in the past could assist water utilities during the decision making process. Hence, among the approaches available to assist water utilities in planning, this work used the case study approach and life cycle assessment (LCA) methodology because they provide a systematic way of documenting the decision-making process and quantifying the environmental impacts due to changes in source water quality.

In low gradient coastal habitats, such as the Gulf of Mexico and eastern and southeastern Atlantic coasts of the U.S., many coastal residential, agricultural, utility, and industrial water users are dependent on groundwater to meet potable and operational water needs. For these water users, there is significant concern related to saltwater intrusion into coastal freshwater aquifers and how saltwater intrusion may impact freshwater availability (Barlow & Reichard, 2010) . In areas where groundwater dependence is high, depleted groundwater levels leading to lowered water tables can increase the likelihood of saltwater intrusion (Werner et al, 2013; Ferguson & Gleeson, 2012; Renken et al, 2005) . In many cases, as coastal regions become more developed, water demand increases from water users. At the same time, changing climatic conditions either have, or are forecast to alter precipitation patterns, potentially increasing drought severity and frequency (Berry et al, 2011; Seager et al, 2009). In addition, changing climatic conditions and sea-level rise have the potential to increase saltwater intrusion into fresh groundwater and surface water supplies (Roehl et al, 2013; Langevin & Zygnerski, 2013; Houston, 2013) . Hence, a complex combination of natural and human activities are creating more challenging environments for coastal water managers (Moser et al, 2012).

Florida, which is second only to Alaska in total coastline length, is highly susceptible to impacts from sea-level rise, including increased risk of saltwater intrusion into coastal aquifers, as the majority of the land area, and human population, is found in the low gradient peninsula region bordered by the Atlantic Ocean and Gulf of Mexico (Noss, 2011; Donoghue, 2011) . Florida is also highly groundwater dependent with more than 98% of its municipal and agricultural water systems using groundwater sources to meet the needs of nearly 20 million citizens and large agricultural operations (US EPA, 2013) . This reliance on groundwater can reduce aquifer levels increasing risk of saltwater intrusion from sea-level rise (Langevin & Zygnerski, 2013; Ferguson & Gleeson, 2012; Berry et al, 2011; Barlow & Reichard, 2010) . The treatment challenges presented by rising sea-levels and the widespread dependence on coastal aquifers by coastal communities for water supply necessitates the development of action plans for existing water plants to plan for the potential impacts of saltwater intrusion on coastal aquifers used for municipal water supply. Overall, saltwater intrusion presents new challenges for the development of informed water treatment operations.

This work used a case history of a recent saltwater intrusion event in a small coastal community (Cedar Key, FL, USA) in combination with LCA methodology to examine the challenges, options, decisions, and environmental impacts during this extreme event. By definition, an extreme event (Solomon et al, 2007) is one where the potential costs to the public are high in terms of human health, safety, and local economic impacts, but the occurrence of the event is rare. The frequency, intensity, and persistence of an event are important characteristics when defining hazards due to an event, as well as the temporal and spatial variability unique to each event (Goodess, 2013). The case study described herein is presented as guidance for other water utilities in similar situations, as properties of an extreme event were present: (1) rarity of event, (2) uncertainty, (3) high and broad consequences, (4) complexity, (5) limited time for decision-making, and (6) encompassing multiple decision makers (Mendonça, 2007).

Accordingly, the objectives of this work were to (1) study the steps taken by the Cedar Key, FL water utility in response to saltwater intrusion to their fresh groundwater supply; (2) conduct an LCA on the water treatment plant before and after the saltwater intrusion event considering real and virtual treatment trains; and (3) discuss the use of LCA as a tool to evaluate and inform the environmental impacts of decision making, especially related to extreme events.

2. Case study on saltwater intrusion at Cedar Key, FL

Cedar Key is a rural town located on a group of small islands (collectively known as the Cedar Keys) in Levy County on the west coast of Florida (29 08 44N and 83 02 30W). Cedar Key has a population of 702 people (US Census Bureau, 2010) and a land area of 5.5 km^2. Cedar Key's economy is based primarily on clam farming and tourism. The Cedar Key Water and Sewer District (CKWSD) provides drinking water and wastewater services for the community. Fig. 1 gives a timeline of significant events at Cedar Key that factored into this case study as described in the following paragraphs.

Fresh groundwater has historically provided drinking water for this small community. According to the U.S. Environmental Protection Agency (EPA), a small water system is one that provides water for a population between 501–3,300 people (US EPA, 2013). Two wells located approximately 8 km inland in a shallow and unconfined area of the Floridan Aquifer pump raw water to the 0.25 MGD (approximately 950 m^3/d) capacity treatment plant. Well 3 was constructed in 1974 to a total depth of 110 ft (34 m) and Well 4 was constructed in 1992 to a total depth of 180 ft (55 m). The groundwater is characterized by high DOC concentration (5.6–7.7 mg/L), high hardness (275–440 mg/L $CaCO_3$), and moderate conductivity (see Table 1). Before 2006, the Cedar Key water treatment plant practiced lime softening and free chlorine addition. The water treatment plant was upgraded in 2006 to more effectively remove DOC due to high levels of trihalomethanes (300–450 µg/L) and haloacetic acids (150–300 µg/L) in the finished drinking water that were above the U.S. EPA maximum contaminant levels (MCLs) (Hotaling et al, 2006). The treatment train as of May 2012, in sequential order, was sodium permanganate addition at the well to oxidize iron, magnetic ion exchange (MIEX) treatment for DOC removal, lime softening for hardness removal, chlorination for disinfection, and sand filters before distribution (see Fig. 2). The CKWSD maintains and operates the water treatment plant, and a citizen-elected water board advises on administrative and financial matters related to water and wastewater services.

Prior to May 28, 2012, daily conductivity in the groundwater was between 500–600 µS/cm, which was representative of conductivity levels in the groundwater since at least 2008 (see Fig. 3). On May 28, 2012, the conductivity of the groundwater entering the plant was 1108 µS/cm, more than double the measured conductivity on the previous day. Plant operators monitored the situation during the following days and observed a steady increase in conductivity. By June 8, 2012, the conductivity of the groundwater had risen to 1718 µS/cm. Because the finished drinking water was not in compliance with the Florida Department of Environmental Protection (FDEP) MCL for sodium (160 mg/L), the CKWSD was required to place a “Do not drink the water” ban on June 19, 2012 (see Fig. 1). Residents and visitors were advised to collect imported freshwater from tanks placed around the island or make use of donated bottled water. Negative publicity in the media associated with the ban on drinking water immediately caused reductions in tourism to Cedar Key (Gainesville Sun Staff, 2012; Smith, 2012). Additionally, commercial aquaculture wholesalers are required to wash shellfish products with water from an approved potable source prior to releasing the products to the retail markets (Department of Agriculture and Consumer Services, 2002). Because the municipal water supply was not approved for use, the aquaculture industry was unable to sell shellfish products. After approximately one week, a variance to the administrative code was granted to allow shellfish products to be sold even as sodium levels were still above FDEP drinking water standards. However, the negative press associated with the saltwater intrusion event impacted the tourism and aquaculture industry causing economic harm to the town.

From May 28 to June 27, 2012, the conductivity of the groundwater entering the plant increased daily and the continued ban on municipal drinking water increasingly made life difficult for residents, business operators, tourists, and local elected officials. As a result, staff of the CKWSD and the citizen-elected water board began exploring treatment or alternative water supply options for addressing the high conductivity in the groundwater wells. From a treatment perspective, the existing unit processes at the water treatment plant were not equipped to desalinate the incoming groundwater and decrease the level of sodium to comply with the FDEP MCL. This led to an assessment of transporting water from the nearest water utility located approximately 35 km away in Chiefland, FL. This option was not considered feasible given the time required to build the pipeline and its cost. With no other apparent options, the CKWSD and water board began to explore the potential for retrofitting the current treatment plant with a reverse osmosis (RO) system designed to desalinate brackish groundwater. Renting an RO unit was originally discussed but the recurring costs deterred the water board from renting and they instead decided to purchase the RO unit. In an effort to keep rates for residents stable, a combination of state and federal grants were used to cover some of the capital cost but rates were ultimately increased due to the RO system’s operational cost. A request for proposals was issued on June 28, 2012 for the purchase and installation of two RO units (a primary and backup), each with the same capacity and specifications. Although the CKWSD was aware of the installation and operating costs associated with adding RO to their existing water treatment plant, no other options were readily apparent to meet immediate and expected future water supply needs.

The nearest groundwater monitoring well (maintained by the Suwannee River Water Management District) is located approximately 6 km northeast of the CKWSD groundwater wells near Rosewood, FL. Groundwater levels for this well are available from December 1981 through present (Fig. 4). Based on observed groundwater levels, the time period from May through August 2012 was a period that included both the lowest observed groundwater levels during the period of record (late May through mid-June 2012) and the largest increase in groundwater levels over a several week period during summer and fall 2012. The steadily decreasing groundwater levels occurred at the same time drought conditions were observed across much of north Florida during late 2011 through mid-June 2012 (Leftwich et al, 2011) and the minimum groundwater levels occurred during the same time period as the saltwater intrusion (see Figs. 3 and 4). Given the limited data available, it suggests the likelihood that these low groundwater levels were a contributing reason for the saltwater intrusion event to occur.

The large increase in groundwater levels during late June to early September 2012 occurred after a second extreme event. While the upgrade to the Cedar Key water treatment plant was in progress, on June 26, 2012, Tropical Storm Debby made landfall on the west coast of Florida approximately 50 km north of Cedar Key. As a slow moving storm, rain from Tropical Storm Debby inundated the Florida coast for several days. Rainfall across the region, including the assumed recharge area for the CKWSD groundwater wells, was reported in excess of 50 cm with amounts up to 73 cm (Kimberlain, 2013). Following this rain event, the Suwannee River crested at its highest level observed in over 40 years and groundwater levels within the region began to rise (see Fig. 4). A groundwater model of this particular area of the Floridan aquifer would have shown the water managers at Cedar Key that Tropical Storm Debby brought sufficient rainfall to recharge the aquifer but without an existing model, the Rosewood well data was the only data available.

The effects of Tropical Storm Debby were also seen in the conductivity measurements in the subsequent months. The conductivity of the groundwater on August 1, 2012 was 891 µS/cm. The average conductivity for the months of August and September 2012 were 751 and 595 µS/cm, respectively, reflecting significant declines from the higher levels observed in June when the saltwater intrusion event occurred, and returning to the background conductivity level observed before the saltwater intrusion event. This suggests that the increase in groundwater levels and associated reductions in conductivity likely negated the necessity for the RO system. But it is important to recognize that this conclusion is only possible in hindsight following the saltwater intrusion and the tropical storm and would have been very difficult to predict.

Staff from the CKWSD initiated the upgrade to the water plant during July 2012 to accommodate the equipment necessary to operate the RO units. Fifty percent of the filter effluent was diverted into two holding tanks before being pumped to the RO units. Prior to the RO process, the filter effluent was dechlorinated using sodium bisulfite in the holding tanks. The RO permeate was mixed with the remaining filter effluent in the clear well. The total chlorine in the blended water was sufficient to maintain a chlorine residual in the distribution system. The RO units were brought online on August 1, 2012, coinciding with the day that the “Do not drink” ban was lifted.

Starting in May 2012 and ending in August 2012, the CKWSD had dealt with two very different extreme events. It began with saltwater intrusion to the fresh groundwater supply that coincided with the lowest groundwater levels observed during the period of record. This was followed by the landfall of Tropical Storm Debby and associated large rainfall leading to aquifer recharge. The aquifer recharge also increased the DOC in the groundwater (see Table 1), which led to new challenges to effectively remove DOC and treat the water. Overall, the sequential extreme events of saltwater intrusion and tropical storm created a complex problem that in hindsight required a systems-thinking approach and toolbox of options to solve.

3. Scenario planning in response to saltwater intrusion event

Prior to deciding upon the installation of the RO units, the CKWSD and water board were faced with several challenges as they navigated the decision-making process regarding their saltwater intrusion situation. First, available data suggested that the conductivity levels were increasing in the groundwater supply wells, and it was likely that when the conductivity levels stabilized the groundwater would be significantly more saline than the existing water treatment plant was designed for. Second, transport of water from an alternative location or existing municipality was not economically feasible. Third, after two weeks without municipal water, quality-of-life for citizens and lost revenues for businesses was causing significant local stress, and calls for a quick solution were increasing. At this time, there were three possible scenarios that the CKWSD could possibly encounter pertaining to conductivity levels in the groundwater supply wells (see Fig. 5). Scenario 1 was the possibility that the conductivity in the groundwater would reach approximately 50,000 μS/cm, the conductivity of seawater (Edzwald & Tobiason, 2010) . This scenario would have been the most extreme possibility with respect to saltwater intrusion and would reflect a conversion of the water supply wells from freshwater to saltwater. Scenario 2 was the possibility that the conductivity in the groundwater would increase to approximately 7000 μS/cm, the conductivity of estuarine and brackish water (Edzwald & Tobiason, 2010) . This scenario seemed plausible given the trends in conductivity and experiences from around the state. Scenario 3 was the possibility that the conductivity in the groundwater would decrease to approximately 300–500 μS/cm, the conductivity of fresh, hard water, similar to the levels observed prior to the saltwater intrusion event (Edzwald & Tobiason, 2010) . While Scenario 3 was ideal for the design of the current water treatment plant, it was not considered to be likely given the increasing trend in conductivity.

Following from the conductivity scenarios, three virtual treatment trains were developed in place of the MIEX and lime softening processes seen in the dashed box in Fig. 2a in order to remove the DOC and hardness, and reduce the conductivity. Virtual treatment train 1 (associated with conductivity scenario 1) would use ferric chloride for flocculation and RO for desalination (see Fig. 2b). Virtual treatment train 2 (associated with conductivity scenario 2) would use nanofiltration (NF) to remove the high hardness and high DOC as a pretreatment for desalination with RO (see Fig. 2c). Results from pilot studies on membranes as a pretreatment for RO, such as NF, show that membranes are successful at removing colloids and suspended particles that conventional pretreatments fail to remove(Greenlee et al, 2009). Virtual treatment train 3 (associated with conductivity scenario 3) was developed in order to simplify the complex treatment used at the Cedar Key water treatment plant by using a single process, NF, to remove DOC and hardness (see Fig. 2d). Other treatment trains are possible, the virtual treatment trains described herein were selected to illustrate the connections among the saltwater intrusion event, conductivity scenarios derived from the saltwater intrusion event, and life cycle environmental impacts of different water treatment technology.

4. LCA before and after saltwater intrusion

4.1. Background

Life cycle assessment is used to study a product's impacts on its surroundings throughout its manufacturing, use, and disposal (Rebitzer et al, 2004). LCA is a useful tool when a manufacturer or operator wants to reduce the overall environmental impacts of the product or process, and wants to highlight the different tradeoffs associated with choices made in manufacturing and operations. This same framework can be applied to decisions on the design of water treatment plants, and this approach has been used for the comparison of chemical intensive processes, such as coagulation, and electricity intensive processes, such as NF and RO (Zhou et al, 2011; Barrios et al, 2008; Vince et al, 2008; Sombekke et al, 1997).

The LCA approach was used to evaluate water treatment options at Cedar Key and the effects of variable source water quality on drinking water treatment. For instance, MIEX has been extensively studied for removal of DOC and inorganic contaminants (Graf et al, 2014; Tang et al, 2013; Ding et al, 2012; Drikas et al, 2011). However, only a few studies have been published that apply LCA to ion exchange treatment (Maul et al, 2014). In addition, there is no previous LCA on the effects of extreme events on water treatment processes, such as occurred at Cedar Key. Thus, the LCA results are expected to aid water utilities and planners that face the complex challenges of variable source water quality in the future.

4.2. Methodology

4.2.1. Goal and scope definition

Three virtual treatment trains, based on the three conductivity scenarios, were compared with the original Cedar Key water treatment plant (see Fig. 2). The functional unit was 1 m^3 of potable water produced and it was assumed that the finished water quality met drinking water standards. The system boundary included the manufacture of chemicals used in treatment, the transport of the chemicals from its most recent location before reaching Cedar Key, and the electricity used by water treatment and pumping. The system boundary did not include the disposal of waste, such as the MIEX waste brine or the RO concentrate. Before saltwater intrusion, ion exchange brine and lime sludge were diverted to a lagoon adjacent to the water treatment plant. This disposal option was assumed to continue with the virtual treatment trains and the assumption is discussed later. The LCAs were conducted on the operational phase of treatment, as it has been shown that the operational phase, relative to the construction and decommissioning phases, contributes to the highest impact in the lifespan of water treatment plants (Bonton et al, 2012).

4.2.2. Inventory analysis

The LCAs were conducted using SimaPro version 8.0.2 (PRé Consultants). SimaPro is a modeling software that calculates impact due to a product or process by using databases of unit processes and impact assessments amassed using various methodologies (Herrmann & Moltesen, 2015) . The inventory analysis for the original water treatment plant, before saltwater intrusion, and the virtual treatment trains is given in Tables 2–5. Inventory values are representative for the amount needed to treat 1 m^3 of water. The tables also include the method that was used to calculate the input value. The Ecoinvent v2 database was primarily used with some inventory items found in the LCA Food and US LCI databases. Ecoinvent consists mostly of inventory items developed in the European context; inventory items developed in the US context were selected when available. Tables 2–5 contain information as to how the inventory items are named and the database they belong to. The transport value for all the chemicals was summed and input as the total transport value because all chemical transport used the same method of transportation.

4.2.3. LCA for original water treatment plant before saltwater intrusion

The operational inventory for the original water treatment plant before the saltwater intrusion event is given in Table 2. The chemical and electricity usage was calculated using data from the plant. Total electricity consumption was estimated to be 0.59 kWh/m^3 of potable water produced based on 1 y of electricity usage at the plant. This includes the electricity used to pump water at the well, run processes at the plant (including electricity needed to run operations in the administrative office), and operate the high service pumps for distribution. Chemicals included $NaMnO_4$, MIEX anion exchange resin, NaCl, lime as CaO, and NaOCl.

Each chemical input was calculated based on additions or calculations from daily use. For example, sodium permanganate is added at a rate of 2.5 cm (1 in) per day from an approximately 210 L drum. Detailed record keeping of the MIEX process allowed for an accurate calculation of the inputs in the inventory for the process. Each addition of virgin MIEX resin and the number of 23 kg bags of NaCl are kept in a spreadsheet dedicated to the MIEX treatment process.

Transport was calculated using the estimated distances of travel from the previous location before reaching Cedar Key. For example, the virgin MIEX resin came from a storage facility in Savannah, GA. MIEX resin is manufactured elsewhere and the distance traveled from that location to Savannah, GA was not accounted for because it would widen the scope of the study. Each chemical input mass value was multiplied by the distance traveled, creating a value with a unit of kg·km. The transport terms, i.e., inventory values with units of kg·km, thus account for both the mass and distance involved in transporting materials required for water treatment, as both of these terms contribute to the environmental impact of transportation.

4.2.4. LCA for virtual treatment trains

The three virtual treatment trains were created using a combination of inventory data collected from previously published studies, i.e., LCA on RO and NF using the same functional unit of 1 m^3 water produced. The RO inventory data were from a study that compared RO with Memstill process (Tarnacki et al, 2012; Fritzmann et al, 2007). The inventory data used in that LCA included the process of pumping and treating saltwater with RO. A previous LCA comparing water treatment plants was used for the inventory data for NF (Bonton et al, 2012). This LCA used inventory data specific to the NF system, therefore the operational data from the NF system was used as is but the electricity term only included the electricity used by NF. The electricity term was added to the electricity term for the wells at Cedar Key in order to include the energy needed for the entire treatment train. Electricity was easily differentiated because Cedar Key receives two separate electricity bills, one for the wells and one for the water treatment plant. Chemical transport was calculated using the same distances from the distributors used by Cedar Key before the saltwater intrusion event.

Inventory data for the virtual treatment trains is given in Tables 3–5. The method column shows the source that was used to find the inputs. In some instances, the addition of values found in published literature and field data was necessary.

4.2.5. Life cycle impact assessment

The life cycle impact assessment was calculated using TRACI 2.1 (Bare, 2011), which was developed by the U.S. EPA. The results are given as ten impact categories: ozone depletion, global warming, smog, acidification, eutrophication, carcinogens, non-carcinogens, respiratory effects, ecotoxicity, and fossil fuel depletion. Each chemical input, the total transport summation, and electricity usage has its own value of impact for each category.

4.3. Results and Discussion

4.3.1. Original water treatment plant before saltwater intrusion

Fig. 6 shows the environmental impact due to each process in the original water treatment plant across ten impact categories as calculated by TRACI 2.1. The impact is scaled to 100% of the total impact in that category and each contributing process has its own percentage within the 100%. The results of the life cycle impact assessment show that electricity is the dominant contributor to nine out of ten impact categories (Fig. 6). On average, 34% of the total impact of the water treatment plant across all impact categories was due to the environmental impacts from the production of chemicals at the plant. In the ozone depletion impact category, chemical usage was dominated by the production of the MIEX anion exchange resin, which had the highest impact at 88% of the total impact. Ozone depletion is attributed to the use of dichloromethane as a solvent after the resins have undergone functionalization with chloromethyl methyl ether and trimethylamine. Overall, impacts due to electricity usage are on average 2.5 times higher than impacts due to chemical usage and transport combined. The impact due to transport is a function of the mass of chemical used and the distance traveled. For Cedar Key, the distances traveled were no farther than 482 km (300 miles) per chemical, which resulted in an average impact of 6% due to transport in all impact categories.

Recommendations to reduce the life cycle environmental impacts can be formulated from the results of the impact assessment, which in turn can be used by the water plant to change existing infrastructure or operating conditions. Overall, reducing the environmental impact of water treatment can be done in two manners: by reducing water demand or by using environmentally conscious treatment processes (Uche et al, 2015). Reducing chemical usage or using alternative chemicals is an area that can be further explored in order to reduce the impacts of a treatment process. For example, lime softening has an impact of 13% or more in four of the nine categories, with its highest impact (23%) seen in the respiratory effects category. An alternative process to remove hardness could be considered in order to reduce the impacts made solely by the lime softening process, such as cation exchange (Comstock & Boyer, 2014) , which does not have the same high impact to ozone depletion as anion exchange resin. The example of reducing the environmental impacts of lime softening illustrates the strength of the LCA methodology whereby the linkages and trade-offs in environmental impacts of alternative processes can be systematically evaluated.

The LCA results on the processes at the original Cedar Key water treatment plant before saltwater intrusion can be compared with results of other published LCAs on water treatment. Electricity use is typically the largest contributor to the overall environmental impact in other water treatment LCAs, regardless of the unit processes used in the treatment train (Lemos et al, 2013; Godskesen et al, 2012; Bonton et al, 2012; Vince et al, 2008; Mohapatra et al, 2002). It has also been shown that chemicals used in the lime softening process, such as lime, soda ash, and CO_2, contribute to 50% of environmental impacts due to water treatment (Vince et al, 2008).

4.3.2. Water treatment considering virtual treatment trains

The major trends in the results of the life cycle impact assessment comparing water treatment before saltwater intrusion with the virtual treatment trains are given in Fig. 7. The results of each LCA are presented showing the three major contributors: chemical inputs, transport, and electricity. Four impact categories are shown in order to describe the impact to categories that affect both global and local systems. Three trends are seen with regards to the original water treatment plant before saltwater intrusion and virtual treatment train 3, which are both treating the same quality groundwater: (1) in the ozone depletion impact category, the before saltwater intrusion LCA has the highest impact overall; (2) in the global warming impact category, the before saltwater intrusion LCA has a slightly higher impact than virtual treatment train 3; and (3) in the carcinogens and eutrophication impact categories, the before saltwater intrusion LCA and virtual treatment train 3 have approximately equal impact. The remaining six categories exhibited the same trend as the global warming potential impact category. Smog, acidification, non-carcinogens, respiratory effects, ecotoxicity, and fossil fuel depletion had the following trend of increasing environmental impact: virtual treatment train 3 < before saltwater intrusion < virtual treatment train 1 < virtual treatment 2 (results not shown). Overall, electricity had the largest impact in all ten impact categories except for ozone depletion. The LCA before saltwater intrusion still had the highest impact in the ozone depletion category due to the anion exchange resin. When comparing the different virtual treatment trains, it can be seen that virtual treatment train 2 (NF followed by RO) had the highest impact in nine out of the ten impact categories. This is because virtual treatment train 2 is the combination of two processes with high electricity usage, however the results for this treatment train are highly dependent on the electricity values that were referenced from similar treatment systems. Virtual treatment train 1 (RO only) had the second highest impact in nine of the ten impact categories. This was due to the amount of electricity that the RO system uses. Virtual treatment train 3 had the least environmental impact when compared with the three possible virtual treatment trains that have been developed because of its simplified water treatment scheme. When comparing the LCA before saltwater intrusion to virtual treatment train 3, it is evident that the impact in each category is dependent on the amount of chemicals used. For example, in the global warming potential category, the treatment before saltwater intrusion has an impact 32% higher than virtual treatment train 3 because of the high impact due to chemical usage.

The results in Fig. 7 suggest that reducing electricity usage and using alternative chemicals are the two most effective methods for reducing the life cycle environmental impacts of water treatment. As a result, previously published LCAs on water treatment have studied alternative treatment trains based on different electricity sources, such as solar, wind, hydroelectric, nuclear, and coal power to evaluate the effect of electricity source on life cycle environmental impacts (Bonton et al, 2012; Tarnacki et al, 2012; Barrios et al, 2008; Sombekke et al, 1997). Cedar Key, like other rural water utilities, does not have the availability of alternative energy sources and therefore finding another way to reduce the environmental impacts is necessary. Chemical inputs attributed, on average, to less than 10% of the total impact towards each category in all three possible virtual treatment trains. Using alternative chemicals could be explored, but it would not reduce the overall impact as much as using alternative energy sources would.

The results of this approach to LCA have some limitations. It was assumed that the data used in the virtual treatment trains was created to treat water similar to that used at Cedar Key. The MIEX resin that is used at Cedar Key was not available in the database used to create the LCAs. The data used was for an undefined type 1 polystyrene anion exchange resin, whereas MIEX is a type 1 polyacrylic resin, but the chemical of concern used in processing is related to adding the strong-base functional group, which both the MIEX resin and the resin in the database have. Also, the LCA comparisons only accounted for operational inputs and did not account for disposal or treatment of waste streams. The inclusion of such data could have increased the overall impact of the virtual treatment trains by increasing chemicals, electricity, and in some cases, transport. For example, the disposal of brine to the ocean contributed 3% of the impact in all impact categories in an LCA conducted on a similar RO system (Shahabi et al, 2015). Yet, it could be conceivable that the impact would be greater if a different method of brine disposal was used in the calculation of environmental impact. This is still an area of active research and very little quantitative values are available on the specific environmental impacts of membrane concentrate disposal.

4.3.3. Sensitivity analysis of LCA outputs

A sensitivity analysis was conducted in order to better understand the major drivers behind each impact category. The results of the sensitivity analysis are listed in Table 6. Chemical, transport, and electricity inputs were increased or decreased by 25% to understand which category of inputs affected the overall impact towards each impact category the most. It was expected that the change in electricity would produce the largest change in overall impact. An increase or decrease of 25% in the electricity inputs had an average of 21% change in each impact category for all virtual treatment trains. Changes in chemical inputs affected the magnitude of impact the greatest in the original water treatment plant before saltwater intrusion because this treatment called for the highest amount of chemicals. The virtual treatment trains developed in response to the conductivity scenarios were only sensitive to electricity changes and variable chemical inputs had little effect on the overall impact of treatment. Having electricity as the most sensitive contributor to the impact of the water treatment process narrows down the methods that a treatment plant can employ to reduce that impact. Transport was not greatly affected because the chemical inputs were small in magnitude. The sensitivity analysis reinforces the results discussed above. Electricity usage has the largest impact in the virtual treatment trains and must therefore be accounted for when deciding on alternative processes. Reducing the electricity used in water treatment can largely reduce the overall impact of the treatment train.

5. Integrating LCA into decision-making process

Decision-making by water utilities during a sudden change in source water quality can be challenging based on the information available and time frame for response. About 82% of water systems in the U.S. are classified by the U.S. EPA as small or very small ($\leq$ 3,300 people) and serve more than 19 million people (US EPA, 2013). When faced with changes in source water quality, such as saltwater intrusion, additional information from previous similar events can be informative in the decision-making process (Fig. 8). In this work, the decision-making process was assumed to include the following metrics: economics, regulatory compliance, ease of operation, and public input. The following paragraphs explore the decision-making process based on the information presented in the Cedar Key saltwater intrusion case study (section 3) and the LCA comparing real and virtual treatment trains (section 4). The following discussion illustrates that environmental impact should also be a consideration during the decision-making process.

Because small utilities often have limited financial resources and seek to minimize costs for ratepayers, economics is often the key consideration when making a decision about changes to water treatment (Starkl et al, 2009; Acreman, 2001). In the case of Cedar Key, the recurring cost of renting an RO unit persuaded the CKWSD and the water board to purchase the RO unit. In addition to considerations on capital cost, RO can increase operating costs due to the increased electricity usage, in some cases by up to 60% (Vedachalam & Riha, 2012) , which can be difficult for small water systems to finance without increasing rates. The CKWSD was able to use a combination of federal and state grants and loans to cover the majority of the capital cost, but did have to increase rates to cover repayment of the loans and increased operating costs.

In addition to economic considerations, water treatment plants must meet state and federal water quality standards. Cedar Key's decision to add RO to the existing treatment train was necessitated by the requirement to comply with the FDEP MCL for sodium because sodium was elevated due to the saltwater intrusion. Generally, the third type of consideration for water utilities is the ease of operation for the plant At Cedar Key, the new RO process was automated, and as a result, required less time from operators than the existing MIEX and lime softening processes (see Fig. 2). Lastly, public input and approval is the final aspect that is typically considered during the decision-making process as applied to water systems. Seeking public input and approval can be difficult because many of the decisions require technical knowledge in order to adequately evaluate and meet the policies set by the regulatory agencies. Often, the water utility and water board must make decisions that affect the resident’s lifestyle. Therefore some municipalities require public selection of the water managers and decision makers (in the case of Cedar Key a citizen-elected board) to ensure that an open, fair dialogue is created to inform the public and decision-makers alike (US EPA, 2013; Dolnicar & Schäfer, 2009) . Specifically, the CKWSD and the water board held multiple meetings with the public from the moment that the saltwater intrusion event occurred until the situation was resolved. For example, meeting minutes show that on June 19, 2012, the water board held a special meeting to discuss the saltwater intrusion event. They discussed the elevated levels of chloride in the wells, the health impacts of having such levels, and were mandated to send out a “Do not drink the water” advisory to all residents. The following week, meeting minutes from June 26, 2012 show that the water board discussed the urgency of installing a system to treat the elevated levels of salt in the groundwater. Plans were made at the end of the meeting that the CKWSD would seek temporary financing from a local bank for the purchase of the RO system and plant operators would move forward retrofitting the plant for its installation. It was finally discussed on August 13, 2012 that the system was producing potable water without complications.

The environmental impact of designing new or upgrading existing water systems is often not given the same level of attention as economics, regulatory compliance, ease of operation, and public approval as discussed in the preceding paragraphs. This is largely because it can be difficult to quantify environmental impacts. As such, the case study on saltwater intrusion at Cedar Key shows that LCA can provide useful information on the life cycle environmental impacts of water treatment that can be incorporated into the decision-making process. Furthermore, the LCA methodology can provide a systematic approach to generate new knowledge on and evaluate the life cycle environmental impacts of existing and virtual treatment trains (Bonton et al, 2012). The idea proposed herein is to create an LCA toolbox that would aid small water systems in the decision-making process, which is a similar idea as other toolboxes that have been developed for water supply planning(Bloetscher et al, 2011). For example, a small water system facing a sudden change in source water quality would document all aspects of the event, including data on the major retrofits needed due to the changes prompted by the event. Researchers would conduct an LCA on the processes available to that water utility. The LCAs would be placed in an easy-to-access database to be used by any water utility or researcher. The LCAs would help document the preventative and adaptive measures that similar water treatment plants have found necessary when facing changes in source water quality. The database could grow in scale with the participation of other water utilities and researchers until reaching the national level and ultimately gaining international participation. This is a similar idea as OpenFluor, an open-source database used by researchers around the world to characterize and document the fluorescence of aquatic organic matter (Murphy et al, 2014). A water utility in need of additional information due to a change in source water quality or extreme event could access the LCA toolbox. The LCA toolbox would not point directly to a final decision, but rather it would be used to add an important element to the decision-making process that is often missing, i.e., environmental impact. The final vision for the LCA toolbox would be a database with an easy-to-use interface that contains LCAs on a wide range of source water quality and the alternative processes that were used to mitigate the changes to the source waters affected. Bridging the gap between research and practical application, and adding communication links among water utilities facing similar changes in their source water quality would be the ultimate goal of the LCA toolbox.

6. Conclusions

- Additional information could have been beneficial to the CKWSD when assessing the possible alternatives to manage the sudden change to their groundwater supply. The case study provided evidence that saltwater intrusion was associated with times of low groundwater levels and drought conditions, which were not assessed in the decision-making process.
- LCA is a tool that can be used to evaluate the environmental impact of an alternative process or treatment train. For the three Cedar Key virtual treatment trains, the environmental impact due to electricity usage was at least 2.6 times higher than chemical usage and transport combined across all impact categories except ozone depletion. If available, alternative energy sources should be considered when a utility desires to have a lower environmental impact but decides to use an electricity-intensive process such as RO.
- An LCA toolbox can be a useful information source for water utilities facing changes in source water quality that have the potential to alter their treatment train. Because environmental impact is not typically considered when making decisions on alternative

water treatment processes, providing new information on environmental impacts can add an important element to the decision-making process that has been neglected in the past.

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Figure 1. Timeline of events that occured at Cedar Key from May 1, 2012 to August 1, 2012; Conductivity refers to daily measurements of groundwater conductivity

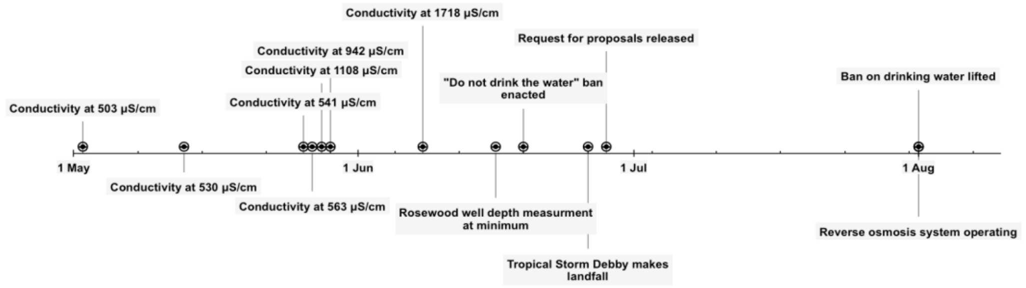

Figure 2. A. Schematic of unit processes at Cedar Key water treatment plant before the saltwater intrusion event; Alternative scenarios are proposed to replace the MIEX and lime softening processes; B. Virtual treatment train 1 was designed to treat conductivity scenario 1 with RO membranes for desalination; C. Virtual treatment train 2 was designed to treat confucitivity scenario 2 with NF and RO membranes for hardness removal, DOC removal, and desalination; D. Virtual treatment train 3 was designed to treat conductivity scenario 3 with NF for hardness and DOC removal; RO and NF chemical additions are found in Table 3–5

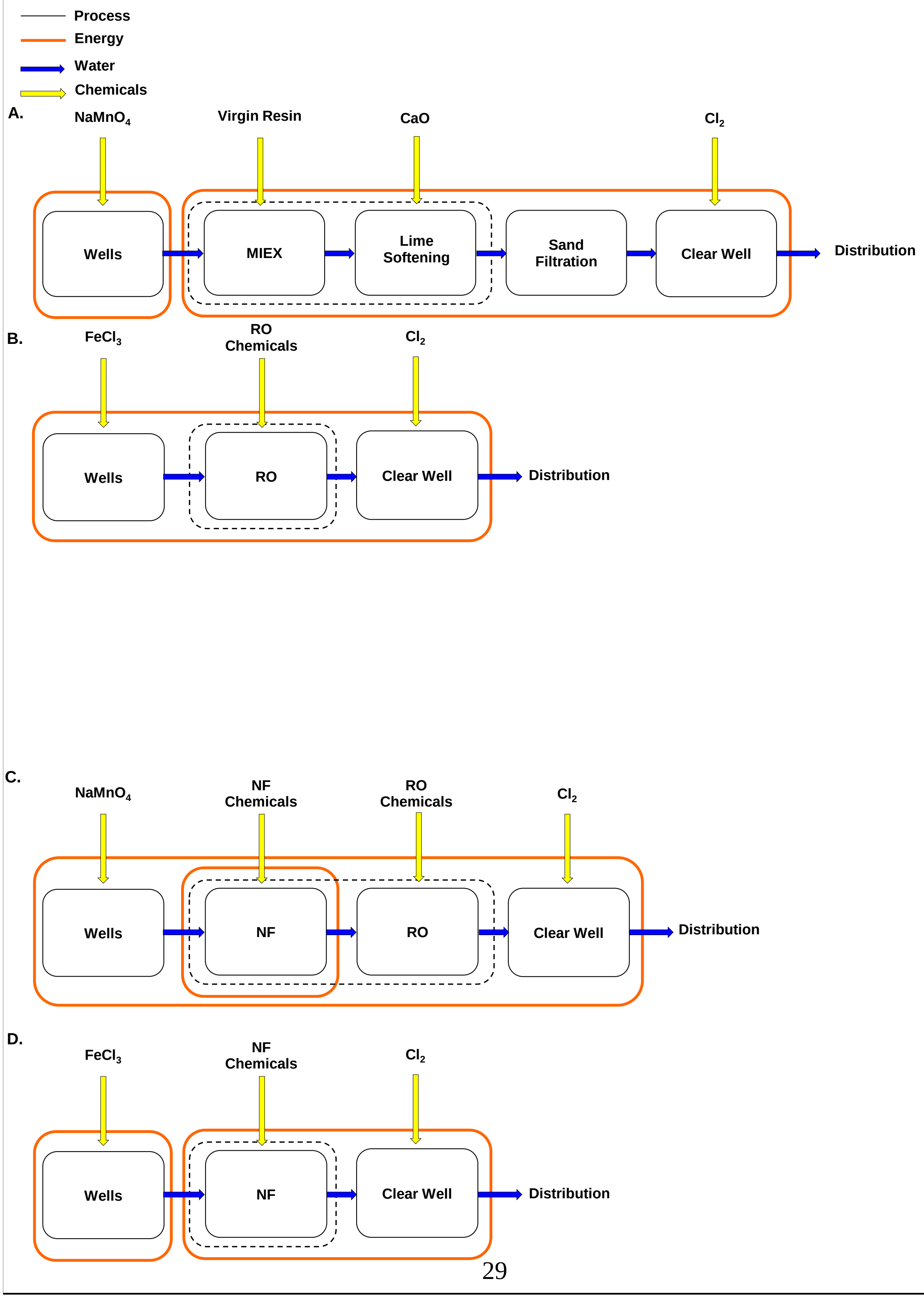

Figure 3. Daily conductivity of Cedar Key groundwater measured at the water plant

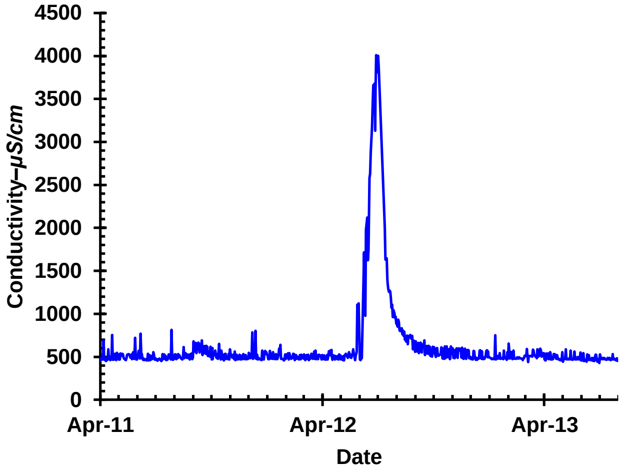

Figure 4. Daily groundwater level measurements taken by the SRWMD at Rosewood, FL from December 1981 to June 2014

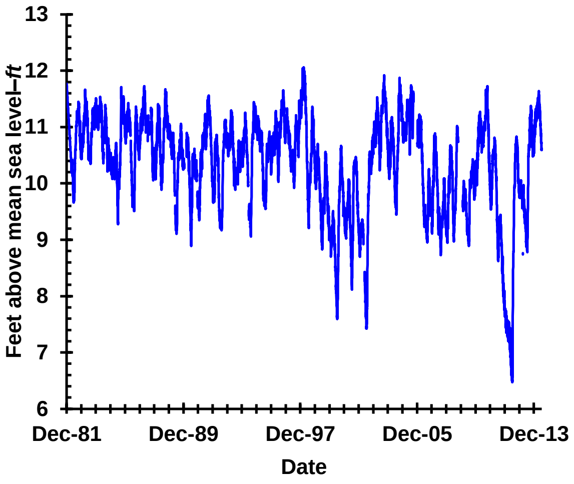

Figure 5. Three possible conductivity scenarios for future planning at Cedar Key; Cedar Key Data is real data and scenario lines follow hypothetical values

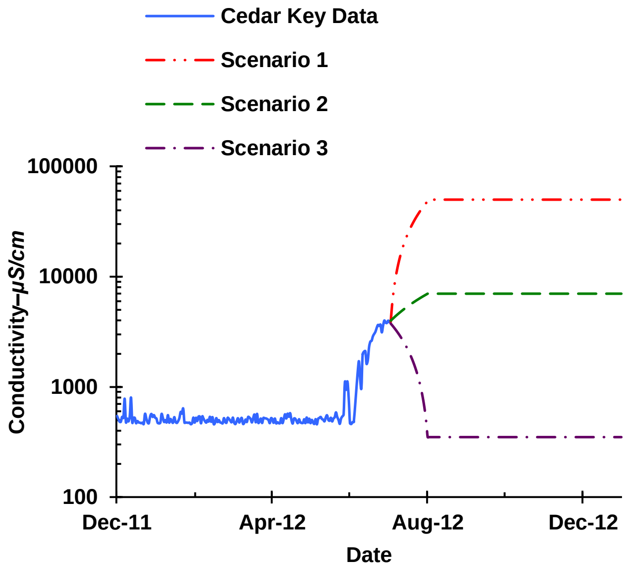

Figure 6. Life cycle impact assessment results for Cedar Key water treatment plant before saltwater intrusion; The length of each bar is equal to 100% of the impact within a given impact category and each colored segment represents an inventory item that contributes to that category

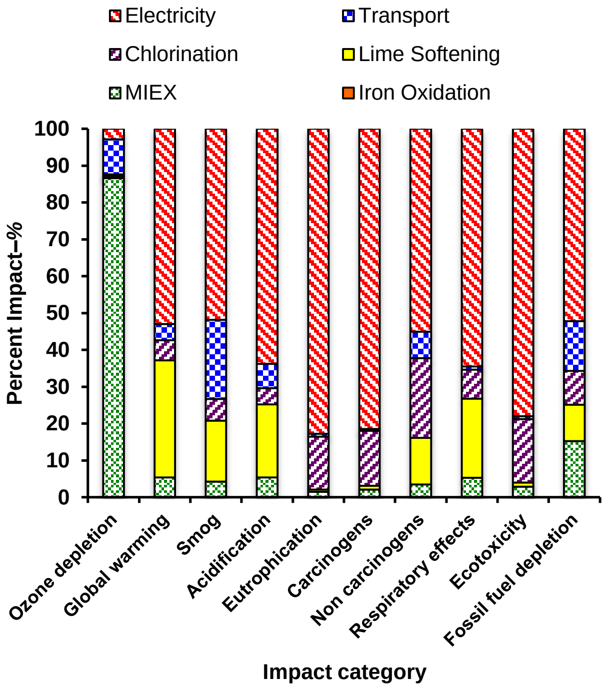

Figure 7. Comparative LCA results for Cedar Key water treatment plant before saltwater intrusion and virtual treatment trains after saltwater intrusion event

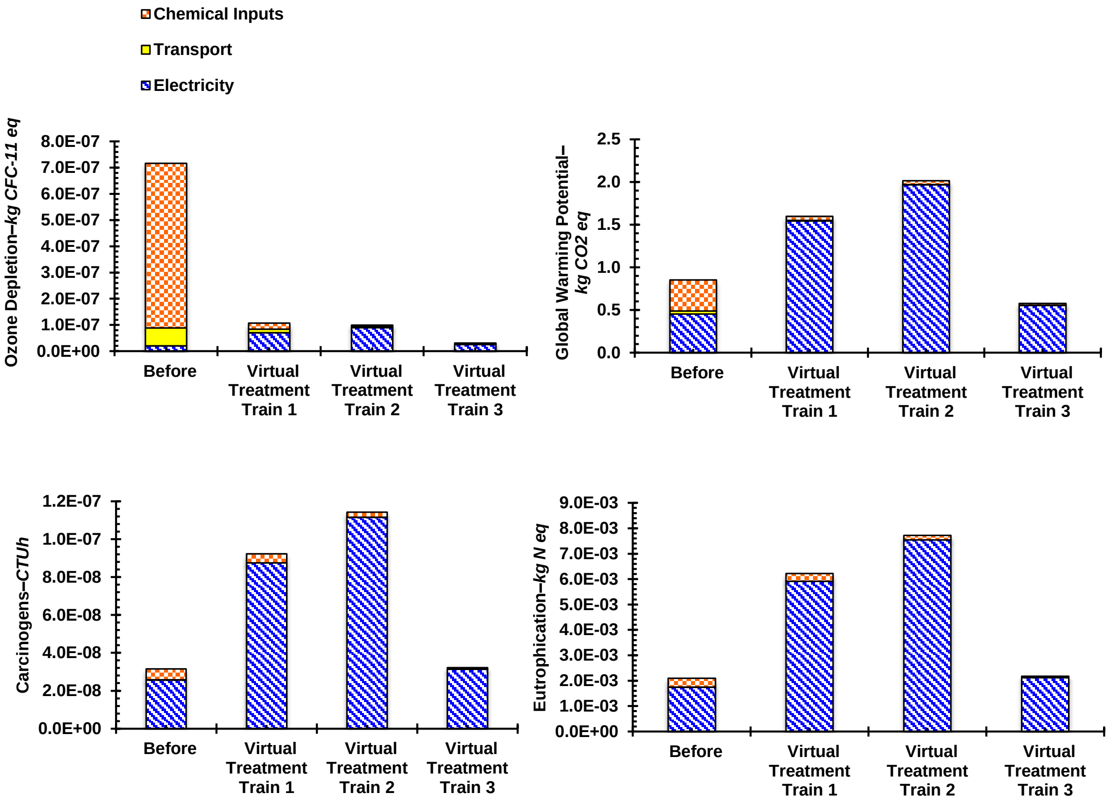

Figure 8. Economics, regulatory compliance, ease of operation, and pubic input are widely used metrics used in the decision-making process; Environmental impact is often neglected

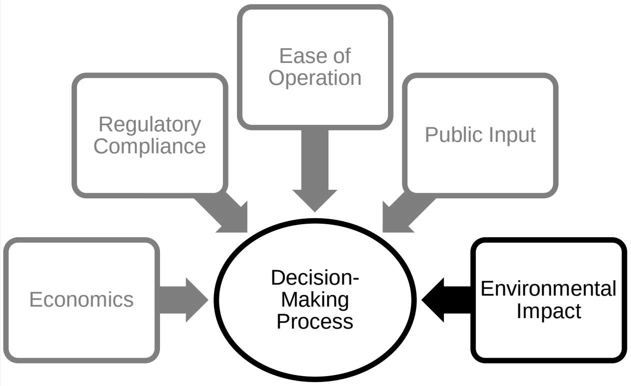

Table 1. Cedar Key water quality data collected during periods of fresh groundwater and during the saltwater intrusion event

Measurements	Pre–saltwater intrusion[a]	Saltwater intrusion[b]	Post tropical storm[c]	Post–saltwater intrusion[d]
pH	7.6	7.3	8.1	7.5
Conductivity (µS/cm)	505	1904	606	553
Total Hardness (mg/L $CaCO_3$)	275	440	287	264
Cl^- (mg/L)	11.8	550	71.2	20.5
Alkalinity (mg/L $CaCO_3$)	244	–	248	306
Total Fe (mg/L)	–	–	2.80	2.83
DOC (mg/L)	5.6	6.1	7.7 (Max. 14.9)	7.7
UV254 (cm^{-1})	0.171	0.169	0.277	0.184

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[a] Average measurements for November 2008 and January, February, and April 2009 (Apell and Boyer, 2010)
[b] Measurements from July 11, 2012
[c] Average measurements from August 1, 2012 to September 26, 2012
[d] Average measurements from February 18, 2013 to May 13, 2013

Table 2. Inventory data for Cedar Key water treatment plant before saltwater intrusion

Component	Value	Unit per m^3	Method	Name in SimaPro
Chemicals				
Sodium permanganate	2.50E-14	kg	Plant database	Potassium permanganate, at plant/RER U[a]
Virgin MIEX Resin	3.60E-03	kg	Plant database	Anionic Resin, at plant, CH/U[a]
Salt	0.2125	kg	Plant database	Sodium chloride, at plant/RNA[b]
Lime	0.1935	kg	Plant database	Quicklime, at plant US[b]
Sodium hypochlorite	5.28E-02	kg	Plant database	Sodium hypochlorite, 15% in H2O, at plant/RER U[a]
Transport				
Sodium permanganate transport	5.39E-12	kgkm	Field measurements + plant database	–
Virgin MIEX Resin transport	1.546	kgkm	Field measurements + plant database	–
Salt transport	45.69	kgkm	Field measurements + plant database	–
Lime transport	41.59	kgkm	Field measurements + plant database	–
Sodium hypochlorite transport	11.35	kgkm	Field measurements + plant database	–
Total transport	100.2	kgkm/m3	Field measurements + plant database	Truck 16t[c]
Energy wells	0.1346	kWh	Plant database	–
Energy plant	0.4522	kWh	Plant database	–
Total Energy	0.5868	kWh	Plant database	Electricity, medium voltage, at Grid/US U[a]

[a] Ecoinvent v2 database
[b] US LCI database
[c] LCA Food DK databse

Table 3. Inventory data for Virtual Treatment Train 1 (RO only)

Component	**Value**	**Unit per m^3**	**Method**	**Name in SimaPro**
Chemicals				
Chlorine	0.00706	kg	Tarnacki et al, 2012	Chlorine, liquid, production mix, at plant/RER S[a]
Ferric chloride	0.00706	kg	Tarnacki et al, 2012	Iron (III) chloride, 40% in H2O, at plant/CH U[a]
Antiscalants	0.00247	kg	Tarnacki et al, 2012	Polycarboxylates, 40% active substance, at plant/RER S[a]
Sodium bisulfite	0.0141	kg	Tarnacki et al, 2012	Sulfite at plant, RER U[a]
Sulfuric acid	0.0588	kg	Tarnacki et al, 2012	Sulphuric acid, liquid, at plant/RER U[a]
Sodium hypochlorite	0.00588	kg	Tarnacki et al, 2012	Sodium hypochlorite, 15% in H2O, at plant/RER U[a]
Transport				
Chlorine transport	1.5179	kgkm	Field measurements + Tarnacki et al, 2012	–
Ferric chloride transport	1.5179	kgkm	Field measurements + Tarnacki et al, 2012	–
Antiscalants transport	0.5311	kgkm	Field measurements + Tarnacki et al, 2012	–
Sodium bisulfite transport	3.0315	kgkm	Field measurements + Tarnacki et al, 2012	–
Sulfuric acid transport	12.6420	kgkm	Field measurements + Tarnacki et al, 2012	–
Sodium hypochlorite transport	1.2642	kgkm	Field measurements + Tarnacki et al, 2012	–
Total transport	20.505	kgkm	Field measurements + Tarnacki et al, 2012	Truck 16t[c]
Total Energy	2.0000	kWh	Tarnacki et al, 2012	Electricity, medium voltage, at Grid/US U[a]

[a] Ecoinvent v2 database
[b] US LCI database
[c] LCA Food DK databse

Table 4. Inventory data for Virtual Treatment Train 2 (NF to RO)

Component	Value	Unit per m^3	Method	Name in Simapro
Chemicals				
Sodium permanganate	2.50E-14	kg	Plant database	Potassium permanganate, at plant/RER U[a]
Sodium hypochlorite	6.00E-04	kg	Plant database	Sodium hypochlorite, 15% in H2O, at plant/RER U[a]
Antiscalants	0.00247	kg	Tarnacki et al, 2012	Polycarboxylates, 40% active substance, at plant/RER S[a]
Sodium bisulfite	0.0141	kg	Tarnacki et al, 2012	Sulfite at plant, RER U[a]
Phosphoric acid	0.0011	kg	Bonton et al, 2012	Sulphuric acid, liquid, at plant/RER U[a]
Carbon dioxide	0.015	kg	Bonton et al, 2012	Carbon dioxide, liquid, at plant, RER U[a]
Calcium hydroxide	0.007	kg	Bonton et al, 2012	Lime, hydrated, loose, at plant, CH U[a]
Membrane cleaning agent (NaOH)	0.0002	kg	Bonton et al, 2012	Sodium hydroxide, 50% in H2O, production mix, at plant/RER S[a]
Membrane cleaning agent (EDTA)	3.36E-04	kg	Bonton et al, 2012	EDTA, ethylenediaminetetraacetic acid, at plant/RER U[a]
Transport				
Sodium permanganate transport	7.02E-12	kgkm	Field measurements + Plant database	–
Sodium hypochlorite transport	1.29E-01	kgkm	Field measurements + Plant database	–
Antiscalants transport	5.31E-01	kgkm	Field measurements + Tarnacki et al, 2012	–
Sodium bisulfite transport	3.0315	kgkm	Field measurements + Tarnacki et al, 2012	–
Phosphoric acid transport	0.2365	kgkm	Field measurements + Bonton et al, 2012	–
Carbon dioxide transport	3.2250	kgkm	Field measurements + Bonton et al, 2012	
Calcium hydroxide transport	1.5050	kgkm	Field measurements + Bonton et al, 2012	–
Membrane cleaning agent transport	0.9030	kgkm	Field measurements + Bonton et al, 2012	–
Total transport	9.561	kgkm	Field measurements + Bonton et al, 2012	Truck 16t[c]
Energy NF	0.5500	kWh	Bonton et al, 2012	–
Energy RO	2.0000	kWh	Tarnacki et al, 2012	–
Total Energy	2.5500	kWh	Tarnacki et al, 2012 + Bonton et al, 2012	Electricity, medium voltage, at Grid/US U[a]

[a] Ecoinvent v2 database
[b] US LCI database
[c] LCA Food DK databse

Table 5. Inventory data for Virtual Treatment Train 3 (NF only)

Component	**Value**	**Unit per m^3**	**Method**	**Name in SimaPro**
Chemicals				
Sodium permanganate	2.50E-14	kg	Plant database	Potassium permanganate, at plant/RER U[a]
Sodium hypochlorite	6.00E-04	kg	Plant database	Sodium hypochlorite, 15% in H2O, at plant/RER U[a]
Phosphoric acid	1.10E-03	kg	Bonton et al, 2012	Phosphoric Acid, fertilizer grade, 70% in H2O, at plant, US U[a]
Carbon dioxide	0.015	kg	Bonton et al, 2012	Carbon dioxide, liquid, at plant, RER U[a]
Calcium hydroxide	0.007	kg	Bonton et al, 2012	Lime, hydrated, loose, at plant, CH U[a]
Membrane cleaning agent (NaOH)	0.0002	kg	Bonton et al, 2012	Sodium hydroxide, 50% in H2O, production mix, at plant/RER S[a]
Membrane cleaning agent (EDTA)	3.36E-04	kg	Bonton et al, 2012	EDTA, ethylenediaminetetraacetic acid, at plant/RER U[a]
Transport				
Sodium permanganate transport	7.02E-12	kgkm	Field measurements + Plant database	–
Sodium hypochlorite transport	1.29E-01	kgkm	Field measurements + Plant database	–
Phosphoric acid transport	0.2365	kgkm	Field measurements + Bonton et al, 2012	–
Carbon dioxide transport	3.2250	kgkm	Field measurements + Bonton et al, 2012	
Calcium hydroxide transport	1.5050	kgkm	Field measurements + Bonton et al, 2012	–
Membrane cleaning agent transport	0.9030	kgkm	Field measurements + Bonton et al, 2012	–
Total transport	5.999	kgkm	Field measurements + Bonton et al, 2012	Truck 16t[c]
Energy Wells	0.1678	kWh	Plant database	–
Energy NF	0.5500	kWh	Bonton et al, 2012	–
Total Energy	0.7178	kWh	Plant database + Bonton et al, 2012	Electricity, medium voltage, at Grid/US U[a]

[a] Ecoinvent v2 database
[b] US LCI database
[c] LCA Food DK databse

Table 6. Percent change in each impact category with an increase or decrease of chemical, transport, or energy inputs; Each input was increased or decreased by 25% before analysis; Results for percent change in the before treatment train and the virtual treatment trains (VTT) are expressed in absolute values

Impact category	**± 25% Chemical**[a]	**± 25% Transport**[b]	**± 25% Energy**[c]	**Impact category**	**± 25% Chemical**[a]	**± 25% Transport**[b]	**± 25% Energy**[c]
Ozone depletion				Carcinogens			
Before	21.91%	2.37%	0.72%	Before	4.49%	0.14%	20.36%
VTT 1	5.37%	3.25%	16.37%	VTT 1	1.29%	0.01%	23.70%
VTT 2	0.95%	1.63%	22.42%	VTT 2	0.59%	0.00%	24.40%
VTT 3	1.54%	3.28%	20.23%	VTT 3	0.64%	0.01%	24.36%
Global warming				Non-carcinogens			
Before	10.66%	1.09%	13.26%	Before	9.45%	1.78%	13.77%
VTT 1	0.75%	0.12%	24.13%	VTT 1	2.59%	0.17%	22.23%
VTT 2	0.53%	0.04%	24.42%	VTT 2	1.05%	0.07%	23.87%
VTT 3	0.92%	0.10%	23.99%	VTT 3	0.95%	0.15%	23.93%
Smog				Respiratory effects			
Before	6.67%	5.37%	12.96%	Before	8.66%	0.22%	16.12%
VTT 1	0.97%	0.58%	23.45%	VTT 1	3.28%	0.02%	21.70%
VTT 2	0.74%	0.22%	24.04%	VTT 2	1.31%	0.01%	23.67%
VTT 3	1.65%	0.46%	22.89%	VTT 3	0.82%	0.02%	24.18%
Acidification				Ecotoxicity			
Before	7.40%	1.67%	15.94%	Before	5.29%	0.20%	19.50%
VTT 1	2.98%	0.14%	21.87%	VTT 1	1.66%	0.01%	23.32%
VTT 2	1.12%	0.05%	23.82%	VTT 2	0.73%	0.01%	24.26%
VTT 3	0.51%	0.12%	24.37%	VTT 3	0.84%	0.01%	24.17%
Eutrophication				Fossil fuel depletion			
Before	4.11%	0.20%	20.70%	Before	8.57%	3.38%	13.05%
VTT 1	1.20%	0.01%	23.78%	VTT 1	1.43%	0.36%	23.21%
VTT 2	0.58%	0.01%	24.41%	VTT 2	1.07%	0.14%	23.79%
VTT 3	0.64%	0.01%	24.37%	VTT 3	1.72%	0.29%	23.06%

[a, b, c] Percent change = (impact category value at baseline – impact category value at ±25%)÷(impact category value at baseline)