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The Stability of Ion Exchange (IX) Water Treatment Technology

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Abstract: This research investigated using a life cycle environmental and economic approach to evaluate IX technology for small potable water systems, allowing for the identification and development of process and design improvements that reduce environmental impacts and costs. The main goals were to evaluate conventional IX in terms of life cycle environmental and economic sustainability, develop a method for improving designs of IX systems from a environmental and economic sustainability standpoint, evaluate potential design improvements, and make the research findings usable to water professionals through user-friendly tools and frameworks that take into account their feedback. This research provides an understanding, from the perspective of life cycle environmental impacts and costs, of the tradeoffs between various reactor designs of IX, the effects of scale, key contributors to impact and cost, design trends that improve sustainability, and how combined cation anion exchange compares to conventional IX. Furthermore, tools were developed that can be used to identify design choices that improve sustainability of IX systems. These tools were made into a user-friendly format to better bridge the gap between research and practice.

Introduction: World population growth and economic development are increasing water demands globally while increasing the scarcity of water sources (Vorosmarty et al., 2000). These increases in water demand as well as improved understanding of environmental impacts associated with water treatment highlight the need for sustainable water treatment technologies (European Environment Agency, 2012; UNEP and IWMI, 2012). Furthermore, potable water systems face various environmental and economic challenges in most regions of the world and in 2013 approximately one fourth of all potable water systems (PWS) in the U.S. were in significant violation of EPA or state rules (USEPA, 2013). This places increased responsibility on PWS to provide environmentally and economically sustainable water treatment.

Small PWS comprise the vast majority of all PWS and often face greater challenges and incur a higher number of legal violations (USEPA, 2013). This is because small PWS often have significantly less resources to operate and maintain their systems. For example, small PWS often have a small customer base, lack funds for implementation or maintenance of treatment systems, have staff that lack a high degree of expertise, and are geographically isolated. Therefore, a significant amount of assistance and resources are provided by the USEPA to small PWS to finance, operate, and maintain their systems (USEPA, 2013). Technologies are therefore needed that can meet the operational needs of small PWS while reducing environmental and economic impacts.

Ion exchange (IX) is a technology that can be used to remove hardness and a wide variety of contaminants from drinking water. IX provides effective and robust technical performance

that is effective under varying water chemistry. IX is also a scalable technology that can be employed in centralized or decentralized systems, such as household treatment or a municipal drinking water facility. IX is also flexible in terms of operation mode, reactor configurations, and sequence in a treatment train. Therefore, IX's advantages provide opportunities for safe, effective, and affordable water treatment.

IX systems, however, can introduce environmental impacts and economic costs due to energy, chemicals, and other materials used throughout their life cycle. Energy usage is required for pumping and mixing, resin is required throughout the operation of the system, large amounts of salt may be necessary for regeneration of the resin, and brine waste resulting from the regeneration process requires disposal. These introduce a number of environmental burdens and incur significant costs in implementation of IX systems. Furthermore, waste brine can also impact external systems, such as wastewater treatment plants, where high salinity can affect plant operation (Maul et al., 2014; Panswad and Anan, 1999). Therefore, if not designed and managed properly, IX can provide significant disadvantages for small PWS.

As IX is becoming more prominent in small PWS (Ali and Gupta, 2007), it is essential to better understand the environmental and economic impacts of their construction and operation as well as developing methods for improving IX designs. Micro-economic and technical considerations have traditionally been paramount in the design of water treatment systems and the traditional approach involves use of design guides, practical experience, and short term cost analysis. However, improved methods are needed to better consider life cycle environmental and economic considerations in IX design.

Life cycle assessment (LCA) is a method of quantifying environmental impacts of systems and is a valuable tool for assessing the environmental sustainability of water treatment technology. Additionally, life cycle cost analysis (LCCA) provides a method for comprehensive economic evaluation of products, systems, and processes. Use of a life cycle approach helps to avoid shifting of environmental and economic burdens from one stage of the life cycle to another and helps to identify technological innovation opportunities. LCA, therefore, avoids the issues of only taking into account site-specific considerations (e.g. only emissions at a particular plant instead of due to the materials and processes upstream) (Azapagic et al., 1999). Few studies have applied LCA to IX technology for drinking water treatment. These studies, as well as their main findings, are shown in Table 1.1. These studies have compared IX technology to other types of drinking water technology, such as RO, catalytic reduction, and adsorption, with target contaminants such as perchlorate, arsenic, nitrate, and hardness. However, the results from the previous studies are often context sensitive. None of the studies consider more than one system and installation, but varying management practices, operation, and environmental or design factors can significantly affect the environmental impacts of the system. Therefore, evaluation of a wider number of systems is needed to provide more complete understanding of how the impacts of the technology can differ in various circumstances.

Furthermore, the impact of scale, the effect of common design and reactor configurations, and the influence of other IX design parameters have not been evaluated in previous studies.

Intellectual Merit: This research advances the understanding of IX technology by using a life cycle approach to evaluate environmental and economic sustainability. It also develops a novel method for assessing and improving the sustainability of IX by tightly integrating process models with LCA/LCCA. The computer model developed through this approach can be expanded upon by the academic community. As further studies are performed on the sustainability of IX systems, new results can be added to the model in a modular fashion, increasing its impact, longevity, and value to the academic community. Furthermore, industry contacts have expressed interest in applying the model developed. Therefore, the simplified design tool will allow for the drinking water community and IX industry to apply the research results in order to identify improved system designs. This research also promotes the role of a life cycle sustainability approach in technology development, which assists in avoiding shifting of environmental and economic impacts from one phase of the life cycle to another.

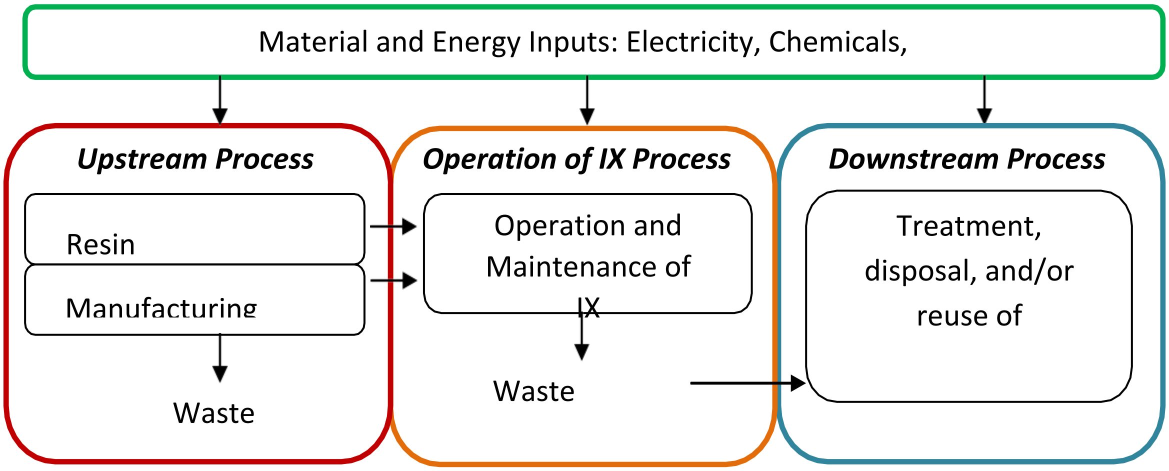
Broader Impacts: This research not only provides a significant step forward in understanding the environmental and economic costs of IX systems, but translates this understanding into methods and tools for technology development that are appropriate for use in both academic and industry settings. Task 4 of this research further engages practitioners in the drinking water community through direct communication of results and use of feedback to develop tools for technology improvement that can be implemented in the field. Furthermore, this research complements other research on sustainability and the water-energy nexus at the University of South Florida (USF) and is developing mutually beneficial research relationships between USF and University of Florida (UF). This research is producing publishable results that are being presented at conferences to engage both the academic and practitioner community.

Environmental and Economic Sustainability of Ion Exchange Drinking Water Treatment for Organics Removal 1 (Task 1): Water treatment infrastructure faces various operational and financial challenges in most regions of the world. Ion exchange is a water treatment technology that can be used to remove various contaminants in drinking water and has shown increased adoption in recent years due to its operational advantages; however, limited research has been conducted on the environmental and economic sustainability of ion exchange systems. This study utilizes life cycle assessment and cost analysis to holistically evaluate environmental and economic impacts of ion exchange technology that is used for reduction of disinfection by-products via organics removal in eight drinking water treatment plants in Rampur. A functional unit accounting for both water quantity and quality was used and showed to have a significant effect on the evaluation results. Impact assessment results show that the construction phase has negligible environmental impact in comparison to the operation phase. Systems that use fixed bed reactors with conventional resin were compared with systems using completely mixed flow reactors with magnetic ion exchange resin. Fixed bed systems evaluated have higher salt usage and brine waste production, but use less electricity, resin, and require less transport of materials. This tradeoff causes fixed bed systems to have a higher environmental impact in categories of eutrophication, carcinogenics, non-carcinogenics, and ecotoxicity but lower impact in other categories. Furthermore, it causes fixed bed systems to have a lower operation cost compared with completely mixed systems. Results also show that both environmental impacts and operation costs per functional unit decrease with scale, similar to economies of scale effects.

Materials and Methods: The study follows International Organization for Standardization (ISO) methodological framework for environmental impact assessment, including Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation (ISO, 2006a; ISO, 2006b).

Goal and Scope: This study is intended to provide an understanding for both industry and academic audiences of the environmental impacts and costs of IX technologies currently in operation for organics removal. From an industry perspective, this understanding can help to improve the environmental and economic sustainability of IX systems through better design, training, and operation. From an academic perspective the assessment results can be used to develop models incorporating the sustainability of IX systems. Furthermore, it provides a baseline of comparison to ensure that IX technology improvements do not shift burdens from one area in the life cycle to another.

Functional Unit Selection: The function of the systems in this study is to remove organic carbon from water. Therefore, the functional unit (FU) chosen was 1 million gallons (MG) of water treated with 1 mg/L DOC removal over the course of 20 years. A 20 year timescale was used because it is the design life for most of the plants studied. In water treatment systems, often a FU is chosen that only takes into account water quantity treated (Barrios et al., 2008; Vince et al., 2008); however, the function of water treatment systems is not only to process a quantity of water, but to improve the water quality to the standard. A system may be designed to process large quantities of water, but if it cannot remove contaminants efficiently, additional infrastructure, materials, and processes will be required. Therefore, taking into account water quality in the FU provides a more fair comparison of systems based on their ability to achieve the desired function. A comparison of the results based on an FU that incorporates water quality and quantity as opposed to the conventional method of using water quantity alone, is presented in section 3.2.2 to demonstrate the advantages and disadvantages of each method. In order to create a FU that incorporates water quality, a common treatment parameter for organic carbon must be measured at the influent and effluent of the IX units. Approximately half of the plants in the study monitored the organic carbon by measuring color while the others measure UV absorbance (UVA254). While these measurements are easier to perform at the treatment plant, DOC provides a more direct measurement of organics. Therefore, all influent and effluent organics concentrations were converted to an estimate of organic carbon, measured as DOC. The relationship between color, UVA254, and DOC can vary, depending on water sources. Therefore, influent and effluent samples were taken from a majority of the treatment plants and the three parameters were measured in all the samples. This was used to create a regression equation describing the relationship between the three parameters for Rampur groundwater, which was used to estimate the influent and effluent DOC concentrations in the plants that could not be directly sampled. The regression equations are included in the Supplementary Information (SI).



Recommendations for Future Study: A number of efforts could be pursued to further develop and build upon the research that was accomplished in this dissertation. While a robust life cycle environmental impact and cost assessment of IX systems that remove DOC was performed in Task 1, this method also needs to be applied to IX systems that remove other types of contaminants because such systems can differ widely in material and energy requirements as well as waste production. One of the factors that can limit the use of IX systems is the brine waste production. Therefore, methods for brine reuse or reduction are particularly needed at this time for IX. The model developed in Task 2 can be expanded to include more applications of IX. This would overall make it more useful in providing comparisons while also making it much more valuable to engineers and other water professionals. Use of CCAE technology using a FBR should be investigated more thoroughly, particularly investigating methods to prevent precipitation and clogging of the fixed bed. The user-friendly tool developed in Task 4 can be expanded to include more functionality. For example, it can provide more interactive visualization of results. It can also allow for more customization of the system inputs. For example, the tool currently does not allow users to customize options such as the price of salt and electricity that the model assumes. These assumptions can have dramatic differences on the model results.

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