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# Life cycle water demand coefficients for crude oil production from five North American locations

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A B S T R A C T

The production of liquid fuels from crude oil requires water. There has been limited focus on the assessment of life cycle water demand footprints for crude oil production and refining. The overall aim of this paper is address this gap. The objective of this research is to develop water demand coefficients over the life cycle of fuels produced from crude oil pathways. Five crude oil fields were selected in the three North American countries to reflect the impact of different spatial locations and technologies on water demand. These include the Alaska North Slope, California's Kern County heavy oil, and Mars in the U.S.; Maya in Mexico; and Bow River heavy oil in Alberta, Canada. A boundary for an assessment of the life cycle water footprint was set to cover the unit operations related to exploration, drilling, extraction, and refining. The recovery technology used to extract crude oil is one of the key determining factors for water demand. The amount of produced water that is re-injected to recover the oil is essential in determining the amount of fresh water that will be required. During the complete life cycle of one barrel of conventional crude oil, 1.71–8.25 barrels of fresh water are consumed and 2.4–9.51 barrels of fresh water are withdrawn. The lowest coefficients are for Bow River heavy oil and the highest coefficients are for Maya crude oil. Of all the unit operations, exploration and drilling require the least fresh water (less than 0.015 barrel of water per barrel of oil produced). A sensitivity analysis was conducted and uncertainty in the estimates was determined.



## 1. Introduction

Petroleum oil is one of the largest sources of energy and its extraction has environmental impacts on air, water, and land (Khoo and Tan, 2006). One of the key environmental indicators is the life cycle water footprint, which can be used to measure the impacts of petroleum oil on water resources (OECD, 2008; Galera et al., 2010). The demand for fuels extracted from petroleum oil is highest in the transportation sector, and there is no expectation that this situation will change in near future.

The U.S., Canada, and Mexico are the three North American countries and each has a key role to play in crude oil production (Stillwell et al., 2011; CAPP, 2014; Sanders et al., 2013). The U.S. is the largest consumer of oil products in the world and in 2016 consumed 19.63 million bbl/d. The country produced 49% of this consumption and imported 51%. The largest oil supplier to the U.S. in 2016 was Canada (38% of the total imports) and Mexico was the fourth largest (7%) after Venezuela (8%) (EIA, 2016a). Canada's total crude oil production in 2015 was 3.85 million bbl/d and is projected to reach 4.93 million bbl/d by 2030, with more than half coming from Alberta's oil sands (CAPP, 2016). Mexico is among the top ten oil producers in the world and the third largest North American producer after the U.S. and Canada, although its production has been in continuous decline since 2005 (EIA, 2014).

The concern about the use of water for energy is high all over the world (IEA, 2012; McMahon and Price, 2011; King et al., 2013; Glassman et al., 2011), and the great challenge in the production of primary fuels is not only the absolute amount of water required for extraction, but also the geographical location of the resources, should these be in an area with limited water. The geographical location of oil resources cannot be controlled by humans, unlike electricity generation or oil refining, for which water availability is a consideration at the plant design phase. The other challenge with petroleum production is that most of water withdrawn is consumed and either not returned to the source or a lower quality water is returned.

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The province of Alberta in Canada is a hub of energy production and in 2005 about 8% of total water allocations were assigned to the petroleum sector. 92% of water withdrawn was consumed and 65% of the water used in the petroleum sector was diverted for oil sands extraction from a single river basin, the Athabasca, which flows close to oil resources. Most (88%) of the total water allocated for the petroleum sector in the Athabasca River Basin is surface water (AENV, 2007). In Alberta, electricity generation plants, refineries, and proposed oil sands upgraders could be located so that they are distributed near different river basins where water use is not a large concern (Hackett et al., 2012; EPCOR, 2004; ATCO, 2016; Griffiths and Dyer, 2008).

Most of the earlier studies conducted on energy sector water demand either focused on a single geographical region (Okadera et al., 2014; Zhang and Anadon, 2013; Grubert et al., 2012), recognized water consumption but not water withdrawals (Okadera et al., 2014; Zhang and Anadon, 2013; Grubert et al., 2012; Gleick, 1994; Wu and Chiu, 2011; Staples et al., 2013), or covered specific unit operations and not over the complete life cycle (Argaez et al., 2007; AER, 2014a). In addition, none of these studies provide a comparative assessment of life cycle water footprints of North American crude oils. In other words, there are few studies on the life cycle water footprint assessment of crude oils and none studies on a comparative life cycle assessment (LCA) of crude oils' water footprint. The authors of this study have conducted complete LCA of water footprints for coal, natural gas, renewable energy-based power generation (Ali and Kumar, 2015, 2016, 2017a), and regression models were developed to determine significant factors affecting thermoelectric power plant water use in the United States (Yang and Dziegielewski, 2007). An early study by the authors included assessment of life cycle water footprint of oil sands (Ali and Kumar, 2017b) but no studies have been done on crude oils. This is a significant gap in the literature, and this paper is aimed at addressing this gap.

The key objectives of this paper are to:

- Develop life cycle water demand coefficients for crude oil produced at five different locations in North America.
- Carry out a comparative LCA of water demand for crude oils.
- Assess the impacts of the re-injection of produced water on water demand over the complete life cycle.
- Assess the impact of different technologies used on the water demand for crude oil production.
- Assess the impact of the water used for refining unit operations on the water demand over the complete life cycle.
- Estimate the uncertainty in the life cycle water footprint for crude oil production at various North American locations.

The second section of this article discusses the methodology followed in the study and the third section gives the background of the five selected oil fields in North America. Assumptions and input data used for the analysis are explained in the fourth section and the obtained results and discussion in the fifth section. The sensitivity analysis and conclusions are presented in the sixth and seventh sections, respectively.

## 2. Methodology

The life cycle methodology used in this paper covers the unit operations involved in crude oil production. Unit operations have been defined for exploration, drilling, extraction, and refining. The standard steps determined by ISO14040 for LCA were followed in this study (Garofalo et al., 2017) by defining the goal of developing water footprints for different unit operations of conventional oil. The inventory is the quantity of water analysed through demand coefficients per functional unit of conventional oil produced (bbl). Water demand coefficients for crude oil is a term used in this paper to include both water consumption coefficients and water withdrawals coefficients. The water withdrawal (WW) is the total water diverted from a source and includes water consumption (WC) and water returned (WR) to the source. Further details on the life cycle water footprint assessment methodology of energy conversion processes are given in earlier publications by the authors (Ali and Kumar, 2015, 2016, 2017a, 2017b). Five crude oil production regions in North America were selected: three in the U.S. (Alaska North Slope, California's Kern County heavy oil, and Mars), one in Mexico (Maya), and one in Alberta, Canada (Bow River heavy oil). These five regions were selected in this study because they are in line with a previous study on GHG emissions for the same recovery method in North America (Rahman et al., 2014). Fig. 1 shows the selected oil production fields on the map of North America. Water demand data for these regions were estimated, and coefficients for unit volume of water per unit volume of oil produced (bbl/bbl) were developed in order to conduct a comparative assessment. The uncertainty in the input parameters was assessed in an extensive sensitivity analysis. The sensitivity analysis was conducted through Monte Carlo simulations (Vose, 2016; Williams et al., 2008; Kullapa and Joe, 2010; Karfopoulos and Anagnostakis, 2010; Soratana and Marriott, 2010) to evaluate the impact of technology variations on the water demand coefficients for the complete life cycle of crude oil production.

The quality and source of water diverted for the selected five regions may differ, but the developed water demand coefficients in this study are meant to represent benchmarks for similar crude oil production technologies. Only fresh water is considered in this study and it is defined based on information from government agencies such as Alberta Environment (AENV, 2008; AESRD, 2011) that specify water with total dissolved solids (TDS) less than 4000 mg per litre (mg/L) is considered fresh water. Beyond this level of water salinity, a diversion license from the Government of Alberta is not required (AESRD, 2011). The raw water could be diverted from the sea with a lower quality than river or groundwater, but when injected for crude oil recovery, sea or produced water has to be treated to a higher quality level considered in the assumed zone of fresh water (less than 4000 mg/L) in this study. The consumption coefficient of fresh water during extraction unit operations was calculated as follows:

$$FW = TWT - PRE * TWP \quad (1)$$

where FW is the consumption coefficient of fresh water (in bbl/bbl), TWT the total water injected (in bbl/bbl), PRE the percentage of produced water re-injected (in %), and TWP the total produced water (in bbl/bbl).

## 3. Selected oil fields

### 3.1. Alaska North Slope

Alaska North Slope (ANS) is one of the largest oil producers in the U.S., although production dropped by an average of 3%/year over the thirty-five years preceding 2015 and was 465 thousand bbl/d that year (EIA, 2016b). Prudhoe Bay is the largest oil field in the Alaska North Slope, the largest in the North America, and the twentieth largest in the world; it had a production rate of 271 thousand bbl/d (IEA, 2012; BP, 2012). The medium crude oil produced from Alaska North Slope is sent to refineries through the Trans-Alaska Pipeline System (TAPS) (Sheridan, 2006). The resulting ANS crude is usually loaded into vessels at the Alaska Marine Terminal and sold to customers on the U.S. West Coast