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PRIMER

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Lithium and water: Hydrosocial impacts across the life cycle of energy storage

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Abstract

As a key ingredient of batteries for electric vehicles (EVs), lithium plays a significant role in climate change mitigation, but lithium has considerable impacts on water and society across its life cycle. Upstream extraction methods—including open-pit mining, brine evaporation, and novel direct lithium extraction (DLE)—and downstream processes present different impacts on both the quantity and quality of water resources, leading to water depletion and contamination. Regarding upstream extraction, it is critical for a comprehensive assessment of lithium's life cycle to include cumulative impacts related not only to freshwater, but also mineralized or saline groundwater, also known as brine. Legal frameworks have obscured social and ecological impacts by treating brine as a mineral rather than water in regulation of lithium extraction through brine evaporation. Analysis of cumulative impacts across the lifespan of lithium reveals not only water impacts in conventional open-pit mining and brine evaporation, but also significant freshwater needs for DLE technologies, as well as burdens on fenceline communities related to wastewater in processing, chemical contaminants in battery manufacturing, water use for cooling in energy storage, and water quality hazards in recycling. Water analysis in lithium life cycle assessments (LCAs) tends to exclude brine and lack hydrosocial context on the environmental justice implications of water use by life cycle stage. New research directions might benefit from taking a more community-engaged and cradle-to-cradle approach to lithium LCAs, including regionalized impact analysis of freshwater use in DLE, as well as wastewater pollution, cooling water, and recycling hazards from downstream processes.

This article is categorized under:
Human Water > Human Water
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energy storage, hydrosocial, life cycle assessment, lithium, water

1 | INTRODUCTION

Listed as a "critical" or "transition" mineral for mitigating climate change, lithium is a key ingredient in lithium-ion batteries used to power electric vehicles (EVs), energy grid storage, and portable electronic devices, in addition to its direct uses in ceramics, glass, and other products (Grosjean et al., 2012; Gruber et al., 2011; Jaskula, 2024; U.S. Geological Survey, 2022). Lithium is the lightest of the elemental metals and plays an important role in carrying a charge between the anode and cathode in batteries (Sanderson, 2023; Scheyder, 2024; Turner, 2023). The International Energy Agency estimates that lithium demand may grow ten fold by 2050 due primarily to rapid deployment of EVs, though this outlook may depend on assumptions about expansion of mining lithium from diverse sources of hard rock, brines, and clays, as well as the adoption of potential substitutes, such as sodium-ion batteries or vanadium flow storage technologies (International Energy Agency, 2024, p. 127; Xu et al., 2020). Despite its potential importance for decarbonization through electrification, researchers and advocates have expressed heightened concerns about the adverse social and ecological impacts of lithium, centered on debates over water (Babidge et al., 2019; Blair et al., 2022; Blair, Balcázar, et al., 2023; Bustos-Gallardo et al., 2021; Jerez et al., 2021; Kramarz et al., 2021; Pollon, 2023; Sovacool, 2021).[1] There are different ways to extract lithium, from conventional open-pit mining and brine evaporation to novel direct lithium extraction (DLE) technologies. These extraction methods, considered to be upstream within the life cycle of lithium, bring different burdens and benefits related to water and the communities tied to it. Downstream approaches to processing, manufacturing, using, and disposing or recycling lithium add further water impacts that merit scrutiny (Figure 1).

This article offers a primer on lithium and water across its life cycle.[2] We consider upstream and downstream impacts on both the quantity and quality of water resources, including depletion and contamination. Taking an interdisciplinary "one water" approach influenced by Indigenous knowledge and science, as well as critical perspectives on integrated watershed management, we argue that a comprehensive assessment of lithium's life cycle must include

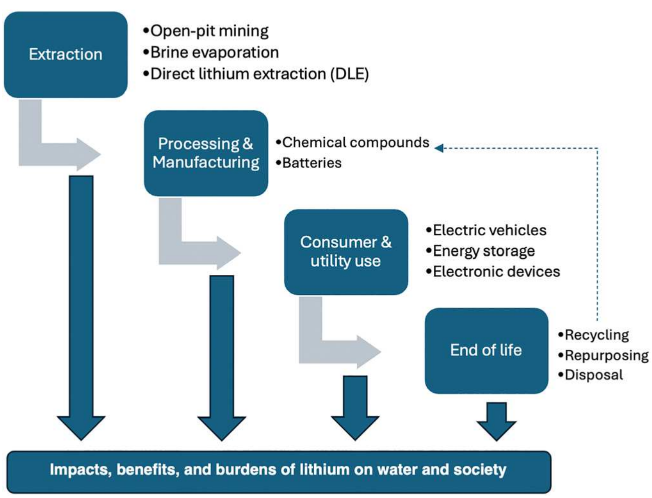

FIGURE 1 Impacts, benefits, and burdens on water and society throughout the life cycle of lithium.

cumulative impacts related not only to freshwater, but also mineralized or saline groundwater, also known as brine (Carse, 2018; Cohen, 2011; Ejeian et al., 2021; Huitema & Meijerink, 2014; Leonard et al., 2023; Mukheibir & Howe, 2015; Neville & Coulthard, 2019; Ochoa Espejo, 2020). While the impacts of mining on freshwater and communities connected to it have been documented, many studies have ignored brine because some legal frameworks treat it as a mineral rather than water, and industry actors often externalize brine as separate from surrounding wetlands and aquifers (Flores Fernández & Alba, 2023). Moreover, given the burdens posed to fenceline communities, it is imperative to account for cumulative impacts of industrial activities across the lifespan of lithium, including potential freshwater use in DLE, wastewater in processing, chemical contaminants in battery manufacturing, water use for cooling in energy storage, and water quality hazards in recycling.

In what follows, we interrogate the contradictions inherent to extracting lithium from diverse material sources, and we discuss potential impacts on water from DLE and downstream processes. By analyzing "hydrosocial" dynamics across the life cycle of lithium (Berry & Cohn, 2022; Boelens et al., 2016; Cantor, 2021), this primer offers a broad overview of the impacts, benefits, and burdens of "green extractivism" on water and society (Blair, Balcázar, et al., 2023; Dunlap & Jakobsen, 2019; Jerez et al., 2021; Mejia-Muñoz & Babidge, 2023; Riofrancos, 2019; Voskoboynik & Andreucci, 2021).[3]

2 | UPSTREAM LITHIUM EXTRACTION

Lithium is mined in three main ways, each with different impacts on water: open-pit mining, brine evaporation, and DLE.

2.1 | Open-pit lithium mining

Open-pit lithium mining currently accounts for more than half the world's production (Tabelin et al., 2021). Australia produces the bulk of lithium from open-pit mining, with other hard rock lithium mines either in production or under construction in China, Brazil, Zimbabwe, Canada, Portugal, and the United States (Jaskula, 2024). Most hard rock lithium reserves are found in spodumene, a pegmatitic igneous rock (Kesler et al., 2012). However, an upsurge in mining of lower grade pegmatite—blended with spodumene to reach battery grade materials—such as lepidolite in China and petalite in Zimbabwe, influenced an increase in global lithium supply by 23% in 2023 (Jaskula, 2024). Approaches are also in development to extract lithium from sedimentary hectorite clays in places like the McDermitt Caldera in the Western United States.

Despite efforts to present lithium mining as a novel, climate-smart form of mining, at its most basic, open-pit lithium mining involves creating massive holes in the Earth that produce huge quantities of tailings and lasting impacts to waterscapes (Baviskar, 2007; Dunlap & Riquito, 2023; Flaminio et al., 2022). For example, the world's largest lithium mine, Greenbushes in Western Australia, is 3.5 km long and 455 m deep, producing 16 million bank cubic meters (Mbcm) of raw material each year for a target spodumene output of 9.5 million tons per annum (Mtpa) (Tianqi Lithium Corporation, 2022). Open-pit mining produces the most significant environmental impacts of any human activity and generates more violent conflicts in which local environmental defenders are assassinated than any other industrial sector (Bozuwa & Mulvaney, 2023; Riofrancos et al., 2023; Scheidel et al., 2020). Mines are often located in close proximity to disadvantaged Indigenous communities, leading to the destruction of sacred sites like 46,000-year-old rock shelter formations at Juukan Gorge in Western Australia's Pilbara region (Block, 2021; Burgess et al., 2021; Burton et al., 2024; Wright, 2021). Residents near the Greenbushes lithium mine have raised concerns about contamination from a proposed tailings facility (Loney, 2019), and Noongar Indigenous peoples and conservationists have begun to protect cultural heritage and restore wetland ecosystems in pit lakes that have formed in decommissioned areas of the mine (Bigby (Cherokee), 2023; Murphy, 2017).

Open-pit lithium mining projects influence both water quantity and quality. Dewatering of mine pits, ore processing, ore transportation, dust mitigation, and waste management all rely on local water sources that may be depleted (Kemp et al., 2010). For example, the Thacker Pass lithium mine under development in Nevada, United States is estimated to use more than 1.6 billion gallons of groundwater each year of its projected 41-year lifespan, and pan-Indigenous groups, like People of Red Mountain, have defended their land from groundwater contamination, as well as encroachment on the site of a massacre of Indigenous peoples (Daly, 2023; Falk et al., 2022; McCullough &

U.S. Department of the Interior, 2020; Mighty Earth, 2023). Landscape alterations associated with open-pit mining can harm water quality by disturbing subsurface sediment, storage of waste products, and use of chemical treatments (Hilson & Hu, 2022; Northey et al., 2016). For example, local residents near the proposed Mina de Barroso lithium mine in Portugal have protested the release of toxic tailings waste flowing into groundwater and rivers (Chaves et al., 2021; Riofrancos et al., 2023; Saleth & Varov, 2023). When mining operations conclude, pits require long-term actions to prevent contamination from polluting local water sources (Wireman & Stover, 2011).

2.2 | Lithium brine evaporation

Even though open-pit mining has become the primary method of global lithium production with 63% of lithium raw materials deriving from hard rock in 2023 (120 kt out of 190 kt), brine evaporation still yielded 70 kt of lithium in 2023, and it remains the conventional lithium extraction method in the arid Andean salt flats of Chile and Argentina (International Energy Agency, 2024, p. 129). Bolivia has also signed agreements with Russian and Chinese firms to develop its significant lithium brine resources, but technical barriers may require DLE rather than just brine evaporation in Bolivian salt flats, which feature higher levels of precipitation and magnesium (Al Bouchi & Caraway, 2023; An et al., 2012; Bos & Forget, 2021; Goodale, 2024; Sanchez-Lopez, 2019). These South American countries have taken different approaches to governing lithium, ranging from federal state-led national strategies in Chile and Bolivia to more decentralized provincial mining concessions to attract foreign investment in Argentina (Barandiarán, 2019). Nonetheless, plurinational movements of Indigenous communities and environmental activists have raised concerns about the potential impacts of lithium brine evaporation on watersheds and wetlands throughout the Andean salt flats (Blair et al., 2022; Fundación Ambiente y Recursos Naturales (FARN), 2019; Jerez Henríquez, 2018; Jerez Henríquez et al., 2021; Pérez et al., 2024).

To extract lithium from these continental brines through the evaporation method, operators typically drill the crust of the salt flat and pump brine at a rate of up to 1600 L/s (the current authorized rate in Chile). The subsurface minerals are distributed into a series of cascading evaporation pools before separation and transfer to a processing plant. The evaporation process takes up to 18–24 months, and around 95% of brine water evaporates (Garcés & Alvarez, 2020).

Brine is mainly liquid: mineralized or saline groundwater. Brine may contain around 75% water and 25% salt and other dissolved solids, but 99% of brine's formation energy comes directly from water (Ejeian et al., 2021). However, laws governing lithium extraction in Chile have interpreted brine as a mineral resource, and salt flats are regulated mainly as mines, even though they may also be understood as wetlands (Flores Fernández & Alba, 2023). Nonetheless, environmental movements have advocated for regulation of brine evaporation as extraction of water (Blair et al., 2022; Pérez et al., 2024). To Indigenous Atacameño or Lickanantay people, there is only one water (*puri* in Kunza) that is alive and includes both brine and surrounding lagoons (Blair, Balcázar, et al., 2023; Flores Fernández & Alba, 2023; Ramos Chocobar & Tironi, 2022). Supporting this Indigenous perspective, critical scholars of green extractivism and water justice have reinterpreted brine evaporation as "water mining" (Bustos-Gallardo et al., 2021; Garcés & Alvarez, 2020; Jerez et al., 2021). Besides brine, freshwater is required to dilute pipes and prepare lime for chemical treatment to remove impurities, as well as sodium carbonate needed to precipitate and separate lithium carbonate from brine (Mousavinezhad et al., 2024). Yet, concerned scientists have demonstrated alternative ways to treat water from brine to produce freshwater and obtain lithium without evaporation (Baspineiro et al., 2020; Cerda et al., 2021; Flexer et al., 2018).

Scientists still have not reached consensus about the way that groundwater interacts with brine (Halkes et al., 2024). Some hydrogeological studies on Chile's Atacama salt flat, supported by the mining and EV industries, assert that brine is recharged mostly through precipitation and transition pool water, while an underground "mixing zone" serves as a saline barrier that separates the geochemically distinct halite brine nucleus from fresh lagoon water (Boutt et al., 2016; Marazuela et al., 2019a; Moran et al., 2022; Munk et al., 2021). Nonetheless, brine and freshwater are interconnected and hydrodynamic rather than static, so concerns remain about the potential depletion of fresh groundwater flowing into salt flats in place of pumped brine (Agusdinata et al., 2018; Alam & Sepúlveda, 2022; Liu et al., 2019; Liu & Agusdinata, 2021; Schomberg & Bringezu, 2023). This may depend on the rate, volume, and location of pumping wells, as well as the maturity, porosity, permeability, and damping capacity of particular salt flats (Amphos 21, 2018; Border & Sawyer, 2014; Flexer et al., 2018; Houston et al., 2011; Marazuela et al., 2019b; Marazuela et al., 2020). Brine takes millions of years to form, so it is not a renewable resource (Flexer et al., 2018, p. 1192). The combined effects of climate change and lithium mining have already directly reduced the local populations of two of the three flagship species of flamingos that depend on surface water and uniquely threatened cyanobacteria as a food source in Andean salt flats (Bonelli & Dorador, 2021; Cubillos et al., 2018; Gajardo & Redón, 2019; Gutiérrez et al., 2022; Marconi et al., 2022; Romero et al., 2012).

2.3 | Direct lithium extraction

To avoid the pitfalls of evaporation, innovative approaches have been proposed to extract lithium from brine solutions within their aqueous saline matrix. These new methods, collectively referred to as DLE, have the potential to process both continental brines and less concentrated sources without the need for evaporation ponds.[4] However, these novel technologies still use and impact freshwater.

DLE methods, including ion exchange, adsorption, liquid–liquid extraction, and membrane processes, rely on freshwater for eluting lithium from the sorbent phase. Ionic exchange resins possess a strong affinity for lithium cations, enabling their adsorption onto small resin particles typically packed within columns (Vera et al., 2023). Following several bed-volumes of adsorption operations, the functional groups on the resins become saturated, requiring regeneration (Stringfellow & Dobson, 2021). Ion exchange resin regeneration poses environmental challenges as it requires substantial amounts of freshwater to prepare solutions. Water is needed to strip lithium chloride and wash hydrochloric acid from sorbents. Some studies have even calculated freshwater requirements exceeding 500 m^3 per ton of Li_2CO_3 during the DLE process (Vera et al., 2023).[5] This is more than 10 times greater than the amount of freshwater reported for industrial use in current brine evaporation activities, underscoring the substantial demand for water in DLE. A thorough quantification of freshwater consumption, as well as potential risks of hydrological disturbances from processing high volumes of brine in DLE, needs to be done, particularly in arid locations where DLE has been developed or proposed, such as the Puna region of Argentina, the Qinghai province of China, and the southwestern United States (Li et al., 2020; Marconi et al., 2022; Mousavinezhad et al., 2024; Sun et al., 2021).

The Fénix Project at the Hombre Muerto Salt Flat in Catamarca, Argentina is one of the only sites where DLE has been used on a commercial scale for decades, even though the operator also uses evaporation ponds for concentration before and after the adsorption DLE process (Grant, 2020). This project's freshwater extraction has resulted in depletion of the Trapiche River—drying up 7 km^2 of the adjacent meadow—in a protected wetland with restrictions on the industrial use of water (Marconi et al., 2022; OPSAL, 2024). In March 2024, the Argentine Court of Justice ruled in favor of the Atacameños del Altiplano Indigenous Community, halting permits and authorizations for further expansion and exploitation in the broader Los Patos River basin until cumulative impacts are accounted for in a comprehensive environmental impact study (OPSAL, 2024).

To use DLE without evaporation, some developers have proposed extracting lithium from geothermal and oilfield brines.[6] Geothermal brines are hot brines that are brought to the Earth's surface and used to flash steam for electricity generation. Even though there are considerable waste streams due to scaling and filter cake material, geothermal developers describe this form of energy as a renewable resource because once the brine is cooled, much of it is reinjected into the same subterranean deposit (Dobson et al., 2023). Geothermal DLE has been under development in Germany's Upper Rhine Graben (Grant, 2019; Kölbel et al., 2023; Sanjuan et al., 2022; Schenker et al., 2024; Weinand et al., 2023), England's Cornwall county (Bridge & Faigen, 2023) and California's Salton Sea in Imperial Valley (Huang et al., 2021; Naimark, 2023; Paranthaman et al., 2017; Slattery et al., 2023; Stringfellow & Dobson, 2021).

However, as life cycle assessments have indicated and environmental justice groups near the Salton Sea have pointed out, geothermal DLE may require even greater quantities of freshwater (Naimark, 2023; Schenker et al., 2024). Water is needed not only for the DLE process, but also for use in cooling towers and brine dilution during geothermal operations. Moreover, improper reinjection of spent brines may lead to the dilution of lithium-rich resources (Dobson et al., 2023). Technical studies and reports have documented instances where improperly injected brines rapidly interfere with production wells and induce seismic activity (Flexer et al., 2018; Horne, 1982; Hymans & Uchikoshi, 2022; Naimark, 2023; Vera et al., 2023).

Seeking to diversify in the transition away from fossil fuels, oil firms have sought to adapt enhanced drilling technologies to deploy DLE in oilfield brines, including produced water from hydraulic fracturing and tar sands tailings ponds (Al-Ghouti et al., 2019; Bense, 2024; Samuel et al., 2022; Scheyder, 2023; Shaffer et al., 2013; Thiel & Lienhard, 2014). This might open up brownfield development opportunities, but it also risks perpetuating reliance on fossil fuels and ignoring critical challenges related to decommissioning and remediation of uncapped oil and gas wells that continue to contaminate the water supply for fenceline communities (Partridge et al., 2023; Wylie, 2018).

3 | DOWNSTREAM LITHIUM LIFE CYCLE

Lithium's full life cycle impacts on water extend beyond extraction to include processing, manufacturing, use, and end of life (Box 1).

3.1 | Processing

Lithium that is extracted from Earth in brines, hard-rock minerals, clays (or recovered from tailings or recycled sources) is processed into several compounds, including lithium carbonate, lithium chloride, lithium hydroxide, or lithium sulfate, depending on the source materials and processing pathways (Figure 2). The material most produced from lithium obtained by way of open-pit mining is lithium hydroxide, though lithium carbonate, lithium chloride, and lithium sulfate are also major products. Most other brine-based sources of lithium are processed into lithium carbonate (Chagnes & Swiatowska, 2015).

BOX 1 Water analysis in lithium life cycle assessments (LCAs)

Water metrics generated by quantitative frameworks such as life cycle assessment (LCA) are often limited or underused in relation to mined materials, including lithium (Awuah-Offei & Adekpedjou, 2011; Kaunda, 2020). Lithium LCAs may offer insights on projected energy consumption and carbon intensity impacts yet lack social and hydrogeographic context, such as degree of water stress on the implications of water use by life cycle stage (Ambrose & Kendall, 2020; Khakmardan et al., 2023; Stamp et al., 2012). LCAs funded directly by major lithium brine evaporation companies exclude brine from water resource analyses that emphasize the relatively high use of energy and freshwater for ore-based lithium from open-pit mining (Kelly et al., 2021). Yet, regionalized impact analyses show that LCAs have underestimated the site-specific environmental and social impacts of brine evaporation, which vary depending on local conditions (Schenker et al., 2022; Stamp et al., 2012). Extended LCAs that do include brine, as well as ore in the scope of analysis, may reveal a more comprehensive water scarcity footprint of lithium-ion batteries, particularly when integrated with local hydrological cycles and downstream processing pathways (Chordia et al., 2022; Halkes et al., 2024; Schomberg et al., 2021; Schomberg & Bringezu, 2023). Research areas deserving further attention include LCAs of freshwater use in DLE (Halkes et al., 2024; Huang et al., 2021; Li et al., 2020; Mousavinezhad et al., 2024; Schenker et al., 2024), as well as cradle-to-cradle impacts from downstream processes (Arshad et al., 2022; Lai et al., 2022).

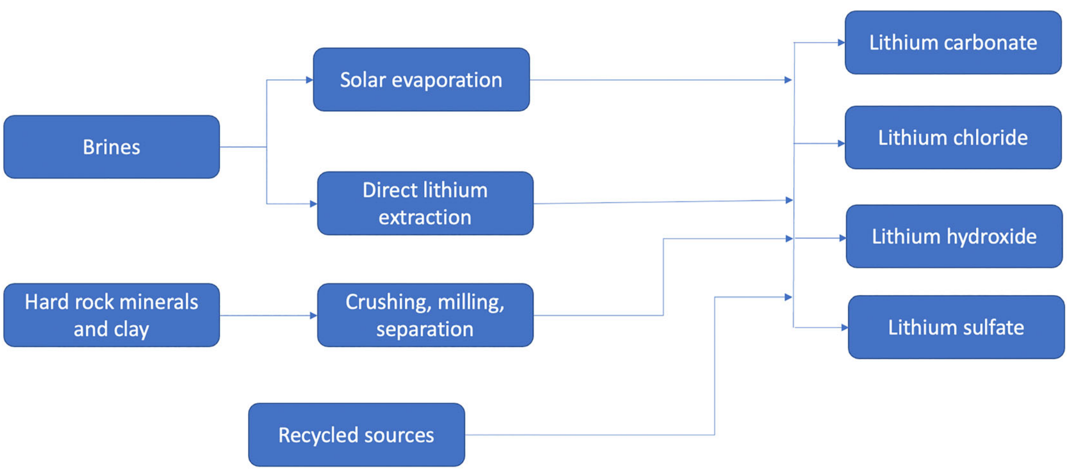

FIGURE 2 Lithium compounds produced through different processing pathways.

Lithium processing can result in freshwater ecotoxicity impacts and significant quantities of wastewater that need to be treated, reinjected, or disposed of some other way (Chordia et al., 2022). Processing wastewater may include heavy metals, other by-product minerals, silica, and solid wastes that require disposal at a materials recovery facility, landfill, or hazardous waste site (Dobson et al., 2023).

For open-pit mining, the first step in processing is leaching lithium from lithium ores using acid and/or bases, which can impact groundwater in a region (Kemp et al., 2010). Once minerals are crushed and milled, they are screened and separated. Onsite water impacts for these tasks in open-pit mining activities can be among the most water-intensive phases in all lithium life cycle stages (Jiang et al., 2020).

For brine sources, processing wastewater from lithium carbonate and lithium hydroxide may be recovered for reuse or reinjection (Flexer et al., 2018; Halkes et al., 2024; Miller et al., 2022). DLE processing techniques can result in potentially hazardous solid waste that requires special handling procedures for storage, disposal, or recovery. Sites of lithium processing, for example, the processing facilities of the proposed Thacker Pass lithium mine, have raised local concerns about the transport of sulfuric materials and the use of water to make and use sulfuric acid on site (Rothberg, 2021).

3.2 | Manufacturing

Lithium compounds are used in a variety of products from batteries to glass, ceramics, greases, and medications. Lithium-based batteries include lithium-ion, lithium-metal, and lithium-ion polymer batteries. The lithium used in lithium batteries is made into battery electrodes. Processed materials are prepared into a battery-grade powder form for use in manufacturing battery electrodes. Active materials, binders, and conductive additives are mixed to make a slurry that is then applied to coat a conductive foil (Lai et al., 2022).

Water use during manufacturing is relatively small at this life cycle stage compared to upstream extractive processes and consumes just 7% of the overall embodied water in a lithium-ion battery (Dai et al., 2019). Battery cell architectures vary considerably and continue to change, but every lithium-based battery contains electrodes, an electrolyte, and a charge separator. Chemicals of concern for water quality from lithium batteries include trichloroethylene (TCE), a widely known industrial water contaminant (Reif et al., 2003; Environmental Protection Agency [EPA], 2023). Battery cells come in a variety of types with different electrical properties, ancillary equipment, and safety requirements, including cooling water (Arshad et al., 2022). There is also embodied water in the various other materials to consider at this phase, which could include cobalt, graphite, nickel, manganese, copper, and other relatively high water-use metals. One study found that 50.8% of water use in the life cycle of photovoltaics is in the preparedness of the mining powders (Dai et al., 2019).

3.3 | Consumer and utility use

Battery storage has begun to play a significant role in the shift away from energy grid reliance on fossil fuels (Grid Status, 2024). Batteries have allowed for increased use of solar and wind power, but the rebound effects of new energy storage technologies are transforming landscapes (Reimers et al., 2021; Turley et al., 2022). Some stationary battery energy storage systems use active cooling water systems for thermal management (Li et al., 2018; Siruvuri & Budarapu, 2020). Cooling water discharges could cause thermal pollution, although not at levels seen with once-through cooling systems for power plants that generate several times over more waste heat per unit energy delivered. Other cooling systems may include heat transfer fluids or be air cooled, requiring no water at all. Lithium batteries are also flammable, and there are potential water quality risks from hazardous materials that could be deposited from fires and water used to put out fires.

3.4 | End of life

There are several processes for recycling lithium batteries, including direct, pyrometallurgical, hydrometallurgical, or bio-hydrometallurgical methods, all of which involve water (Baum et al., 2022; Lai et al., 2022; Meng et al., 2021; Mishra et al., 2022; Swain, 2017). Recycling techniques, such as the use of solvents, may result in water quality hazards (Bae & Kim, 2021; Hossain et al., 2023). Battery recycling can also result in greenhouse gas emissions, air pollution, and toxic exposure (Liang et al., 2021; Mrozik et al., 2021; Zhang et al., 2018). Landfilled batteries and informal/illegal processing of batteries can generate toxic leachate which can pollute groundwater (Meshram et al., 2014; Mrozik et al., 2021; Winslow et al., 2018). Fires at landfills or recycling facilities present another hazard and can result in toxic gas emissions and water pollution (Harper et al., 2023; Mrozik et al., 2021). An alternative for spent EV lithium batteries would be reuse or repurposing in "second life" applications: once a battery's useful lifespan in an EV is exhausted, the battery may support other energy storage functions (Casals et al., 2019).

4 | CONCLUSION

In sum, lithium has different impacts on water and society depending on its life cycle stage, its specific place-based geographies, as well as the mode of extraction or processing pathway. Open-pit mining uses significant quantities of freshwater and can contaminate local waterways. Brine evaporation exacerbates water depletion, especially when brine is factored into regional water assessments. While it is framed as sustainable by comparison, DLE may require more freshwater than brine evaporation. Processing lithium results in wastewater, and battery manufacturing may involve chemical contaminants. Regarding the use of lithium batteries for energy storage, significant amounts of water are used for cooling. Although battery recycling may appear to be a more circular approach than landfills, it still presents hazards for water quality.

A comprehensive assessment of cumulative impacts on local environments and fenceline communities requires a holistic regulatory framework that includes brine as water and attends to the past, present, and future impacts of lithium on water quantity and quality. The most promising scientific developments take a precautionary approach to ensure water justice at the basin scale amid expansion of conventional mining and deployment of novel DLE technologies to source new battery materials for the energy transition. New research directions might consider taking a more community-engaged and cradle-to-cradle approach to lithium LCAs, including impact analysis of freshwater use in DLE, as well as wastewater pollution, cooling water, and recycling hazards from downstream processes.

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James J. A. Blair: Conceptualization (lead); data curation (lead); formal analysis (lead); funding acquisition (supporting); investigation (equal); methodology (equal); project administration (lead); writing – original draft (equal); writing – review and editing (lead). **Noel Vineyard:** Conceptualization (supporting); formal analysis (supporting); funding acquisition (supporting); investigation (equal); methodology (equal); writing – original draft (equal); writing – review and editing (supporting). **Dustin Mulvaney:** Conceptualization (supporting); formal analysis (supporting); funding acquisition (supporting); investigation (equal); methodology (equal); visualization (supporting); writing – original draft (equal); writing – review and editing (supporting). **Alida Cantor:** Conceptualization (supporting); formal analysis (supporting); funding acquisition (lead); investigation (equal); methodology (equal); visualization (lead); writing – original draft (equal); writing – review and editing (supporting). **Ali Sharbat:** Investigation (equal); methodology (equal); writing – original draft (equal). **Kate Berry:** Conceptualization (supporting); formal analysis (supporting); funding acquisition (supporting); investigation (equal); methodology (equal); writing – original draft (supporting); writing – review and editing (supporting). **Elizabeth Bartholomew:** Conceptualization (supporting); formal analysis (supporting); investigation (equal); methodology (equal); writing – original draft (supporting). **Ariana Firebaugh Ornelas:** Data curation (supporting); investigation (equal); methodology (equal); project administration (supporting).

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CONFLICT OF INTEREST STATEMENT

There is no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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ENDNOTES

[1] We recognize that fossil fuels have negative impacts on waters and peoples, and that the electrification of transportation and energy systems is an important component of addressing climate change. Yet, following the principles of environmental justice, it remains critical to understand how the energy transition shifts impacts, benefits, and burdens across geographies and communities unevenly, through distributive, procedural, and representational inequities (Bouzarovski, 2022; Bridge et al., 2013; Morena et al., 2019; Newell & Mulvaney, 2013; Pellow, 2000; Stark et al., 2023; Stevis & Felli, 2016; Wang & Lo, 2021).

[2] This primer is not exhaustive but offers a general introduction to key concepts and debates about lithium and water. Our method to review the relevant literature has drawn from social scientific research and qualitative data analysis. The authors have engaged directly in research with affected communities on issues related to water and environmental justice across the life cycle of energy storage. This has involved a range of methods, including semi-structured interviews, participant observation, document analysis, Q methodology, and comparative governance analysis, We also use qualitative data analysis software (Quirkos) to code and analyze data collected to identify and characterize burdens and benefits of lithium for water and society. However, this primer results mainly from secondary source literature following a citation tracing process for review. We collected relevant publications from academic journal databases and categorized them by relevance to the life cycle stage to synthesize key findings. After drafting the review, we synced Zotero library collections corresponding to each life cycle stage with the Research Rabbit Discovery application to uncover and map networks of additional connections with similar, earlier, and later work. This iterative process has allowed us to trace citations, screen references for selection, and sufficiently saturate the most salient concepts for the primer.

[3] Social scientists conceptualized the hydrosocial cycle to overcome dualisms between nature and society and uncover hydrology's historical conditions, including anthropogenic impacts of extractive industries, such as lithium mining (Bakker, 2002; Liao & Schmidt, 2023; Linton, 2010; Linton & Budds, 2014, p. 170; Schmidt, 2019; Swyngedouw, 2004; Swyngedouw et al., 2002). We build on the related concept of "hydrosocial territories" to shed new light on green sacrifice zones disproportionately affected by water-intensive transitions to renewable energy (Berry & Cohn, 2022; Blair,

Gutierrez, & Balcázar, 2023; Boelens et al., 2016; Cantor, 2021; Duarte-Abadía et al., 2015; Hommes & Boelens, 2017; Zografos & Robbins, 2020).

[4] DLE encompasses various technologies, including but not limited to ion exchange resins (also known as ion sieves), adsorption to desorption, liquid–liquid extraction (also known as solvent extraction), electrodialysis membrane processes, membrane nanofiltration, and electrochemical ion pumping (Battistel et al., 2020; Joo et al., 2020; Khalil et al., 2022; Nie et al., 2017; Park et al., 2020; Somrani et al., 2013; Song et al., 2017; Swain, 2016; Torres et al., 2020; Vera et al., 2023; Wang et al., 2022; Xu et al., 2016; Zavahir et al., 2021).

[5] The water footprint of DLE may vary in life cycle assessments depending on the electricity source (Mousavinezhad et al., 2024).

[6] Seawater has also attracted some interest as a potential lithium source but has not generally been considered sustainable or commercially viable (He et al., 2020; Liu et al., 2020; Mends & Chu, 2023; Nishihama et al., 2011; Stamp et al., 2012; Yang et al., 2018; Zhao et al., 2019).

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