Geoforum 58 (2015) 38–50

Contents lists available at ScienceDirect

Geoforum

journal homepage: www.elsevier.com/locate/geoforum

A political–industrial ecology of water supply infrastructure for Los Angeles

Joshua J. Cousins *, Joshua P. Newell

School of Natural Resources and Environment, University of Michigan, 440 Church Street, Ann Arbor, MI 48109, USA

ARTICLE INFO

Article history:
Received 5 February 2014
Received in revised form 30 September 2014

Keywords:
Urban political ecology
Industrial ecology
Urban metabolism
Carbon footprints
Water resources
Life cycle assessment

ABSTRACT

This paper develops a political–industrial ecology approach to explore the urban water metabolism of Los Angeles, which sprawls for thousands of miles across the American West. Conventional approaches to quantify urban carbon footprints rely on global, national, or regional averages and focus narrowly on improving the efficiency of flows of resources moving into and out of the city. These approaches tend to "black box" the methodologies that guide the carbon emissions calculus and the social, political, ecological, and economic processes that perpetually reshape nature–society metabolisms. To more fully delineate the water supply metabolism of Los Angeles, this paper combines theory and method from urban political ecology and industrial ecology. Specifically, we infuse spatiality into the traditional life-cycle assessment (LCA) approach by coupling it with GIS. By illustrating how decisions about system boundaries, emissions factors, and other building blocks fundamentally shape the end result, this intervention at once destabilizes and advances the LCA enterprise. Then, using interviews and historical analysis, we provide a critical analysis of how LA's various water supply infrastructures came to be and illustrate how a sustainable transition based on a narrow carbon calculus is problematized by historical circumstances and strategic (and often conflicting) new paradigms to secure water resources. The political–industrial ecology approach offers valuable insights into the spatiality of material metabolisms and the socio-political processes (re)shaping the relations between nature and society.

1. Introduction

> "*Owens Lake, the terminus of the [Owens R]iver, sat at an elevation of about four thousand feet. Los Angeles was a few feet above sea level. The water, carried in pressure aqueducts and siphons, could arrive under its own power. Not one watt of pumping energy would be required. The only drawback was that the city might have to take the water by theft*".
>
> [Reisner, 1986, 61]

While theft may no longer be an option in Los Angeles's quest to secure and increase its water supply, Reisner draws attention to two important aspects that this paper seeks to address. The first aspect is the embodied energy and emissions of Los Angeles's water supply metabolism. Los Angeles, like other global cities, has established programs for reducing GHG emissions while making overt references to reduce their reliance on distant and uncertain resource flows and infrastructures (Bulkeley and Betsill, 2013; Bulkeley, 2010; Rice, 2010). These concerns over "urban ecological security" reflect exposure to regulatory, climatic, and political drivers that influence how the City of Los Angeles is managing its water supply through the development of local and decentralized systems to build greater self-sufficiency and reliance while simultaneously reducing GHG emissions (Hodson and Marvin, 2009; Hughes et al., 2013; LADWP, 2010a). Indeed, climate models indicate that snowpack in the Sierras may decrease from its mid-20th century average by 25–40% by 2050 reducing the water available via the Los Angeles Aqueduct (CDWR, 2008). This, coupled with ongoing drought conditions, is driving policy makers and planners to rework the socio-technical systems delivering water to the region.

Faced with simultaneous pressure to reduce GHG emissions while securing a stable supply, cities like Los Angeles have begun to assess the nexus between water and energy consumption by measuring the carbon footprint of their water systems. The methodology guiding these analyses is life-cycle assessment (LCA), an important tool in industrial ecology that quantifies environmental impacts of products and processes during each phase of its "life"—from material extraction to disposal (Freidberg, 2013; Graedel and Allenby, 2003; Newell and Vos, 2011). In theory, once the carbon

---

* Corresponding author.
E-mail addresses: jojaco@umich.edu (J.J. Cousins), jpnewell@umich.edu (J.P. Newell).

http://dx.doi.org/10.1016/j.geoforum.2014.10.011
0016-7185/© 2014 Elsevier Ltd. All rights reserved.

emissions burden—or the relative impact or footprint of the respective life phases, process, or product—is known, strategies to facilitate low-carbon and sustainability transitions can be made (Bulkeley, 2010; Bulkeley et al., 2013; Hodson and Marvin, 2010; Smith et al., 2005). This calculative process of urban environmental governance centered on "carbon control" often drives interventions to re-work urban socio-technical systems (Bulkeley and Castán Broto, 2012; Jonas et al., 2011; While et al., 2010). To increase local supplies, LADWP is focusing on projects that increase recycled water, expand water conservation, enhance stormwater capture, and establish green building initiatives (LADWP, 2010a, 2010b; Solorio, 2012; Villaraigosa, 2008). The objective is to make water demands more efficient while developing supply sources that are less vulnerable to climate change (LADWP, 2010a; Villaraigosa, 2008). But this (re)development of socio-technical systems to re-work Los Angeles's water metabolism may not always align with the desired emissions targets or foster a social and environmentally just system.

The second aspect this paper addresses is the historical and political processes shaping the water supply metabolism of Los Angeles, a metabolism that extends to the watersheds of the Sacramento and Colorado Rivers and to the Owens Valley and High Sierras (Fig. 1). Building the 233-mile Los Angeles Aqueduct (LAA), for example, required the construction of 120 miles of railroad track, 500 miles of roads and trails, 240 miles of telephone line, and 170 miles of transmission line (Reisner, 1986). The relationships and interdependencies among and between these infrastructures represent a unique political ecology, one that materialized out of the political and economic support for William Mulholland's vision to bring the waters of the Owens Valley to Los Angeles. The social–ecological transformation of the Valley that followed was the result of failed protests, legal challenges and national laws, rules, negotiations, and agreements between Valley residents and the City of Los Angeles. With current concerns over carbon emissions, however, the low emissions burden of water conveyed via the LAA brings into contrast the contradictions between reducing emissions and the internal properties, politics, and contestations that are hidden or "black boxed" (Latour, 1987) when focusing only on the input–output analysis of reducing GHG emissions or supplying a city with water.

We investigate these aspects through a framework that utilizes industrial ecology (IE) and urban political ecology (UPE) to examine the energy and material flows of Los Angeles's urban water metabolism. The approach integrates spatiality and critical theory from geography to develop a political–industrial ecology approach to the study of urban metabolisms. This is done by building a spatially-explicit LCA to model the embodied energy and emissions of Los Angeles's water supply sources. The analysis is scaled down to the utility to provide a finer grained analysis of the city's water supply metabolism and as a means to advance LCA by integrating spatial differentiation into the modeling process. While the GIS–LCA coupling provides a well-suited approach to explore the spatialized emissions and some environmental impact questions, it is limited in its ability to consider the socio-political dimensions of GHG emissions. To address this limitation, we link the LCA–GIS model with insights from political ecology to explore the planning

Fig. 1. Map of water supply sources for the City of Los Angeles.

contradictions that arise when managing water through the lens of carbon emissions. To do this, we interviewed water managers in Los Angeles and examined policy documents and newspaper articles to situate the urban metabolism within the everyday practices of the governmental agencies and societal groups who participate in (re)shaping it. By revealing the spatiality of material and energy flows and the internal and heterogeneous social, political, economic and ecological properties that (re)structure them, this approach helps open up the black box of both the input–output methodologies that underlie the measurement of GHG emissions and the processes that guide environmental decision-making.

The following section provides an overview of literature in IE and UPE, paying particular attention to how the metabolism metaphor is used in each field in order to develop the political–industrial ecology approach. We then outline our method, which combines LCA and spatial analysis with interviews and document analysis to explore the "interwoven knots of *social process*, *material metabolism* and *spatial form*" (Swyngedouw and Heynen, 2003, p. 906) that shape Los Angeles's water supply metabolism. Section 4 presents and discusses the results of the spatially-explicit LCA of Los Angeles's water supply and compare it to conventional LCA approaches. The analysis provides a critique of conventional LCA approaches by revealing how decisions and assumptions about the scoping of system boundaries can alter the result of an LCA, but also advances the method by elucidating how *spatial form* influences the *material metabolism* of Los Angeles's water supply. Section 5 expands the analysis to the *social processes* that (re)structure Los Angeles's urban water metabolism.

2. Theoretical framings: urban metabolisms and socio-technical systems

As mediators of resource consumption and disposal, socio-technical systems—the interrelated social and physical components of urban infrastructural networks—have multi-scalar and multi-sited effects on climate, biotic communities, and the health of humans and non-humans within and beyond the city, metropolis, and region (Bulkeley and Castán Broto, 2012; Bulkeley et al., 2013; Furlong, 2010; Hodson et al., 2013; Lawhon and Murphy, 2011; Mollinga, 2013). To grasp this dynamism, scholars have begun to point toward the value of developing integrated approaches that utilize urban metabolism as a conceptual framework, bringing together theory and method from industrial ecology, political ecology, and other disciplines (Castán Broto et al., 2012; Hodson et al., 2012; Kennedy et al., 2012, 2011; Newell and Cousins, 2014; Pincetl, 2012; Pincetl et al., 2012; Ramaswami et al., 2012). The utility of the urban metabolism concept is its ability to capture a range of perspectives that engage with urban sustainability while offering insights into how to make production and consumption patterns in cities more efficient and equitable. To be useful as an interdisciplinary boundary metaphor (Newell and Cousins, 2014), however, urban metabolism research needs to successfully integrate approaches and perspectives across fields. In this section, we focus our attention on the convergence of the metabolism metaphor between IE and UPE.

2.1. Industrial ecology

Urban metabolism is typically defined among industrial ecologists as "the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" (Kennedy et al., 2007, 44). The term itself was popularized in 1965 by the sanitary engineer Abel Wolman after the publication of his seminal article in *Scientific American* where he quantified the metabolic inputs (water, food, and energy) and outputs (waste) of a hypothetical American city. The formal development of IE, however, was forged by physicists and engineers in the late 1960s in an effort to use "nature" as a model to research existing industrial systems and develop more efficient and resilient urban forms (Frosch, 1992; Jelinski et al., 1992; Newell and Cousins, 2014).

Industrial ecologists in the Wolman tradition apply mass-balance accounting methodologies such as material flow analysis (MFA) to quantify the "stocks" and "flows" of the urban metabolism (Baccini and Brunner, 2012; Baccini, 1996). MFA can be viewed as a methodology to quantify indicators of urban (un)sustainability that inform strategies to optimize resource use through efficiency gains, dematerialization, and waste reuse (Barles, 2009; Hodson et al., 2012). Influential case studies have examined a range of cities from Hong Kong (Newcombe et al., 1978; Warren-Rhodes and Koenig, 2001) and Tokyo (Hanya and Ambe, 1976) to Paris (Barles, 2009, 2007a, 2007b) and Vienna (Hendriks et al., 2000) among many other cities. This emerging school of research is demonstrating the robustness of MFA as a methodology to understand and quantify urban metabolisms.

Scholars in IE are beginning to utilize LCA in place of, or coupled with, MFA, as an alternative approach. LCA, which traditionally focuses on the "cradle-to-grave" environmental impacts of products and processes (Guinée, 2002; Keoleian and Menerey, 1994), offers possibilities for more fully capturing "upstream" and "downstream" environmental impacts of resource flows that extend beyond urban borders (Newell and Vos, 2011; Pincetl et al., 2012). The International Standards Organization (ISO) 14040 protocol demarcates a standardized set of rules and requirements for LCA procedure (Freidberg, 2013; Newell and Vos, 2011). The standard LCA method includes the definition of the goal and functional unit, delimitation of scope or system boundary, life-cycle inventory (LCI) or the accounting of pollution and resource extraction in each phase, and life-cycle impact assessment (LCIA) (Newell and Vos, 2011). The final LCIA stage focuses on improving the performance of the product or process in question.

2.2. Urban political ecology

In contrast, scholars under the banner of UPE have typically criticized the IE approach. For Erik Swyngedouw, "studies on urban metabolism have often uncritically pursued the standard IE perspective based on some input–output model of the flow of 'things.' Such analysis merely poses the issue, and fails to theorize the making of the urban as a socio-environmental metabolism" (2006b, 35). Other scholars such as Keil and Boudreau (2006, 43) point toward the "restrictiveness" of traditional IE urban metabolism studies in that they offer a weak analysis of the political context, capitalist economy, and social patterns that shape the metabolism. Gandy (2004) asserts that the "relational" notions of urban metabolism dominant in UPE are now more appropriate metaphorical conceptualizations of urban space than the "functional-linear" or neo-organismic ones that are derived from "technocratic urban models." The approach used by industrial ecologists is typically interpreted by UPE scholars as an apolitical platform, one undergirded by a logical positivism that typically leads to neo-Malthusian conclusions and outcomes (Harvey, [1974] 2001).

In place of input–output models based on the "flow of things", urban political ecologists frequently draw upon Marxist notions of metabolism to characterize the hybrid and relational aspects of economic, political, and ecological processes that form uneven urban social–ecological systems (Gandy, 2005; Heynen et al., 2006; Swyngedouw and Heynen, 2003; Swyngedouw, 2006a). Gandy (2002), for example, explores the production of "metropolitan natures" to demonstrate how nature is transformed by and enrolled into the political, economic, and social practices that shape New York City's form and function and its metabolic relationship to distal geographies. His exploration unveils how capitalist processes of urbanization link engineered systems conveying water to the ongoing transformations of distant natures and geographies. Similarly, Swyngedouw's (2004) analysis of water politics in Guayaquil, Ecuador moves beyond a singular focus on the flows of water by situating water in a "socio-environmental metabolism" that is entangled with the complexities of social power, control, and capital accumulation. Although not drawing on Marx, Cronon (1991) also shows how Chicago is a metropolis forged out of its metabolic relationship with its hinterland. Rather than accounting for the material inputs and outputs of the metabolic system, the focus in UPE is on the social and political processes and outcomes reconfiguring urban metabolic circulations in socially and geographically uneven ways.

2.3. Linking IE and UPE: toward a political–industrial ecology

On the surface these approaches and perspectives may appear incompatible. We argue, however, that approaches from industrial ecology to quantify the various stocks and flows coursing into and out of the city and critical approaches from political ecology can be used to gain new perspectives into nature–society relations. While IE may provide a latent set of quantitative methods for UPE to capture the broader impacts of resource flows and the environmental impacts of products and industrial processes, the measurement and modeling techniques lack critical insights into the historical, social, political, and economic mechanisms that influence metabolic urbanization. Adding a political ecology framework to traditional IE pushes inquiry toward an expanded approach to urban metabolisms that incorporates spatiality to develop more robust LCAs and includes a focus on issues of power in environmental decision-making to move beyond the apolitical tendencies of IE that focus narrowly on "win–win" scenarios between the economy and environment.

Practically speaking, in addition to quantifying stocks and flows, a political–industrial ecology refers to an analysis of the broader historical, political, social, technological and economic mechanisms shaping the relationships between a product, commodity or material process, its primary inputs and outputs, and the relevant social and ecological implications. The urban water metabolism of Los Angeles, for example, is dependent on energy inputs for water to circulate and flow within the hydrosocial cycle, requires industrial and infrastructural processes to pump, treat, and distribute water, and emits carbon as a primary output. The metabolic circulation of water, however, is reliant on a set of social and political relations that shapes and is shaped by its relationship to water. Linking political and industrial ecology provides a compelling way to begin to think through these type of quantitative and qualitative socio-ecological transformations.

Taking a political–industrial ecology approach that couples LCA with GIS, for example, provides a quantitative method for spatializing the specific water, food, waste, and energy metabolisms that connect urban and rural space (Newell and Vos, 2011). This further develops the potential for spatial and quantitative analysis in UPE while enhancing core UPE insights into the co-production of urban and rural space. Other quantitative measures have been used within UPE to measure and quantify the metabolic transformation of urban forests (Heynen, 2006; Heynen et al., 2006), the differences in air pollution monitoring techniques (Buzzelli, 2008), and the neighborhood level effects of urban densification and gentrification (Quastel et al., 2012). Through engagement with methods from IE, such as LCA, our approach provides an additional means to capture the social, political, industrial, and spatial variation of environmental impacts from material metabolisms, resource flows, products, and processes within and beyond the city and on urban socio-ecological systems. Specifically, we couple GIS and LCA to quantify the spatialized emissions of Los Angeles's water supply metabolism and utilize political ecology theory to explore the socio-political processes that (re)structure urban socio-natural landscapes.

2.4. Why water

In Los Angeles where the water supply metabolism extends to the watersheds of the Sacramento and Colorado Rivers and requires both local and imported sources (Fig. 2), the complexity of urban resource flows become apparent. Starting with water as the primary object of concern provides a bridge to explore linkages between two disparate approaches (IE and UPE) to understand the relationship between resource flows and urbanization. Water represents the largest component of all material flows within the urban metabolism (Decker et al., 2000; Kennedy et al., 2007), yet it is also one of the most political and contested objects of the urbanization process (Kaika, 2005; Swyngedouw, 2004). Furthermore, water flows present a geography that is nested within watersheds and sub-watersheds, thereby allowing urban water flows to be relatively spatially bounded, unlike most post-Fordist commodity chains and networks. Among other things, this enables industrial ecologists to locate and draw system boundaries in order to quantify the stocks and flows.

Moreover, as Matthew Gandy notes, "the history of cities can be read as a history of water" (Gandy, 2002, 22). Modernist theories of development in the nineteenth and twentieth centuries to rationalize the urban landscape involved the rolling-out of large socio-technical systems that influenced the form and function of the city. Water technologies and infrastructures, in particular, have received significant attention from urban political ecologists for their role in producing spaces of the modern city (Gandy, 2004, 2002, 1999; Kaika and Swyngedouw, 2000; Kaika, 2005; Loftus, 2012; Meehan, 2013a; Swyngedouw et al., 2002) and in mediating relationships between the human and non-human world (Birkenholtz, 2013; Budds and Sultana, 2013; Kaika and Swyngedouw, 2012; Swyngedouw, 2009). Studies of the Global North focus primarily on dams and large infrastructural systems or "mega projects" to supply and sanitize urban water (Gandy, 2002, 1999; Kaika and Swyngedouw, 2000; Kaika, 2005, 2003; Swyngedouw, 2013, 2007). In contrast, research centered in the Global South has examined tubewells, groundwater technologies, informal technologies of water provision, and the fragmentation

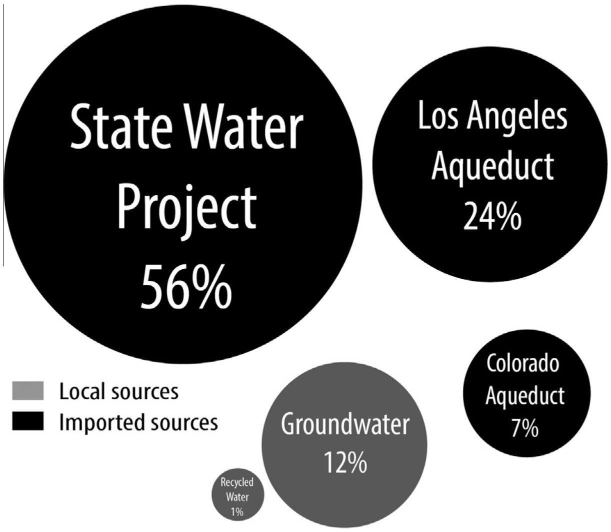

Fig. 2. Water supply by percent quantity. *Source:* LADWP (2010a).

of water supply networks (Birkenholtz, 2013, 2009a; Kooy and Bakker, 2008; Meehan, 2013a, 2013b; Sultana, 2013, 2011).

Whether in the Global North, Global South, urban or rural, water technologies are developed, implemented, and contested in heterogeneous ways that reflect the social histories of place, situated networks of power and knowledge, and the discourses of development (Birkenholtz, 2013, 2009b, 2008; Rocheleau and Roth, 2007; Rocheleau, 2008; Sultana, 2013). The outcome is a hydro-social transformation that re-works the relationships between water and society in socially and geographically uneven ways. The "complex network of pipes, water law, meters, quality standards, garden hoses, consumers, leaking taps, as well as rainfall, evaporation, and runoff" (Bakker, 2003, 337) that comprise the hydrosocial cycle gives shape to how water circulates as a resource through nature and society. Urban water metabolisms, in other words, reflect technological, institutional, and individual practices as much as the hydrological cycle in a "socio-natural process by which water and society make and remake each other over space and time" (Linton and Budds, 2013, p. 6).

The metabolic circulation of water in and through urban space transforms social and physical environments, albeit with the aid of energy. The pumping of groundwater, recycling water, or desalinating water all depend on energy inputs to flow and circulate. The hydro-social cycle is thus highly entangled with issues of energy and infrastructure (McDonnell, 2013), which have material impacts on global climate change through their emissions burden and on local ecologies and peoples during their construction, implementation and use phases. In California, nearly 20% of the total electricity consumption is devoted to the sourcing, collecting, transporting, and treatment of water (TCR and WEI, 2013). Water supplied to Southern California is especially energy intensive—approximately 50 times more so than to Northern California (CEC, 2005)—where an estimated one-third of household electricity use is devoted to water delivery (MWD, 1999). The broader impacts of the water–energy nexus are made relevant to planners and decision-makers through GHG accounting methods and supports low-carbon infrastructural developments. Re-shaping Los Angeles's urban water metabolism based solely on an IE carbon calculus, however, impedes considerations of power relations in environmental decision-making that can (re)distribute costs and benefits unevenly across race, class, and geography. In the following sections we provide an exploratory attempt for bringing together UPE and IE approaches to generate an urban political–industrial ecology of the metabolism.

3. Methods

We combine LCA and spatial analysis with interviews and document analysis to model the energy and emissions intensity of Los Angeles's water supply sources and to reveal its UPE. We first infuse spatiality into LCA by using GIS to "downscale" the modeling effort and compare and contrast it to the standard eGRID approach. This is done for multiple reasons. First, it offers the opportunity to open up the black box of the carbon modeling, measurement, and calculation process that drives urban climate governance by revealing the spatiality of carbon emissions. Second, it pays attention to areal differentiation that can significantly alter the actual carbon footprint of water. This at once destabilizes the carbon footprint accounting process, but also advances the method by rendering it more detailed and sensitive to the particular sites where GHG emissions are produced. For example, conventional LCA approaches typically use LCIs consisting of activity data and emission factors that are essentially global or national averages or drawn from studies of Western Europe where LCIs are well developed (Curran, 2006; Newell and Vos, 2011). Consequently, the minimization of areal differentiation in the production of a LCA is not only a practice that is aspatial and "flattens" geography (Newell and Vos, 2011, 732), but also masks the uneven spatiality of urban carbon emissions among and between socio-economic classes (Rice, 2014).

Second, we utilize perspectives from UPE and qualitative interviews to explore the social and environmental dimensions typically lost in quantitative approaches to urban metabolisms. The goal is to reveal the contradictions that arise when governing water through the lens of carbon and energy emissions. The analysis includes considerations of the social and environmental justice issues of these flows of water and carbon as well as the social practices of water resource management. The way carbon is modeled and measured is certainly a technical project performed by expert communities, but the black boxed result is also a political project with the power to re-work socio-technical systems. Insights from political ecology provide a means to interrogate how decision-makers use carbon metrics and narratives of urban ecological security to re-shape urban metabolisms.

3.1. Methods for a spatially-explicit LCA of Los Angeles water supply sources

Some within the LCA community are slowly developing procedures to make LCIs more spatially-explicit, and a small cadre of LCA and IE scholars are exploring the potential of GIS–LCA hybridity to incorporate geographic variability through case studies of land-use change and biodiversity (Geyer et al., 2010), energetic utilization of biomass via conditioned biogas (Dresen and Jandewerth, 2012), energy crop production (Gasol et al., 2011), and the sourcing of material for building and road infrastructure (Reyna and Chester, 2013).

Efforts to model the energy intensity and emissions burden of water are not particularly new, nor are they new to the California region. Wilkinson (2000, 2007), for example, has examined the energy footprint of water utilities and regions of California. The utilities themselves have conducted and commissioned studies of the energy and/or emissions profiles for portions of their water distribution systems (IEUA, 2009; LADWP, 2010a).

By coupling GIS and LCA, our study differs from these previous approaches in one significant way. We "downscale" to more accurately estimate the emissions associated with water supply. The default approach to obtaining the emissions factors of utilities is to use statewide, regional, or national averages (Marriott and Matthews, 2005; Soimakallio et al., 2011). Studies rely heavily on sources such as the Environmental Protection Agency's eGRID, a database that provides generalized emissions factors for electric power plants generating in the United States. In eGRID, California and portions of surrounding states fall within the CAMX (California–Mexico) Subregion. Essentially, energy and emissions factors are derived for CAMX by averaging energy and emissions profiles of plants for that entire subregion.

However, this emissions factor is not necessarily an accurate representation given that Los Angeles obtains water from five different sources across thousands of miles. The supply portfolios of California's utilities also vary significantly (Fig. 3). For example, Pacific Gas and Electric (PG&E) relies heavily on hydropower; thus it has a cleaner emissions profile than the CAMX average. In contrast, the LADWP grid mix remains heavily reliant on coal, producing a dirtier emission profile than the CAMX average. We were interested; therefore, in better understanding how the different grid mixes and utility sources along the water supply system would affect the city's carbon footprint and the potential implications this has for managing the water–energy nexus. To evaluate the respective importance of downscaling to the utility scale we contrast the results of our GIS–LCA method with the standard accounting approach.

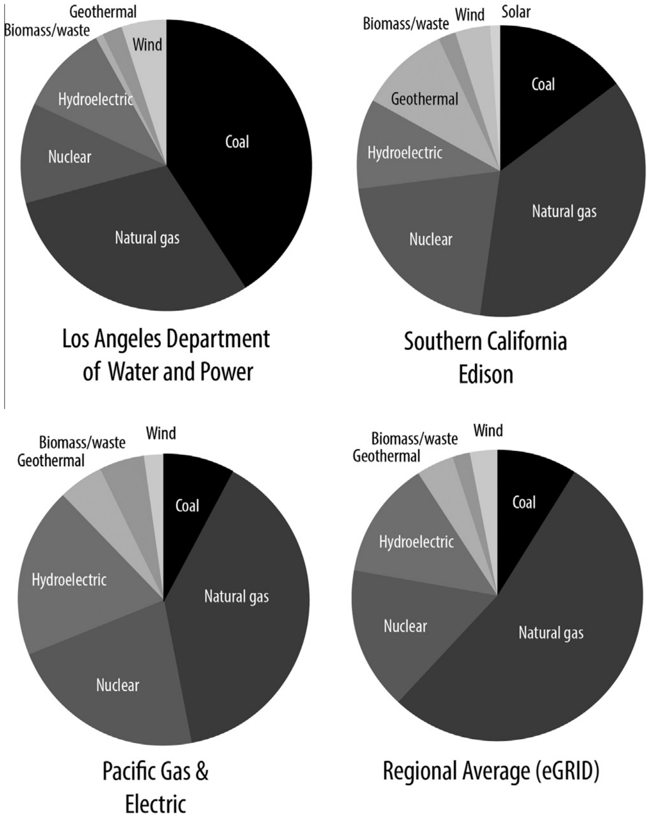

Fig. 3. Grid mix portfolios of major utilities. *Source:* LADWP (2010b) and Southern California Edison (2010).

3.1.1. System boundary and steps

We studied the portion of the water–energy nexus centered on providing water to consumers. The "system boundary" of the study is thus limited to three phases of water delivery: sourcing and conveying, treatment, and distribution to consumers (Fig. 4). We deliberately chose these phases as spatial variation can significantly influence them. However, this meant that other stages fell outside of the system boundary. For example, the "use" and disposal phases—or cleaning phases in the case of water—were excluded. In-home energy usage associated with heating and cooling water was also excluded, but it is widely recognized as the most intensive portion of the energy footprint of water. Our LCA also excluded the energy and emissions associated with the initial construction (e.g., energy embedded in the concrete used to construct aqueducts) and the "use" or maintenance phase of water infrastructure. In the case of infrastructure, the latter is typically much larger than the former. Reyna and Chester (2013) found, for example, the GHG emissions from the maintenance and rehabilitation associated with roads in Los Angeles County are more than four times higher than the emissions resulting from their initial construction, over the lifetime of the roadway network. These choices impose limits to the LCA analysis done, but the goal of this relatively simple LCA is to highlight how spatial variation and system boundary delineation can fundamentally change the carbon footprint of a product or process.

Our "functional unit" was one acre-foot (AF) of water delivered to Los Angeles and we measured the energy budget in terms of grams of CO_2e generated for each kW h. The activity data for the study—the quantity of water imported by source, energy intensity (kW h/AF), utility grid mix, water pumping, recycling, and treatment plant efficiency—came from a variety of sources, such as the LADWP Urban Water Management Plan (2010a). We developed emissions factors for the utility emissions and the energy sources in two primary steps:

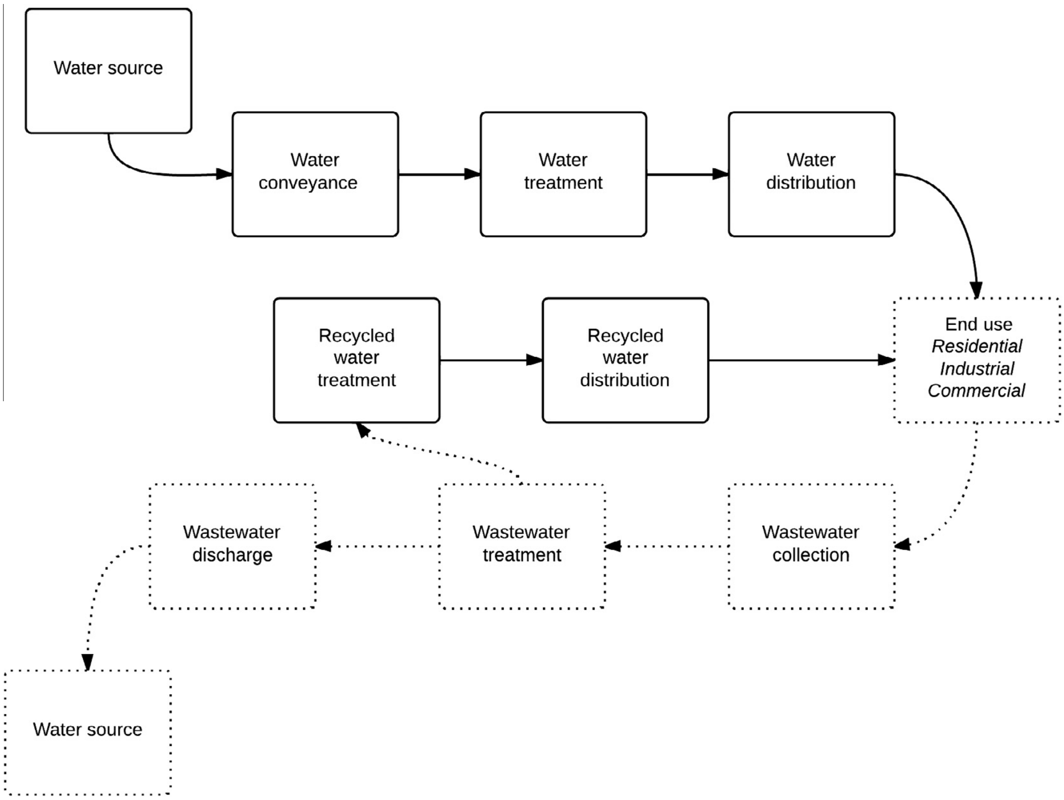

Fig. 4. Water supply system boundary. Scoped around water conveyance, treatment, and distribution moving from source to end use, including recycled water. *Source:* Adapted from CEC (2005).

1. Assign specific utility for pumping and transport, treatment, and distribution phases

We used GIS to map the water supply infrastructure for the five water supply sources. Some of these data were publicly available; others were obtained from the LADWP and the Metropolitan Water District (MWD). Data on the locations of the pumping plants were obtained using physical maps from agency publications (CDWR, 2011; MWD, 2009) and the California Energy Almanac and geocoded by cross-referencing the estimated X, Y coordinates in Google Maps. We then assigned each of these plants to a particular Electricity Utility Service Area (EUSA), a geographic area where a specific utility operates and supplies electricity. Los Angeles's groundwater and recycled water supply sources fall entirely within the LADWP service area and were assigned emissions burdens accordingly. Information on which utility to assign to the treatment plant was based on written correspondence with MWD and LADWP officials (Table 1). After the treatment phase, water is distributed uniformly throughout the city regardless of the source and requires the same amount of energy for all water sources (196 kW h/AF). Consequently, the sole utility assigned for the distribution phase is LADWP. Finally to determine the grid mix (coal, hydro, solar, etc.) for each utility and the corresponding emissions factors we used state-mandated power content labels.

2. Calculate the energy and emissions burden for the three life-cycle phases

For this step, we multiplied the activity data and the emissions factor for each of the three phases. Each of the pumping and treatment plants has different efficiencies, measured in kW h/AF, as well as energy inputs for a specific volume of water. Emissions profiles for each pumping plant were also generated based upon the distribution of net electricity consumption that could be attributed to each EUSA based on the annual electricity usage. The Colorado River Aqueduct (CRA) and State Water Project (SWP) conveyance systems are coupled with power generation, making it necessary to determine how much electricity was self-generated. We did not give these conveyance systems emissions credits for the hydropower generated (and sold to partner utilities) based on the assumption that this hydropower would be credited in the utility's generation portfolio. Hydropower used by the conveyance systems for pumping water was added to purchased electricity from the EUSA in order to determine an overall emissions factor for both systems. SWP reports PG&E, California Independent System Operator, and Southern California Edison as transmission providers; we assumed that daily spot purchases would be made on these grids.

3.2. Revealing the political ecology

In order to situate the quantitative measurement with the more qualitative aspects of water supply infrastructures we conducted 17 interviews, between December 2013 and June 2014, with water resource managers at city, county, and federal agencies and staff members of environmental NGOs. During these interviews we asked questions about the environmental, legal, political, and economic drivers of water sourcing and the role of new technologies and innovations in driving transitions. More specifically, the questions probed how sustainability was measured and calculated in terms of water resources and the impacts of these technologies and sourcing strategies on social and ecological systems. To better understand the everyday practices that guide the production and use of LCAs and the reshaping of urban metabolism, these interviews were supplemented with an analysis of policy documents, newspaper articles, and agency reports.

4. The spatialized energy metabolism of Los Angeles's water supply

The energy intensity of Los Angeles's multiple water supply sources is unequal and heterogeneous across phases of transportation, distribution, and treatment and source. As the LCA demonstrates, Los Angeles's geographically diverse water sources have

Table 1
Los Angeles Water Treatment Plants by utility provider and water source. *Source:* Interviews.

Water Treatment Plant	Electricity supplier	CRA (%)	LAA (%)	SWP (East) (%)	SWP (West) (%)	Gray water (%)	Total (%)
Robert A. Skinner	SCE	45		55			100
Joseph Jensen	LADWP				100		100
F.E. Weymouth	SCE	45		55			100
Robert B. Diemer	SCE	45		55			100
Henry J. Mills	CoR			100			100
LAAFP[a]	LADWP		55			45	100
Recycled water[b]	LADWP						0

[a] Los Angeles aqueduct filtration plant.

[b] Water reclaimed after delivery, use, and waste treatment.

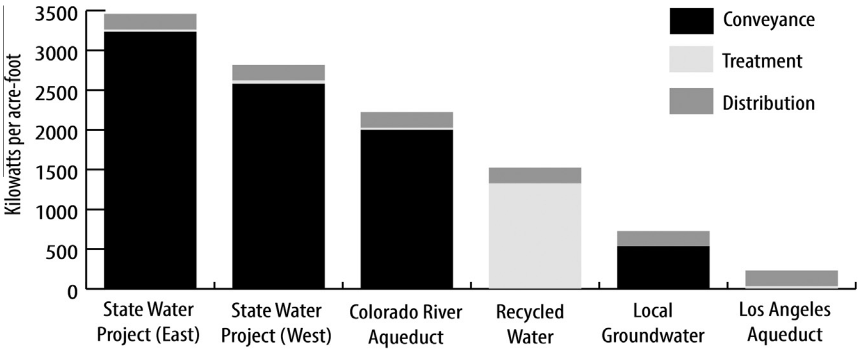

Fig. 5. Energy intensity of water supply sources, by phase, for Los Angeles. *Source:* LADWP (2010a).

widely varying energy and emissions profiles (Fig. 5). Water sourced from Northern California and the Sacramento Delta via the State Water Project (SWP) is the most expensive and energy intensive, requiring six pumping plants to carry it over the Tehachapi Mountains before it breaks into the East Branch (3459 kW h/AF) and the West Branch (2817 kW h/AF). Water from the Colorado River (2223 kW h/AF) is imported via the Colorado River Aqueduct (CRA) and requires five pumping stations to carry it to its terminus at Lake Matthews. In contrast, water sourced from the Eastern Sierra watershed and Owens River Valley via the LAA requires no net input of energy in the pumping and transport stages since the aqueduct is mainly gravity fed (230 kW h/AF). Other sources of water for southern California include local groundwater (726 kW h/AF) and recycled water from the San Fernando Valley (1524 kW h/AF).

For all water sources combined, the transport stage represented 88% of the energy footprint, followed by distribution (10% of the total), and treatment (2%). Part of the reason for the enormous transport footprint is Los Angeles's reliance on water supply from two major sources—SWP (56% of total water supply) and CRA (7% of total). By contrast, the gravity-fed LAA aqueduct has no transportation footprint. Local recycled water has a large treatment footprint as the water has to be made potable. In our study, we did not do specific modeling for different types of treatment technologies for recycled water (i.e., stormwater vs. industrial); these are likely to have differing energy footprints, but with important implications due to the desire of water utilities to increase the portion of recycled water in the overall water supply portfolio.

Although we only looked at these three phases, other studies of cities with remote water supply sources indicate a similar profile for the transport stage (Stokes and Horvath, 2009; Wilkinson, 2000). This is in contrast to many other resources and products such as food (Basset-Mens and van der Werf, 2005; Weber and Matthews, 2008) and forest products (Gower, 2006; Newell and Vos, 2011; Subak and Craighill, 1999) that indicate that transportation emissions are a comparatively small portion of overall emissions. These latter findings counteract "buy local" narratives that pervade discourses about local food, which by overemphasizing transport as an emissions source, conflate "greenness" with local sourcing. In the case of water, however, the water–energy nexus presents a complicated relationship between energy emissions and the collection, treatment, transport and disposal of water across geographic space.

4.1. eGRID vs. spatially-explicit accounting methodology

In terms of the emissions, the results of our spatially-explicit approach yielded a 38% lower emissions footprint than the eGRID approach (Fig. 6). It significantly reduced the emissions burden of water sources supplied by MWD, but increased the emissions burden of those sources supplied by LADWP. It was especially higher for groundwater (41%) and recycled water (54%); this is due to the relatively dirty grid mix of LADWP as compared to the cleaner eGRID average and grid mix of MWD where over 50% of Los Angeles's supply comes from. In particular, recycled water had a greater emissions footprint per acre-foot than water from the Colorado River. This highlights the relative importance of energy supply sources for the particular utilities, so much so that it outweighs the energy intensity of long distance transport of water from the Colorado. The results support the findings of Weber et al. (2010), which demonstrate how electricity emissions can vary depending on the spatial scale adopted, from nation, state production, state consumption, to eGRID subregion, and based on Energy Information Administration data.

4.2. Opening up the black box

At a more general level, what this relatively simple calculus reveals is how decisions such as system boundary delineation and degree of areal differentiation incorporated into activity data and emission factors can significantly alter the result. The comparative analysis of the eGRID approach with our spatially-explicit model exposes how geographic variability in Los Angeles's water supply sources (re)shapes the emissions profiles for each supply source and illustrates the challenges of calculating precise carbon footprints. The approach reveals the indeterminacy of the overall footprint of water whereby assumptions (the non-spatiality) about the grid mix shape the result. The relative neglect of spatiality into LCA exemplifies how assumptions about the focus of scientific inquiry are often built into the models explaining it (Jasanoff, 2004), much like critical geographers have shown for obesity (Guthman, 2011), and often reflect the economic and political motivations that shape how spatiality and system boundaries are negotiated and created.

In this regard, our method offers a "hatchet" by providing a critique of conventional LCA approaches, but also offers a "seed" by stressing alternative ways to understand and measure urban metabolisms in Los Angeles and beyond (Robbins, 2012). This seed is not limited to improved, albeit more contingent, carbon accounting due to better areal differentiation through the LCA–GIS coupling. Rather, the insertion of spatiality into LCA provides an opportunity to point toward the spatial location of "hotspots," or the life-cycle phase with the greatest social and environmental impacts, along the supply chains. Similarly, spatially disaggregating carbon emissions can point toward important socio-economic differences among and between urban populations and point toward policy and outreach that targets those populations most responsible for carbon emissions. As such, these empirical

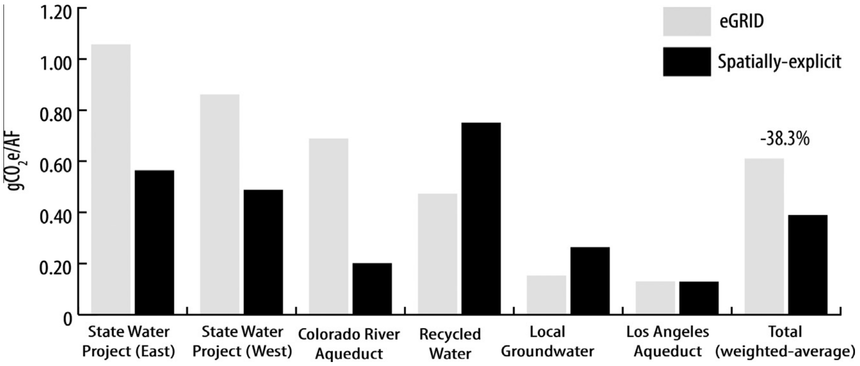

Fig. 6. Energy emissions burden by water source, eGRID vs. spatially-explicit LCA.

observations open up a set of intellectual possibilities that allow the mapping out and contextualization of the key phases, network agglomerations, and hotspots associated with a political ecology of urban water metabolisms. If combined with GIS and theoretical framings such as those found in UPE, the LCA method has the potential to be used and deployed for progressive purposes rather than as a narrowly conceived and technocratic device in the promotion of ecological modernization (Desfor and Keil, 2004).

To further link the results of the LCA with political ecology, we turn to an analysis of the least energy intensive water supply sources and those central to Los Angeles's vision for enhanced urban ecological security: the LAA and local sources (groundwater and recycled water). Both of these supply sources, if viewed only through the lens of carbon emissions, would be the preferred choices from which to acquire and to develop future water supplies. However, using a carbon calculus to guide transitions to a more sustainable water supply is not so simple. Utilizing insights from UPE are necessary to move beyond the limited scope of an LCA perspective to urban metabolisms.

5. The UPE of Los Angeles's water supply metabolism

Throughout its development, water has featured prominently in Los Angeles politics and the formation of its geographies. How the socio-technical systems tasked with conveying water came into being, however, reflect the diverse ways that the social histories of place, networks of power, and discourses of development are implemented and fought over at specific sites and times (Sultana, 2013). As such, the water supply metabolism of Los Angeles cannot be understood outside of this context. We situate our analysis within the historical and geographical networks of power, people, and institutions that emerge to reshape Los Angeles's hydro-social metabolism. The approach challenges dominant explanations and proposes alternatives on how infrastructures and GHG emissions come to matter politically (Forsyth, 2003; Furlong, 2010; Meehan, 2013b). In this section we provide a brief history of the development of the LAA. We then direct our focus to current shifts and transitions in the governance of Los Angeles's water supply to reflect on historical and contemporary political ecologies of urban water.

5.1. LA water: a brief history

On November 5, 1913, William Mulholland (in)famously proclaimed, "There it is. Take it." as water flowed through the LAA toward Los Angeles. For some, this was the instant that the modern city of Los Angeles was materially forged (Ulin, 2013). The socio-technical systems conveying water to Los Angeles, however, were discursively set into motion as early as 1904 when LADWP released its first report stating that "the time has come when we shall have to supplement the supply from some other source" (Klusmire, 2013; Reisner, 1986). By 1905, in an imperial quest for more water, city representatives began venturing to Owens Valley to buy parcels of land from local residents (McWilliams, 1949; Stringfellow, 2013). As McWilliams (1949) notes, Los Angeles had plenty of water, but speculation of future population growth fueled this water imperialism. Indeed, it was a project "founded in prospect," designed to meet the demands of an imagined future rather than the needs of the present (Kahrl, 1982).

The story of the LAA and the construction of large-scale technological infrastructures to convey water to Los Angeles's is well-documented (Kahrl, 1982; McWilliams, 1949; Reisner, 1986), but salient for this paper is how the transformation of Los Angeles's hydro-social environment involved the rolling-out of large socio-technical systems, producing new natures and new waterscapes by altering the flow, availability, and value of water in the process. The construction of the LAA certainly created new opportunities for long-term capital investment in Los Angeles, but the infrastructure also provided a key innovation that accelerated and structured the material metabolism of Los Angeles while increasing its presence and control over greater expanses of its hinterland. The production of this socio-nature emerged out of an uneven configuration of social, cultural, economic, and political power relations that reshaped Los Angeles's hydro-social metabolism.

Water scarcity issues were discursively constructed as the collective challenge facing California. This deflected attention away from issues such as social justice, land distribution, and the environment in places like Owens Valley while benefitting an elite syndicate of individuals in the San Fernando Valley. Negotiations over land and water rights between representatives of the City of Los Angeles and 1800 farmers and town lot owners between 1905 and 1935 resulted in the acquisition of 95% of the farm acreage and 88% of the town properties in the Owens Valley (Libecap, 2005). This enabled the City of Los Angeles to capture and control ever greater catchments of water resources, but the urban water metabolisms also disabled the social and environmental conditions of those residing in the Owens Valley.

However, an overlooked aspect of the development of the LAA was the role of hydropower. When Fred Eaton first ventured into Owens Valley, he was fully aware of the hydro-electrical potential an aqueduct would serve and oversaw that the LAA was designed to capture the economic aspects that would accrue if the potential of hydropower was realized (Kahrl, 1982). At the time, engineers estimated that the LAA would be capable of generating energy in excess to that being consumed in Los Angeles and neighboring cities (Kahrl, 1982). This economic potential of hydropower was not lost on Mulholland while pushing the project when he stated to the people of Los Angeles "I believe that the people have in the possible power development from the aqueduct an investment which 20 years hence will turn back to the city treasury the entire $24.5 million provided for the construction of the aqueduct with interest" (Heinly, 1910, 595).

Mulholland's vision to bring the water of the Owens Valley required a re-scaling of the "networks of interests" (Swyngedouw, 2007) where the political and economic elites of Los Angeles could envision the potential of forging new spatial links between Los Angeles, the Owens Valley, and the San Fernando Valley. The primary focus beyond supply and economic development was the enviable fact that the water flowed "downhill." The metabolic inputs and outputs of energy and waste influenced the discourse driving the historical development Los Angeles water supplies and provides the historical linkage to the urban metabolization of water, carbon, and energy.

A similar logic focused on the water–energy nexus guides current efforts by the City of Los Angeles to reduce its reliance on imported sources of water while shrinking its carbon footprint. From the perspective of the carbon calculus, the LAA emerges as the most desirable form of water supply in terms of energy intensity and emissions burdens, but the lasting social and environmental justice issues bring into question the overall sustainability of such a project. A new scalar vision is currently re-shaping urban water infrastructures and metabolisms, which we turn to next.

5.2. Urban ecological security

In May 2008, the City of Los Angeles released the blueprint for their Water Supply Action Plan, titled *Securing L.A.'s Water Supply*. The emergent logic centers around increasing local water resources through an approach that includes investments in new technologies, rebates and incentives, the installation of "smart" technologies such as sprinklers, washers and toilets, long-term measures to expand water recycling, cleaning local groundwater supplies, and decreasing reliance on imported water (Villaraigosa, 2008). The goal of the program is to meet new water demands of 100,000 acre-feet per year through a combination of water conservation and water recycling programs. Other water supply initiatives, at a cost of roughly 10% of LADWP's annual budget, include stormwater capture, restoring the San Fernando Groundwater Basin, expanding groundwater storage, outreach, and expanding and enforcing prohibited uses of water (LADWP, 2013a).

These projects mark a transition from regional infrastructures to a distributed water framework that entails a re-scaling of ecological resources and infrastructures primarily through a market environmentalist framework to tackle both environmental and economic problems (Bakker, 2005; Hodson and Marvin, 2009; Swyngedouw, 2013, 2007). The goals, according officials, is to blend opportunities for economic growth with efficiency gains in water and energy use and environmental conservation to more reliably manage water resources at a local level. The allure of these types of frameworks, as Bakker (2005, 543) suggests, "lies in the promise of simultaneously addressing and mobilizing water scarcity, in the pursuit of continued economic growth." The techniques utilized to support these water supply initiatives include cost-benefit analyses to direct funding, but also carbon footprint calculations to evaluate climate change adaptation and mitigation goals. What is unique in this approach, however, is the recognition of the link between new investments in water supply infrastructure and GHG emissions.

A number of other regulatory, climatic, and political changes are also driving the development of local water sources and conservation measures (Hughes et al., 2013). Recent regulatory restrictions on importing water from the San Joaquin and Sacramento River deltas, for example, are driven by the enforcement of the Endangered Species Act to protect Delta smelt. Other regulatory restrictions are the outcome of the LAA's lasting social and environmental impact on the Owens Valley. Owens Lake, which dried up as a result of losing its source to supply Los Angeles, is now a salt flat and major environmental justice issue causing respiratory problems in the nearby town of Lone Pine (Siegler, 2013). After extended litigation with local communities in the Owens Valley, the city finally agreed to the Owens Lake Dust Mitigation Project, but it requires up to 95,000 acre-feet of water annually, or roughly the same amount of water consumed by San Francisco each year, at a cost of $1 billion dollars a year (LADWP, 2013b). The Water Resources Control Board Mono Lake decision also limits the ability of LADWP to import water from the Mono Basin by requiring water to be allocated to restoring streams that fill Mono Lake (Villaraigosa, 2008). This reallocation of water for environmental mitigation and enhancement reduces the delivery of water from the LAA to roughly one-third of LADWP's supply (Villaraigosa, 2008). LADWP, however, continues to fight the regulatory drivers forcing the city to use water from the Sierras to control dust on the dried up Owens Lake (Sahagun, 2013).

Climate change is also presenting a challenge to water managers in Los Angeles by creating uncertainty in predicting future supply. Increased temperatures and weather extremes, reduced snow pack, and sea level rise are all likely effects of climate change in California (CDWR, 2008). Adding the effects of climate change to ongoing drought conditions, researchers say, is likely to cause severe decline in runoff with shortfalls in scheduled water deliveries (Ackerman and Stanton, 2011). The future amount of water available for human consumption is not likely to be the same, nor is it likely to be a linear projection of past trends. The Colorado River has undergone an historic drought that has brought increased attention to its changing hydrology and the potential climate change impacts on water supplies (CDWR, 2008). The coming together of a climate and water crisis is provoking city leaders to take bold actions to reduce carbon emissions and adapt to future changes (Villaraigosa, 2007). As multiple city officials noted, "reliability not sustainability" is often the driving motive to rework water supply systems and advance what appears on the surface to be more sustainable technologies that can drive mitigation and adaptation to climate change.

However, at the intersection of climate change and regional conflicts over water resources, a series of centralized and decentralized strategies emerge as a potential fix to the recurrent uncertainties surrounding water supply. Water capture and recycling technologies are technological fixes to overcome Los Angeles's water supply deficit, ones that allow policymakers to temporarily avoid serious consideration of the many long-term trade-offs between different values and uses of water such as future development and growth. As one water manager noted, "we all want more recycled water . . . we've [LADWP] been planning it, and [the increase] in recycled water is not necessarily a supply issue but part of an ongoing approach to accelerate local supply goals related to city policy that wants to reduce dependence on outside supply [from MWD]." With population growth expected to increase by approximately 367,300 new residents by 2035, meeting the future demands in supply that accompany development and growth with local sources will allow the city to become more self-sufficient in water provisioning on a city scale (LADWP, 2010a). The approach will also lead to considerable savings for LADWP as Los Angeles will be able to reduce the costs associated with purchased water from MWD as the city reduces external reliance on supply and builds up local centralized and decentralized systems. While guided by a market environmentalist framework, the socio-technical strategy combines ecological and water security priorities into LADWP's attempts to assure development and economic growth.

Furthermore, the rolling-out of new technologies to supply water may also compound the water–energy nexus. As our analysis shows, the pumping of local groundwater supplies and recycling water are both more energy intensive than water conveyed by the LAA. Capturing water may present a means to secure more local water supplies, but the cleansing and recycling of the water for potable use may lead to an increase in carbon emissions. The outcome is an ironic situation whereby proposed solutions to water scarcity caused by climate change actually contribute to and potentially exacerbate the conditions creating climate change. One water manager said, "recycled water, in terms of energy, can be competitive with SWP," but tradeoffs inevitably emerge between maintaining a reliable supply and mitigating carbon emissions. This is especially true with respect to proposed desalination plants that increase local water capacity, but are highly energy intensive (LADWP, 2010a). As another prominent water manager stated, "stormwater recharge and recycled water is certainly less intense than the CRA, but you still have to pump it back out with the well. . .It's actually more cost-effective to do groundwater desalinization [than recycled water]." Local groundwater supplies may certainly be less carbon intensive than water from the CRA, but in Los Angeles recycled water supplies become more energy intensive when emissions are made spatially-explicit and demonstrates the need for more robust and spatially-explicit data for decision-making.

However, relying solely on the least energy intensive source of water presents a different set of planning contradictions. Water sourced from the LAA, for example, may present the least energy intensive form of water supply, but it is also a source permeated with a history of social and environmental injustices—past and present. From the "empire builders" who conspired to take Owens Valley water to the continued struggles over how to mitigate the environmental damages caused by diverting water out of the

Owens Valley, the LAA continues to play a controversial role in the water politics of Los Angeles. The LAA is also a less resilient form of infrastructure due to seismic risk and reduced reliability on the snowpack in the Eastern Sierra (Davis and O'Rourke, 2011; LADWP, 2010a). Reductions in the water conveyed to Los Angeles via the LAA due to environmental mitigation have the consequence of increasing Los Angeles's reliance on imported supplies from the SWP and the Colorado River through the CRA. The outcome increases Los Angeles's reliance on more energy intensive water supplies imported from MWD, thereby raising the overall energy intensity of Los Angeles's water supply.

Beyond efficiencies, however, water managers say that water recycling, stormwater capture, and other approaches to increase supply locally are generally always a money issue. In order to direct the funding of projects, LADWP has developed, or is developing, a range of master plans on topics from recycled water to stormwater to point toward what water managers describe as "all of the low hanging fruit." According to one official, projects for stormwater are likely to lead to some large centralized projects because "most rain falls in two weeks of the year and the city needs to grab large chunks of water." The goal, as another official noted, "is to go where the water is and develop centralized projects to capture it." For large-scale water managers in Los Angeles, these local solutions make the most economical sense—at least in the short term—and are indicative of the logic guiding urban environmental governance and management in Los Angeles.

6. Conclusion

Our analysis demonstrates the shortcomings of undertaking solely an LCA for a problem that is spatially complex and enmeshed within a set of socio-political and historical processes that have shaped Los Angeles's water supply metabolism. Typical IE assessments focus narrowly on the stocks and flows of resources, such as water, coursing through the city, thus restricting itself to mass-balance approaches and improving efficiencies of resource use while ignoring the nature–society processes that (re)shape urban metabolisms (Gandy, 2004; Keil and Boudreau, 2006; Newell and Cousins, 2014; Swyngedouw, 2006b). Rather than critiquing LCA as an aspatial and technocratic tool of ecological modernization, we harnessed the method to map out and think through the complex assemblages associated with conveyance, treatment, and distribution of water in Los Angeles. Combining LCA with GIS not only spatializes the metabolic flows that assemble the city, but also provides an opportunity to link conventional IE approaches that focus on inputs and outputs to the political ecology of resource metabolisms. This political–industrial ecology broadens considerations of metabolisms, urban or otherwise, by being attentive to the metabolic inputs and outputs of products and processes and how they are shaped by politics, history, and social power.

Given the need to understand multiple dimensions of environmental change, establishing a political–industrial ecology provides an exciting opportunity to develop and consider sustainable transitions. Political ecologists have provided trenchant insights into the structures of power that shape relationships between nature, society, and technology (Birkenholtz, 2013; Heynen et al., 2006; Meehan, 2013b), and the scalar and geographic dimensions of environmental decision-making (Cohen and Bakker, 2013; Heynen, 2003; Lawhon and Patel, 2013). Extending these insights to approaches in industrial ecology, the field can provide important analyses to foster more sustainable and resilient futures. A challenge for future research will be balancing the social and political dimensions of environmental change with the measurement of the material impacts of urban metabolisms. Utilizing the metabolism metaphor to engage with the strengths of IE and UPE provides a starting point for this type of integrated analysis. With few engaged in this type of research, great potential exists for expanding these insights into wider investigations into the socio-political aspects shaping how geographic complexity is included, excluded, negotiated, and communicated in the production, application, and circulation of LCAs, and in coupling spatially robust LCA–GIS analyses with considerations of the historical and socio-political aspects that (re)shape metabolic inputs and outputs. A political–industrial ecology offers a constructive approach to facilitate and expand these type understandings of resource flows and metabolisms.

Acknowledgements

The authors are very grateful to those who took their time to contribute to this study including the interviewees, Andrew Fang, Brandon List, the editor Sarah Hall, and the anonymous reviewers for their helpful comments. This research was supported by a University of Michigan M-Cubed funding program to foster interdisciplinary scholarship and the John Randolph and Dora Haynes Foundation.

References

Ackerman, F., Stanton, E.A., 2011. The Last Drop: Climate Change and the Southwest Water Crisis. Somerville, MA.

Baccini, P., 1996. Understanding regional metabolism for a sustainable development of urban systems. J. Urban Technol. 4, 27–39.

Baccini, P., Brunner, P.H., 2012. Metabolism of the Anthroposphere: Analysis, Evaluation, Design. MIT Press, Cambridge, MA.

Bakker, K., 2003. Archipelagos and networks: urbanization and water privatization in the South. Geogr. J. 169 (4), 328–341. http://dx.doi.org/10.1111/j.0016-7398.2003.00097.x.

Bakker, K., 2005. Neoliberalizing nature? Market environmentalism in water supply in England and Wales. Ann. Assoc. Am. Geogr. 95, 542–565. http://dx.doi.org/10.1111/j.1467-8306.2005.00474.x.

Barles, S., 2007a. Urban metabolism and river systems: an historical perspective – Paris and the Seine, 1790–1970. Hydrol. Earth Syst. Sci. Discuss. 4, 1845–1878.

Barles, S., 2007b. Feeding the city: food consumption and flow of nitrogen, Paris, 1801–1914. Sci. Total Environ. 375, 48–58.

Barles, S., 2009. Urban metabolism of Paris and its region. J. Ind. Ecol. 13, 898–913.

Basset-Mens, C., van der Werf, H.M.G., 2005. Scenario-based environmental assessment of farming systems: the case of pig production in France. Agric. Ecosyst. Environ. 105, 127–144.

Birkenholtz, T., 2008. Contesting expertise: the politics of environmental knowledge in northern Indian groundwater practices. Geoforum 39, 466–482. http://dx.doi.org/10.1016/j.geoforum.2007.09.008.

Birkenholtz, T., 2009a. Irrigated landscapes, produced scarcity, and adaptive Social Institutions in Rajasthan, India. Ann. Assoc. Am. Geogr. 99, 118–137.

Birkenholtz, T., 2009b. Groundwater governmentality: hegemony and technologies of resistance in Rajasthan's (India) groundwater governance. Geogr. J. 175, 208–220.

Birkenholtz, T., 2013. "On the network, off the map": developing intervillage and intragender differentiation in rural water supply. Environ. Plann. D: Soc. Space 31, 354–371.

Budds, J., Sultana, F., 2013. Exploring political ecologies of water and development. Environ. Plann. D: Soc. Space 31, 275–279.

Bulkeley, H., 2010. Cities and the governing of climate change. Annu. Rev. Environ. Resour. 35, 229–253.

Bulkeley, H., Betsill, M.M., 2013. Revisiting the urban politics of climate change. Environ. Polit. 22, 136–154.

Bulkeley, H., Castán Broto, V., 2012. Government by experiment? Global cities and the governing of climate change. Trans. Inst. Br. Geogr., 1–15.

Bulkeley, H., Castan Broto, V., Maassen, A., 2013. Low-carbon transitions and the reconfiguration of urban infrastructure. Urban Stud.. http://dx.doi.org/10.1177/0042098013500089.

Buzzelli, M., 2008. A political ecology of scale in urban air pollution monitoring. Trans. Inst. Br. Geogr. 33 (4), 502–517. http://dx.doi.org/10.1111/j.1475-5661.2008.00316.x.

Castán Broto, V., Allen, A., Rapoport, E., 2012. Interdisciplinary perspectives on urban metabolism. J. Ind. Ecol. 16, 851–861.

CDWR, 2008. Managing an Uncertain Future: Climate Change Adaptation Strategies for California's Water.

CDWR, 2011. California State Water Project at a Glance.

CEC, 2005. California's Water–Energy Relationship. Sacramento, CA.

Cohen, A., Bakker, K., 2013. The eco-scalar fix: rescaling environmental governance and the politics of ecological boundaries in Alberta, Canada. Environ. Plann. D: Soc. Space 32. http://dx.doi.org/10.1068/d0813.

Cronon, W., 1991. Nature's Metropolis: Chicago and the Great West. W.W. Norton, New York.

Curran, M.A., 2006. Report on activity of task force 1: data registry – global life cycle inventory data resources. Int. J. Life Cycle Assess. 11, 284–289. http://dx.doi.org/10.1065/lca2006.06.255.

Davis, C., O'Rourke, T., 2011. ShakeOut scenario: water system impacts from a Mw 7.8 San Andreas earthquake. Earthq. Spectra 27, 459–476.

Decker, E.H., Elliott, S., Smith, F.A., Blake, D.R., Rowland, F.S., 2000. Energy and material flow through the urban ecosystem. Annu. Rev. Energy Environ. 25, 685–740.

Desfor, G., Keil, R., 2004. Nature and the City: Making Environmental Policy in Toronto and Los Angeles, Nature and the City: Making Environmental Policy in Toronto and Los Angeles. The University of Arizona Press, Tucson.

Dresen, B., Jandewerth, M., 2012. Integration of spatial analyses into LCA—calculating GHG emissions with geoinformation systems. Int. J. Life Cycle Assess. 17, 1094–1103.

Forsyth, T., 2003. Critical Political Ecology: The Politics of Environmental Science. Routledge, New York.

Freidberg, S., 2013. Calculating sustainability in supply chain capitalism. Econ. Soc. 00, 1–26. http://dx.doi.org/10.1080/03085147.2012.760349.

Frosch, R.A., 1992. Industrial ecology: a philosophical introduction. Proc. Natl. Acad. Sci. USA 89, 800–803.

Furlong, K., 2010. Small technologies, big change: rethinking infrastructure through STS and geography. Prog. Hum. Geogr. 35, 460–482. http://dx.doi.org/10.1177/0309132510380488.

Gandy, M., 1999. The Paris sewers and the rationalization of urban space. Trans. Inst. Br. Geogr. 24, 23–44.

Gandy, M., 2002. Concrete and Clay: Reworking Nature in New York City. MIT Press, Cambridge, MA.

Gandy, M., 2004. Rethinking urban metabolism: water, space and the modern city. City 8, 363–379.

Gandy, M., 2005. Cyborg urbanization: complexity and monstrosity in the contemporary city. Int. J. Urban Reg. Res. 29, 26–49.

Gasol, C.M., Gabarrell, X., Rigola, M., González-García, S., Rieradevall, J., 2011. Environmental assessment: (LCA) and spatial modelling (GIS) of energy crop implementation on local scale. Biomass Bioenergy 35, 2975–2985.

Geyer, R., Stoms, D.M., Lindner, J.P., Davis, F.W., Wittstock, B., 2010. Coupling GIS and LCA for biodiversity assessments of land use. Int. J. Life Cycle Assess. 15, 454–467.

Gower, S.T., 2006. Following the Paper Trail: The Impact of Magazine and Dimensional Lumber on Greenhouse Gas Emissions. Washington, DC.

Graedel, T.E., Allenby, B., 2003. Industrial Ecology, second ed. Prentice Hall, Upper Saddle River, NJ.

Guinée, J.B., 2002. Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Kluwer Academic Publishers, Dordrecht.

Guthman, J., 2011. Weighing. In: Obesity, Food Justice, and the Limits of Capitalism. University of California Press, Berkeley and Los Angeles.

Hanya, T., Ambe, Y., 1976. A study on the metabolism of cities. In: Science for a Better Environment. HESC: Science Council of Japan, Tokyo.

Harvey, D., 2001. Population, resources, and the ideology of science. In: Spaces of Capital: Towards a Critical Geography. Routledge, New York.

Heinly, B.A., 1910. Carrying water through a Desert. Natl. Geogr. Mag. 21, 568–596.

Hendriks, C., Obernosterer, R., Müller, D., Kytzia, S., Baccini, P., Brunner, P.H., 2000. Material flow analysis: a tool to support environmental policy decision making. Case-studies on the city of Vienna and the Swiss lowlands. Local Environ. 5, 311–328.

Heynen, N.C., 2003. The scalar production of injustice within the urban forest. Antipode 35, 980–998.

Heynen, N., 2006. Green urban political ecologies: toward a better understanding of inner-city environmental change. Environ. Plann. A 38 (3), 499–516. http://dx.doi.org/10.1068/a37365.

Heynen, N., Kaika, M., Swyngedouw, E., 2006. Urban political ecology: politicizing the production of urban natures. In: Heynen, N., Kaika, M., Swyngedouw, E. (Eds.), In the Nature of Cities Urban Political Ecology and the Politics of Urban Metabolism. Routledge, New York, pp. 1–20.

Hodson, M., Marvin, S., 2009. "Urban ecological security": a new urban paradigm? Int. J. Urban Reg. Res. 33, 193–215. http://dx.doi.org/10.1111/j.1468-2427.2009.00832.x.

Hodson, M., Marvin, S., 2010. Can cities shape socio-technical transitions and how would we know if they were? Res. Policy 39, 477–485. http://dx.doi.org/10.1016/j.respol.2010.01.020.

Hodson, M., Marvin, S., Robinson, B., Swilling, M., 2012. Reshaping urban infrastructure. J. Ind. Ecol. 16, 789–800. http://dx.doi.org/10.1111/j.1530-9290.2012.00559.x.

Hodson, M., Marvin, S., Bulkeley, H., 2013. The intermediary organisation of low carbon cities: a comparative analysis of transitions in Greater London and Greater Manchester. Urban Stud. 50, 1403–1422. http://dx.doi.org/10.1177/0042098013480967.

Hughes, S., Pincetl, S., Boone, C., 2013. Triple exposure: regulatory, climatic, and political drivers of water management changes in the city of Los Angeles. Cities 32, 51–59.

IEUA, 2009. Annual Water Use Report for IEUA Service Area.

Jasanoff, S., 2004. The idiom of co-production. In: Jasanoff, S. (Ed.), States of Knowledge: The Co-Production of Science and Social Order. Routledge, London, pp. 1–12.

Jelinski, L.W., Graedel, T.E., Laudise, R.A., McCall, D.W., Patel, C.K., 1992. Industrial ecology: concepts and approaches. Proc. Natl. Acad. Sci. USA 89, 793–797.

Jonas, A.E.G., Gibbs, D., While, A., 2011. The new urban politics as a politics of carbon control. Urban Stud. 48, 2537–2554. http://dx.doi.org/10.1177/0042098011411951.

Kahrl, W.L., 1982. Water and Power: The Conflict Over Los Angeles Water Supply in the Owens Valley. University of California Press, Berkeley and Los Angeles.

Kaika, M., 2003. Constructing scarcity and sensationalising water politics: 170 days that Shook Athens. Antipode 35, 919–954.

Kaika, M., 2005. City of Flows: Modernity, Nature, and the City. Routledge, New York.

Kaika, M., Swyngedouw, E., 2000. Fetishizing the modern city: the phantasmagoria of urban technological networks. Int. J. Urban Reg. Res. 24, 120–138.

Kaika, M., Swyngedouw, E., 2012. Cities, natures and the political imaginary. Archit. Des. 82, 22–27.

Keil, R., Boudreau, J.-A., 2006. Metropolitics and metabolics: rolling out environmentalism in Toronto. In: Heynen, N., Kaika, M., Swyngedouw, E. (Eds.), In the Nature of Cities: Urban Political Ecology and the Politics of Urban Metabolism. New York, pp. 41–62.

Kennedy, C., Cuddihy, J., Engel-yan, J., 2007. The changing metabolism of cities. J. Ind. Ecol. 11, 43–59.

Kennedy, C., Pincetl, S., Bunje, P., 2011. The study of urban metabolism and its applications to urban planning and design. Environ. Pollut. 159, 1965–1973.

Kennedy, C., Baker, L., Dhakal, S., Ramaswami, A., 2012. Sustainable urban systems. J. Ind. Ecol. 16, 775–779. http://dx.doi.org/10.1111/j.1530-9290.2012.00564.x.

Keoleian, G.A., Menerey, D., 1994. Sustainable development by design: review of life cycle design and related approaches. Air Waste 44, 645–668.

Klusmire, J., 2013. Not Everyone is Celebrating. Inyo Regist.

Kooy, M., Bakker, K., 2008. Splintered networks: the colonial and contemporary waters of Jakarta. Geoforum 39, 1843–1858.

LADWP, 2010a. Urban Water Management Plan.

LADWP, 2010b. Building a New Los Angeles: Water & Power Long Term Strategy.

LADWP, 2013a. Developing a Local Water Supply. Los Angeles, CA.

LADWP, 2013b. Owens Lake Master Project. Los Angeles, CA.

Latour, B., 1987. Science in Action: How to Follow Scientists and Engineers through Society. Harvard University Press, Cambridge, MA.

Lawhon, M., Murphy, J.T., 2011. Socio-technical regimes and sustainability transitions: insights from political ecology. Prog. Hum. Geogr. 36, 354–378. http://dx.doi.org/10.1177/0309132511427960.

Lawhon, M., Patel, Z., 2013. Scalar politics and local sustainability: rethinking governance and justice in an era of political and environmental change. Environ. Plann. C: Gov. Policy 31, 1048–1062. http://dx.doi.org/10.1068/c12273.

Libecap, G.D., 2005. Chinatown: Owens Valley and western water reallocation—getting the record straight and what it means for water markets. Texas Law Rev. 83, 2055–2089.

Linton, J., Budds, J., 2013. The hydrosocial cycle: defining and mobilizing a relational–dialectical approach to water. Geoforum. http://dx.doi.org/10.1016/j.geoforum.2013.10.008.

Loftus, A., 2012. Everyday Environmentalism: Creating an Urban Political Ecology. University of Minnesota Press, Minneapolis, MN.

Marriott, J., Matthews, H.S., 2005. Environmental effects of interstate power trading on electricity consumption mixes. Environ. Sci. Technol. 39, 8584–8590. http://dx.doi.org/10.1021/es0506859.

McDonnell, R.A., 2013. Circulations and transformations of energy and water in Abu Dhabi's hydrosocial cycle. Geoforum, 1–9. http://dx.doi.org/10.1016/j.geoforum.2013.11.009.

McWilliams, C., 1949. California: The Great Exception. University of California Press, Berkeley.

Meehan, K., 2013a. Disciplining de facto development: water theft and hydrosocial order in Tijuana. Environ. Plann. D: Soc. Space 31, 319–336.

Meehan, K.M., 2013b. Tool-power: water infrastructure as wellsprings of state power. Geoforum. http://dx.doi.org/10.1016/j.geoforum.2013.08.005.

Mollinga, P.P., 2013. Canal irrigation and the hydrosocial cycle. Geoforum. http://dx.doi.org/10.1016/j.geoforum.2013.05.011.

MWD, 1999. Fact Sheet on Electric Industry Restructuring. Los Angeles, CA.

MWD, 2009. Energy Management and Reliability Study. Los Angeles, CA.

Newcombe, K., Kalma, J.D., Aston, A.R., 1978. The metabolism of a city: the case of Hong Kong. Ambio 7, 3–15.

Newell, J.P., Cousins, J.J., 2014. Boundaries of urban metabolism: towards a political–industrial ecology. Prog. Hum. Geogr.. http://dx.doi.org/10.1177/0309132514558442.

Newell, J.P., Vos, R.O., 2011. "Papering" over space and place: product carbon footprint modeling in the global paper industry. Ann. Assoc. Am. Geogr. 101, 730–741. http://dx.doi.org/10.1080/00045608.2011.567929.

Pincetl, S., 2012. Nature, urban development and sustainability – what new elements are needed for a more comprehensive understanding? Cities 29, S32–S37.

Pincetl, S., Bunje, P., Holmes, T., 2012. An expanded urban metabolism method: toward a systems approach for assessing urban energy processes and causes. Landsc. Urban Plann..

Ramaswami, A., Weible, C., Main, D., Heikkila, T., Siddiki, S., Duvall, A., Pattison, A., Bernard, M., 2012. A social–ecological-infrastructural systems framework for interdisciplinary study of sustainable city systems. J. Ind. Ecol. 16, 801–813.

Reisner, M., 1986. Cadillac Desert: The American West and Its Disappearing Water. Penguin, New York.

Reyna, J., Chester, M., 2013. Metropolitan-scale Building Infrastructure Environmental Life Cycle Assessment: Los Angeles' Embedded Impacts.

Rice, J.L., 2010. Climate, carbon, and territory: greenhouse gas mitigation in Seattle, Washington. Ann. Assoc. Am. Geogr. 100, 929–937.

Rice, J.L., 2014. An urban political ecology of climate change governance. Geogr. Compass 8, 381–394. http://dx.doi.org/10.1111/gec3.12134.

Robbins, P., 2012. Political Ecology: A Critical Introduction, second ed. Wiley-Blackwell, Malden, MA.

Rocheleau, D., 2008. Political ecology in the key of policy: from chains of explanation to webs of relation. Geoforum 39, 716–727. http://dx.doi.org/10.1016/j.geoforum.2007.02.005.

Rocheleau, D., Roth, R., 2007. Rooted networks, relational webs and powers of connection: rethinking human and political ecologies. Geoforum 38, 433–437. http://dx.doi.org/10.1016/j.geoforum.2006.10.003.

Sahagun, 2013. DWP Lawsuit Over Owens Lake Dust Dismissed by Federal Judge. Los Angeles Times.

Siegler, K., 2013. Owens Valley Salty as Los Angeles Water Battle Flows Into Court. Natl. Public Radio.

Smith, A., Stirling, A., Berkhout, F., 2005. The governance of sustainable socio-technical transitions. Res. Policy 34, 1491–1510. http://dx.doi.org/10.1016/j.respol.2005.07.005.

Soimakallio, S., Kiviluoma, J., Saikku, L., 2011. The complexity and challenges of determining GHG (greenhouse gas) emissions from grid electricity consumption and conservation in LCA (life cycle assessment) – a methodological review. Energy 36, 6705–6713. http://dx.doi.org/10.1016/j.energy.2011.10.028.

Solorio, J., 2012. The Future of Stormwater: Capture, Store and Supply.

Southern California Edison, Power Content Label, 2010. https://www.sce.com/wps/wcm/connect/861a514f-a20b-4548-9526-66ce424b3baa/2010_SCE_PowerContentLabel.pdf?MOD=AJPERES.

Stokes, J.R., Horvath, A., 2009. Energy and air emission effects of water supply. Environ. Sci. Technol. 43, 2680–2687. http://dx.doi.org/10.1021/es801802h.

Stringfellow, K., 2013. Owens valley and the aqueduct. Boom A: J. Calif. 3.

Subak, S., Craighill, A., 1999. The contribution of the paper cycle to global warming. Mitig. Adapt. Strateg. Global Change 4, 113–136.

Sultana, F., 2011. Suffering for water, suffering from water: emotional geographies of resource access, control and conflict. Geoforum 42, 163–172. http://dx.doi.org/10.1016/j.geoforum.2010.12.002.

Sultana, F., 2013. Water, technology, and development: transformations of development technonatures in changing waterscapes. Environ. Plann. D: Soc. Space 31, 337–353. http://dx.doi.org/10.1068/d20010.

Swyngedouw, E., 2004. Social Power and the Urbanization of Water: Flows of Power. Oxford University Press, Oxford.

Swyngedouw, E., 2006a. Circulations and metabolisms: (Hybrid) Natures and (Cyborg) cities. Sci. Cult. (Lond.) 15, 105–121.

Swyngedouw, E., 2006b. Metabolic urbanization: the making of cyborg cities. In: Heynen, N., Kaika, M., Swyngedouw, E. (Eds.), In the Nature of Cities: Urban Political Ecology and the Politics of Urban Metabolism. Routledge, New York, pp. 21–40.

Swyngedouw, E., 2007. Technonatural revolutions: the scalar politics of Franco's hydro-social dream for Spain, 1939–1975. Trans. Inst. Br. Geogr. 32, 9–28.

Swyngedouw, E., 2009. The political economy and political ecology of the hydro-social cycle. J. Contemp. Water Res. Educ. 142, 56–60.

Swyngedouw, E., 2013. Into the sea: desalination as hydro-social fix in Spain. Ann. Assoc. Am. Geogr. 103, 261–270.

Swyngedouw, E., Heynen, N.C., 2003. Urban political ecology, justice and the politics of scale. Antipode, 898–918.

Swyngedouw, E., Kaika, M., Castro, E., 2002. Urban water: a political-ecology perspective. Built Environ. 28.

TCR, WEI, 2013. California's Water–Energy–Climate Nexus: Energy and Greenhouse Gas Emissions Embedded in Water.

Ulin, D.L., 2013. There it is. Take it. Boom A: J. Calif. 3.

Villaraigosa, M.A.R., 2007. Green LA: An Action Plan to Lead the Nation in Fighting Global Warming. Los Angles, CA.

Villaraigosa, M.A.R., 2008. Securing L.A'.s Water Supply: City of Los Angles Water Supply Action Plan.

Warren-Rhodes, K., Koenig, A., 2001. Escalating trends in the urban metabolism of Hong Kong: 1971–1997. Ambio 30, 429–438.

Weber, C.L., Matthews, H.S., 2008. Food-miles and the relative climate impacts of food choices in the United States. Environ. Sci. Technol. 42, 3508–3513.

Weber, C.L., Jiaramillo, P., Marriott, J., Samaras, C., 2010. Life cycle assessment and grid electricity: what do we know and what can we know? Environ. Sci. Technol. 44, 1895–1901.

While, A., Jonas, A.E.G., Gibbs, D., 2010. From sustainable development to carbon control: eco-state restructuring and the politics of urban and regional development. Trans. Inst. Br. Geogr. 35, 76–93. http://dx.doi.org/10.1111/j.1475-5661.2009.00362.x.

Wilkinson, R., 2000. Methodology for Analysis of the Energy Intensity of California's Water Systems, and an Assessment of Multiple Potential Benefits through Integrated Water–Energy Efficiency Measures. Calif. Inst. Energy Effic.

Wilkinson, R., 2007. Analysis of the Energy Intensity of Water Supplies for West Basin Municipal Water District. Carson, CA.