Energy analysis of reclaimed water application for irrigation in arid and semi-arid regions

Derek T. Nguyen, Linda Y. Tseng, Reza Sobhani and Diego Rosso

ABSTRACT

Freshwater availability is the major constraint to agriculture in arid and semi-arid regions. The groundwater and energy conservation of applying reclaimed water for irrigation was analysed, using Southern California as the spatial domain for model testing. An extensive compilation of the most recent publicly available datasets was used to calculate the energy intensity for each water supply source, the associated carbon footprint reduction and the monetary savings associated with using reclaimed water over groundwater. Our results indicate that for 1998–2010 in California the fractional water use for agriculture is 0.81 and for urban use is 0.19. During this same period, an average of 4.2×10^{10} m^3 of water were used for crop irrigation, of which 1%, 46.8% and 52.2% came from reclaimed water, groundwater, and surface water, respectively. Each of these three main water sources is associated with a range of energy intensity (in kWh m^{-3}), depending on the process and environmental characteristics of the end-use location. Our analysis of multiple process and environmental configurations produced a detailed energy intensity database, with the associated carbon footprint. These databases are used to quantify the energy and carbon footprint difference between applying the current groundwater source and reclaimed water for irrigation.

Key words | carbon footprint, climate, conservation, energy, irrigation, reclaimed water

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INTRODUCTION

California's unique geography and climate have allowed the state to become one of the most productive agricultural regions in the world. Situated across an arid and semi-arid region, California's agricultural industry benefits from its naturally warm and dry summers, and mild winters, with average yearly temperature ranging between 13 and 21 °C (National Oceanic and Atmospheric Administration (NOAA) 2015). The local government reported a record 43.5×10^9 USD in cash receipts in 2011 for overall agricultural production, making it the largest agricultural producer in the United States (California Department of Food and Agriculture (CDFA) 2012).

The history of California's agricultural industry and the limit of its growth are connected to the current water shortage created by a prolonged drought (California Department of Water Resources (CDWR) 2013). Although there exist extensive water resources within the state boundaries, like in most Mediterranean climatic regions, the majority of the population resides along the water-scarce coastal region, which in California corresponds to the southern region. Today, California's water resources support over 38 million people (California Department of Finance (CDOF) 2013), a 2.2 USD y^{-1} trillion economy (World Bank 2013) and the agricultural region with the largest cash receipts in the United States (CDFA 2012). In a typical year, Californian agricultural land (approximately 2.5×10^3 ha) is irrigated using approximately 4.2×10^{10} m^3 of groundwater (CDWR 2013). To accommodate the growth in population, the State of California and the US Federal Government built a complex hydraulic infrastructural network (dams, aqueducts,

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canals, reservoirs, and pumping facilities) to harness the inland water supply and deliver it to the cities and agricultural areas (Reisner 1993; Nadeau 1997; Hundley 2001).

Reduced water supply and a growing population are exacerbating the effects of multi-year droughts in many regions, threatening the already stressed and fragile water systems. Previous studies (Alcamo *et al.* 2003; Oki & Kanae 2004; Smakhtin *et al.* 2004; Famiglietti 2014) have shown that California's water supply is severely under stress. This is the case where the water to meet demand from urban areas, industry, ecosystems, agriculture and other sectors is nearing its limit under current management practices (Sabo *et al.* 2010). In the coming decades, the agricultural throughput is projected to match the population expansion both within California and in North America (Rosegrant *et al.* 2002). For these reasons, the cost of providing water continues to rise as municipalities seek to create and expand capital-intensive infrastructure to secure a reliable water supply (Miller 2006). In many parts of California, the growing demand for water is outstripping the available supply, thus it is imperative to take proactive steps in conserving and augmenting the limited water supply resources (Chen & Chen 2013). Increasing attention has been directed in recent years to the use of reclaimed urban wastewater (Pereira *et al.* 2011). In fact, with advances in technology, reclaimed water is expected to meet the stringent potable quality requirements at a competitive cost, providing a more sustainable resource for the industry in a drought-resilient fashion (Levine & Asano 2004; Kiziloglu *et al.* 2008; Molinos-Senante *et al.* 2011). The potential uses for reclaimed water in urban landscaping and agricultural irrigation provide an effective way to relieve the water resource demand in arid and semi-arid regions (Gunston 2008). Many studies have also confirmed the benefits (cost savings, resource conservation, reliability, etc.) of using reclaimed water for crop irrigation (Yadav *et al.* 2002; Parsons *et al.* 2010; Rebora *et al.* 2010).

The goal of this research is to analyse the energy advantage of applying reclaimed water for crop irrigation, and to quantify the associated carbon footprint reduction of using reclaimed water versus traditional groundwater pumping in arid and semi-arid areas. Using California as a case study, the water, energy, and carbon-equivalent flows were quantified. In addition, the monetary advantage of substituting traditional water supply sources with reclaimed water, where possible, was assessed.

METHODS

Model structure

Using data previously reported by Wilkinson (2000, 2007), United States Bureau of Reclamation (USBR 2002), California Energy Commission (CEC 2005) and California Department of Water Resources (CDWR 2013), a dataset was compiled, including each of the $i = \{1,..,s\}$ sources, $Q(i)$ ($\mathrm{m}^3\,\mathrm{y}^{-1}$) in the water supply portfolio Q ($\mathrm{m}^3\,\mathrm{y}^{-1}$), the energy intensity of each water supply source $e(i)$ (kWh m^{-3}), and the carbon emission intensity $k(j)$ ($\mathrm{kg}_{\mathrm{CO2eq}}$ kWh^{-1}) for each of the power generation sources $j = \{1,.., p\}$ in the area of study. Using the conceptual model illustrated in Figure 1, for each point in space (x,y) the water supply portfolio Q is:

$$Q = \sum_{i=1}^{s} Q(i) \qquad \forall\,(\mathrm{x},\mathrm{y}) \quad i = \{1, .., s\} \tag{1}$$

For each source s, the energy footprint of the source $E(s)$ (kWh y^{-1}) is calculated as:

$$E(i) = Q(i) \cdot e(i) \qquad \forall\,(\mathrm{x},\mathrm{y}) \quad i = \{1, .., s\} \tag{2}$$

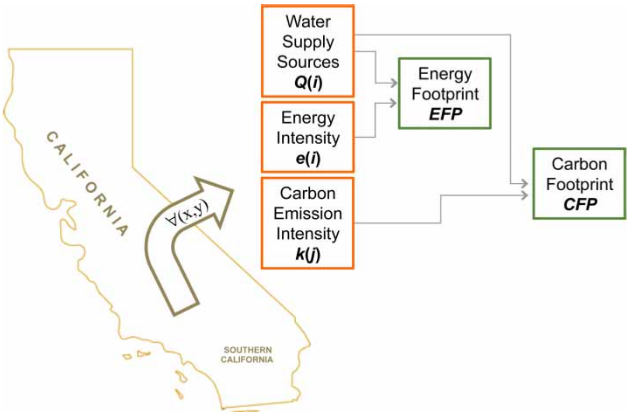

Figure 1 | Illustration of the rational procedure to calculate energy and carbon footprint for the $i = \{1,..,s\}$water supply sources in each point (x,y), using their associated energy footprint $e(i)$, and the carbon-equivalent emission of the power generation $k(j)$ for each $j = \{1,..,p\}$ power source used to supply the point (x,y).

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Thus, the overall energy footprint EFP (kWh y^{-1}) for each point is:

$$EFP = \sum_{i=1}^{s} E(i) = \sum_{i=1}^{s} [Q(i) \cdot e(i)] \qquad \forall (\mathrm{x}, \mathrm{y}) \quad i = \{1, .., s\} \tag{3}$$

The area studied may be supplied by power utilities from a diverse power generation portfolio relying on p sources (such as hydroelectric, nuclear, thermoelectric, eolic, photovoltaic, etc.) associated with different carbon emission intensities $k(j)$ ($\mathrm{kg_{CO2eq}}$ kWh^{-1}). For each point (x,y) where the water source i is supplied, the carbon-equivalent emission has to be calculated from the weighted-average carbon emission intensity $<k>$ ($\mathrm{kg_{CO2eq}}$ kWh^{-1}):

$$<k> = \frac{\sum_{j=1}^{p} [k(j) \cdot W(j)]}{\sum_{j=1}^{p} [W(j)]} \qquad \forall (\mathrm{x}, \mathrm{y}) \quad j = \{1, .., p\} \tag{4}$$

where $W(j)$ (kWh) is the energy produced for each of the $j = \{1,..,p\}$ power sources employed to supply power to the point (x,y).

Hence, the carbon emission intensity of each water source $c(i)$ ($\mathrm{kg_{CO2eq}}$ m^{-3}) is:

$$c(i) = e(i) \cdot <k> \qquad \forall (x, y) \quad i = \{1, .., s\} \tag{5}$$

Therefore, the carbon footprint for each water source $C(i)$ ($\mathrm{kg_{CO2eq}}$ y^{-1}) can be calculated as:

$$C(i) = c(i) \cdot Q(i) = e(i) \cdot <k> \cdot Q(i) \quad \forall (x, y) \quad i = \{1, .., s\} \tag{6}$$

The overall carbon footprint CFP ($\mathrm{kg_{CO2eq}}$ y^{-1}) is then:

$$CFP = \sum_{i=1}^{s} C(i) = \sum_{i=1}^{s} [e(i) \cdot <k> \cdot Q(i)] \qquad \forall (\mathrm{x}, \mathrm{y}) \quad i = \{1, .., s\} \tag{7}$$

Spatial domain

Southern California was selected to test this model. This 10^5 km^2 area includes six counties (Ventura, Los Angeles, San Bernardino, Orange, Riverside and San Diego), collectively amounting to more than 54% of California's population at the time of this study (CDOF 2000, 2013).

Water reclamation processes

For this study, the authors assumed that a typical Southern California water use cycle follows the process diagram identified in Figure 2. The use of reverse osmosis (RO) as the technology to reclaim wastewater for aquifer recharge is currently practised in many areas of this region.

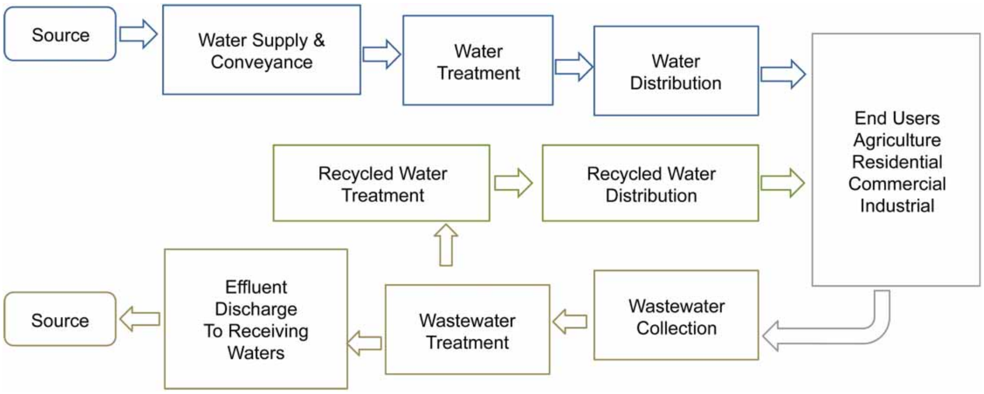

Figure 2 | Schematic of the water use cycle of an urban system interacting with nearby agricultural areas (after Wilkinson 2007).

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A typical advanced water and wastewater treatment facility utilizes the RO process diagram, similar to Figure 3. The following equation (USBR 2002) was used to determine the size of the RO treatment system:

$$Q_F = \frac{(TDS_S - TDS_D)}{1 - R - L + (R + L) \times TDS_S} Q_D \tag{8}$$

where Q_F, feed flow ($m^3\ d^{-1}$); Q_D, demand (i.e., target) flow ($m^3\ d^{-1}$); TDS_D, total dissolved solids demand (i.e., target; $mg\ l^{-1}$); TDS_S, total dissolved solids source ($mg\ l^{-1}$); R, membrane salt rejection (%); L, volumetric loss (%).

The membrane salt rejection is the fraction of ions rejected by the membrane, which typically exceeds 90% for the brackish water RO membranes employed in water reuse (MWH 2013). For this study, the authors followed the assumptions from USBR (2002) for volumetric loss of 20%, i.e. $Q_P/Q_F = 0.8$.

Based on the information presented in Figures 1–3, the authors calculated the energy intensities for water supply sources across Southern California using the energy intensity $e(i)$ for each of the water supply sources $i = \{1,..,s\}$.

Water conveyance and lift

Using the method previously reported by Sobhani *et al.* (2012), the energy intensity for conveyance and lift were calculated as:

$$e_C(i) = \xi \cdot z \tag{9}$$

$$e_L(i) = \omega \cdot h \tag{10}$$

where ξ, energy requirement per unit conveyance (1.86 10^{-3} kWh km^{-1}); z, conveyance distance (km); ω, energy requirement per unit lift (3.43 10^{-3} kWh m^{-1}); h, conveyance distance (m).

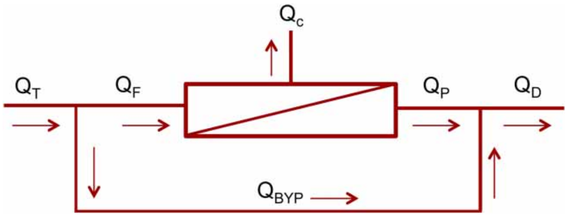

Figure 3 | Reverse osmosis process diagram (USBR 2002). Key: Q_T = total flow; Q_F = feed flow into RO treatment system; Q_C = concentrate flow; Q_P = permeate flow; Q_D = demand flow; Q_{BYP} = bypass flow.

Carbon footprint

To calculate for the carbon footprint associated with the water usage in each point (x,y), the authors used a value for the carbon emission intensity $k = 0.5\ kg_{CO2eq}\ kWh^{-1}$ as an average representation of the Southern California basin. Since each point (x,y) within this spatial domain may have a different k(x,y), plausibly ranging between 0.3 and 0.7 $kg_{CO2eq}\ kWh^{-1}$, a sensitivity analysis was performed to show the effect of k variations on the overall carbon footprint CFP.

Costs and savings

For monetary savings, an agglomerate electric rate of 0.135 USD kWh^{-1} was assumed. Due to the equilibrium nature of this model, the electric rate incorporates without discrimination the service and peak power demand charges, the averaged electric tiered rates, and all applicable taxes. The electric rate used in our calculation is consistent with the utility rate currently being applied to large treatment facilities ($>5 \times 10^4\ m^3\ d^{-1}$) by Southern California Edison, the largest electrical utility provider in the state of California (CEC 2015).

RESULTS AND DISCUSSION

The results show that from 1998 to 2010, the annual average water used in crop irrigation was $4.2 \times 10^{10}\ m^3$, 46.8% of which came from groundwater, and 52.2% from surface water, while only 1% came from reclaimed urban wastewater. During the same period, the authors found that the average annual urban water use was approximately 19.4% of the total $5.21 \times 10^{10}\ m^3$ used for the entire state, while 80.6% was used for crop irrigation. The time domain of the available data is set by the release schedule of public records. Within much smaller spatial domains, it is conceivable that direct measurements can be carried out with any desired frequency, however the modelling effort at the regional scale must rely on public programmes for data collection and compilation in published repositories.

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Urban water reclamation can be used for landscape and crop irrigation without the need for membrane filtration or reverse osmosis treatment, both of which are required to address public health concerns (i.e., pathogen abatement). In areas where groundwater recharge was practised to replenish aquifers for potable end use (i.e., Los Angeles, Orange, and Riverside counties), reverse osmosis and membrane filtration were used. In these instances, the calculated energy intensity for water reclamation to meet the potable water standard was 0.640 kWh m^{-3}.

Our results show that there are savings in both groundwater supply and energy resources when applying reclaimed water for crop irrigation: the use of gravity filtration to reclaim water is the most economical method to meet regulatory compliance for landscape and irrigation end uses (Table 1). In fact, where microfiltration membranes or reverse osmosis have energy intensities of 0.52 kWh m^{-3} and 0.64 kWh m^{-3}, respectively, gravity filtration (assumed here to be carried out with dual media filters) has an energy intensity of 0.32 kWh m^{-3}. Since reverse osmosis is not required for the production of reclaimed water suitable for irrigation, the energy intensity value for gravity filtration was selected as the comparison term with the current groundwater scenario. The authors found that for Southern California the minimum energy requirement for groundwater pumping was 0.770 kWh m^{-3} while reclaimed water production with gravity filtration was 0.324 kWh m^{-3}. Hence, the energy advantage of applying reclaimed urban wastewater for crop irrigation over groundwater pumping within this spatial domain would be 0.446 kWh m^{-3}, as shown in Figure 4.

Table 1 | Water supply sources and associated energy intensities calculated from datasets for Southern California

Water supply source, *i*	**Energy intensity, *e*(*i*) [kWh m^{-3}]**
Reclaimed water (Title 22 Gravity Filtration)	0.32
Reuse water – recharge grade	0.64
Groundwater pumping	0.77
Groundwater (ion exchange water)	0.85
Groundwater desalination (RO water)	1.38
Colorado river aqueduct	1.62
State water project	2.04
Ocean desalination (RO)	3.57

The calculated energy savings for applying reclaimed water in lieu of traditional groundwater results in a 57.9% reduction of energy usage. Annually, this amounts to approximately 187 GWh y^{-1} of energy savings for California, resulting in a reduction of 4.68×10^7 $MTCO_2E$ (metric tonne of CO_2 equivalent) of carbon emission. If reclaimed water use were increased from 1% to 5%, 10%, 15%, or 20%, the respective total energy savings, monetary savings and carbon footprint reduction would increase linearly, as tabulated in Table 2.

The calculated energy intensities for other supply sources such as imported water from Northern to Southern California and from the Colorado River Aqueduct system, ocean desalination, and impaired groundwater recovery were also calculated. Reclaimed water (obtained through gravity filtration) required the least amount of energy, whereas ocean desalination had an energy intensity approximately 11 times higher. When compared to traditional groundwater pumping, the energy intensity associated with water reclamation was discounted by 58%, highlighting the importance of reclaimed water as a potential competitive source.

When considering the energy requirements for water distribution along 10 km of horizontal conveyance and 100 m of vertical lift (the average elevation for urban areas in Southern California), the energy contributions for conveyance and lift were 0.026 kWh m^{-3} and 0.34 kWh m^{-3}, respectively. Therefore, to account for the full energy requirements from point of treatment to point of use, the energy intensities for horizontal and vertical conveyance must be added to the calculated data presented in Table 1.

The authors recognize that there may exist infrastructural and administrative limitations among water agencies and agricultural users within a region as to the extent in which reclaimed water can be produced, conveyed, applied, and accepted. Also, locations without proper infrastructure or with cultural incompatibility with reclaimed water may be unable to consider water reclamation as an option for their water supply portfolio. However, it is important to frame the transition to reclaimed water within the context of energy savings and monetary benefits. At the present moment, California would be unable to substitute all its groundwater use for reclaimed water, due to limits in existing infrastructure for both production and conveyance. Furthermore, the majority of the population within this

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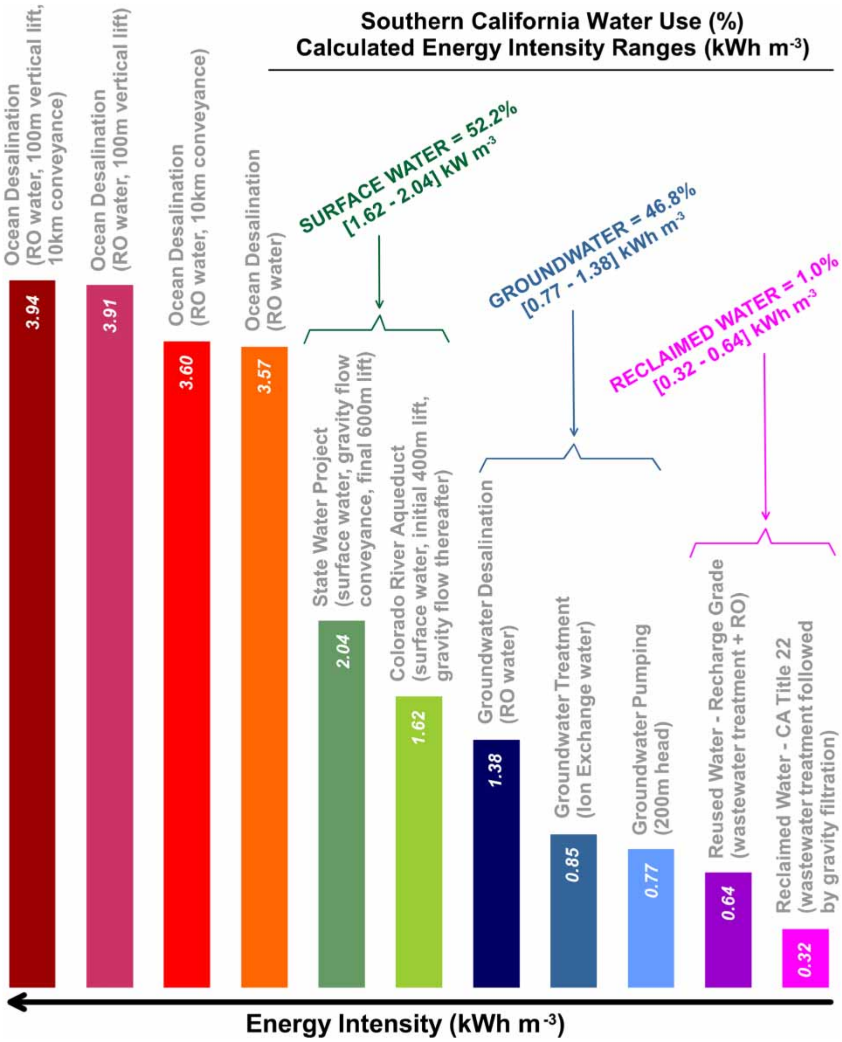

Figure 4 | Energy intensity (kWh m^{-3}) for different sources of the Southern California water portfolio.

Table 2 | Energy savings (kWh y^{-1}), monetary savings (USD^{+} y^{-1}) and carbon footprint reduction (MTCO$_2$E y^{-1}) per year as a function of reclaimed water use

	Percentage of applied reclaimed water use				
Average annual agricultural water use in California (4.2×10^{10} m^3)	**1%**	**5%**	**10%**	**15%**	**20%**
Reclaimed water use (10^6 m^3)	420	2,099	4,199	6,298	8,398
Total energy savings (GWh y^{-1})[a]	187	935	1,870	2,805	3,740
Monetary savings (USD^{+} y^{-1})[b]	\$25.2M	\$126.4M	\$252.5M	\$379.4M	\$506.3M
Carbon footprint reduction (MTCO$_2$E y^{-1})[c]	4.68×10^7	2.34×10^8	4.68×10^8	7.01×10^8	9.35×10^8

[a] Calculated using energy savings of 0.446 kWh m^{-3} (difference between groundwater energy intensity of 0.77 kWh m^{-3} and reclaimed water energy intensity of 0.324 kWh m^{-3}).

[b] Calculated using electric rate of 0.135 USD^{+} per kWh.

[c] Calculated using conversion factor, k = 0.5 kg$_{CO2,eq}$ kWh^{-1}; $^{+}$2015 dollars.

spatial domain is located in the southern coastal region, hence investments in infrastructure would be necessary to deliver reclaimed water from urban areas to places where agricultural activity is abundant, such as in the Central Valley, Coachella Valley, and the Imperial Valley farming areas. However, when the water source for water

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reclamation is brackish agricultural runoff (Lee & Jones-Lee 2007) or brackish groundwater (Sobhani *et al.* 2012) from areas near or corresponding to the agricultural production, the energy requirements for conveyance and lift may be substantially abated.

It is important to recognize the long-term benefits of matching water quality with the actual end use application. Reclaimed water should be used for crop irrigation, while pristine groundwater should remain reserved for potable consumption. Given that water demand for urban, agricultural, and environmental needs is projected to rise (CDWR 2013), resource allocation efficiency and demand management must be taken into consideration during the policymaking. Thus, decision makers should consider the energy intensity of water (i.e., including the contributions from conveyance and lift) as quantitative metrics to support the other factors in the evaluation of projects. Moreover, by requiring end users to apply the least energy-intensive source of supply, whenever feasible, the regulatory framework would not only promote monetary savings but also accomplish the goal of placing the appropriate value to all water sources, a task impossible to achieve when differential pricing, incentives and subsidies, and lack of regulation are applied to some but not all water sources.

Comparison with other energy uses

When examining the average energy requirements for agricultural harvest and crop processing in California, the California Energy Commission reported 3.7×10^3 GWh y^{-1} (CEC 2008). However, future research should revisit this value to discriminate between crops and final product. In contrast, the energy consumed to provide an estimated 1.9×10^{10} m^3 of groundwater pumping for crop irrigation was calculated here at 1.5×10^4 GWh y^{-1}, making the energy requirement for groundwater irrigation the largest energy contributor in the food production chain, at approximately 4.1 times higher than the energy required to harvest and process all crops. Further examination of other energy uses in California indicated that the energy consumed in agriculture, predominantly in food production (planting, tilling, watering, harvesting, processing, waste/refuse processing), was approximately 7% of the total energy produced in California, 2% higher than the energy used in transportation, communication, and utilities combined, and 6% higher than the annual electricity required for all street lighting in California (CEC 2009).

In 2012, the California agricultural industry reported an export value of 18.18×10^9 USD, a record 42.7% cash receipt for all crops produced in the state (CDFA 2013). As the country's sole exporter of many agricultural commodities, supplying >99% of almonds, artichokes, dates, figs, raisins, kiwi, olives, peaches, pistachios, plums, pomegranates, rice, and walnuts, California's agricultural export is expected to continue to rise (CDFA 2013). One area of knowledge gaps is the quantification of the water embedded in agricultural exports. Further research in this area is needed to determine how the agricultural exports from one region affect the overall water portfolio for that region and the region receiving its water-bearing produce.

Climate change effects

Following a global trend, California has undergone a warming trend in recent decades with more rain than snow in total precipitation volume (CDWR 2013). Increasing temperatures are melting the snowpack earlier in the year and pushing the snowline to higher elevations, resulting in less snowpack storage. The current trend is projected to become more frequent and persistent for the region. As a result, the surface water supply is projected to erode with time, while rainfall will experience increased variability, possibly leading to more frequent and extensive flooding (Fissekis 2008). Rising sea levels will also increase the susceptibility to coastal and estuarine flooding and salt water intrusion into coastal groundwater aquifers (Hanak & Moreno 2008). In California that sea level is estimated to rise between 150 and 610 mm by 2050 (CDWR 2013). As the reliability of surface water is reduced due to the effects of climate change, if water reclamation is not implemented with higher market penetration, the demand on groundwater pumping is expected to increase, resulting in higher energy usage for crop irrigation. Should water reclamation penetrate the water supply portfolio at high levels (e.g., the higher bounds of our calculations), additional storage capacity might be necessary. However, the current extended drought periods are making available existing capacity in storage basins (Famiglietti 2015) that may offset or outnumber the additional demand.

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Our calculations show that for every per cent increase in groundwater pumping over 2015 values, the state would consume an additional 323 GWh y^{-1} of energy, generating a net increase of 8×10^4 $MTCO_2E$ y^{-1}. This additional energy usage will amount to approximately 43.7×10^6 USD for every per cent increase in groundwater pumping applied to crop irrigation, calculated in 2015 dollars. Further research is warranted to determine the effect of climate change on the carbon footprint associated with the energy requirements for irrigation water, particularly for crops grown exclusively for export, and how this carbon emission compares with other societal compartments of the energy portfolio.

Effects of varying power generation portfolios

A sensitivity analysis was performed to show the effect of variable k on the overall carbon footprint associated with the energy savings of applying reclaimed water in lieu of traditional groundwater pumping. For this analysis, k values ranging between 0.3 and 0.7 kg_{CO2eq} kWh^{-1} were used to account for the different k(x,y) within the spatial domain analysed in our study. Furthermore, this sensitivity analysis addresses the global drive to mandate increasing shares of renewables in power generation portfolios (Lucas 2015). For example, in 2011 California Senate Bill No. 2 requires electric service providers to increase procurement from eligible renewable energy resources from 20% to 33% by 2020 (California Public Utility Commission (CPUC) 2015). The amount of carbon footprint reduction is directly proportional to the carbon emission intensity of the power generation source used to produce the reclaimed water. For this study, the weighted average carbon emission intensity of $k = 0.5$ kg_{CO2eq} kWh^{-1} was used within the spatial domain of Southern California as reported by CEC (2009). The calculated reduction in carbon footprint is directly proportional to the percentage of reclaimed water use and the carbon emission intensity factor of the power generation portfolio used to produce the water, as shown in Figure 5. For example, if reclaimed water use is applied at 5% using the weighted average carbon emission intensity of $k = 0.5$ kg_{CO2eq} kWh^{-1}, the calculated carbon reduction is 2×10^5 $MTCO_2E$. If a different k value is used for power generation relying more heavily on coal or nuclear power, the k values span from 0.7 kg_{CO2eq} kWh^{-1} to 0.3 kg_{CO2eq} kWh^{-1}, thus resulting in different total carbon reduction.

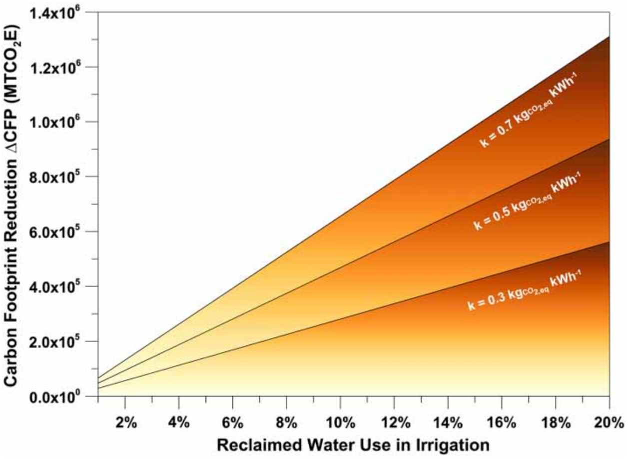

Figure 5 | Sensitivity analysis: effect of carbon-emission intensity *k* on the annual carbon footprint reduction ΔCFP associated with replacing groundwater with reclaimed water in irrigation.

Extension to other regions

In 1994, in its General Assembly meeting to combat desertification in countries experiencing serious droughts, the United Nations defined arid and semi-arid regions as areas having the ratio of annual precipitation to potential evapotranspiration within the range of 0.05 to 0.65 (United Nations Convention to Combat Desertification (UNCCD) 1994). According to this definition, regions in California and other Mediterranean climate countries such as Chile, Spain, France, Italy, South Africa and portions of Australia are classified as arid and semi-arid regions. Other regions of the world such as Central Asia, South Asia, East and Southern Africa, Central Africa and West Africa also meet this definition. The information presented in our research is intended to serve as a baseline for reference in areas sharing similar climate conditions as defined by the UNCCD.

SUMMARY AND CONCLUSIONS

The study found that currently the use of reclaimed water application in California for the agricultural industry is very low, an average 1% for the period 1998–2010. For every per cent increase in reclaimed water use in agriculture, the resulting energy saving is 187 GWh y^{-1}, which at the current energy cost equates to more than 25×10^6 USD. Aside from the energy saving and economic benefit, the application of

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reclaimed water for crop irrigation also produces a direct safeguard of $4.2 \times 10^8\ m^3$ in groundwater supply and a reduction in carbon footprint of 4.68×10^7 MTCO2E y^{-1}.

If reclaimed water use increased from the current 1%, the energy savings, carbon footprint reduction, and economic benefits were calculated for both the current power generation portfolio and for the projected increase of renewable energy. Even in the scenario of a substantial reduction of CO_2-equivalent emissions by meeting and exceeding targets for renewable energy, the increase in reclaimed water use would still provide a net carbon footprint reduction.

This research is intended to serve as a baseline reference and be used as a planning tool to help water resources planners. Specific location, availability of reclaimed water supply, conveyance infrastructure and methods of treatment will influence the calculated results and associated costs presented. It is important to note that while Title 22 water is suitable for irrigation use and is permitted under the current California regulatory framework, effluent from advanced treatment technologies such as desalination is being proposed and advocated for direct potable reuse. Thus from a water quality and technological perspective, desalinated effluents are produced with higher degrees of quality with no micropollutants relative to conventional Title 22 water. The analysis provided in this study however, is intended to demonstrate the cost savings of producing Title 22 water in comparison to all sources of water currently available in Southern California including desalination. It is also important to note that new methods based on hybrid physio-chemical – biological and natural treatment options such as ozonation – biological activated carbon – microfiltration or ultrafiltration and ozonation – soil aquifer treatment as alternative treatment methods for secondary effluent are the object of current investigation (Gerrity *et al.* 2013; Snyder *et al.* 2014), reporting new possibilities of using the advanced oxidation process or biological activated carbon as possible alternatives for indirect and direct potable reuse. In our study we focused on using conventional sand filtration and chlorine disinfection as tertiary treatments to meet Title 22 standards, hence potable reuse is outside this investigation scope. The energy calculations provided in this study will vary if newer technologies are applied, and thus will require broadening of the analysis boundaries. Nonetheless, the results of this study will help further our current understanding on the role of reclaimed water in curbing groundwater withdrawal in an arid and semi-arid region like that of Southern California, by providing the context of its existing usage, estimated energy consumption, carbon footprint reduction, and potential monetary savings that can be realized. The trends observed in this study may be applicable to other regions of the world where water scarcity, energy costs, and climatic conditions require the use of reclaimed water as a sustainable water source.

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