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Towards bridging the water gap in Texas: A water-energy-food nexus approach

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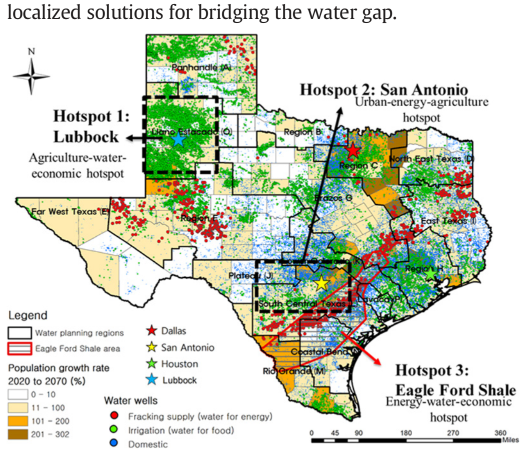
HIGHLIGHTS

- Bridging Texas water gap requires multi-stakeholder, holistic, localized approaches.
- Potential savings of 3 billion gal of water in Lubbock by treating water and dryland agriculture
- Potential of adding 47 billion gallons to water supply in San Antonio by LID implementation
- Economic advantages vs. impact on local water quality and quantity of Hydraulic Fracturing

GRAPHICAL ABSTRACT

Spatially distributed distinct and complex hotspots, which require a holistic system of system approach, yet with localized solutions for bridging the water gap.



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ABSTRACT

The 2017 Texas Water Development Board's State Water Plan predicts a 41% gap between water demand and existing supply by 2070. This reflects an overall projection, but the challenge will affect various regions of the state differently. Texas has 16 regional water planning zones characterized by distinct populations, water demands, and existing water supplies. Each is expected to face variations of pressures, such as increased agricultural and energy development (particularly hydraulic fracturing) and urban growth that do not necessarily follow the region's water plan. Great variability in resource distribution and competing resource demands across Texas will result in the emergence of distinct hotspots, each with unique characteristics that require multiple, localized, interventions to bridge the statewide water gap. This study explores three such hotspots: 1) water-food competition in Lubbock and the potential of producing 3 billion gallons of treated municipal waste water and encouraging dryland agriculture; 2) implementing Low Impact Developments (LIDs) for agriculture in the City of San Antonio, potentially adding 47 billion gallons of water supply, but carrying a potentially high financial cost; and 3) water-

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energy interrelations in the Eagle Ford Shale in light of well counts, climate dynamics, and population growth. The growing water gap is a state wide problem that requires holistic assessments that capture the impact on the tightly interconnected water, energy, and food systems. Better understanding the trade-offs associated with each 'solution' and enabling informed dialogue between stakeholders, offers a basis for formulating localized policy recommendations specific to each hotspot.

1. Introduction

With global population projected to reach 10 billion by 2050 (United Nations, 2017), growing economies (World Bank, 2018), and stresses caused by the impacts of climate change (IPCC, 2014), resource systems are, and will remain, under pressure. In 2017, 844 million people lacked access to safe drinking water; 1.1 billion lacked access to energy; about 815 million did not have secure access to food (WHO, 2017; IEA, 2017; FAO, 2017; Stephan et al., 2018). As a result of the tight interdependence between the growing demands around water, energy, and food systems, resource hotspots will emerge in different regions globally (Hoff, 2011; Mohtar and Daher, 2012; Mohtar and Daher, 2017). Addressing these "Water-Energy-Food Nexus hotspots" requires that we account for the interconnections between them by developing the analytics to catalyze a dialogue about the trade-offs associated with future resource allocation pathway options (Mohtar and Daher, 2016). In this paper, the authors focus on distinct hotspots within the state of Texas in the United States; they develop tools that allow quantification of the interlinkages between water, energy, and food, and explore the trade-offs associated with the different scenarios presented.

The state of Texas risks a 41% (8.9 billion m^3) water gap by 2070, due to projected 70% growth in population between 2020 and 2070, that will increase water demand by 17% and decrease water supply by 11% (TWDB, 2017). In an effort to promote sustainable water management, the Texas Water Development Board (TWDB) issues a 5 year state water plan that includes recommendations for implementation in each of 16 state planning regions. Municipal growth, agricultural expansion, and energy development all combine to place water resources under significant pressure (TWDB, 2017). The Texas cities of Houston, Dallas, San Antonio, and Austin rank among the fastest growing cities in the United States (US) (Forbes, 2015), further increasing pressures on resources and infrastructure. Texas is a major US producer of cattle, dairy, and cotton (USDA, 2016). TWDB predicts that more than 70% of available water will be allocated for irrigation by 2020. As for energy development: Texas contains the Eagle Ford, one of the world's major shale plays, whose shale gas production during the past decade has significantly increased (Murphy et al., 2016).

While revolutionary in terms of providing additional energy security, the hydraulic fracturing industry also puts substantial demand on existing water systems: it is projected that, by 2040, nearly 50% of the total gas production will come from shale resources (USEIA, 2013), for which 5.6 million gallons of water are required, on average, throughout the lifecycle of a well (FracFocus, 2015; Jiang et al., 2014). In the US, natural gas produced from shale resources increased from 0.1 to 3 trillion ft^3 (TCF) during the past decade. Efforts are underway in the hydraulic fracturing industry to reduce those water demands through new technologies. However, such technologies are often more expensive than traditional methods, thus still not commonly used (Brino and Nearing, 2011). The quantity of water needed through the lifetime of a well has been reduced by exploiting opportunities to recycling flowback water (Kondash and Vengosh, 2015; Rassenfoss, 2011). However, groundwater contamination, and the treatment and disposal of "produced water" continue to pose concerns as hydraulic fracturing grows.

The growing competition for water between the three sectors (municipal, energy, and agriculture), and increased stresses such as drought (2015 brought the end of a five-year drought, 2011 was the driest year in the state's recorded history), caused TWDB to dedicate a special section in their new water plan to specifically address drought response projects for the coming years. TWDB proposed a list of 5500 water management strategies meant to boost water supplies and improve conservation and reuse, including desalination and aquifer storage recharge by 2070 (TWDB, 2017).

Each TWDB water planning zone demonstrates different trends of water demand and supply projections. The middle and eastern regions suffer from water scarcity due to high municipal water demands and low surface water availability. Northern Texas requires high water allocation for food production, although ground water (GW) supplies are expected to decrease and alternate sources, such as treated wastewater, are under consideration. South central Texas includes the Eagle Ford shale play, which will demand up to 48,738 m^3 of water for mining by 2020. The main water resource for hydraulic fracturing is GW, projected to decrease by up to 19% between 2000 and 2050.

Planning for and bridging the anticipated water gap demands that existing interconnections with the agricultural and energy sectors be better understood in terms of their spatial and temporal distributions. Although water demanded for mining is less than 5% of the total overall state water demand, this figure is much higher in regions such as the Eagle Ford, often in competition with urban growth and increasing agricultural production.

This work highlights the spatial and temporal attributes of water, energy, and agricultural systems, and quantifies the interconnections and trade-offs among them to identify different pathways forward by:

- **Spatially identifying** the competition for water resource allocation across Texas, given projected population increases, municipal growth, energy development, and expanded agricultural activity;
- **Developing** appropriate tools that follow a water-energy-food holistic assessment methodology to study distinct hotspots and provide trade-offs for informing decision makers;
- **Demonstrating** case studies that represent specific nexus hotspots across the state;
- **Identifying** localized interventions and their potential contributions to bridging the overall Texas water gap.

2. Overarching approach and motivation

The central challenge presented by a growing demand for water is its sustainable allocation across different competing sectors. To provide a solid basis for planning future resource allocations and minimize associated unintended consequences, those areas more prone to resource stress or competition must be identified and assessed for possible interventions and the associated trade-offs. This identification and assessment should be based on understanding the highly interconnected water-energy food (WEF) resource systems. To accomplish this, the authors identify WEF Nexus hotspots across the state of Texas and customize analytics that quantitatively capture the interlinkages between the three resource systems (Daher and Mohtar, 2015), and affecting externalities. Those analytics are then used to facilitate analysis of the trade-offs associated with the pathway options. These analytics will become a powerful tool to facilitate dialogue among stakeholders (Fig. 1).

TWDB data clearly identify areas in which competition exists between municipal, agricultural, and energy sectors. Different "hotspots" have distinct characteristics: resource availability, resource demand,

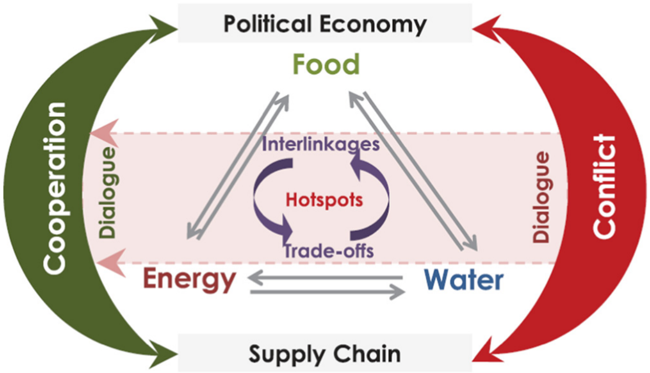

Fig. 1. WEF Nexus framework (Mohtar and Daher, 2016).

and external stresses (Mohtar and Daher, 2016). Therefore, interventions to bridge that water gap need to be localized for each hotspot.

Fig. 2 shows the projected population growth rate across the state. It is clear that most of the growth is expected to happen in the larger municipal areas of Houston, San Antonio, and Dallas/Fort Worth, and expected, in some regions, to reach 200–300% between 2020 and 2070. The figure also indicates water withdrawal for domestic (blue), agricultural (green), and hydraulic fracturing (red). Along the Eagle Ford Shale, competition over water for energy and water for municipal growth is clear; in western and parts of northeastern Texas, the energy sector (oil extraction) also competes with the agriculture and municipal sectors for the needed water resource.

The characteristics of an identified hotspot, depend not only on the spatial attributes of the resources, but also upon their temporal attributes: each crop has a distinct cropping cycle and thus, a different timetable for water use (Daher et al., 2018). Water resource availability is subject to temporal changes related to seasonal variation and overall climate. Accordingly, depending on the source and amount of water available, certain months might be designated for agricultural production, while others might be more heavily allocated to energy production or municipal use. Understanding temporal availability and sectoral demand of resources, potentially allows better management of allocation; it also can potentially lessen stress or competition between sectors for the same resource.

Overlaying the *location* of water abstracted for agriculture, energy, municipal water supply, and population growth rate (Fig. 2), this work identifies three hotspots for further investigation.

Hotspot 1: **Lubbock**, with competition between water for agriculture and municipal use.

Hotspot 2: **San Antonio Region**, with competition between water for energy, municipal, and agricultural.

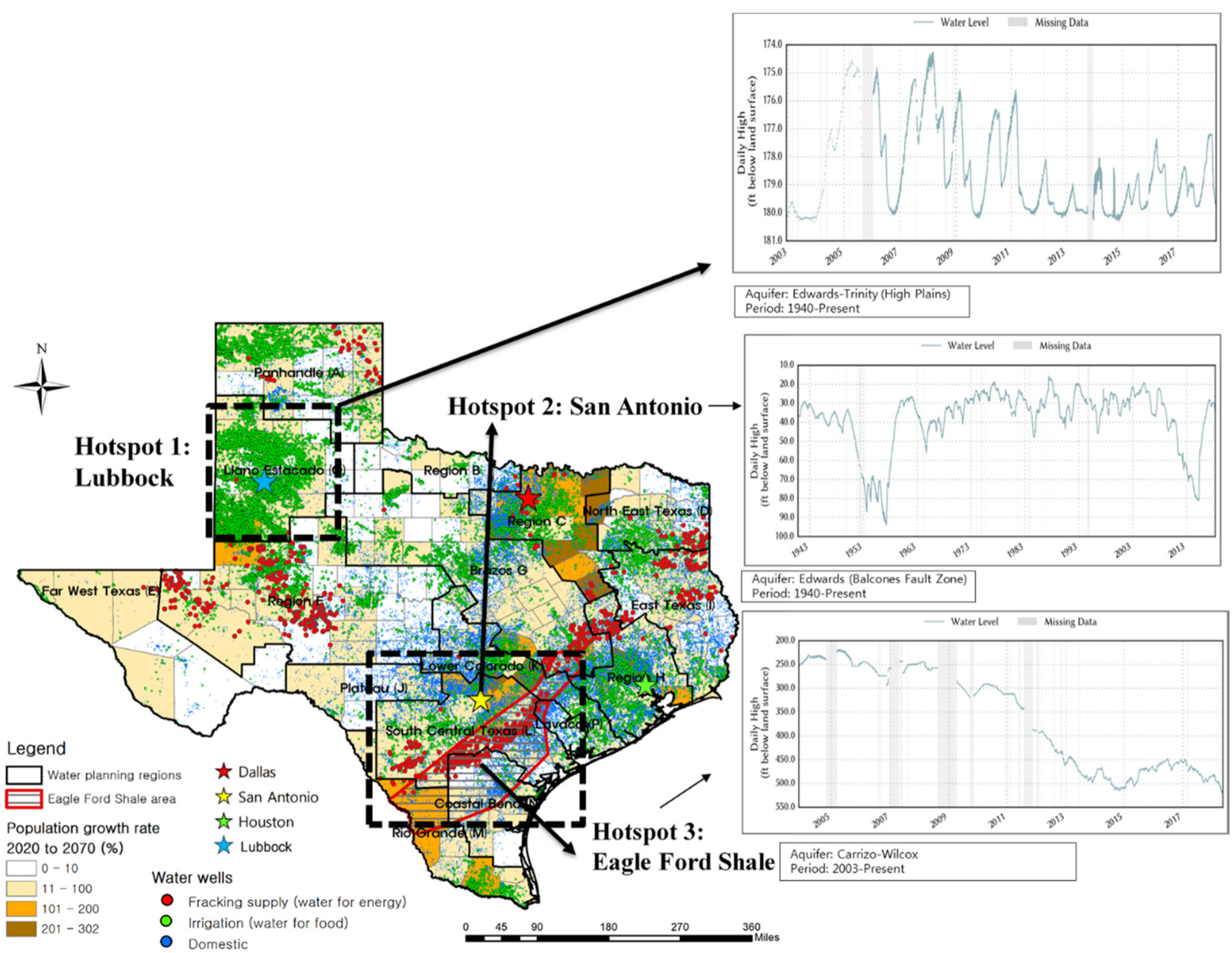

Fig. 2. Spatial distribution of water demands for agricultural, energy, and domenstic use across Texas, USA.

Hotspot 3: **Eagle Ford Shale play**, with competition between water for energy development (hydraulic fracturing), agriculture, and municipal use.

3. Case studies: Exploring three hotspots

The selected case studies, or Hotspots, differ in location, resource availability, relevant critical questions, and hotspot characteristics. The interlinkages between water, energy, and food systems in each Hotspot are explored in terms of the ways in which each of these sectors might contribute to bridging the anticipated Texas water gap. Specifically, Hotspot 1 “food centric” (Lubbock) considers trade-offs associated with water portfolio choices for food production; Hotspot 2 (San Antonio Region) considers the competition between water for energy, municipal, and agriculture in terms of the potential of water from Low Impact Developments (LIDs) as a supplemental source for irrigation; and Hotspot 3 (Eagle Ford Shale Play) explores current and projected development and the trade-offs associated with possible future scenarios.

3.1. Hotspot 1 - Food centric: Developing a water portfolio for the city of Lubbock

3.1.1. The issue

Once known as “the land of underground rain”, the city of Lubbock now faces severe drought conditions, which will persist unless adequate steps are taken for remediation (Brambila, 2014). Per capita water consumption from 1998 to 2004, was 190 gal per day. 50% of the water abstracted within the Lubbock city area in the summer goes to irrigate cotton, winter wheat, and sorghum (Williams, 2012). Its three major water sources Lake Meredith, Lake Alan Henry, and the GW of the Ogallala aquifer, are depleting very rapidly. Nearly 65% of Lubbock's water comes from the Ogallala Aquifer (Personal Communication by phone, City of Lubbock Office, 2014), which is recharged with only 10–15% of the extracted volume, resulting in an annual drop of 2.7 ft (White and Kromm, 1995).

Aquifers are vast underground reservoirs, and the Ogallala aquifer is the biggest in the country.

GW extraction at current rates (65% of the city of Lubbock's water use) is unsustainable: in 2013, the Ogallala dropped nearly one and a half feet. Present-day recharge of the aquifer (replenishment with fresh water) occurs at an exceedingly slow rate, suggesting that much of the water in its pore spaces is paleowater, dating back to the most recent ice age and probably earlier (Wayback Machine, 2018).

The strategic plan of the City of Lubbock identified four future potential water sources: reclaimed, ground, surface, and conservation. Groundwater has a very low recharge rate in the mostly arid area of the state, and surface water is subject to high evaporation due to high temperatures in the region; these facts make reclaimed water and conservation the alternatives worthy of investigation in terms of their potential contributions to bridging the water gap. This case study addresses the *water source* portfolio for Lubbock while sustaining or enhancing the current level of agricultural production; it also explores the impact of agricultural practices that, if adopted, could positively impact a reduced water gap.

3.1.2. Framework

Different sources of water can be used for agricultural production: water could be pumped from GW or surface water, or transported from treatment facilities. Energy inputs are needed for pumping and transport for irrigation. Different sources could supply the energy needed and depending upon the energy portfolio adopted, would result in different levels of emissions: more emissions are associated with a portfolio using gasoline than one using solar energy. Energy is needed to pump and treat water, but is also an input for agricultural production processes such as tillage, harvesting, and fertilizer production.

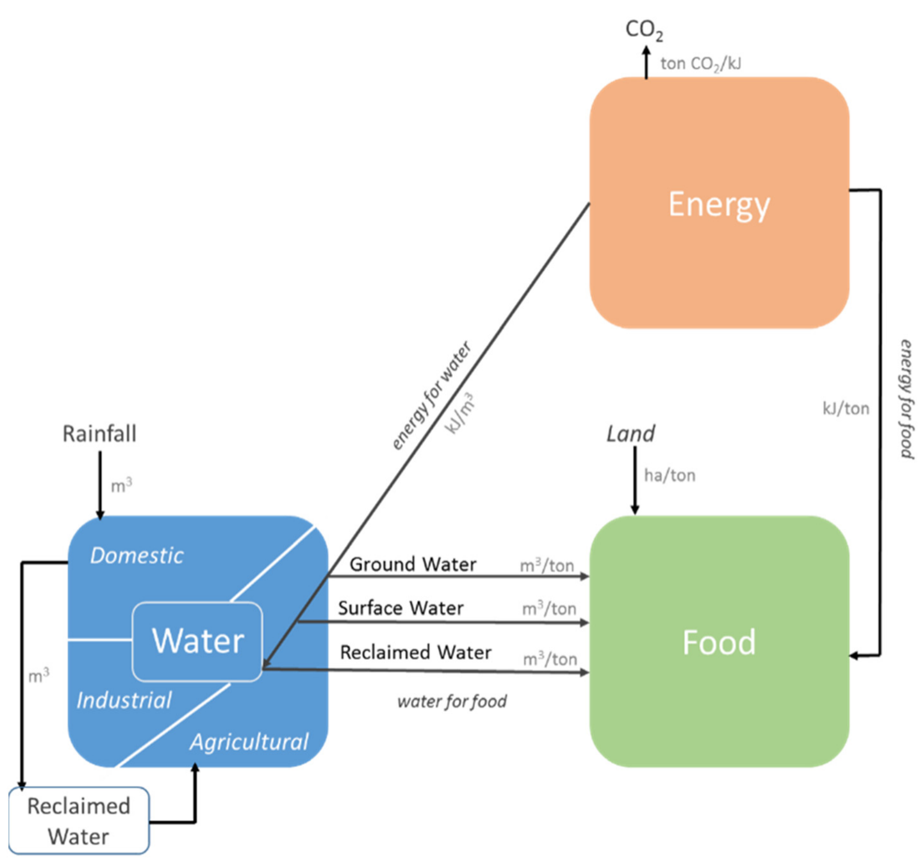

Fig. 3. System boundaries and processes. Externalities to this case include climate change (rainfall and temperature), policies, technologies, and societal behavior.

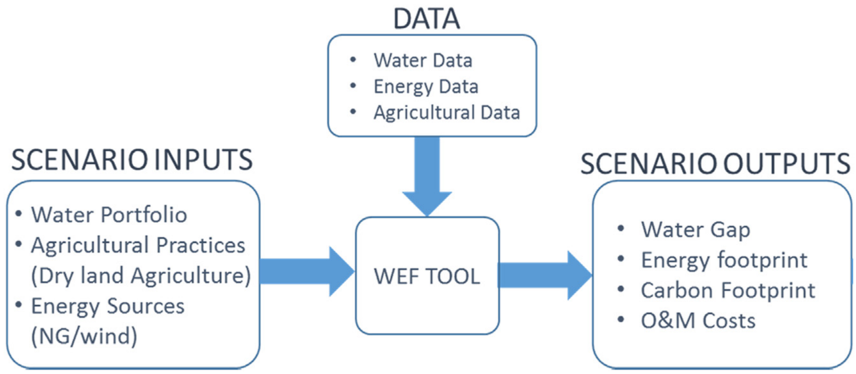

Fig. 4. Lubbock WEF tool flow structure.

Supplying food to local markets, domestic and international trade of goods, requires water and energy: the use of water and energy must be quantified and considered for each case (Fig. 3).

3.1.3. Analytics and data

An excel-based tool was developed to allow assessment of the different scenarios and capture the identified interlinkages of water competition in Lubbock. Users can select values for population growth, precipitation, water and energy portfolios, trade reduction, and percentage of land used for dry land agriculture. Outputs are represented by:

1) *Water gap reduction*: a function of water supply for industrial/agricultural/municipal uses.
2) *Energy footprint*: a function of ground/surface/wastewater treatment plant pumping and nutrient removal.
3) *Carbon footprint*: a function of % of natural gas or wind energy used
4) *Cost*: a function of capital investment (renewable energy/wastewater reclamation plant), cost of water treatment (Fig. 4.)

To determine a portfolio of options for bridging Lubbock's water gap, several scenarios were considered and assessed according to a list of four outputs (Table 1): water gap, energy footprint, carbon footprint and cost. For details of the equations used, see Appendix I.

3.1.4. Scenario outputs and trade-offs

Five possible scenarios were run and analyzed to understand the existing competition between water, energy, and food resource systems, and to contribute to policy development and increased awareness regarding improved resource allocation over time (Fig. 5). Traditional reliance on the Ogalalla makes GW very important to meeting the city's water demands. Thus, it is important to: conserve and monitor GW levels; ensure their proper recharge; and be cognizant of the implications and impacts of increasing population and its consequent demand for more resources. More diverse and novel forms of resource use are necessary to meet future demands. Table 2 summarizes the advantages, risks and costs of each of the five scenarios assessed.

There are negligible differences between energy and carbon footprints for *Scenarios 1 to 5*, however, a new wastewater reclamation plant, though costly, will meet the water demand. The heavy use of water in the vast agriculture sector is unsustainable: it is good agriculture practice to conserve water and maintain product yield by switching to dryland agriculture. The cost variable includes the costs of a new wind energy generation plant and of pumping water. The cost of a wastewater reclamation plant was estimated to be around $94.6 million and treatment costs at $3.71 per 1000 gal (Young, 2012).

The water profile scenarios clearly indicate the importance to and dependence of the population on ground water: even a 70% reduction

Table 1
Scenario components.

	Water	Agriculture	Energy
Base scenario year 2015	- 100% of current ground water (GW) and surface water is used for: (13.5 billion gallons of water per annum from surface and GW resources.) - 0% reclaimed water	- 30% of the total cotton production practices dry land agriculture - 62% is for sorghum - 54% is for winter wheat.	- 100% natural gas - No wind energy
Scenario 1	- 0% of current surface water use - 75% of current GW extraction - 100% use of all reclaimed water.	- 30% of the total cotton production practices dry land agriculture - 62% is for sorghum and - 64% is for winter wheat.	- 100% natural gas - No wind energy
Scenario 2	- 75% of current surface water use - 75% of current GWH extraction - 100% use of all reclaimed water	- 60% of the total cotton production practices dry land agriculture - 70% is for sorghum and - 60% is for winter wheat.	- 50% natural gas - 50% wind energy
Scenario 3	- 60% for surface water use - 30% of current GW extraction - 100% use of all reclaimed water.	- 80% of the total cotton production practices dry land agriculture - 80% is for sorghum and - 80% is for winter wheat.	- 100% natural gas - No wind energy
Scenario 4	- 100% of current surface water use - 60% of current GW extraction - 100% use of all reclaimed water.	All farming is dry land farming.	- 80% natural gas - 20% wind energy
Scenario 5	- 100% of current surface water use - 100% of current GW extraction - 100% use of all reclaimed water.	- 60% of the total cotton production practices dry land agriculture - 70% is for sorghum and - 60% is for winter wheat.	- 20% natural gas - 80% wind energy

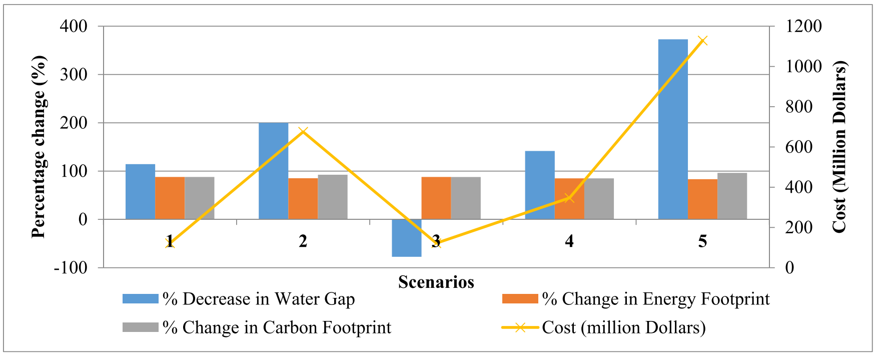

Fig. 5. Output of the six assessed scenarios.

in GW extraction, with introduction of all reclaimed water, results in little water availability. The population of Lubbock depends heavily on GW, which though not regulated, is clearly important to the economy of Lubbock. GW needs laws regulating its extraction: quantities extracted using private wells should be monitored to maintain long-term water sustainability in support of improved food security for Lubbock. Research is needed to estimate the quantity extracted, and measures should be taken to protect its quality. Agricultural activities are heavily dependent on GW: food security goals should focus on conservation of this primary source of water.

The practice of dryland agriculture would reduce water intake for food production and make water available for other uses. However, the impact of changing water supplies on land use and the growth rate of crops cannot be overlooked: research and training to make dryland agriculture more productive is recommended. The water-energy nexus shown in this case study demonstrates that reducing dependence on natural gas as the primary source of energy saves substantial water that is otherwise used for energy production: increasing the use of wind energy would save water while drastically reducing the carbon footprint.

3.1.5. Contribution to bridging the Texas water gap

Scenario 1 is favorable: it emphasizes the use of recycled wastewater for potable purposes, eliminates the use of surface water, and reduces GW extraction by 25%. This scenario also reflects the importance of dry land agriculture as a contributor to bridging the water gap (nearly 60% savings). Achieving such a scenario requires investment: it is associated with a cost of about $121 million. *Scenario 3* does not contribute to bridging the water gap and has a cost of investment equal to that of scenario 1 (although less than all other scenarios). *Scenario 4* bridges a little less than 150% of the water gap, at a minimum cost of $346 million. *Scenario 5* provides an additional 191,217,806 m^3 of water, bridging the water gap by 372% by reclaiming 100% of wastewater and practicing dryland agriculture (60–70% of all the agricultural practices). This scenario also meets 80% of the city's energy needs through the use of wind energy (significant for Lubbock due to its high velocity winds). Despite these advantages, Scenario 5 is very costly and thus highly unlikely to be adopted in the short term. Additionally, other ways to recharge the Ogallala aquifer may rely on playas (such as cropland), which represent faster pathways for aquifer recharge by 1–2 orders of magnitude than more impermeable areas (Gurdak and Roe, 2010).

3.2. Hotspot II – Water centric: The potential of produced water from low impact developments (LIDs) for supplemental irrigation: A water-energy nexus approach

3.2.1. The issue

The case study proposes to contribute to bridging the Texas water gap by utilizing a “new” water source for irrigation: storm water runoff, collected from impervious surfaces in highly urbanized areas and transported to croplands in close proximity. The case study explores the use of low impact development (LIDs) technologies to mimic predevelopment hydrological conditions to collect unused water resources. Three techniques are considered: rainwater harvesting (RWH), bio retention basins (BRB), and permeable pavements (PP).

A representative region, with large impervious surface areas for storm water capture, in close proximity to abundant agriculture was selected. Because the agricultural land surrounding San Antonio grows corn, cotton, sorghum and winter wheat: four crops that account for the majority of the agricultural water demand in Texas, **San Antonio** and its neighboring agricultural land were used to offer scale-up potential to other areas in Texas. The annual precipitation in San Antonio is also a good median of Texas rainfall, with an average annual precipitation of 32 in. (U.S. Climate Data, 2015). The Hotspot 2 case study assesses the feasibility and associated costs of implementing LIDs as a means to collect water for use as supplementary irrigation in farms. A holistic nexus perspective is used to assess scenarios including

Table 2
Scenario trade-offs - hotspot 1.

Scenario	Advantages	Risks/costs
1. Recycle wastewater for reuse as potable water	• Meets existing 25% water gap (about 51,292,330 m^3 (City of Lubbock, personal communication, 2014). • Dependence on surface water eliminated • GW extraction reduced to 75% of current rates.	• Sharply increases energy requirement • Sharply increases carbon emissions. • Infrastructure cost (water reclamation plant)
2. Increased surface water use	• 200% reduction of water gap	• Overexploitation of GW and surface water • High capital costs due to increased dependence on wind energy to meet energy demands.
3. Wastewater reuse	• Only 30% of current GW supply is used	• Increases the water gap • Infrastructure cost (water reclamation plant)
4. Switch to dryland agriculture	• Decrease GW extraction • 141% increase in water supply	• Infrastructure cost (water reclamation plant)
5. Maximize existing resources and reuse wastewater		• High capital costs due to increased dependence on wind energy to meet energy demands

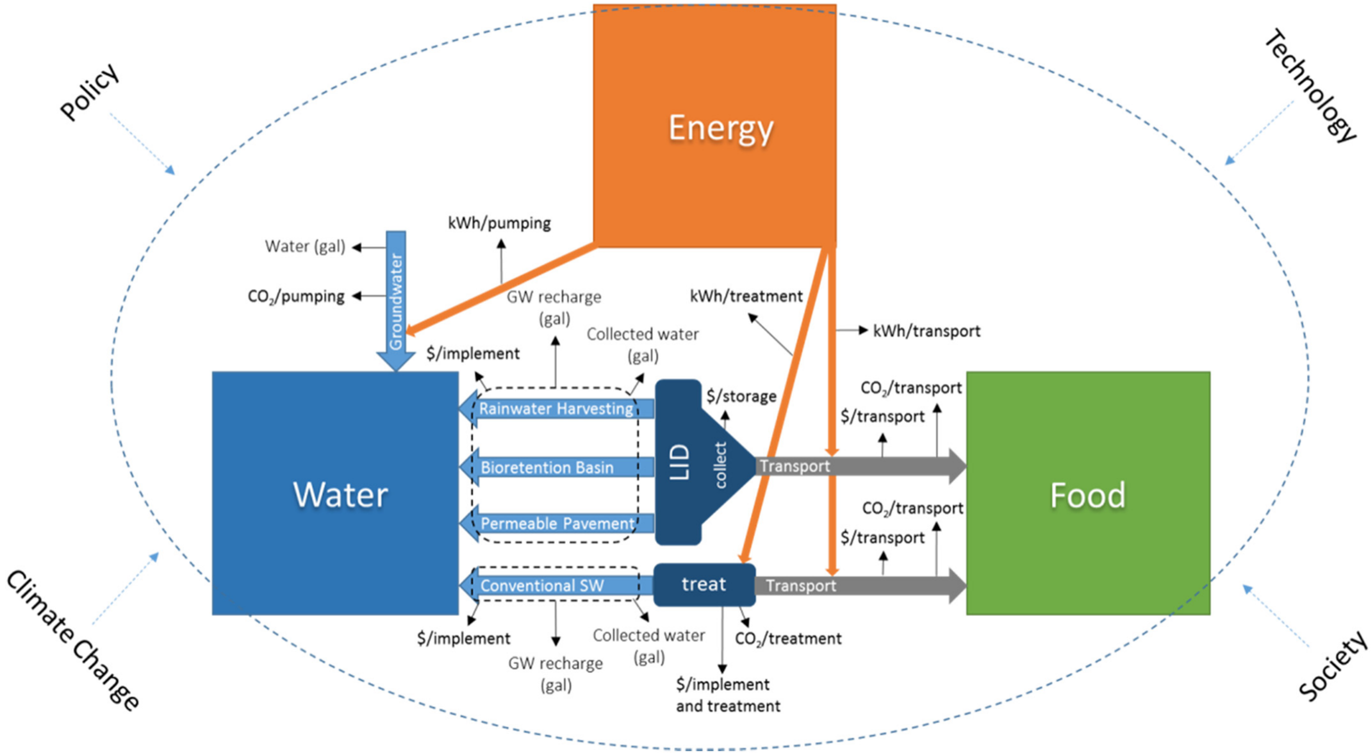

Fig. 6. The inter-linkages between water, energy, and food within the irrigation and LID system, and the externalities (outside of the dotted circle) affecting the system.

quantification of potential collected water, groundwater (GW) recharge, financial cost, energy requirement, and associated carbon emissions.

3.2.2. Framework

An assessment tool was developed to compare trade-offs between various scenarios and evaluate each in terms of its sustainability. Fig. 6 shows the inter-linkages of LIDs for irrigation systems and the externalities affecting them. The study focuses on two aspects of the inter-linkages: water-food and energy-water. Water is interconnected to food through the irrigation process. Energy is needed for the transport and treatment of water. The externalities affecting the system include: climate change, policy, technology, and society (Fig. 6). Climate change will affect weather patterns and precipitation levels, altering the amount of water available for storm water runoff collection. Policy plays a role in facilitating the implementation of the needed infrastructure. Improvements in LID and irrigation technology will improve as the system efficiency increases. LID implementation will have a positive effect on the environment: reducing storm water run-off, improving natural water quality, and offering society visual aesthetics and job opportunities.

3.2.3. Analytics and data

The land cover data analysis yielded a total area of approximately 710 sq. mi. in San Antonio. An impervious area of 25% was assumed, based on the descriptions and approximations for impervious surfaces (USGS, 2011). The available area was further reduced to take into account that it would be unfeasible to implement LIDs across all impervious areas. The percentages applied to the 25% impervious area were: 50% for RWH, 10% for BRB, and 10% for PP. A more accurate delineation of the available area for LID implementation requires a detailed analysis to assess specific factors, such as roof age or quality, land slopes, high traffic flows, or other location limitations for the entire city.

This resulted in drainage areas of 89 sq. mi. (RWH), 18 sq. mi. (BRB), and 18 sq. mi. (PP). This information was combined with precipitation data obtained from the National Climatic Data Center (NCDC, 2015) and used to determine the quantity of water available for harvesting with LIDs. Table 3 summarizes the percentage of the total potential area occupied by each LID, the form of transportation used, and whether or not treatment is needed. *Scenario 3* was chosen to compare different scenarios of LIDs utilizing the current storm water system with treatment for agricultural use. However, for the conventional system, the 100% refers to a direct percentage of the storm water runoff volume captured by the conventional system. Scenario 4 indicates leaving the urban and agricultural system as it is (neither transport nor treatment), water was pumped from GW wells on the agricultural fields; storm water was not collected for agricultural use.

Precipitation data collected from San Antonio by the National Climatic Data Center was analyzed for 1990 to 2010, and used to determine wet and dry crop years (NCDC, 2015). To offer a real-world scenario, crop year April 2005 to June 2006 was chosen to represent a typical wet year and April 2006 to June 2007 was used to serve as a normal dry year. The Food and Agriculture Organization of the United Nations FAO, (Allen et al., 2006) method was used to calculate evapotranspiration, surrounding soil type, rainfall in the area, and quantity of water required for irrigation. Again, using FAO methodology, a water balance analysis (water needed for crop growth) was conducted for both a wet and a dry year (wet year: 105,104 ac-ft and dry year: 102,742 ac-ft) and the results were found to be misleading due to the necessity of timing irrigation (or rainfall) with the maturation and water needs of the crop grown. It was evident that the “dry” year rainfall was optimal for crop growth; therefore, it was determined that an

Table 3
Sample scenarios (where % BRB is the % of available area for bio retention basins, % PP for permeable pavements, % RWH for rainwater harvesting, and % CNV for conventional storm water system).

	% BRB	% PP	% RWH	% CNV	Transportation	Treatment
Scenario 1	50	20	70	0	Pipeline	No
Scenario 2	100	100	100	0	Pipeline	No
Scenario 3	0	0	0	100	Pipeline	Yes
Scenario 4	0	0	0	100	None	None

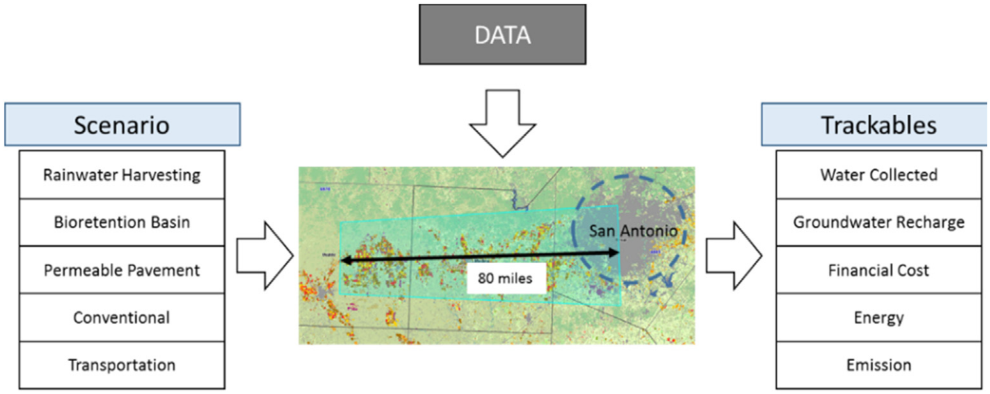

Fig. 7. A customized W-*E*-F Nexus tool structure for holistic assessment of various LID implementation scenarios.

average of the wet and dry years would be used to gain a better understanding of the water demand.

3.2.4. Scenario outputs and trade-offs

Fig. 7 shows the tool structure, including scenarios, location, input data, and outputs. Five outputs were tracked for each scenario: storm water collected, GW recharged, financial cost, energy needed, and emission quantity in pounds of carbon equivalent. Table 4 shows the sources of equations used to quantify the various outputs. For these outputs, equations were input into an Excel spreadsheet and the inter-linkages between the various outcomes quantified. Results from the developed Excel tool were normalized by calculating the ratio of the required resources over base line resource needs. After normalizing, each resource requirement was given a weight between 0 (not important) and 1 (most important). The sum of all five weights is 1. The results of the tool produced an index for each of the five outcomes and was then normalized and multiplied by the respective weights. Financial cost, emissions, and energy outputs were multiplied by negative one (−1) to signify their negative impact on the scenario's overall sustainability. In this study, for demonstration, weights were assigned as 0.8, 0.195, 0.0025, 0.00125, and 0.00125 for water collected, GW recharge, financial cost, energy and emissions, respectively.

$$Individual\ Resource\ Sustainability = \frac{calculated\ resource}{baseline\ resource} \times weight$$

3.2.5. Results and discussions

The resource requirement results are summarized in Figs. 8 and 9. Water collection and GW recharge increases with implementation of LIDs or conventional system collection, however, these alternatives would come at a high financial cost. Results indicate an annual decrease in energy and emissions, once the LIDs and a pipeline are in place. Conversely, a conventional collection and treatment system would exponentially increase the energy and emissions requirements, due to the high energy demanded for treatment of the large quantity of water.

Given the chosen weights, *Scenario 2* was determined the most sustainable solution (Fig. 10), due to the weights chosen for each of the outcomes. Financial cost was minimally weighted, thus did not significantly impact the sustainability index; it also illustrates that the weights chosen by stakeholders can have a powerful role in determining the sustainability of a given scenario. This makes it apparent that stakeholder dialogue is needed regarding which aspects of the system are of greater importance in order to clarify the sustainability of each scenario. It is worth noting that the financial cost of transportation accounts for 25% of the total financial burden, making it reasonable to assume that a more feasible solution is localizing agriculture to urban environments to minimize transportation and allow for the water collected to be used on site (or close by), nearly eliminating transportation requirements.

3.2.6. Contribution to bridging the Texas water gap

Scenario 2 would supply an additional 47,798,690,193 gal (146,688 ac-ft) for agricultural water annually in San Antonio Region, reducing by 1.7% the 8.4 million ac-ft shortfall in the demand for agricultural irrigation water predicted by the Texas Water Development Board for 2060, through 100% implementation of each of the LIDs in San Antonio (TWDB, 2012). It is important to point out that San Antonio does not appear to be an ideal location for this kind of large scale shift, based on lack of uniformity across the region. To implement a solution similar to the one proposed in this study, it would be vital to locate a

Table 4
The various outputs and calculation sources for each output.

Trackable	Item	Calculation sources
Collection	RWH	TWDB, 2005
	BRB	SCS, 1972
	PP	SCS, 1972
	CNV[1]	Purdue Agriculture and Biological Engineering, n.d
GW recharge	Percentage	Assumption[1]
Financial cost	Implementation (LID)	TWDB, 2005; Jaber, 2015
	Maintenance	Assumption[2]
	Transportation	Jaber, 2015
	Storage	Assumption[3]
	Treatment	U.S. Energy Information Administration (USEIA); Reliance Building Company
Energy requirement	Transportation	USEIA; California Energy Commission
	Treatment	California Energy Commission; Water Reuse Association
	GW pumping	Edwards Aquifer Authority, 2015; USEIA, 2015a, 2015b
Emissions	Transportation	California Energy Commission; Oak Ridge National Laboratory, 2014
	Treatment	California Energy Commission
	GW pumping	USEIA

[1] Author's estimate, based on volume of precipitation that did not reach the collection system and was assumed to fall onto pervious areas. Therefore, GW recharge is equivalent to the volume remaining after consideration for collection efficiency of each LID and loss of GW. A collection efficiency of 35% and 49%, based on experimental data from the Dallas Agricultural Research and Extension Center was used for the PP and BRB; (Jaber, 2015). An 85% collection efficiency of RWH was used due to the direct flow of runoff into this technology. A 10% loss for BRB and PP and 5% for RWH loss of GW were included to account for evapotranspiration, GW discharge to nearby water bodies, or leaks onto impervious areas. A GW recharge of 2.5% to account for potential leaks in the system and a collection efficiency of 90% was used for the CNV method.

[2] Author's estimate based on similar previous studies.

[3] No storage cost is generated for LID as it is part of the implementation cost. Storage is taken into account for CNV under the treatment cost.

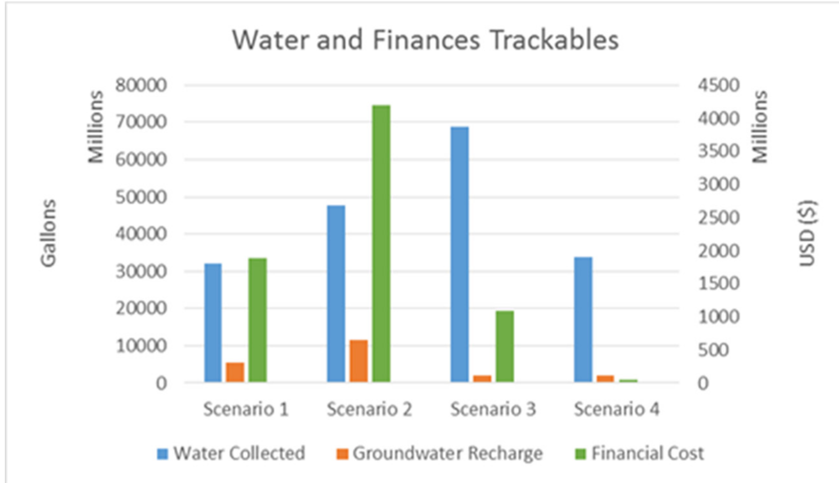

Fig. 8. Water and finances resource requirements.

city with the appropriate physical features and appropriately motivated stakeholders to maximize efficiency. If this strategy was carried out in multiple cities fitting the above criteria, the gap would significantly decrease. The key lies in shifting the perception of large cities from solely a water demanding region to a prospective source of water. With the correct investment in urban infrastructure, large impervious cities could be transformed into water resource pools, enabling re-allocation towards various water demanding activities. While this by no means provides a complete solution to the Texas water gap, it could be an effective contributor to closing it.

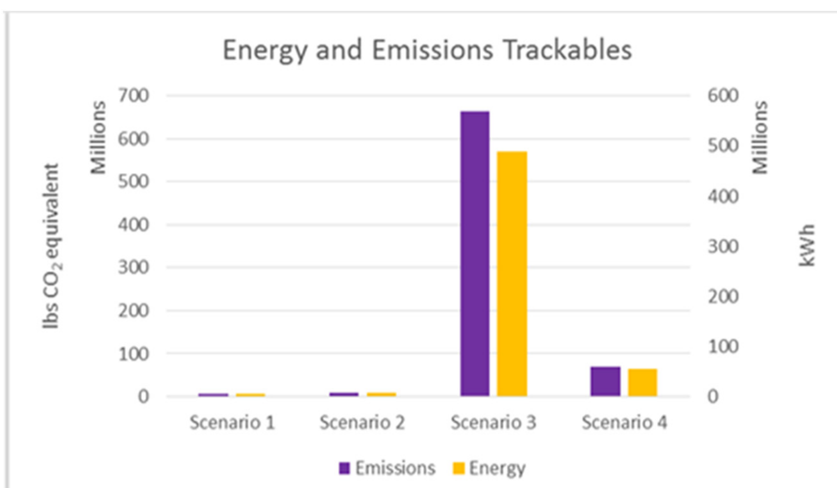

Fig. 9. Energy and emissions resource requirements.

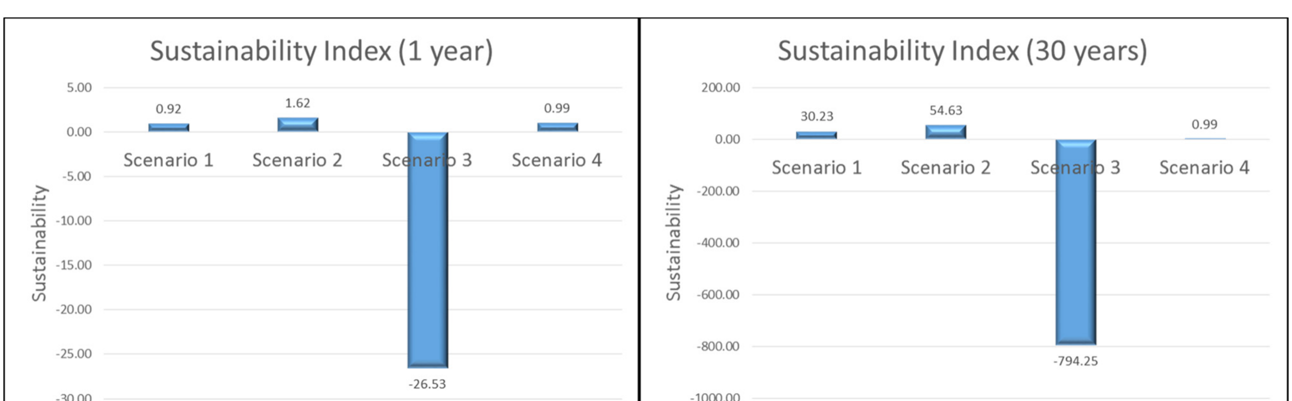

Fig. 10. Sustainability index over 1 year and 30 years.

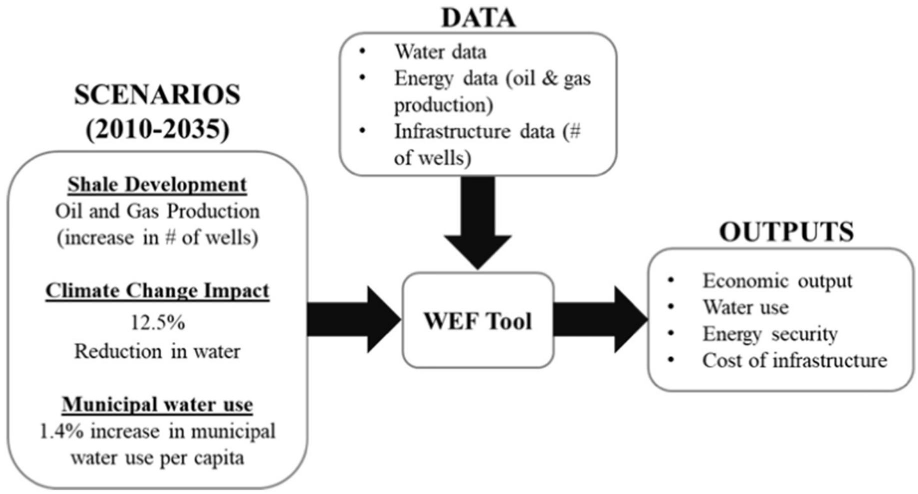

Fig. 11. Eagle Ford WEF tool flow structure.

3.3. Hotspot III - Energy centric: Water-shale oil/gas nexus: The case of eagle ford shale play

3.3.1. The issue

The Eagle Ford shale play in south-central Texas, extends from Brazos County to Webb County, passing through 23 Texas counties and covering an area roughly 50 by 400 miles. With recently developed, economically feasible technology, the area has witnessed massive growth in hydraulic fracturing. Texas Railroad Commission statistics indicate over 200 active operators and a jump between 2008 and 2014 from only 26 new drilling permits to 5613 permits (Arnett et al., 2014). This case study offers quantification of the interrelations between shale oil, gas production, and GW consumption in the Eagle Ford shale play. Future water use in the area is estimated under scenarios of climate change and population growth.

3.3.2. Framework

Water is essential for the hydraulic fracturing process, which competes with other water demanding sectors. To define a baseline for estimating the variation in total water due to different scenarios, a mass balance of the total GW (235,107 acre-feet, 2.9E + 08 m^3) in the counties overlying the Eagle Ford shale play was considered. Two different scenarios were envisioned: a) business as usual, including the same total precipitation, climate, and water consumption in different sectors, so the total balance of GW remains constant (same as baseline); and b) changing factors, including oil and gas levels of development, municipal water consumption, and climate change, to estimate the consequences of 'what if scenarios' for changes to the current situation. Three (low, medium, high) scenarios for climate change and oil and gas development are considered, one scenario was developed for municipal water consumption growth. In this regard, any changes including increase in water consumption or decrease in input water to the system (such as decrease in precipitation due to climate change) were considered to be a change in mass balance, which should be applied to the total GW of the Eagle Ford counties (Fig. 11).

3.3.3. Water consumption by hydraulic fracturing in the Eagle Ford (EF)

Water consumption is defined as the difference between water used for construction, drilling, hydraulic fracturing (HF), well closure and the total water that is recycled. The largest amount of water used in this process is in the HF step. Water use depends on factors such as geology, depth of drilling, and length of the horizontal wellbore. While the geology and depth are assumed to be the same for all wells because the location is similar for all wells, the horizontal portion of the wellbore can impact water use. Per industry sources, 5000 ft lateral length is the desired condition for optimum production (Arnett et al., 2014). Given 2012 data for EF (Arnett et al., 2014) estimates of water required for gas and oil well are:

$$\text{Water per gas well (acre ft)} = 2.13 + 0.0022^{*}\ \text{lateral length (ft)} \tag{1}$$

$$\text{Water per oil well (acre ft) l} = -0.18 + 0.0025^{*}\ \text{lateral length (ft)} \tag{2}$$

In this research, a 5000 ft lateral length was assumed as the desired condition for optimal production. Due to the high level of uncertainty in predicting a number of wells, it was also assumed that gas and oil wells use almost equal amounts of water.

The effects of three parameters on Texas water are considered in the defined scenarios: hydraulic fracturing, climate change, and growth in municipal water consumption. The independent effects of these parameters are major assumptions made reasonable on the macro scale because climate change does not directly affect HF nor does HF have a substantial effect on the population. However, on the micro scale, those relations are more pronounced. Using a 2010 baseline for municipal water use (similar to the baseline for fracturing), 15 counties will face a 0.4% increase by 2020 and a 1.4% increase by 2040 in municipal

Table 5
Water consumption for hydraulic fracturing.

Scenarios	Number of wells	Production		Water consumption for hydraulic fracturing (acre-feet)
		Oil	Gas	
		(B/Day)	(mmcf/day)	
Scenario 1	10,000	1,745,580	3926	131,335.7
Scenario 2	18,000	3,142,043	7066	236,323.1
Scenario 3	22,000	3,840,275	8637	288,857.4

Table 6
The amount of GW use during 2008 and 2012 in 15 counties in the EF by sector (acre-feet).

Year	Municipal	Manufacturing	Mining	Electric power	Irrigation	Livestock	Sum	% mining from the sum
2008	38,759	2150	1600	6637	179,178	12,739	241,063	0.66%
2009	41,240	2092	3721	8048	193,471	12,791	261,363	1.42%
2010	39,679	2100	5905	7247	166,412	13,944	235,287	2.51%
2011	46,566	2025	20,339	8078	250,359	14,265	341,632	5.95%
2012	45,429	2114	37,115	8491	191,786	10,234	295,169	12.57%

Source: Texas Water Development Plan.

Table 7
Impacts of shale development, municipal growth, and climate change on water security.

Scenario	HF effects	Climate change effects	Municipal growth effects	Total reduction of water resource	Water volume (acre-feet)
Scenario 1	2.2%	12.5%	1.4%	16.1%	37,941.4
Scenario 2	4.0%			17.9%	42,157.1
Scenario 3	4.9%			18.8%	44,265.0

water use. Thus, for the water management scenarios in the EF, a 1.4% increase in municipal water consumption due to population growth was applied. TWDB provides total municipal water use for the years 2000–2012, and simple linear regression was used to estimate water use for a municipality by changing population figures.

$$\text{Water consumption for municipal} \\ = 2,198,380 + 0.090293^{*}\text{Population} \quad (3)$$

There are differing opinions regarding the impact of climate change on Texas water; different rates of climate change are provided by different studies (EPA, 2017; Nielsen-Gammon, 2011; Modala, 2014). The relationship between climate change and water supply are assumed to be linear; the climate change effect is assumed to be 12.5% over 25 years, as a worst case scenario reflecting the maximum effect of climate change effect on water resources.

3.3.4. Results and discussion

Given the more than 2000 drilled oil and gas wells reported by 2012 and 5613 permits issued for drilling in 2014, three different HF scenarios are considered for the industry in EF. The total number of operational wells, at the end of the projected time frame, is 10,000, 18,000, and 22,000. Using the equations provided above, the required water for each well and ultimately for the total number of wells was calculated.

Table 5 quantifies the water consumed by HF in three scenarios. For the 10,000 new wells, 55% of the GW used in 2010, or 131,300 acre-feet (161,956,165 m^3) of water is needed. Since 2010, the south Texas region has faced severe GW depletion, nevertheless GW used for HF has increased annually since 2010 (Arnett et al., 2014).

3.3.5. Contribution to bridging the Texas water gap with HF, climate change, and municipal growth

This study focused on the 15 counties in the EF shale play where most HF activities happen. The main water resources for HF in these counties is fresh GW, accounting for 90% of water used. Table 6 shows the amount of GW consumed 2008–2012 by different sectors. Mining, including HF, increased from 0.66% of total GW consumption in 2008 to 12.5% of total GW consumption in 2012, in Texas, and could be as high as 50% in some counties.

The HF water, climate change, and municipal growth could all affect GW resources and the water gap in south Texas. Using provided equations, water use for HF under three scenarios with the number of wells at 10000, 18000, and 22,000 equals 2.2%, 4.0% and 4.9% of defined baseline water (GW of EF counties: 235107 acre-feet, 2.9E + 8 m^3). Applying the effects of two other effective parameters (climate change and municipal growth) to the baseline yields a total reduction in water resources (Table 7).

Water used for mining comprises a high proportion of the total water used in EF area, thus increased shale development could affect the water gap through demand for HF: a serious threat in south Texas, where increased municipal water consumption due to population growth and reduced GW due to climate change are both expected. The approach used here provides a rapid assessment for interrelations between energy development and water scarcity, allowing an understanding of trade-offs for different levels of production.

3.4. Sustainability of shale development by economic values

The values in Tables 6 and 7 can be converted to real point values by considering the change in oil and gas prices. The price of oil was estimated at \$90/B, gas at 3500 \$/MMCF for 2013, although oil and gas prices were much lower in the past years and remain subject to change. In this study, the price of oil and gas are assumed to be \$50/B and \$3500/MMCF (Million Cubic Feet) for the scenarios and a study prepared by the Center for Community and Business Research at the University of Texas at San Antonio's Institute for Economic Development (Tunstall et al., 2014) was used. It is estimated that the oil and gas industry produced \$72 billion in 15 counties in EF in 2013. The price of water is set at \$0.12/G, considering \$0.78/G price at the stores in this area. Required infrastructure for transportation is highly important in this sector. According to available reports, the transportation costs per well are \$133,000.[1] This value is considered one of the costs related to hydraulic fracturing in EF. Moreover, HF is expected to increase the level of energy security in the US. According to Griffin (2009), the savings to the US in terms of energy security is \$5/B of produced oil. This is represented as a security benefit throughout the analysis. The value is considered a benefit in calculations for different scenarios. Given these rates and different sets for defined scenarios, oil and gas production, economic output, water cost, security benefit, the cost of infrastructure and eventually "net value" can be estimated. The cost of infrastructure and the water costs were subtracted from the summation of economic output and security benefit. The effect of municipal water consumption, climate change, and hydraulic fracturing are reflected in water consumption and, eventually, water cost. Table 8 is an example of monetizing for three scenarios of HF and low effect of climate change.

3.5. Impact of shale development on water gap

The interrelation of shale oil and gas production in the EF was quantified in relation to GW consumption; future water use estimated for the

[1] DeWitt County Commissioners Court. 2015. "ROAD DAMAGE COST A LOCATION STUDY." Accessed March 7. http://eaglefordshale.com/wp-content/uploads/2012/07/DeWitt-County-Road-Damage-Cost-Allocation-Study.pdf.

Table 8
Sample monetizing calculations.

Scenarios	Estimated value (billion $)				
	Economic output	Water cost	Security benefit	Cost of infrastructure	Net value
Scenario 1	72.81	−1.11	0.01	−1.33	70.38
Scenario 2	131.1	−1.93	0.02	−2.39	126.8
Scenario 3	160.2	−2.34	0.02	−2.93	154.9

area, using alternative other scenarios that included climate change and population growth. The net benefit of shale oil and gas production was monetized, as was the cost of water. Benefits are economic output and energy security; costs are water consumption and infrastructure deterioration. Four different sets of weights are applied to the benefits and costs corresponding to higher focus and value on each benefit and cost element. According to the analysis, future net benefits of the HF industry are huge for Texas, but the actual amount of these benefits will vary as greater value is placed on other natural resources, such as water. Future research should investigate the real price of water in the region, considering locations in arid zones with historically low rates of precipitation. It is vital to evaluate the efficiency of GW depletion rates in terms of increased sustainability: declining water availability will impact all economic activities, including shale oil and gas development. Therefore, improved practice, such as encouraging the use of brackish and produced water, is necessary to preserve water availability and prevent its possible interruption.

4. Conclusions

Business as usual growth in water demand trends across different sectors, coupled with declining conventional water sources, will cause a serious water gap that requires solutions beyond the water system itself. Bridging the Texas water gap requires multi-stakeholder, holistic, localized approaches. The high level of interconnectedness between water, energy, and food systems indicates that a nexus approach would be useful in accounting for the associated trade-offs and competition between these systems. The holistic view provided by the nexus approach accounts for the interlinkages between water and other resource systems interconnected with it. Due to the **spatial and temporal variability** of available water and the demands for that water by the different sectors, hotspots emerge. Each of these '**nexus hotspots**' must be individually understood and analyzed in order to prescribe the necessary, localized solutions to reduce existing stresses (Fig. 12).

The authors acknowledge the limitations of this study: the use of preliminary assessments and assumptions to address the different hotspots. Nevertheless, a main goal of this study was contributing to the conversation on addressing water-energy-food nexus hotspots and localizing solutions by highlighting existing trends in different regions in Texas. As such, this work could be a useful springboard for more detailed studies that further explore the possibilities within each of these hotspots.

Stakeholders differ from one region to another, making it important to understand who the players are, what their preferences and priorities are, and the manner in which they interact: each should be part of any prescribed solution for addressing a given hotspot. The developed nexus analytics must be customized to address stakeholder questions and **facilitate dialogue**. The challenge with such localized

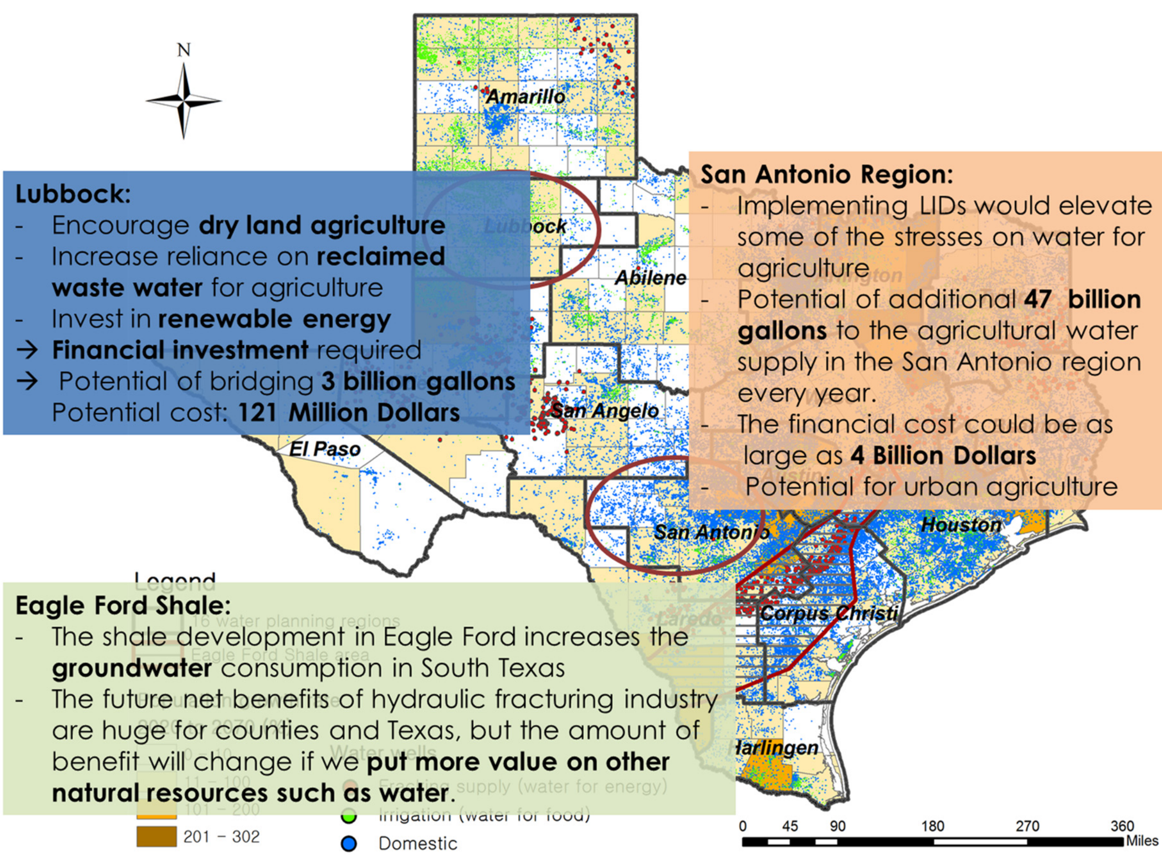

Fig. 12. Summary of different interventions and potential contribution to bridging the Texas Water Gap.

recommendations is the necessity of including different stakeholders in the discussion and allowing the developed analytics in each region to drive that dialogue. Preferences must be properly reflected and bring forward solutions that relieve local stresses while contributing to stress relief of larger, statewide issues. Proposed interventions need to be put forward with clear **finance plans**, whether public, private, or in partnership. **Governance** at difference scales and across sectors need to be coherent, so that policies do not compete.

Building on the data files made available by the Texas Water Development Board and based on the hotspot map shown in this study, it is recommended to augment existing regional water planning zones with a **WEF nexus hotspot map** that can help focus the discussions on areas under stress and bring the relevant stakeholders to assess possible ways forward. The hotspots identified in this study are often not contained within the borders of a single regional water planning zone, but overlap two or more regions. Thus, complementing the present water planning regions with regions that capture both present and projected future resource hotspots, could offer information that leads to more holistic solutions and more inclusive trade-offs dialogues.

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Appendix I. Equations for case study 1

Equations used to determine trackable values in the excel spreadsheet model.

i. Water gap

To determine the change in the water gap, first the water gap in the base case must be determined. This is done by subtracting the municipal, industrial, and agricultural use in the base case from the supply as seen in Eq (1).

$$WG_{Base} = Supply - (MU_{Base} + IU_{Base} + AU_{Base}) \quad (1)$$

Similarly, the water gap is calculated for the scenario as in Eq. (2).

$$WG_{Scenario} = Supply_{Scenario} - (MU + IU + AU) \quad (2)$$

Several additional steps are used to calculate each term. First to determine the water supplied in the scenario, user inputs for the water portfolio are multiplied by the current supplies (see Eq. (3)). This multiplies the percentage selected by the user by the volume currently supplied or, in the case of the wastewater treatment plant, by its capacity.

$$Supply_{Scenario} = GW_{Base}(\%GW) + SW_{Base}(\%SW) + WWTP(\%WWTP) \quad (3)$$

In this analysis, no impacts on municipal or industrial use are considered, but there will be some increase based on population increase. In order to calculate the scenario values of each of these uses, the base case will be multiplied by a population ratio as seen in Eqs. (4) and (5). The population ratio is the expected population multiplied by a percentage selected by the user. If the user selects a value of 1, then the population growth will be the 22% anticipated increase. A user selected value above 1 means accelerated growth; a value below 1 means slowed growth.

$$MU = MU_{Base}P \quad (4)$$

$$IU = IU_{Base}P \quad (5)$$

Agricultural water use is the most complicated within the excel model. Eq. (6) shows the general form of this equation.

$$AU = W_{Cotton} + W_{Sorghum} + W_{Wheat} \quad (6)$$

The water needed for each crop considered in the model, cotton, sorghum, or wheat, must be calculated. The specific equations for cotton are presented; the same equations are applied to the other two crops. Eq. (7) shows the general form of the equation used to determine the water need for cotton.

$$W_{Cotton} = W_{C,Irrigated} + W_{C,Dryland} - W_{C,VWR} \quad (7)$$

The water needed for irrigated agriculture and dryland must be calculated separately (Eq. (8)), as the area of land used for cotton multiplied by the yield of cotton, the water need for cotton, and the percentage of the acreage to be used for irrigated agriculture and as selected by the user.

$$W_{C,Irrigated} = Acres_C(\%Irr_C)(Y_{C,Irrigated})(WN_C) \quad (8)$$

Similarly, the water required for cotton under dryland agriculture is determined as in Eq. (9). To calculate the supplemental irrigation water needed by the crop that has not received precipitation during the crop's growing season. The precipitation in this equation is determined by NOAA data and can be altered to reflect a dry, normal or wet year by the user.

$$W_{C,Dryland} = Acres_C(\%Dry_C)(Y_{C,Dryland})(WN_C - Precip) \quad (9)$$

The final component of the water requirement is the quantity removed when production of the crop traded is reduced. It is calculated by multiplying the total water need by the percentage of trade reduction, as selected by the user (Eq. (10)). Similar calculations are performed for sorghum and winter wheat within the excel model.

$$W_{C,VWR} = Acres_C(\%VWR_C)(WN_C) \quad (10)$$

Once the water gaps for the base case and the scenario are calculated, these values are subtracted (Eq. (11)) to establish the decrease in water gap that will be multiplied by the policy weight for the water gap.

$$Decrease_{WG} = WG_{Base} - WG_{Scenario} \quad (11)$$

ii. Energy footprint

Similar to the water gap, the base energy footprint must be calculated for comparison among the scenarios to be evaluated. This is done by adding the energy used for pumping groundwater, surface water, water within the wastewater treatment plant, and the energy required for nutrient removal (Eq. (12)).

$$EF_{Base} = EF_{GWTB} + EF_{SWTB} + EF_{WWTPB} + EF_{NRTB} \quad (12)$$

Each is determined individually by multiplying the energy use per gallon for each process by the gallons of water that flow through that process. The steps are summarized in Eqs. (13) through (16)

$$EF_{GWTB} = EF_{GW}GW_{Base} \tag{13}$$

$$EF_{SWTB} = EF_{SW}SW_{Base} \tag{14}$$

$$EF_{WWTPTB} = EF_{WWTP}WWTP \tag{15}$$

$$EF_{NRTB} = EF_{NR}WWTP \tag{16}$$

The same terms are calculated for the scenario analyzed and are summed as seen in Eq. (17).

$$EF_{Scenario} = EF_{GWT} + EF_{SWT} + EF_{WWTP} + EF_{NRT} \tag{17}$$

However the individual terms are calculated differently: the volumes for each process may change in a given scenario, depending on the selections made by the user. Eqs. (18) through (21)

$$EF_{GWT} = EF_{GW}(GW_{Base})\%GW \tag{18}$$

$$EF_{SWT} = EF_{SF}(SW_{Base})\%SW \tag{19}$$

$$EF_{WWTPT} = EF_{WWTP}WWTP \tag{20}$$

$$EF_{NRT} = EF_{NR}(WWTP)(1-\%WWTP) \tag{21}$$

As in the case of the water cap, the change in energy footprint is determined by subtraction (Eq. (22)).

$$Change_{EF} = EF_{Base} - EF_{Scenario} \tag{22}$$

iii. Carbon footprint

The carbon footprint is based on the energy portfolio selected. In the case of Lubbock, only natural gas and wind energy are considered. The base case is the carbon footprint of each of these sources (Eq. (23)).

$$CF_{Base} = CF_{NGB} + CF_{WB} \tag{23}$$

For each energy source, the carbon footprint is determined by calculating the amount of energy supplied by that source and then multiplying by a unit carbon footprint for the energy source (Eqs. (24) and (25)).

$$CF_{NGB} = EF_{Base}\%NG_{B}CFNG_{U} \tag{24}$$

$$CF_{WB} = EF_{Base}\%W_{B}CFW_{U} \tag{25}$$

The carbon footprint of the scenario is determined similarly, but the energy footprint for the scenario is used instead of the base (Eqs. (26) through (28)).

$$CF_{Scenaro} = CF_{NGS} + CF_{WS} \tag{26}$$

$$CF_{NGS} = EF_{Scenario}\%NG_{S}CFNG_{U} \tag{27}$$

$$CF_{WS} = EF_{Scenario}\%W_{S}CFW_{U} \tag{28}$$

As in the energy footprint, the change in carbon footprint is calculated by subtraction (Eq. (29)).

$$Change_{CF} = CF_{Base} - CF_{Scenario} \tag{29}$$

iv. Cost

The trackable cost is shown in Eq. (30) and includes three terms: cost of renewable energy, trade loss, and the cost of nutrient removal.

$$C = C_{RN} + C_{TL} - C_{NR} \tag{30}$$

The cost of renewable energy is the amount of energy provided by wind multiplied by a unit cost of wind energy (Eq. (31)).

$$C_{RN} = EF_{S}[\%W_{S}C_{w}] \tag{31}$$

The cost of trade loss is calculated by crop and summed (Eq. (32)).

$$C_{TL} = TL_{Cotton} + TL_{Sorghum} + TL_{Wheat} \tag{32}$$

The trade loss equation for cotton is shown; similar equations are applied for other crops considered. Eq. (33) calculates the total trade reduction multiplied by a unit price for cotton.

$$TL_{Cotton} = Acres_{C}\left[\%Dry_{C}\left(Y_{C,Dry}\right) + \%Irr_{C}\left(Y_{C,Irrigated}\right)\right](\%VWR_{C})(P_{C}) \tag{33}$$

The cost of nutrient removal is determined by multiplying the total energy required for nutrient removal by the weighted cost of the energy based on the energy portfolio determined by the user (Eq. (34)).

$$C_{NR} = EF_{NR}\{C_{TE}(\%NG) + C_{RNE}(\%W)\} \tag{34}$$

v. Sustainability index

The sustainability index is calculated in the excel model following Eq. (35).

$$SI = Change_{WG}PW_{WG} - Change_{EF}PW_{EF} - Change_{CF}PW_{CF} - CostPW_{Cost} \tag{35}$$

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