Optimal Water Allocation Planning Using a Water-Energy-Food (WEF) Nexus Approach: The Case of Matagorda County

Muhammed Imran Kulat, Texas A&M University

Abstract

Conventional methods for analyzing the influences of water planning decisions frequently miss the dynamic interconnections between WEF resources. This study presents a platform to analyze the feasibility of potential interventions and scenarios to enhance WEF resource sustainability. A water-centric framework includes a unique analytic tool for analyzing the scenarios and a sustainability analysis to draw recommendations for future water allocation in light of WEF inter-linkages. The applied case is Matagorda County, which, despite ample water resources, is considered one of the most water stressed area of Texas due to high demands on water resources from agriculture and energy sectors.

Introduction

This study builds a water-energy-food (WEF) nexus based analytical framework to quantify tradeoffs between various tenants of the nexus when multiple interventions are applied across all ranges of water consumers. Possible intervention scenarios include: conventional and unconventional water supplies, existing, new or improved infrastructure, and changing cropping patterns. An excel based WEF nexus tool analyzes each scenario while considering water, energy, food, land allocation, financial and environmental cost parameters. A sustainability analysis using the data produced by the tool enables presentation of water, food, or cost -centric scenarios.

The case selected for the study is Matagorda County: once famous for lucrative rice farms, and home to one of two nuclear power plants in the state of Texas, Matagorda County's recent water shortages have resulted in dramatic changes in crop patterns. The nuclear power plant consumes nearly 31% Matagorda's existing water supplies. Recent licenses for proposed reactors would more than double energy production there, further exacerbating its natural resources. Texas Water Development Board (TWDB), a state agency producing short and long term water plans, expects 57% water gap in supplying total water demand of the county as can be seen in Figure 1.

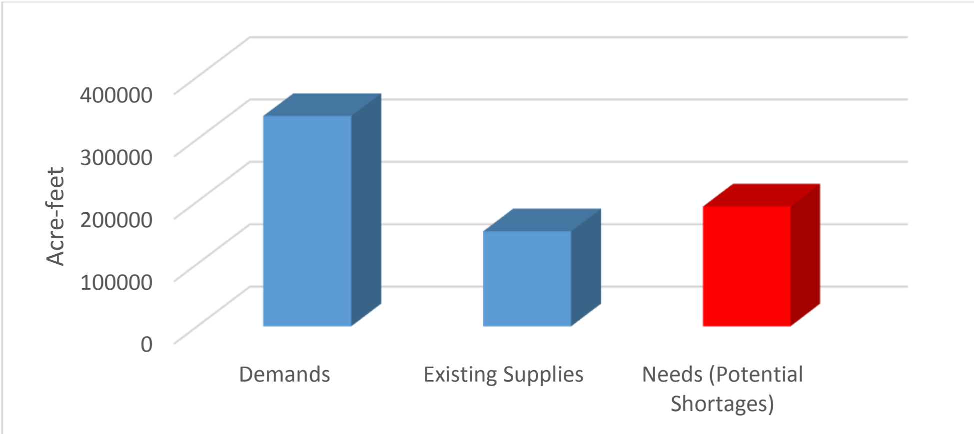


Figure 1. Matagorda Potential Water Needs in 2020 (TWDB - 2017, 2016).

Literature Review

Water Infrastructure Systems

People tend not to think about how water enters their homes, croplands, and facilities. Often a water infrastructure system interfaces seamlessly with nature: natural or constructed reservoirs, storage tanks that make water available on demand, pumping station that extract water from aquifers, and even rivers that transport the water naturally. Treatment facilities, moreover, process raw water or wastewater for a specific end-use (Duffy, 2013). Desalination plants can be considered as water infrastructure that increases available fresh water by converting seawater, drainage water, and brackish water (Beltran & Koo-Oshima, 2006). Water distribution systems can be a network of open channels, covered tunnels, and pipes that convey water through wild fields, rural lands and urban areas to its ultimate end-users (Duffy, 2013).

Until the end of the last century, water management and planning focused on physical water distribution to users. In the United States, for example, 800,000 miles of freshwater pipelines, and 600,000 miles of sewer lines exist in addition to reservoirs and treatment facilities by 2004 (GAO, 2004). As governments completed their hydraulic infrastructures, governmental water resource policies increasingly focused on managing water allocation (Kemerink, et al., 2016), first in developed countries and gradually developing countries as well.

Systems thinking in Water Resources Systems: A solution to complexity

As societies industrialized and populations boomed, rising living standards brought increased water demand for energy production, and mining. (Duffy, 2013). Sharp rise in complexities of managing not only water but also other resources began to take the attention of the scientific community to systems theory (Arnold & Wade, 2015). After World War II in particular, systems approaches were increasingly applied to real life cases, and used to define components, interrelationships, and analyze complex problems (Hughes & Hughes, 2011). Systems thinking, which forms systems theory, is a holistic approach to analyzing and solving problems in consideration of effective parameters and components at multiple levels and with regard to the relationships with the whole (Meadows, 2008). In building a more sustainable future systems thinking relies upon three pillars of sustainability: economic, social, and environmental, to provide better understanding (Cattano, et al., 2011). Wurbs and James describe the characteristics of systems analysis, (on which the nexus approach was built (Mohtar, 2015)), in water resources planning and management in the table below (Wurbs & James, 2002).

Table 1. Characteristics of Systems Analysis for Water Planning and Management

✓ Systematic quantitative approach to determining the optimum solutions to complex systems
✓ Decision-making support
✓ Comprehensive integrated systems focus
✓ Interdisciplinary aspects
✓ Reliance on mathematical models and computers

Shift to Inclusive Management Approaches: From IWRM to the Nexus

By the 1990s, not only the scientific communities but also global agency networks recognized the challenges of governing the integration between sectors utilizing limited fresh water resources and the necessity of integrated water resource management (IWRM) emerged (Mohtar & Lawford, 2016). IWRM can be defined as "a process which promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare without compromising the sustainability of ecosystems and the environment." (GWP, 2010). The WEF Nexus approach is relatively newer.

IWRM aims to reconcile the diverse water resource demands of multiple stakeholders, which may or may not include food and energy sectors, whereas, the nexus initially focuses on interrelationships of WEF resources, and the dual relationships between water, energy and food. Water is a relatively local resource compared to food and energy resources that are transported across continents. IWRM plays an effective role in water-related activities within a basin; the system of the WEF nexus boundary varies depending upon the focus of the study. Likewise, depending upon the problem, the nexus approach may focus on a specific sector within the system rather than, as IWRM, on specific water resources (Mohtar & Lawford, 2016). Translating science into strategic policy across multilevel governance remains ambiguous and clarifies the need for more local nexus approaches for future sustainability (Benson, et al., 2015). The nexus should be seen as a cooperative way to solve conflicts and based on WEF nexus analytics. Dialogue is vital for the transition between policy makers, supply chain environment, and consumer. The WEF Nexus platform begins by assuming an interrelation between water, energy, and food systems. Existing disciplinary approaches behind each system are not be replaced, but rather these disciplinary pillars provide the basis for solutions of increasing efficiency (Mohtar & Lawford, 2016), and goes on to address challenges and mitigate burdens not only on water resources, but also those of energy, and food. From these perspectives, the WEF nexus approach is more holistic for building a more sustainable future (Global Forum on Environment, 2014).

FAO describes the WEF Nexus platform as “a useful concept to describe and address the complex and interrelated nature of our global resource systems, on which we depend to achieve different social, economic and environmental goals” (FAO, 2014). Each system has boundaries that depend on the perceptions and interests of the other. The organization, analytics, tradeoffs and complex implications can be solved while limiting the systems boundaries (Morgan, 2005). Thus, a WEF nexus study is built upon implementation area goals. Whether national, regional, local.

Methodology

This planning study focuses on future sustainability. The year 2070 selected to provide a nearly 50-year projection that coincides with TWDB’s statewide water plans. All data for water, energy, and food portfolio are projected to 2070 for analytics. Possible severe conditions, such as drought, high population rate, are taken into account. Water resources are limited to existing water rights and permits. Additionally, environmental flow requirements and recommended groundwater withdrawal values are considered as constraints. Reliability of water diversion for municipal and industrial consumption is selected at 100%, whereas agricultural water supply can be lower. Municipal and industrial users, including energy producers, would have sufficient water in any case scenario. The WEF nexus model is drawn after analyzing data and describing system components, boundaries, stakeholders and observers. The WEF nexus model and framework of the study is formed as described below.

Overview of the Nexus Model

Figure 3 shows the layout of the nexus model and the tradeoffs for development and analysis of scenarios in Matagorda County. The connections between the water, energy, and food tenants of the nexus with the primary processors are illustrated. Also, possible interventions that can mitigate risks and vulnerabilities of the primary resources are indicated in blue rectangles. The outer ring comprises the external driving factors of the nexus. It is assumed that current conditions in Matagorda County will remain at their current state and only the addition of new scenarios which include interventions could improve the sustainability of the county.

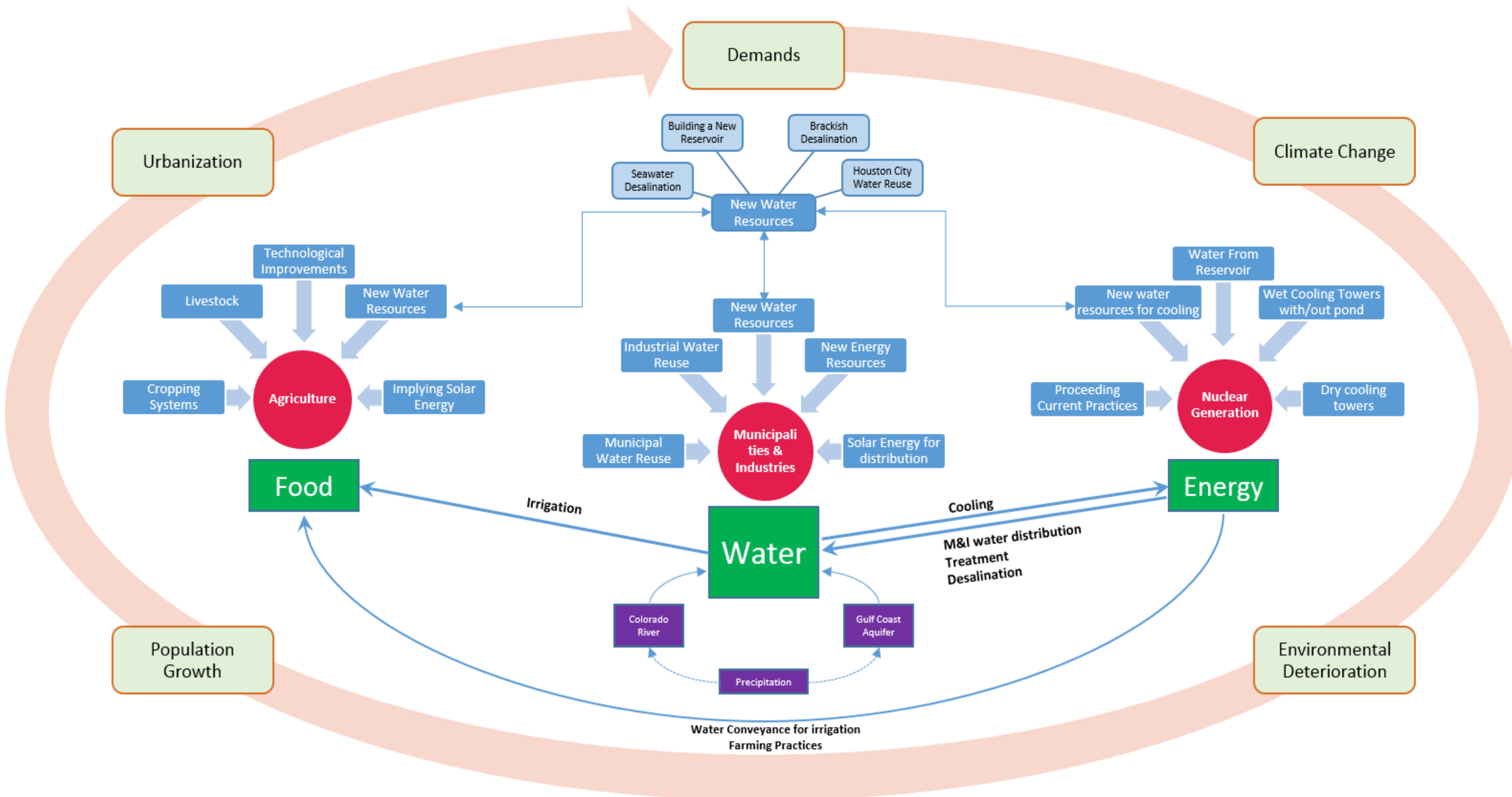


Figure 2. Schematic Overview of WEF nexus model and tradeoffs

Framework

The framework is devoted to optimum water allocation analysis; as seen in Figure 3, this framework has 8 major steps to reach recommended solutions.

Figure 3. Flowchart of the Framework

Understanding the interconnections between primary resources is essential. Water-food, water-energy, and food-energy nexus reflect the general resource allocation for the study area. Available data related to interlinkages are inclusively analyzed to determine the main processors in the study area. A processor can be an entire sector: industry, a governmental organization, municipality, etc. At the third stage, interventions that can build or increase sustainability are identified: each intervention depends on only one processor, but can contribute to multiple resources. A produced intervention may be feasible in the study area, but may be neither sustainable nor advisable. At the fourth step, interventions form scenarios: a great number of scenarios can be built for analysis. The analytic WEF nexus tool, step six, can solve the complex, comprehensive interconnections between primary resources in accordance with various scenarios. The tool must include all elements upon which the allocation analysis is based. The next stage is scenario output and is acquired from the analytic WEF nexus tool. Based on scenarios, six kinds of outputs include water requirement, energy production and requirement, food production, cost, CO2 emission, and land allocated. The outputs do not produce results that can be directly applicable, since each scenario has several dimensions. Evaluations and assessments for scenarios are done in the seventh step using the six outcomes of each scenario. The developed sustainability and resource indexes are the key parameters of the study. Finally, water-centric, food-centric, cost-centric, and the other recommended outcomes are based on the interests of various users.

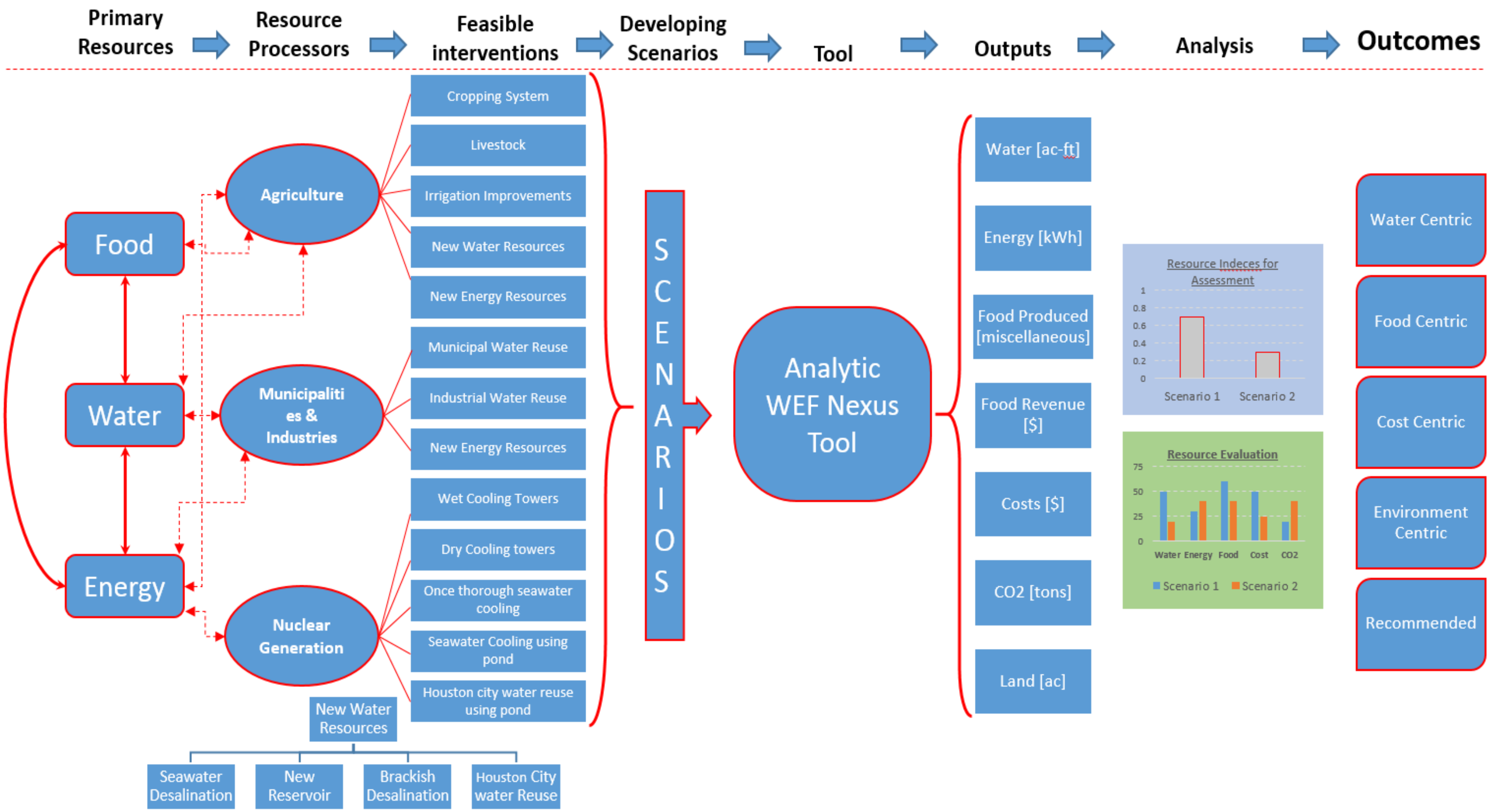


Figure 4. Framework

Overview of the tool analytics

In order to represent current water allocations and make projections for the future, a number of scenarios are developed across multiple sectors. Each scenario can be put into operation to determine the optimal selection of scenarios. The operation is performed using the tool, which basically uses the scenarios as input to produce quantitative results (output) as presented below.

Table 2. The parameters as quantitative results of the tool

Symbol	**Parameter**	**Unit**
W	Water	Acre-feet (ac-ft)
E	Energy	Kilowatt-hours (kWh)
F	Food Produced	Based on the crop or animal (bushel, lb etc.)
R	Food Revenue	US dollars ($)
C	Costs	US dollars ($)
CO2	Carbon Footprint	Ton (ton)
L	Land Area	Acres (ac)

While some data for future projections for 2070 exist, more frequently, projected data must be developed. Historical values play an essential role, as they may indicate trends.

- *Water Calculations*

Water is the indispensable element required for several purposes in the WEF nexus model. The water requirements considered in this study are those for agricultural production, municipal and Industrial demands, and energy generation.

$$\boldsymbol{W = W_{ag} + W_{m\&i} + W_{en}}$$

Where,

W= Total Water Requirements (m^3)

W_{ag}= Total agricultural water requirement (m^3)

$W_{m\&i}$= Annual M&I water use (m^3)

W_{en}= Water for energy production (m^3)

The water need of each crop is calculated using FAO's radiation method. The green water [see assumptions] contribution is extracted from the water needed for the irrigation need, and a 10% extra safety factor is applied for irrigation scheduling. Water intake by animals is included in the total agricultural water requirement.

Municipal water consumers include residential and commercial uses. Municipal demand is directly linked to population size and local trends which depend upon climate, season, culture, welfare, water availability, pricing, infrastructure, etc. As for industrial applications, the production process of goods and power, mining is considered as industrial use in this study. Water use amounts in industry vary tremendously, hence, each industrial company must be considered separately.

Production of power is studied independently under a processor due to its direct contribution to energy resources. Water is needed energy production due to cooling requirements of nuclear reactors in this study. Cooling requirements include natural evaporation, seepage, induced evaporation and conveyance losses.

- *Energy Calculations*

This study includes energy needs due to agricultural crop production and covers machine farm operations and irrigation, water supply for municipal and industrial uses, and pumping for cooling. Energy requirements also include treatment and desalination processes, if applied.

$$\boldsymbol{E = E_{ag} + E_{m\&i} + E_{en}}$$

Where,

E= Total energy requirements (kWh)

E_{ag}= Total energy requirement for agriculture including livestock (kWh)

$E_{m\&i}$= Energy need for M&I water use (kWh)

E_{en}= Energy need for conveying cooling water to energy plant (kWh)

Along with water conveyance and treatment processes, agriculture consumes energy during farming operations: tillage, planting, cultivation, harvesting, fertilizing, forage blowing, stalk shedding, etc. Energy requirements vary with the proposed crop pattern. In the analytics, each crop is evaluated individually based on their water and farming operation needs.

Water supply for municipal and industrial use requires energy. For municipalities, both indoor and outdoor use are considered. Industrial energy use includes only energy requirement for water supply process.

Water for cooling requires energy for water conveyance from source to plant. Therefore, the energy requirement for conveyance depends on the distance between plant, water source, and hydraulic energy loss.

- *Food Calculations*

Production varies depending upon the crop or livestock: this study is able to convert each crop production unit to a dollar currency for analysis. Thus, agricultural revenue is asserted as one parameter for sustainability analysis. Each crop has unique performance under diverse climate, soil type, irrigation amount and scheduling, water quantity, and fertilizer. When historic yields per unit area are studied, it is seen that crop yield per unit land rates tends to rise continually. Consequently, the formula below is developed and applied to project the food production for a given year. Increasing crop yield amounts are used.

$$\boldsymbol{Y_{Projected} = Y_{trend} - Y_{max} \times 0.5 + Y_{max}}$$

Where,

$Y_{Projected}$= Regulated trend of unit values for a certain crop yield (unit/ac)

Y_{trend}= Linear trend of unit values for a certain crop yield (unit/ac)

Y_{trend}= Maximum historic unit value for a certain crop yield (unit/ac)

The total amount of food can be found for a specific year as follows:

$$\boldsymbol{F_i = Y_i + L_i}$$

Where,

F_i= Total yield amount of a certain crop (unit)

Yi= Unit of projected yield value for a certain crop (unit/ac)

L_i= Land allocated for a certain crop (ac)

The yield amount varies mainly because of lack of irrigation. FAO's response to water method (FAO, 2012) is utilized to reflect real yield production with deficit irrigation.

The projection of the food prices is complicated as understood from the tremendous variable historic price values. Several factors, including climate, demand, oil price, inflation, policy, etc. influence the agriculture market. For more flexible and inclusive analysis, several food pricing options are available. Along with linear trend, historic maximum, average, and minimum agricultural market prices are available in the nexus tool. Total agricultural revenue value can be found as stated below.

$$\boldsymbol{R_i = F_i + U_i}$$

Where,

R_i= Revenue of a certain crop ($)

F_i= Yield of a certain crop (unit)

U_i= Unit of projected market value ($/unit)

$$\boldsymbol{R = \sum R_i}$$

Where,

R= Total agricultural revenue ($)

- *Carbon Footprints*

In the nexus framework, greenhouse emissions are considered as environmental cost. The model considers CO2 to assess sustainability of resource allocations. Greenhouse emission occurs due to the aforementioned energy consumption.

$$\boldsymbol{CO2 = CO2_{ag} + CO2_{m\&i} + CO2_{co}}$$

Where,

CO2 = Total CO_2 emission (ton)

$CO2_{fo}$ = Carbon-dioxide emission due to agriculture sector (ton)

$CO2_{tr}$ = Carbon-dioxide emission due to M&I water use (ton)

$CO2_{co}$ = Carbon-dioxide emission due to cooling water conveyance (ton)

The energy consumed in various sectors may have different sources. For example, farming operations use diesel while pumping for irrigation is through electricity produced in the nuclear plant. Each consumption is evaluated independently. Energy sources considered in this study are fossil fuels, nuclear, solar.

$$\boldsymbol{CO2_i = E_i + \Delta_i}$$

Where,

Δ = Tons of CO_2 per kJ energy (ton/kJ). It depends on energy sources.

E_i = Various energy consumptions in the nexus (kJ)

- *Financial Costs*

Costs occur due to nexus interventions. Strategy project and investment costs are annualized for consistency with other input values. A discount rate must be selected to keep the analysis consistent across all projects. Applying the most recent construction costs is the convenient way for the analysis.

$$\boldsymbol{C = \sum C_i}$$

Where,

C = Total costs ($)

C_i = Cost of each strategy projects considering capital and annual costs ($)

- *Land Allocations*

Land is directly linked to agricultural production, including livestock, in the study. Type of cropping system and altering current crop combinations may decrease water, energy, and food outputs. Effects of urbanization can be reflected in the scenarios. Historic decrease in cropland and pastureland give the nexus a sign for future projections.

$$\boldsymbol{L = \sum L_i}$$

Where,

L = Total crop and posture lands (ac)

L_i = Land allocated for a specific crop or posture (ac)

During operation, land allocation is used as input through interventions (see simulations).

Sustainability Analysis

After operated scenarios, output parameters (demands of water, energy, cost, agricultural revenue, carbon-dioxide emission) of each scenario are presented. Normalization operations are carried out to standardize various units. The resource index is found using the formulas below.

$$\boldsymbol{Resource\ index_i = \frac{Output_i}{\max(Output_i)}};$$

$$\boldsymbol{W_i = \frac{W_i}{max(W_i)},\quad E_i = \frac{E_i}{max(E_i)},\quad R_i = \frac{R_i}{max(R_i)},\quad C_i = \frac{C_i}{max(C_i)},\quad CO2_i = \frac{CO2_i}{\max(CO2_i)}}$$

A number of weighting factors are applied to reflect the perspectives of stakeholders or observers. To rank scenarios, sustainability index is developed for each scenario. In doing so, for more sustainable scenarios, water, energy, cost demands and carbon-dioxide emission are expected to be less whereas agricultural revenue is high. Therefore, resource indexes of agricultural revenue are made negative and then summed in the sustainability index formula below.

$$\boldsymbol{Sustainability\ Index_i = 1 - \left(\sum Wf_i \times Resource\ Index_i\right)}$$

Scenarios are ranked while reflecting the stakeholder preferences through weighting factors, from least sustainable,0 to most suitable. In doing so, 6 kinds of indexes are presented. Therefore, water, energy, food, cost, environmental -centric and overall optimum scenarios are determined after ranked.

Simulations

After inclusively working on available data, three processors that utilize the primary resources were determined: Agriculture, M&I, Nuclear Generation. Interventions such as building a desalination plant, improving existing irrigation conveyance system, changing crop patterns, to build, increase sustainability or reflect the current situation were designated. The tool runs with scenarios consisting of interventions. A great number of scenarios consisting of interventions depend upon the stakeholders and can be built to analyze. Scenarios were simulated in the tool which can solely solve the complex and comprehensive interconnections between primary resources in compliance with various scenarios. Outputs of scenarios gained from the tool were analyzed using sustainability analysis method. The perspectives of various tenants of WEF nexus were reflected using weighting factors.

Data Collected

A large variety of data sources were needed to utilize for Matagorda County case study. Data for M&I water demand, groundwater depth, and existed and planned conveyance system was provided from TWDB. Data for local food production and its water use trends were borrowed from Department of Agriculture (USDA) as well as market values of crops and livestock. Various climate data available from National Oceanic and Atmospheric Administration (NOAA) was utilized. Data regarding nuclear energy production and its water consumption was provided from (International Atomic Energy Agency) IAEA and Nuclear Regulatory Commission (USNRC). Carbon emission while consuming energy data were provided from EIA. National Renewable Energy Laboratory's (NREL) the System Advisor Model (SAM) was selected to determine the most recent solar energy application. To bring historical project cost values to today or future projection required some financial data from Bureau of Reclamation (USBR), and USDA. In addition to these, several studies were utilized for the need for data regarding population, wastewater from Houston, recommended groundwater withdrawals, water treatment and desalination, farming practices, existed water infrastructure.

Assumptions for the Case Study

- ✓ The latitude of the city of Palacios, 28.7 N, average 3m county-wide average altitude was selected for the calculation of crop water requirements.

- ✓ It was assumed that Matagorda farmers use 10% of more water due to irrigation scheduling and management practices.
- ✓ Green water was defined as water from precipitation to soil that leaves the soil via evaporation. 75% of precipitation was assumed to go back to hydrologic cycle via evaporation as green water while the rest can be either run-off or infiltrated.
- ✓ The new irrigation system applied as a new technology was assumed to have 95% efficiency whereas the existing one to have 70%. Also, it was assumed that 30% of total agricultural land was not available for on-farm improvements.
- ✓ It was assumed there was no need to treat fresh groundwater for any purposes.
- ✓ The available brackish groundwater was assumed to be 100,000 ac-ft if needed.
- ✓ The future allocation of the Lane City Reservoir near to Matagorda, which was still under construction, had not been released. It was assumed that farmers in Matagorda will have 35,000 ac-ft of total 100,000 ac-ft expected annual supply.
- ✓ Beside water intake by animals, 20% of extra water intake requirement was estimated for waste of water in ranches and other needs as shower in hot summers.
- ✓ Calculations for livestock was revolved around water and food but not energy since there was no direct data available for energy use of cattle.
- ✓ Even though aquaculture was playing an essential role in the economy of Matagorda County, it was not taken into account because of lack of data and the gap in the literature regarding WEF nexus interlinkages of aquaculture.
- ✓ This study suggested that wastewater from Houston could be used for agricultural water resources and cooling for nuclear plants. Some wastewater was directly treated in Houston but future has uncertainties. In this study city wastewater was assumed to be already treated in Houston and directly transferred to Matagorda using pipelines and pumps. The distance between Houston and Matagorda to construct pipelines was defined as 50 miles and elevation difference was 100ft considering variable earth surfaces. While calculating pipeline cost values, it was assumed that 67% of distance where pipelines were constructed was in rural areas and 33% in urban.
- ✓ Water treatment of M&I wastewater was considered separately. After treatment, water reuse was applied to the original.
- ✓ The unstable future of fossil fuels, historic fluctuations in production, absence of produced water data, controversies about offshore platforms, and uncertainties of future projections caused us not to take oil & gas production into account.

Interventions

Interventions are the levers of the primary resources and aimed mitigating resource insecurity and ensuring a more sustainable future. However, deciding on the interventions at multiscale levels requires inclusiveness of the influences of other resources and stakeholders. Along with current practices, interventions for processors selected for this study are shown below.

The solar farm was included as an intervention, regardless of processor and expected to reduce energy requirements of interventions if built.

Table 3. Possible Interventions

<table>
<tr><th colspan="3">Agriculture</th><th colspan="2">M & I</th><th>Nuclear Gen.</th></tr>
<tr><th>Land Allocation*</th><th>Irrigation Improvements</th><th>Water Resources</th><th>Municipal Water Reuse</th><th>Industrial Water Reuse</th><th>Cooling System</th></tr>
<tr><td>(1) More Ag. Land, Less Water Demanded Cropping</td><td rowspan="2">Improvements on water conveyance systems</td><td>New Reservoir</td><td rowspan="4">Water Treatment and Ruse As 50% or 80% of consumed</td><td rowspan="4">Water Treatment and Ruse As 50% or 80% of consumed</td><td>Water from New Reservoir</td></tr>
<tr><td>(2) More Ag. Land, More Water Demanded Cropping</td><td>Seawater Desalination</td><td>Once through seawater</td></tr>
<tr><td>(3) Current Land, Less Water demanded Cropping</td><td rowspan="2">Improvements on- farm Irrigation Systems</td><td>Brackish Desalination</td><td>Seawater using pond w/out Reservoir water</td></tr>
<tr><td>(4) Urbanization, Current Allocation Distribution</td><td>Houston Reuse</td><td>Houston Reuse water</td></tr>
<tr><td colspan="6">Solar Farm</td></tr>
</table>

Pre-feasibility study is a must to determine feasible interventions that can be further analyzed. For example, once through seawater cooling (direct) had been an option at first but it was removed from the sustainability analysis after the analytics of the tool indicated that cooling system required half of total energy production of the plant.

Scenarios

A large number of scenarios could be developed using the possible interventions stated above. For Matagorda case study, 25 scenarios were developed which pretty much cover the possible combinations of interventions and help figure out what the optimum decisions for stakeholders and policy makers were to mitigate water scarcity and increase sustainability.

Table 4. Interventions in Scenarios (indicates Land Allocation options match with Table 3)*

Processor	Intervention		(ac-ft)	Scenario																								
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Agriculture	Land Allocation*	1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓															
		2												✓	✓	✓	✓	✓										
		3																	✓	✓	✓	✓	✓					
		4																						✓	✓	✓	✓	✓
	Irrigation Applications	Cnvy. Syst. Impro.		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓
		On-farm syst. Impro.				✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓
	Water Resources	New Reservoir			✓	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓
		Desalination	50,000										✓				✓											
			100,000				✓			✓						✓		✓			✓	✓				✓		
		Brackish Groundwater	50,000					✓		✓						✓							✓					
			100,000									✓	✓				✓	✓		✓		✓					✓	✓
		Houston Water Reuse	50,000																									✓
			100,000								✓										✓							
			200,000															✓					✓					
M & I	Municipal Water Reuse	Water Reuse	50%										✓		✓					✓	✓							
			80%		✓				✓	✓	✓	✓				✓	✓	✓				✓	✓		✓	✓	✓	✓
	Industrial Water Reuse	Water Reuse	50%												✓					✓	✓							
			80%		✓				✓		✓	✓						✓				✓			✓		✓	
Nuclear Generation	Cooling System	Current Practice		✓	✓		✓							✓		✓			✓	✓			✓	✓	✓			
		Water from reservoir					✓	✓	✓				✓			✓		✓		✓		✓	✓		✓		✓	
		Seawater using pond						✓	✓	✓		✓	✓				✓	✓				✓				✓	✓	
		Houston water reuse				✓					✓				✓						✓							✓
	Solar farm										✓	✓	✓			✓		✓			✓	✓	✓			✓	✓	✓

Outputs and Analysis

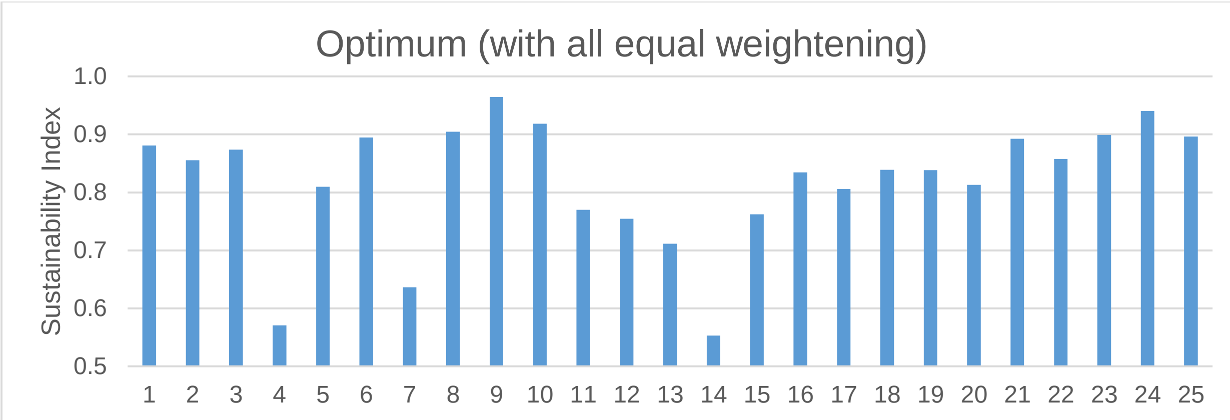
After operated 25 scenarios including combinations of interventions as seen in Table 4, various output parameters were presented. Normalization process was then applied to determine resource indexes. Each resource index was multiplied by weighting factors which reflect the perspectives of stakeholders or observers. Consequently, the sustainability indexes were ranked to indicate water-centric, energy-centric, food-centric, cost-centric, environment-centric, overall optimum scenarios.

Table 5. Weighting Factors(Wf)

Output Parameters	Symbol	Water-Centric	Energy-Centric	Food-Centric	Cost-Centric	Environ-Centric	All Equal
Water Demand (m^3)	W	0.4	0.15	0.15	0.15	0.15	0.2
Energy Demand (kWh)	E	0.15	0.4	0.15	0.15	0.15	0.2
Agricultural Revenue ($)	R	0.15	0.15	0.4	0.15	0.15	0.2
Cost ($)	C	0.15	0.15	0.15	0.4	0.15	0.2
CO2 Emission (ton)	CO2	0.15	0.15	0.15	0.15	0.4	0.2

Results and Discussions

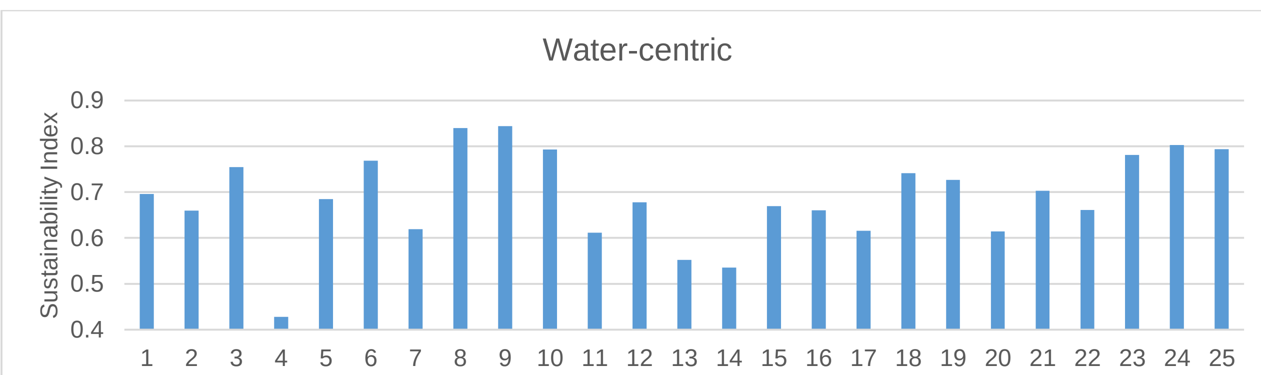
This study asserts that only through analyzing the water issue from various angles can we arrive at a warranted conclusion. Results of optimum sustainability analyses which consider all parameters equally indicates that Scenario-9 is the optimal scenario.

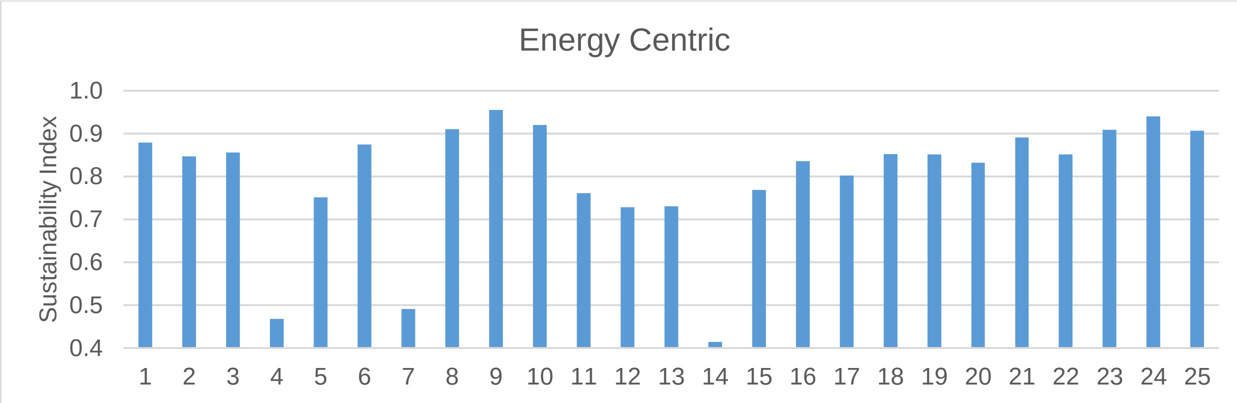


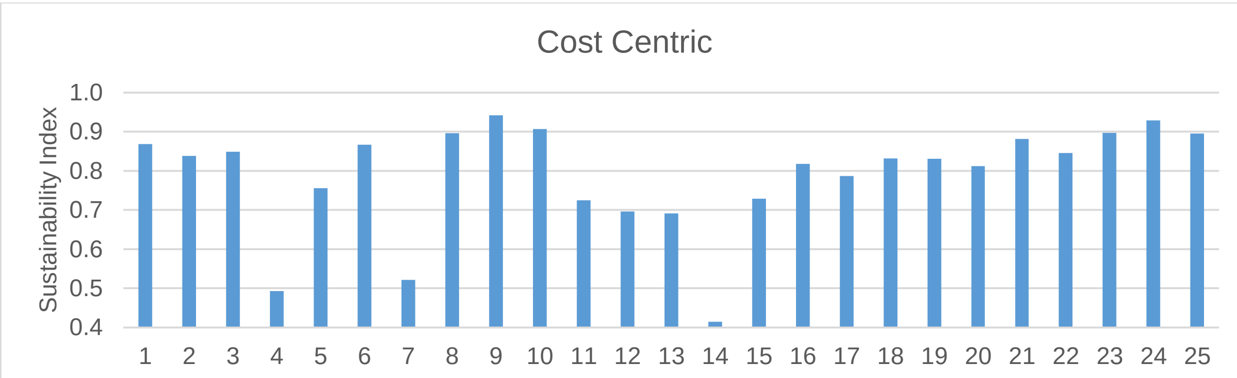
Scenario-9, as can be seen from Table 4, includes current land allocation and crop pattern, irrigation applications, water supply from new reservoir and brackish groundwater, 80% water reuse for both municipal and industrial water use, altering cooling water from river water to seawater, and solar farm installation. As least sustainable scenario, scenario-14 comes forefront. As distinct from scenario-9, the most sustainable scenario, scenario-9 has more agricultural land for cultivation which demands more water, desalination, no water reuse for industrial use and no solar farm. First scenario is a base scenario which has no intervention.

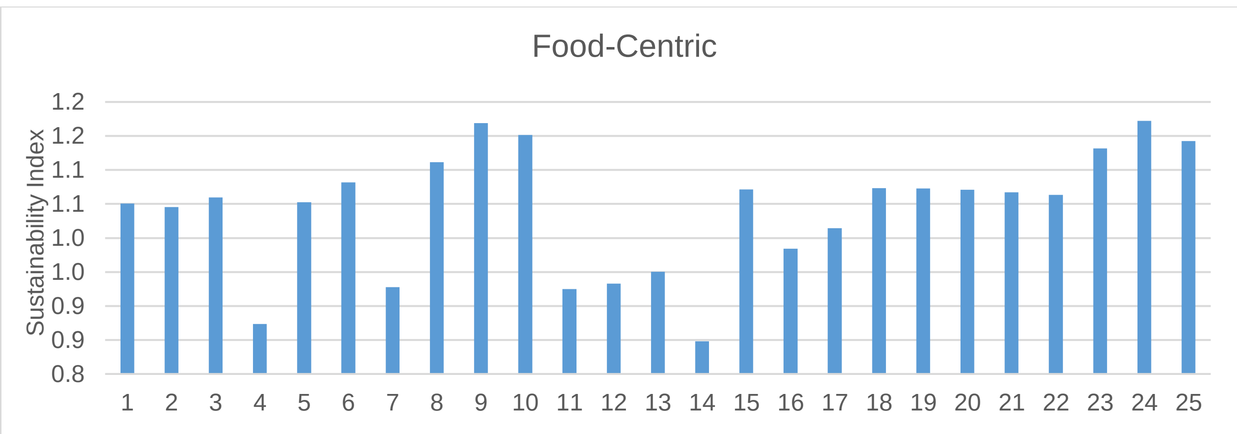
In order to validate the results of sustainability analysis, outputs from the tool is reviewed. In this regard, water demand of the county is 374.874 ac-ft for scenario-1 (base scenario), while it is 253,887 ac-ft for scenario-9 (most sustainable). As for worst sustainable scenario, scenario-14, 481,776 ac-ft water is demanded. Similar records could be seen for other parameters as well as water.

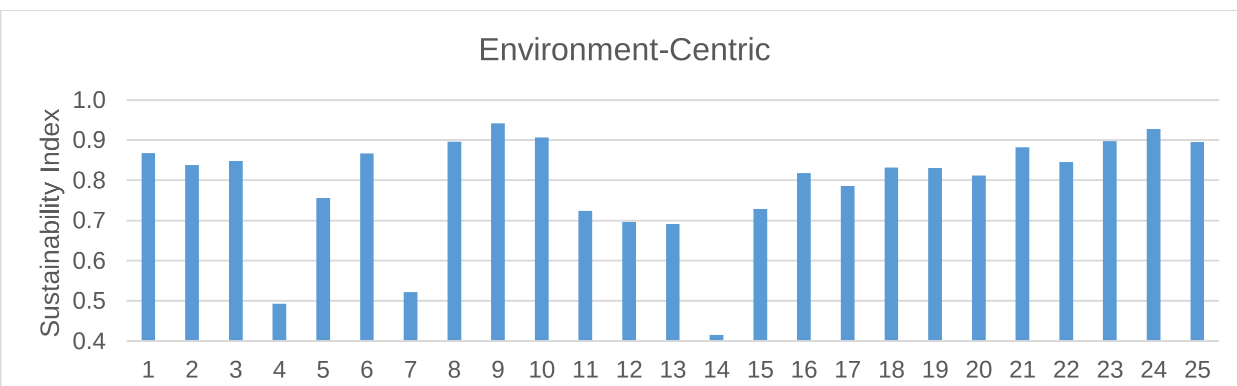
In the results, scenario-9 is also ranked first for water, energy, cost, environment -centric analyses. However, scenario-24 gets first place with regard to agricultural revenue. Sustainability results of diverse perspectives can be seen in the graphs below.




Energy Centric
Sustainability Index
1.0
0.9
0.8
0.7
0.6
0.5
0.4
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25


Cost Centric
Sustainability Index
1.0
0.9
0.8
0.7
0.6
0.5
0.4
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25


Food-Centric
Sustainability Index
1.2
1.2
1.1
1.1
1.0
1.0
0.9
0.9
0.8
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25


Environment-Centric
Sustainability Index
1.0
0.9
0.8
0.7
0.6
0.5
0.4
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25

Conclusion

Achieving the most sustainable water allocation requires multi-dimensional analysis since primary resources are inextricably linked. The WEF nexus approach built in this study help analyze various angles of interventions and produce optimal scenarios for stakeholders, observers and policy makers. Matagorda County is well suited for a case study for the water energy- food nexus due to its current and projected water shortages, high water demands for electric power production and agricultural use. In Matagorda County case study, a developed analytic tool reflected complex and dynamic relationships between water-energy-food resources along with environmental and financial costs when multiple interventions (mostly water-related infrastructure) applied. A sustainability analysis method was carried out to standardize various kinds of outputs. In doing so, it was intended to provide a platform that can help bridge the gap between science and policy. Further contributions to the platform such as adding environmental responses to interventions, applying more coherent data, considering stakeholder behavior (willingness to apply recommendations) would increase the validity and accuracy of results presented in the paper.

References

Arnold, R. D. & Wade, J. P., (2015). A Definition of Systems Thinking: A Systems Approach. *Procedia Computer Science,* Volume 44, pp. 669-678.

Beltran, J. M. & Koo-Oshima, S., (2006). *Water desalination for agricultural applications,* Rome: FAO.

Benson, D., Gain, A. K. & Rouillard, J. J., (2015). Water Governance in a Comparative Perspective: From IWRM to a 'Nexus' Approach?. *Water Alternatives,* 8(1), pp. 756-773.

Cattano, C., Nikou, T. & Klotz, L., (2011). Teaching Systems Thinking and Biomimicry to Civil Engineering Students. *ASCE - JOURNAL OF PROFESSIONAL ISSUES IN ENGINEERING EDUCATION & PRACTICE,* 137(4), pp. 176-182.

Duffy, M., (2013). *Challenges in the Water Industry: Infrastructure and its Role in Water Supply (Whiye Paper).* [Online]
Available at:
http://www.amwater.com/files/ChallengesintheWaterIndustryInfrastructureanditsRoleinWaterSupply.pdf
[Accessed 26 November 2016].

FAO, (2012). *Irrigation and Dranagine Paper no. 66: Crop Yield Response to Water,* Rome,: FAO.

FAO, (2014). *The Water-Energy-Food Nexus: A new approach in support of food security and sustainable agriculture,* Rome: Food and Agriculture Organization if the United States.

GAO, (2004). *Water Infrastructure: Comprehensive Asset Management has Potential to Help Utilities Better Identify Needs and Plan Future Investments,* s.l.: General Accounting Office.

Global Forum on Environment, (2014). *New Perspectives on the Water-Energy-Food Nexus,* Paris: OECD.

GWP, (2010). *About GWP (Global Water Partnership).* [Online]
Available at: http://www.gwp.org/en/About-GWP/
[Accessed 19 November 2016].

Hughes, A. C. & Hughes, T. P., (2011). *Systems, Experts, and Computers.* s.l.:Dibner Institute Studies in the History of Science and Technology.

Kemerink, J. S. et al., (2016). Why infrastructure still matters: unravelling water reform processes in an uneven waterscape in rural Kenya. *International Journal of the Commons,* 10(2).

Meadows, D., (2008). *Thinking in Systems (Edited by Diana Wright).* s.l.:Chelsea Green Publishing.

Mohtar, R., (2015). *Rabi Mohtar on Food-Energy-Water Nexus (Video).* [Online]
Available at: https://www.youtube.com/watch?v=WaajIUCgKM0
[Accessed 15 October 2016].

Mohtar, R. H. & Lawford, R., (2016). Present and future of the water-energy-food nexus and the role of the community of practice. *Journal of Environmental Studies and Sciences,* 6(1), pp. 192-199.

Morgan, P., (2005). *The Idea And Practice Of Systems Thinking And Their Relevance For Capacity Development,* s.l.: European Centre for Development Policy Management.

TWDB - 2017, (2016). *2017 State Water Plan.* [Online]
Available at: http://www.twdb.texas.gov/waterplanning/swp/2017/ [Accessed 12 December 2016]

Wurbs, R. A. & James, W. P., (2002). 11. Water Resources Systems Analysis. In: *Water Resources Engineering.* s.l.:Prentice Hall, p. 709.