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MODELING THE WATER-ENERGY NEXUS FOR THE PHOENIX ACTIVE MANAGEMENT AREA

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ABSTRACT

Phoenix, an Active Management Area in the desert Southwest US, is the 5th most populated city in the US. Scarce local groundwater and water transported from external resources must be managed in the presence of different types of energy sources. Local and regional decision-makers are faced with answering challenging questions on managing water, energy supply, and demand over a few years to several decades. Prediction and planning for the interdependency of these entities can benefit from modeling the water and energy systems as well as their interactions with one another. In this paper, the integrated WEAP and LEAP tools and a modeling framework that externalizes their hidden linkage to an interaction model are described and compared using the Phoenix AMA. Loose coupling enabled by interaction modeling is a key for decision-policies that should be grounded at the nexus of the water-energy system of systems.

1 INTRODUCTION

The water use and energy production are often managed through both independent and interdependent local and state government policies alongside non-governmental social and monetary forces. On the one hand, water is required for generating electricity, for example, using hydroelectric stations and extracting and process fuel. On the other hand, energy is needed, for example, to pump and transport water across wide regions (Siddiqi and Anadon 2011). These relationships form the Water-Energy Nexus (WEN). Although studies on the nexus have been underway for many years, policymakers in recent times are becoming more dependent on improved WEN modeling, simulation, and evaluation (Hamiche et al. 2016; Khan et al. 2018, Dai et al. 2018).

According to a report from the U.S. Department of Energy an integrated water and energy management approach is needed as population and climate trends are increasing the vulnerability of these

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two systems (Bauer et al. 2014). A prime study area for the Water-Energy Nexus is the Phoenix, Arizona, the 5th populated metroplex in the United States. As a drought-prone region with limited freshwater resources, the water supply systems are limited, for example, because of limited groundwater supply and inter-basin surface water transfers. Yet, there is a growing dependence on water due to population growth and nuclear power plants, among others (Arizona Corporation Commission 2020).

In this paper, we detail the use of an Interaction Model (IM) (Fard and Sarjoughian 2020) developed for composing models that can be developed using the Water Evaluation and Planning (WEAP) (SEI, WEAP 2020) and Long-range Energy Alternatives Planning (LEAP) (SEI, LEAP 2020) systems. We show the water, energy, and their nexus can be modeled independently and loosely integrated to create a whole WEN model. This hybrid modeling framework lends itself to simulate the Phoenix Active Management Area (Phoenix AMA), thus helping to study proposed alternative sustainable water and energy demand and supply predictions under local and regional governance policies. The aim of this paper is to demonstrate the use of the interaction modeling method for composing the water and energy models of the Phoenix AMA. We evaluate the computational cost of the loosely coupled C-WEAP and C-LEAP models with a KIB model relative to the internally linked WEAP and LEAP systems for the Phoenix AMA.

2 BACKGROUND

The proprietary WEAP and LEAP tools used in this research are specialized for water and energy systems. The WEAP system is a modeling, simulation, and evaluation tool for studying water supply and demand. A water system can be modeled using predefined entities, forming a graph of nodes overlaid on a geospatial map. The parts of a water system classified as river, diversion, reservoir, groundwater, desalination plant, wastewater treatment plant, demand site, transmission link, catchment, return flow, and flow requirement entities. Each entity has some Data variables. The dynamics of a water system is defined according to mass balance equations amongst the entities and links. The dynamics of any WEAP model is available for use as Data variables and Result reports. Time granularity for a year can be defined by dividing a year into *a finite number of* equal time-steps ranging from one day up to one year. A variable can have yearly (one values per year) or time-step based values (one values for each time-step).

The LEAP system is a policy analysis and climate change mitigation assessment for modeling the predefined Demand, Transformation, Process, Resource, and Effect entities. A model in LEAP, as in WEAP, has some Data variables and Result reports with dynamics defined using mass balance equations. In the LEAP system, the time granularity for a year can be defined using time-slice, which is the same as the time-step defined for the WEAP system. The sum of all time-slices must equal to a whole year. Like WEAP, values for Data variable and Results report can be yearly or time-slice based values.

Both WEAP and LEAP systems execute in non-interruptible discrete time steps for any given simulation scenarios with predefined start and end times. The Data variables and Result reports can have different values relative to each scenario. The defined time-steps/time-slices in the model apply to all scenarios. Furthermore, both systems provide Application Programming Interfaces (APIs) to access data from the Data variables and Result report). The execution of both systems can be externally controlled via built-in APIs for the WEAP and LEAP systems.

The Componentized WEAP (C-WEAP) and Componentized LEAP (C-LEAP) RESTful frameworks are counterparts to the WEAP and LEAP systems (Fard and Sarjoughian 2019). Each entity in the WEAP/LEAP is presented as a component with some inputs (the Data variables of the entity) and outputs (the Result reports of the entity). In each of these frameworks, all model components with their data as input and output are accessible externally via the APIs. Components are differentiated to *Node*, *Link*, and *Flow* types in the C-WEAP framework (relative to the entities in the WEAP system). Likewise, components are differentiated to *Resource*, *Transformation*, *Process*, *Demand*, and *Effect* types in the C-LEAP framework (relative to the entities in the LEAP system). The C-WEAP and C-LEAP frameworks have the same schema for a project, its scenarios, components, and the input/output variables that belong to each component. The returned data via different RESTful APIs is in the JSON format. The C-WEAP framework has a negligible computational cost. The C-LEAP framework has a higher computational cost compared to the LEAP system due to the necessity of using flat files for data read and write.

3 RELATED WORK

In recent years, there has been a significant increase in studying the Water-Energy Nexus. The number of studies and the ability of the scientific community to assess has been on the rise, mainly to understand much better the water and energy interactions. One study examined 35 methods, tools, and frameworks related to the WEN based on the geographical scale and the nexus scope, focusing on the interactions between water, energy, and others including environment, food, land, and climate (Dai et al. 2018). The Stockholm Environment Institute conducted research on integrated analysis of water, energy, and greenhouse gas (GHG) emissions in California (Mehta 2012).

A study on the water and energy systems in Sacramento, California over the period 1980–2001 with weekly time-step was undertaken on four climate scenarios represent the impact of future temperature and precipitation extremes (Dale et al. 2015). In another study, four possible scenarios with a direct impact on demand and supply water and energy systems on Jajrood river, Tehran, Iran, over the period 2016-2026 with monthly time-step was undertaken (Javadifard et al. 2019). The impact of changing water demand, GHG emissions, and cost-effectiveness via nine different scenarios on the Western Canadian province of Alberta is another study (Agrawal et al. 2018). This study forecasts water consumption and GHG emissions from the power sector for the 2015-2050 period.

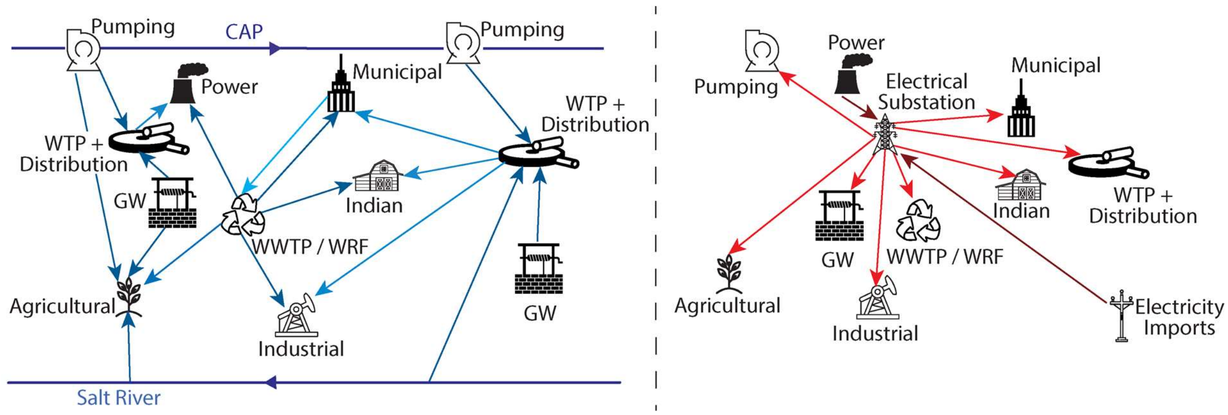
Two comprehensive studies focusing on water and energy for the Phoenix AMA were carried using the WEAP and LEAP systems. In one study, five possible future scenarios were developed and analyzed for the 2010-2060 time period (Guan et al. 2020). In the other study, four possible forecasts of the future energy demand and supply are generated for the 2019-2060 time period (Mounir et al. 2019). These research findings underscore the importance of modeling and understanding water and energy systems interactions flexibly and at high fidelity.

4 PHOENIX ACTIVE MANAGEMENT AREA WATER-ENERGY NEXUS MODELING

The metropolitan Phoenix, a city in the US desert southwest, is a subject study area for understanding the water and energy nexus. As an Active Management Area (AMA) region, sustainable aquifer withdrawal/recharge is one of the primary goals to be achieved by 2025 (Guan et al. 2020). Both water and energy serve as both demand and supply. They form a supplier and consumer collective where they control one another. There are other players that directly or indirectly affect or affected by the water-energy feedforward and feedback relationships. In the context of this research, a study of water and energy system for the Phoenix AMA is carried out using the WEAP and LEAP systems (Guan et al. 2020; Mounir et al. 2019). To develop and calibrate water and energy models for the Phoenix AMA, the WEAP and LEAP systems and publicly available data sources (Guan et al. 2020; Mounir et al. 2019). Data sets from 1985 through 2009 are used to develop the water and energy models. Simulation scenarios cover the period starting in 2008 and ending in 2018.

An illustration of the water and energy entities for the Phoenix AMA is shown in Figure 1. This visualization of the water-energy system provides a simplified representation of all the Phoenix AMA entities that are developed and validated. The water system is supplied by four primary sources: the Salt River Project (SRP), the Central Arizona Project (CAP), groundwater, and reclaimed water. Also, the main water demands in the area are for irrigation, municipal, industry, Indian communities, riparian, and energy generation (power plants) (Guan et al. 2020). The water needs to be transmitted from the supply sources to the demand nodes. This high-fidelity water model has two *River* (SRP and CAP), two *Groundwater*, and two *Wastewater Treatment Plant* entities, collectively representing the water supply. This model has twelve *Catchment* (for irrigation) and six *Demand Site* (for the rest demands) entities, representing the water demand. The water supply and demand entities form a network using fifty-six *Transmission Link* and five *Return Flow* entities.

The energy model defines by (Mounir et al. 2019) for the Phoenix AMA has the goal of tracking the energy embedded in all water uses and infrastructures. The energy model is supplied by two utilities: Salt River Project (SRP) and Arizona Public Service Company (APS). They mainly use Coal, Nuclear, Natural Gas, and Renewable (solar and wind) primary resources to generate electricity. The energy is supplied via two entities: one for electricity generation, and another for electricity transmission and distribution. All customer electricity demand is provided by APS, SRP, and CAP. The energy demands are defined via three main sectors: Residential, Commercial, and Industrial. The first two sectors are affected by the population growth (e.g., required energy for water heating), but the last sector is for satisfying the water-related energy demands required for pumping, water treatment, and distribution. The Industrial sector also has a subsector for water treatment facilities (Wastewater Treatment Plant (WWTP) and Water Reclamation Facilities (WRF)). The energy model has nine *Resource*, one *Transformation* with twenty-seven processes, and ninety-three *Demand* entities.



Water Model Energy Model

Figure 1. An illustration of a model for the Phoenix AMA water-energy system.

The internal linkage and interaction modeling approaches for combining models for the water and energy systems in the Phoenix AMA will be presented in the following sections. In the first approach, the built-in linking between the WEAP and LEAP systems is used (Yates et al. 2005). In the second approach, two separate models interact via an Interaction Model defined according to the Knowledge Interchange Broker (KIB) specification (Sarjoughian 2006). This approach to modeling the interactions is used to couple the water and energy models that can be developed in WEAP and LEAP and, therefore, the C-WEAP and C-LEAP frameworks (Fard and Sarjoughian 2020). This interaction modeling approach replicates the WEAP-LEAP internal linkage as an independent model, thus simplifying modeling of complex interactions generally needed for exploratory studies. The focus of our work is on model composability, which is different from simulation interoperability. Although infrastructures such as Web-Services (Richardson and Ruby 2008) or High-Level Architecture (Dahmann et al. 1998) may be used for simulating the IM, C-WEAP, and C-LEAP to interoperate, currently none are used.

4.1 The Internal Linkage

The bi-directional connection for the projects, scenarios, and time granularities of the WEAP and LEAP systems must be defined using two mapping forms. The WEAP and LEAP projects must have the same period (i.e., the start years and end years for the water and energy simulation scenarios are identical) and the same time granularity in a year. The water and energy models can have different time granularities. After defining the connection, each model has access (via user-defined algebraic equations) to read the Data and Result variables of different entities from the other model. Each equation used in either a water or an energy model uses a path to an entity and a specific Data and/or Result variable of the other model. All equations must be defined in the expression part of the Data variable of the destination model. Variables can have yearly or time-step/time-slice time granularity. The used variables in any equation should have the same time granularity. Otherwise, data variables of a fine-grain temporal scale model are lost when used in a coarse-grain temporal scale model. Data variables of a coarse-grain temporal scale model must be augmented to be used in the fine-grain temporal scale model. From the execution perspective, the modeler must decide and manually execute the water and energy models in the

WEAP-LEAP internal linking. Consider a situation that both models are reading the Result reports of the other model; the Results are zero before simulating the water or energy models. The WEAP and LEAP tools must be installed on the same machine to be used together.

An illustration of a portion of the water and energy models for the Phoenix AMA is shown in Figure 2. A portion of the schematic of the water model and the Data views (tree structures) for the water and energy models are shown, as well. The connections between the water and energy model entities are hand-drawn as solid and dotted lines. The dotted blue lines from the water model to energy model illustrate the flow from the transmission link entities to the demand entities. The calculations for the amount of the energy that can be produced given the amount of water that can be made available are defined in the energy entities (e.g., Kyrene Generating Station). The solid red lines illustrate the flow of power (electricity) from the energy model to the water model. Similarly, the amount of water that can be supplied to meet demand depends on the amount of energy. These calculations are defined in the appropriate water entities (e.g., demand site). The *Power Plant* demand site entity in the water model needs to know the amount of generated electricity by nine processes in the *Electricity Generation* transformation entity in the energy model (to fill the *Monthly Demand* variable). Also, the *Treatment and Distribution* demand entity in the energy model needs to know the amount of flow in the transmission links from *Groundwater* and *GW-Backup* to the *Municipal* in the water model (to fill the *Final Energy Intensity* variable). Calculations for aggregating and/or converting the generated electricity in the energy model must be defined in the *Power Plant* demand site entity in the water model. Similarly, calculations for aggregating and/or converting the amount of flow in the water model must be defined in the *Treatment and Distribution* demand entity in the energy system.

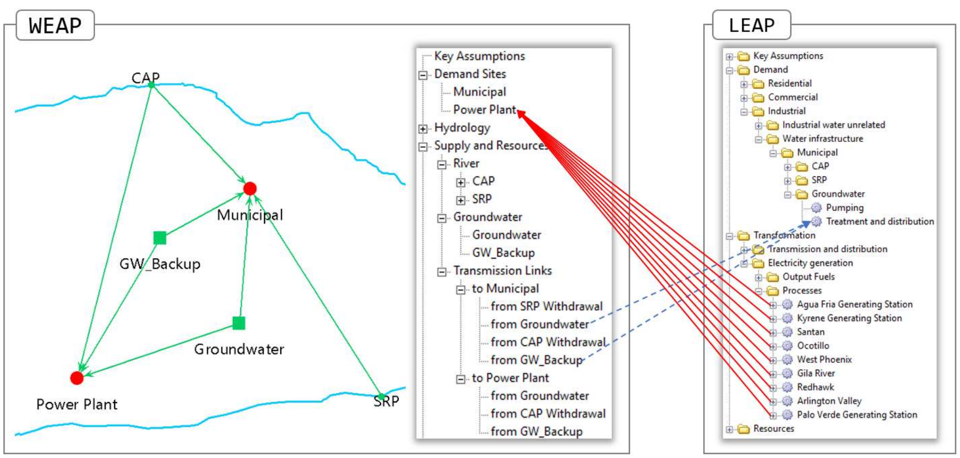


Figure 2: A portion of the water model Schematic and Data View, energy model Data view, the water-energy model, and illustrated connections linking the water and energy models for the Phoenix AMA.

4.2 The Interaction Model

The C-WEAP and C-LEAP systems, the encapsulated WEAP and LEAP systems in RESTful frameworks, are coupled using an Interaction Model (Fard and Sarjoughian 2020). The coupling follows the Knowledge Interchange Broker (KIB) approach, where relationships between the two disparate models are defined as a separate model (Sarjoughian 2006). A portion of the internally linked water and energy model (see Figure 2) is depicted in a component view in Figure 3. This diagram illustrates the logical specifications for the water and energy model interactions. An interaction model has a set of modules, each responsible for transforming data from one model for use by another model. Each module has its own input/output ports to receive/send the data from/to water and energy models. The module's ports are connected to specific entities and variables in the C-WEAP and C-LEAP models. The structure of the received or sent data in the module's ports must be defined in the interaction model. Each module has one-to-many transformations, where each transformation has its input and output ports. Three types of coupling are allowed between the module and/or transformation ports. They are modules' input to transformations' input, transformations' output to transformations' input, and transformations' output to modules' output (see Figure 3). Each transformation can process one or more data values on its input ports and send data values on its output ports. The interaction model has a cyclic, time-step, synchronous execution protocol for concurrent and bidirectional data transformations between water and energy models. With the use of the interaction model, the water and models do not need to have direct knowledge of each other. The WEAP model has the data (input and output) of the type *Flow,* and the LEAP model has the data (input and output) of the type *Electricity*. Since the water and energy models are decoupled, they can execute concurrently with one another and the interaction model in every simulation cycle.

The interaction model is responsible for receiving, processing, and sending the data required for the water and energy models, as depicted in Figure 3. The *Treatment and Distribution* demand component in the energy model does not have any knowledge about the water source. It receives the required generated electricity from the module named *Mun-GW.treat* port of the interaction model. In this example, the *Treatment and Distribution* demand entity in the energy model and the *Groundwater to Municipal* and *GW_Backup to Municipal* transmission components in the water model are coupled using the transformation *F-E* (Flow to Electricity) in the module named *Mun-GW*. The processes in the *Electricity Generation* transformation component in the energy model and the *Power Plant* demand site component in the water model are coupled using the transformation *E-F* (Electricity to Flow) in the module named *Elect-Flow*. The port names defined for the modules and transformations in the Interaction Model are provided in Figure 3.

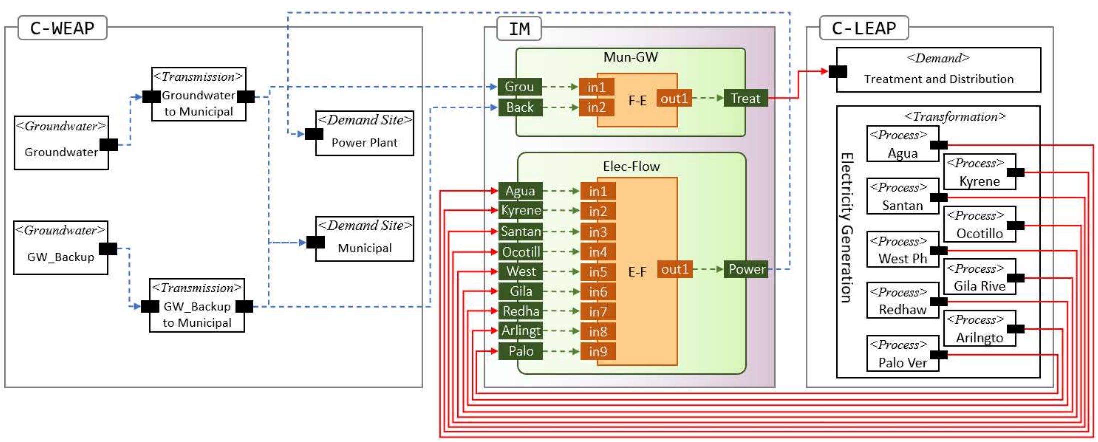


Figure 3: An illustration of the interaction model for a portion of the Phoenix AMA water-energy model.

The IM communicates with the C-WEAP and C-LEAP using their designated APIs. According to the signature of the C-WEAP and C-LEAP framework's APIs, every module's ports need to know the *project name*, *component type*, *component name*, *variable type*, *variable name*, and *scenario name* of the componentized water and/or energy models. The structure of the incoming/outgoing messages to/from the interaction model are defined according to the APIs of the C-WEAP and C-LEAP RESTful frameworks. In the AMA interaction model, the data from the water and energy models (WEAPMessage and LEAPMessage) share the same structure. Each message has a finite number of time intervals; each time interval has a *year* value and a finite number of data; each data has a *time-step/time-slice* and a *value*.

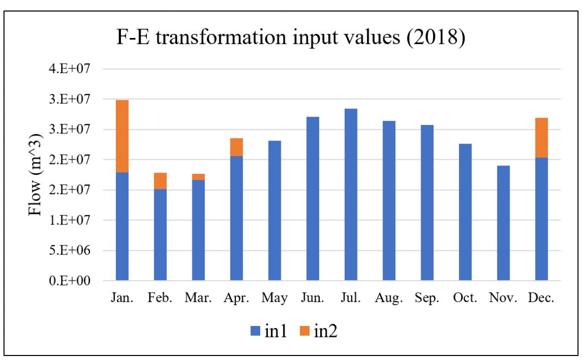
In the Phoenix AMA model, the demand for the energy model needs the *Flow* result variables of two transmission links in the water model. The value of the *Flow* result variable (m^3) is converted to a value (KW/h) for the *Energy Intensity* variable of a demand entity in the energy model using a coefficient. Essentially, the *F-E* transformation defines data conversion from *Groundwater to Municipal* and *GW-Backup to Municipal* transmission entities (in the C-WEAP model) to the *Treatment and Distribution* demand entity (in the C-LEAP model). Similarly, the electric data from the energy model is read and converted to water quantity for the water model (in the *E-F* transformation of the IM). The required computation in the interaction model handles by the transformations. The data conversion calculation for the Phoenix AMA interaction model is shown in equation (1). Transformation's input ports are read (based on the year and time-step/time-slice) and multiplied by a factor F to calculate the output values. The range of the year and time granularity (time-steps in the WEAP and time-slices in the LEAP) parameters are assigned by the corresponding values in the source model of the transformation.

$$Out.v_{y,ts} = \sum_{in \in tran.inputs} \left[in.v(y,ts) \times F_{in,y,ts} \right] \tag{1}$$
$$\mathrm{y \epsilon N, startYear \leq y \leq endYear;\ ts \epsilon N, 1 \leq ts \leq \#timeGranularityForYear;}$$

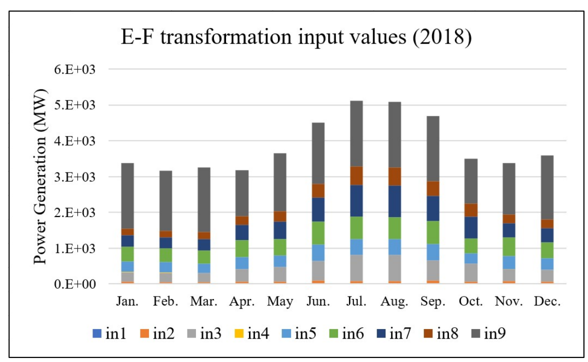
The factor F in equation (1) can be constant for all input values or specified for each input port, year, and time-step/time-slice. For example, F is $130.34 \times 0.000810714$ for all the input ports, years, and time-steps in the *F-E* transformation in Figure 3. For the *E-F* transformation in Figure 3, F is different based on the input ports, years, and time granularities (months). Equation (2) shows the computation in the *E-F* transformation. The value for each k is predefined to be the number of days d for a month in each year multiplied by 24. For example, the value of k is 31×24 for Jan. 2018. The simulation duration is 11 years ($2008 \leq y \leq 2018$) with monthly time granularity ($1 \leq ts \leq 12$). The charts in Figure 4 show the input and output port values of the transformations (*E-F* and *F-E*) for 2018.

$$\begin{aligned} Out1.value_{y,ts} = {} & in1.v(y,ts) \times F_{in1} + in2.v(y,ts) \times F_{in2} + in3.v(y,ts) \times F_{in3} + in4.v(y,ts) \times F_{in4} \\ & + in5.v(y,ts) \times \begin{Bmatrix} F_{in51} & y < 2013 \\ F_{in52} & otherwise \end{Bmatrix} + in6.v(y,ts) \times \begin{Bmatrix} F_{in61} & y < 2013 \\ F_{in62} & 2013 < y < 2017 \\ F_{in63} & otherwise \end{Bmatrix} \\ & + in7.v(y,ts) \times F_{in7} + in8.v(y,ts) \times F_{in8} + in9.v(y,ts) \times F_{in9} \end{aligned} \tag{2}$$

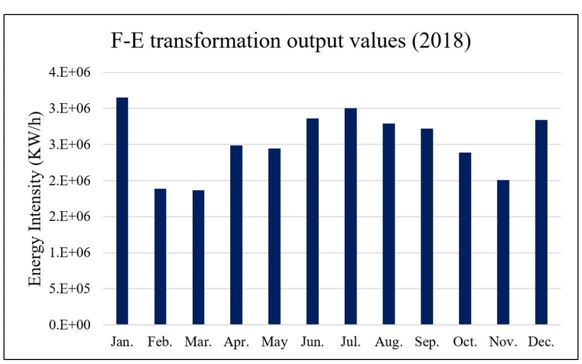
$$F_{in1} = 1.9 \times k;\ F_{in2} = 3.1 \times k;\ F_{in3} = 1.3 \times k;\ F_{in4} = 4.4 \times k;\ F_{in51} = 3.2 \times k;\ F_{in52} = 1.6 \times k;$$
$$F_{in61} = 7 \times k;\ F_{in62} = 4 \times k;\ F_{in63} = 2 \times k;\ F_{in7} = 1.08 \times k;\ F_{in8} = 1 \times k;\ F_{in9} = 6.006 \times k;$$



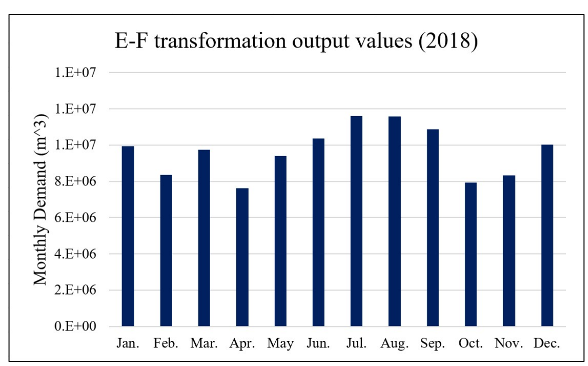
(a)



(c)



(b)



(d)

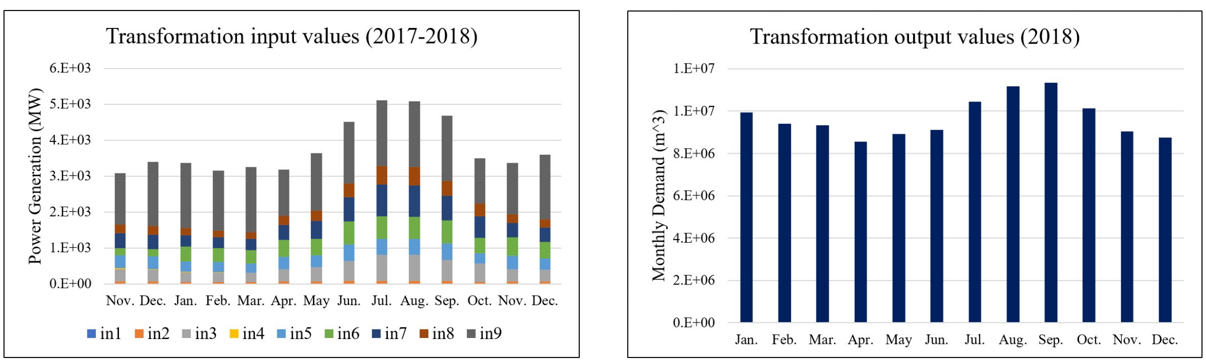
Figure 4: The input and output data of the interaction model simulation for the Phoenix AMA area. (a) the *F-E* transformation inputs, (b) the *F-E* transformation output, (c) the *E-F* transformation inputs, and (d) the *E-F* transformation output.

Specifying transformations depends on the specifics of the water and energy models. However, using interaction modeling, data transformations can be defined as separate dynamical models instead of making changes to the water and energy models. For example, equation (3) is a hypothetical data conversion calculation from the energy output to the water input. The transformation's input ports are read (based on the year and time-step) and multiplied by a factor F. The output value for a given year and time-step/time-slice is the average of the previous p time steps in the source model of the transformation.

$$Out.v_{y,ts} = \sum_{in \in tran.inputs} \frac{\sum_{i=ts-p}^{ts} \begin{Bmatrix} in.v(y-1, TG+i) \times F_{in,y-1,TG+i} & i < 1 \\ in.v(y,i) \times F_{in,y,i} & i > 1 \end{Bmatrix}}{p} \qquad (3)$$

$$y \in \mathrm{N}, \mathrm{startYear} \le y \le \mathrm{endYear};\ ts \in \mathrm{N}, 1 \le ts \le \#\mathrm{timeGranularityForYear(TG)};\ p \in \mathrm{N};$$

The charts in Figure 5 show the input and output port values of a hypothetical transformation for the Phoenix AMA interaction model. Each month's output value is the average of the current and its previous two months in the LEAP model (see Equation 3). For example, the output for Feb. 2018 is the average of the Feb. 2018, Jan. 2018, and Dec. 2017 inputs values. As expected, the outputs in Figure 4 (d) and Figure 5 (b) are two different interactions between the water and energy models, representing two different water-energy nexuses. This example in Figure 5 shows one of many alternative ways the nexus dynamics of the water-energy model could have regulated the data exchanges between the energy and water models. In a standalone fashion, the interaction model serves to explore different nexus policies that can satisfy combined supply and demands both within and between water and energy systems.



(a) (b)

Figure 5: The input and output data of the interaction model simulation for the Phoenix AMA area. (a) the transformation inputs from Nov. 2017 to Dec. 2018, (b) the transformation output for 2018.

The schemas of the complete Phoenix AMA nexus model via the WEAP-LEAP internal linkage and the interaction model is shown in Figure 6. The blue and red arrows between the componentized water and energy models and the interaction model represent the *Flow* and *Electricity* data of the source entity (or component), respectively. The water and energy model components are depicted as boxes with black borders and including their ports as filled black boxes without names. The ports located on the left (right) side of every component are designated as inputs (outputs). In Figure 6(a), the Municipal demands in the energy model read the *Flow* Result variables of the corresponding transmission links of the water mode. The SRP and CAP demands need to read the *Flow* of one transmission link, whereas the groundwater demands need to read the *Flow* of two transmission links. In Figure 6(b), the interaction model illustrates receiving the *Flow* output from the transmission components of the C-WEAP model (WEAPMessage), transform the data based on the time-step and/or time-slice, and send the transformed data

(LEAPMessage) to the corresponding demand components of the C-LEAP model. The Indian and Industrial demands are the same as the Municipal demands. Figure 6(c) shows the WEAP-LEAP internal linkage, and Figure 6(d) illustrates the interaction model for the Agricultural demands. Each CAP, SRP, and Groundwater demand in the LEAP model needs to read the *Flow* result variable of 8, 10, and 12 different transmission links, respectively. Modules and transformations in the interaction model have the same functionality as described for the Municipal demands, except the module *Agr-CAP* which has many transformation's output ports. All the conversions with one output and multiple inputs in the Phoenix AMA interaction model in Figure 6 are calculated using a formula with different configurations. Interaction modeling provides flexibility to make changes to each module independently of other modules as well as decomposing complex interactions to simpler ones in a systematic fashion.

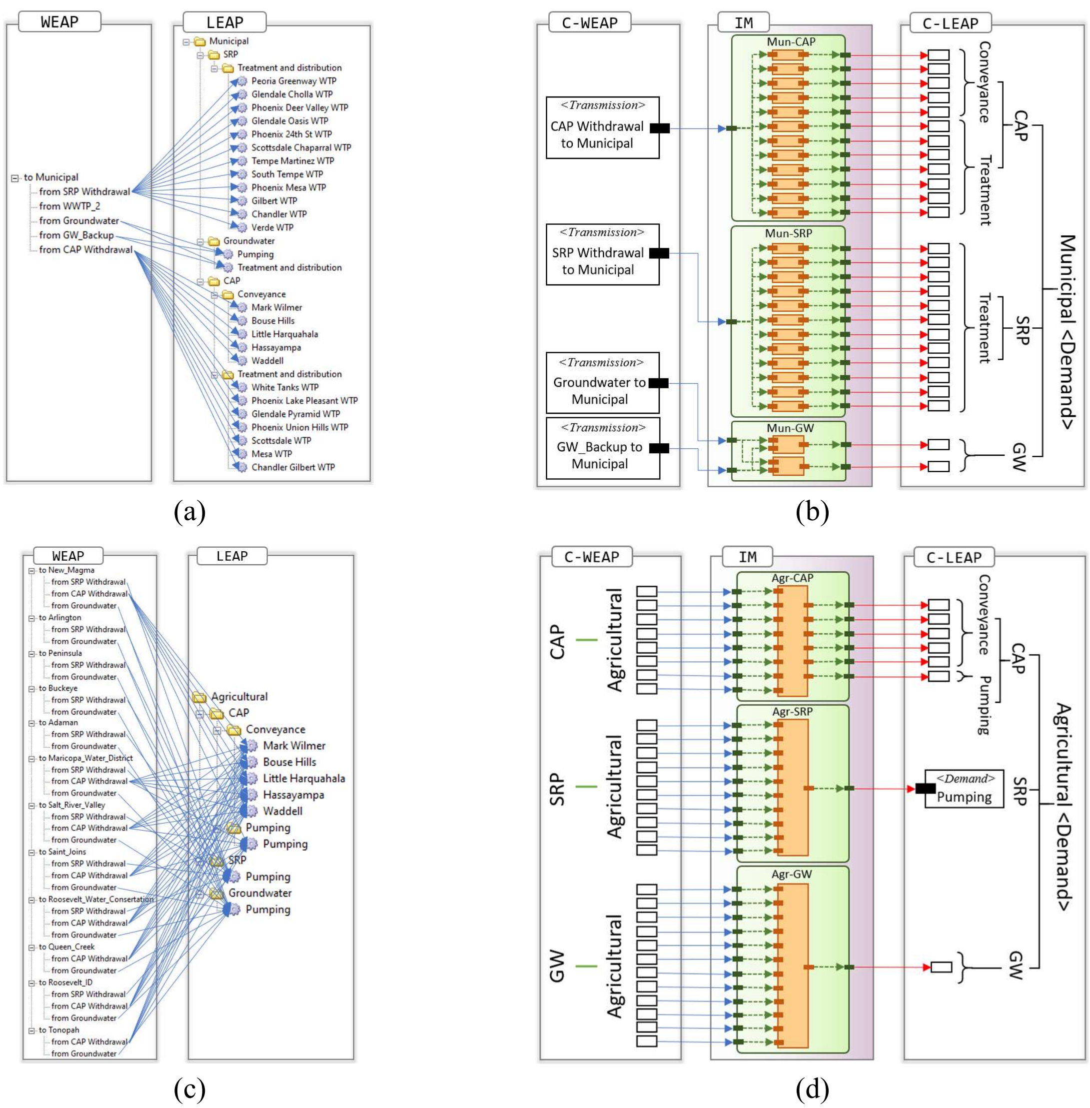
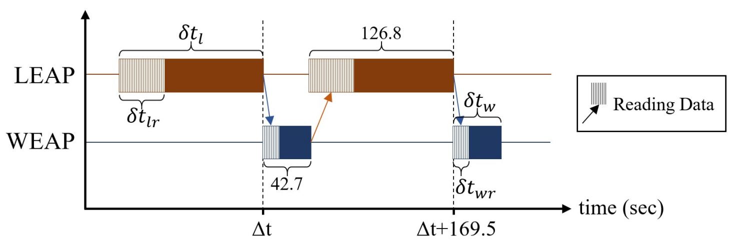


Figure 6: Comparing the WEAP-LEAP internal linkage and the Interaction Model for the Phoenix AMA model. (a) the internal linkage for the required electricity by the Municipal demands. (b) the interaction model for the required electricity by the Municipal demands. (c) the internal linkage for the required electricity by the Agricultural demands. (d) the interaction model for the required electricity by the Agricultural demands.

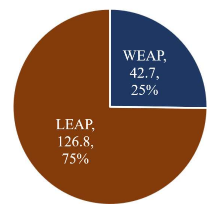
4.3 Internal Linkage and Interaction Model Performance Evaluations

To better understand these different approaches of the water-energy nexus modeling described in the previous sections, the stages in their execution cycles, as shown in **Error! Reference source not found.**, can be examined in detail. The execution steps show holistic computation time periods for simulating the Phoenix AMA water and energy models and their nexus. This model has a total of 85 WEAP's entities and 103 LEAP's entities and 13 modules and 82 transformations in the Interaction model.

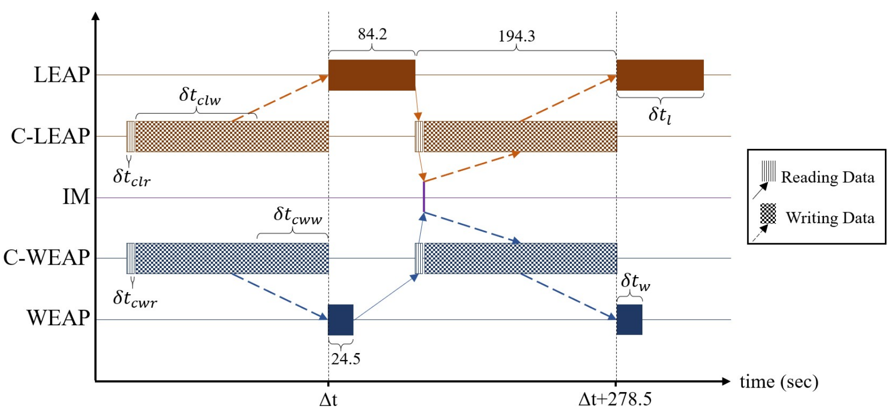
Considering the models shown in Figure 2 and Figure 6(a) and (c), it can be seen every simulation cycle is comprised of computations for executing the entities of the water model and all the entities of the energy model. **Error! Reference source not found.**(a) shows the computation time for every cycle that includes reading the data needed for executing the water and energy models. The total time for an execution cycle for the internal linkage approach is $\delta t_w + \delta t_l$. The time periods for the water and energy model to read data from one another are δt_{wr}, $0 < \delta t_{wr} < \delta t_w$ and δt_{lr}, $0 < \delta t_{lr} < \delta t_l$. The computation times for the WEAP-LEAP Internal Linkage is 169.5 seconds with 25% and 75% consumed by the WEAP and LEAP systems (see **Error! Reference source not found.**(b)).



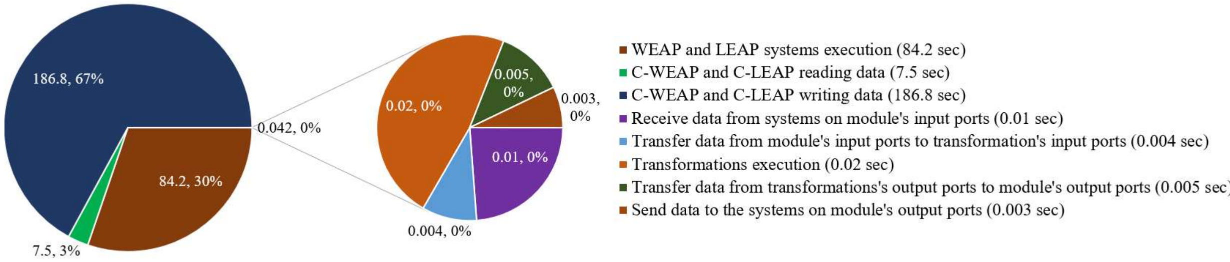
(a)



(b)



(c)



(d)

Figure 7: Stages for modeling the Phoenix AMA nexus using the internal linkage and interaction model. (a) Execution periods for the WEAP-LEAP Internal Linkage. (b) Execution time percentages for the WEAP-LEAP Internal Linkage. (c) Execution periods for the Interaction Model. (d) Execution

time percentages for the Interaction Model.

The breakdown of the computation time for the interaction models is shown in **Error! Reference source not found.**(c). The computation time for a complete execution cycle is the maximum of the δt_w for executing the water and δt_l for the energy models. The computation times for the WEAP and LEAP systems are 24.5 and 84.2 seconds, respectively. The APIs for the C-WEAP and C-LEAP frameworks, executed in parallel on multiple CPU cores, consume time for receiving and reading and data ($\delta t_{cwr} + \delta t_{clr}$) from the WEAP and LEAP systems. The $\delta t_{cwr} + \delta t_{clr}$ period is shown for the C-WEAP and C-LEAP parts of the execution cycle. The $(\delta t_{cwr})/(\delta t_{cwr} + \delta t_{clr})$ portion of the $\delta t_{cwr} + \delta t_{clr}$ section belongs to the C-WEAP framework, and the rest belongs to the C-LEAP framework. The portion of the execution cycle time for writing and sending data to the WEAP and LEAP systems is $\delta t_{cww} + \delta t_{clw}$. As shown in **Error! Reference source not found.**(c), the IM consumes a small portion of time for all the computations in the IM modules. **Error! Reference source not found.**(d) shows the breakdown of periods consumed for executing the interaction model. The periods for $\delta t_{cwr} + \delta t_{clr}$ and $\delta t_{cww} + \delta t_{clw}$ are 7.5 and 186.8 seconds, respectively. The period for transformations in the modules is 42 milliseconds. The periods allocated to different tasks in the Interaction Model are shown in **Error! Reference source not found.**(d). The execution time for the interaction model is 64% higher than the time needed for the internal linkage. The Phoenix AMA model was simulated ten times using the internal linkage and ten times using the interaction modeling approaches. A standalone desktop computer with Windows10 64-bit OS with four Core i5 Intel CPU and 20 GB RAM is used for all the experimental results included in this paper.

5 CONCLUSIONS

Dependent systems must invariably interact in multiple ways with another. Therefore, knowing how each system interacts with another system is essential to understand them together. Considering this need, this paper shows modeling the relationships between water and energy systems in two different ways. In one, the internal linkage provided for the WEAP and LEAP systems is used to model the nexus for the Phoenix AMA. In another, an interaction model that couples the water and energy systems is developed. This interaction model replicates the same nexus developed using the internal linkage. This realistic modeling of the water and energy nexus has details that lend itself to flexibly formulating and developing high-fidelity interactions between water and energy models at scale. Water-energy nexus models can have multiple levels of abstraction in a modular fashion. Interaction modeling serves as an approach that can scale to the complexity of water-energy nexus. From a higher abstraction view, the structure of the interaction model with its execution protocol can be used or changed as needed for other systems.

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