Integrated Design of Adaptation Pathways for Food, Energy, and Water Sectors Susceptible to Sudden and Chronic Perturbations

Nicholas Giles, Dr. Meghna Babbar-Sebens

Oregon State University

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Abstract

As resources are stretched thinner and thinner by growing populations, changing climate, and changing policies, the need for adaptation planning is becoming increasingly more important to a systems long-term wellbeing. The challenge in adaption planning and decision making on a basin-wide scale, is that actions made by one sector may impact another sector. It is important to identify these interconnections, and develop an adaptation pathway (set of actions) which results in system-wide wellbeing. The objective of this study is to build a hydrologic model used to examine the impacts different actions have on the Food, Energy, and Water Sectors, while developing a framework for conceptualizing, and quantifying the possible combinations of actions (pathways) taken on a system-wide level.

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Introduction

Actors within their respective sectors (being food, energy, or water) are often interdependent in several ways. That is, the decisions made by an actor in the water sector not only effect that actor, but will also effect the food and energy sectors in one way or another (Bazilian et al., 2011). Because these three sectors are so closely related, they share many of the same issues and concerns. The FEW (food, energy, water) nexus is composed of the interactions and decisions between these three sectors. As we observe a changing climate, increasing populations, and growing water demands, many of these concerns are centered around water availability and water quality (Oppenheimer & Anttila-Hughes, 2016). It is clear that we must begin to adapt our systems and management practices to increase resilience to these likely perturbations.

The challenge in adaptive decision making within a FEW lies in the numerous, complex relationships between the three sectors. An actor within the energy sector is generally a company producing energy, whether that be coal, nuclear, hydro, or any other type of energy production. While the method of power generation may vary, they all depend greatly on water. While hydropower is obviously water-dependent, forms such as coal and nuclear also rely greatly on water for cooling (Bazilian et al., 2011). The demand for energy is driven by the other two sectors, as both use power. This means that the energy sector is not only dependent on the other two sectors, but the decisions made in the energy sector effect the food and water sectors and their decisions. The food sector is mainly composed of farms and food processing plants. Like the energy sector, the food sector is greatly dependent on the other two sectors, as food production and processing requires huge amounts of water and energy. Again, like the energy sector, the deterioration of water quality often related to the food sector effects decisions made in the other two sectors.

The number of, and intense complexity of the interconnections within a FEW nexus makes adaptive decision making challenging. However, we can assist the human decision-making process with the use of computer modeling. By integrating models to represent factors such as hydrology, economics, policy change, and climate change, we can predict outcomes of different adaptation plans. With the right framework, predicting outcomes will allow us to optimize our decisions, allowing for effective adaptation, making a more resilient FEW nexus. However very little research has been done on creating an effective framework for modeling and optimizing FEW systems (Bazilian et al., 2011). This research project aims to create a baseline model to build upon in the future, to assist in developing framework to aid the adaptive decision-making process. The project focuses on the Umatilla watershed, as this region has several actors in each sector. The scenario which this study focuses on is the chronic groundwater depletion in the basin. A large portion of the groundwater within the Umatilla River Basin is defined as "critical" by the Oregon Water Resources Department (OWRD, 2006). The baseline model will be built using Soil and Water Assessment Tool (SWAT) through its ArcMap interface (ArcSWAT). This baseline model will allow for the identification and quantification of perturbations, and outcomes between the food, energy, and water sectors.

The key points of this research include:

- Develop a baseline SWAT model for the Umatilla watershed;
- Identify indicators, and quantify impacts of decisions; and
- Examine scenarios impacting the FEW nexus.

Literature Review

Modeling Large Scale Watersheds using Soil and Water Assessment Tool (SWAT):

Soil and Water Assessment Tool (SWAT) was developed in 1998 with the goal of creating a large-scale hydrological model capable of predicting the effects of water management policies (Arnold, Srinivasan, Muttiah, & Williams, 1998). Since SWAT was originally released it has been continuously improved to allow the model to simulate the outcomes of more management practices (Jayakrishnan, Srinivasan, Santhi, & Arnold, 2005). SWAT is a continuous time, spatially semi-distributed model, meaning that the SWAT model is capable of simulating hydrologic processes on a daily time-step, while accounting for spatially varying inputs such as soil type (Bouraoui, Benabdallah, Jrad, & Bidoglio, 2005). The major model parameters consist of three GIS data layers: a digital elevation model, soil type, and land use (Santra & Das, 2013). Because this model is GIS data heavy, it is often prepared through the ArcSWAT interface, which allows users to generate the model through an ArcMap extension. With the input data, SWAT generates hydrologic response units (HRUs). Each HRU corresponds to a certain composition of soil type, slope, and land cover. The use of HRUs greatly reduces the time and computational power required to run the model (Srinivasan, Zhang, & Arnold, 2010).

SWAT is capable of modeling several different natural processes such as river flows, aquifer recharge, and return flows. SWAT has several input files which are initially set to zero, however, if utilized can simulate anything from crop rotations, to pumping schedules, to building ponds (Arnold et al., 2012).

Significance of FEW Nexus within the Umatilla River Basin

Oregon is the second largest producer of hydropower in the United States, but more importantly, over half of the energy produced in Oregon is by means of hydropower (EIA, 2016). While there are several different locations in Oregon which produce hydropower, the most significant lie along the Columbia River. The Umatilla River Basin is home to two large dams along the Columbia: the McNary and John Day dams. With such a large portion of power production in Oregon coming from hydropower, the importance of energy production (specifically hydropower) in this region is incredibly significant.

If you were to drive through the Umatilla River Basin, along the Columbia, the importance of agriculture to the region would be obvious. The largest industry in the region, by far, is agriculture. The Oregon Department of Agriculture reported that the 2012 market value of Umatilla River Basin agricultural products sold at 1.3 billion USD (ODA, 2017). Tied closely to agriculture, is water. As previously stated, the Oregon Water Resources Department considers this region to have critically low groundwater levels, however it is also one of three Groundwater Management Areas (GWMA's) in Oregon (Richerson, 2012). A region is deemed a GWMA by the Department of Environmental Quality once it is determined that the groundwater in the given area has elevated levels of contaminates. The Umatilla River Basin is currently facing high levels of Nitrate contamination, further compounding their groundwater issues (Richerson, 2012).

Modeling a FEW Nexus:

Within a FEW nexus lies many complex relationships, both physical and societal in nature. While issues within different sectors may arise due to varying reasons, the impacts are often closely related and must be identified to help aide in effective decision making (Bazilian et al., 2011). Brazilian et al. explains how the inputs and outputs of a FEW model will vary based upon the perspective of the model user (Brazilian et al., 2011). If a user is in the food sector, water and energy will be inputs, whereas a user in the water sector would require energy and food. There are a seemingly endless number of ways in which food, energy, and water sectors are related, making management difficult. To adapt management practices to become more resilient to likely perturbations a very robust, integrated model is required (Brazilian et al., 2011). Brazilian et al. notes that while there are some examples of a basic frameworks, further research is required to better integrate models to simulate these complex relationships (Brazilian et al., 2011). A model such as SWAT is very valuable when modeling a FEW nexus, as it can model not only water, but also crop yields (food). In cases where hydropower is the dominant method of power generation, SWAT can also be useful in providing water levels which can easily be converted into net head difference across a dam, which can then be turned into power generation (Vukosavic, Divac, Stojanovic, Stojanovic, & Vuckovic, 2009).

Methods

Adaptation Case Study Problem

For this case study, it is assumed that due to the chronically depleted ground water levels, the Water Sector will seek to alleviate this issue by taking one or more actions to recharge the aquifer over time. This scenario takes place (is modeled) from the year 2010 through the end of 2015, in subbasin 6 in the Umatilla Basin (see Figure 1). However, while the Water Sector is most concerned with replenishing groundwater in the region, the Food Sector is much more worried about crop yields. To assure that they are able to be competitive, the Food Sector would like to increase the rate at which they are pumping water, meaning, in theory, they are able to increase revenue. In this scenario the Energy Sector isn't specifically worried about the groundwater levels, or the rate of water being pumped, however they wish to see that the

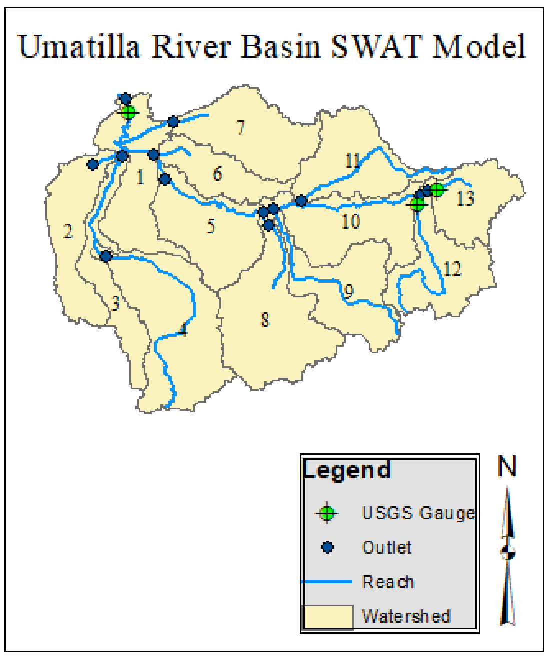

Figure 1: SWAT Model

streamflow of the stream located in subbasin 6 stays fairly constant. In other words, they do not want the stream to experience a large reduction in flow due to another sector's actions.

Simulation of Surface and Groundwater Systems

Using ArcSWAT, a hydrological model was created for the entire Umatilla River Basin (see Figure 1). NLCD 2011(National Land Cover Database) was used for the land cover data. SSURGO soil data was not available for the entire region, the more course, but complete STATSGO soil dataset was used for the soil data. Once the model was created, it was manually calibrated, comparing simulated flows to observed flows at three separate USGS river gauges, over the span of two years (2008, 2009). While the model was set to run from the year 2010 through the year 2015, two years (2008, and 2009) were used as warm up years, which the model was ran without producing any outputs. Once the model is adequately calibrated, the SWAT model is capable of modeling the changes and impacts due to any single action, or combination of actions.

Definition of Sector Goals and Possible Adaptation Actions

For this case study, each sector was assigned a single goal. It should be noted that these goals were assumed, and further research needs to be conducted to determine and define sector-specific goals. The goals of each sector and their corresponding threshold value are in Table 1, where the threshold value is defined as the tipping point, meaning if the respective variable drops below the threshold, that goal is not being met. Similar to the goals, the threshold values were estimated as a likely value sought by each individual sector to promote sustainable growth, and further research should be conducted to verify these values.

Table 2: Sector Goals and Threshold Values

Sector	Goal	Threshold Value	Possible Actions
Food	Increase pumping to sustain agricultural growth	Increase pumping rate to $8m^3/s$	D- Increase pumping rate (from aquifer) to $8m^3/s$ E- Increase pumping rate (from stream) to $8m^3/s$ F- Increase pumping rate (from aquifer) to 12 m^3/s
Energy	Maintain current streamflow to protect hydropower production	Maintain streamflow +/- 5% of current streamflow	No actions likely for this scenario
Water	Increase aquifer recharge to reverse depletion of groundwater levels	Increase aquifer recharge by $1*10^6$ m^3/yr	A- Build 5 hectares of ponds B- Build 10 hectares of ponds C- Build 15 hectares of ponds

Simulation of Different Actions within SWAT Model

Once the initial SWAT model was calibrated initial values for stream flow (FLOWOUT_cms, found in output.rch), and aquifer recharge (PND_SEP, found in output.wtr) were recorded as base conditions. By altering select parameters throughout several runs, the impacts resulting from each individual action were found. Table 2 lists each parameter which was changed to represent different actions being taken.

All parameters related to irrigation (IRRSC, IRRNO, IRRSC, DIVMAX) are located in the .mgt input files. There is an .mgt input file for each HRU in each subbasin. These parameters, when changed, were changed for each HRU within the subbasin. In this study the two possible actions with regards to irrigation were to withdraw from the stream, or from the aquifer, at varying rates. The IRRNO code varied based upon the IRRSC code. For example if the IRRSC code was 1 (meaning the water is being withdrawn from the stream) then the IRRNO code was set to 6, meaning from stream 6 (the stream within subbasin 6); whereas if the IRRSC code was set to 3 (meaning from a shallow aquifer) the IRRNO was again set to 6, but this time representing that the aquifer being withdrawn from was located in subbasin 6. The FLOWFR was set to a constant 1.0 when pumping, to simulated unrestricted pumping (up to the limit set by the action) from the stream. Setting the FLOWFR parameter to a lower value would restrict pumping to a certain fraction of the streamflow, which was not defined in the action description.

Table 3: Varied Parameters to Model Sector Actions

Parameter	Description	Variations
IRRSC	Defines type of water body in which water is being drawn from for irrigation	0 (no irrigation) 1 (stream) 3 (shallow aquifer)
IRRNO	Defines source of irrigation (varies based on IRRSC)	0 if IRRSC=0 6 if IRRSC=1[E] 6 if IRRSC=3 [D,F]
DIVMAX	Maximum daily flow diverted for irrigation (10^4 m^3/s)	0 0.0008[D,E] 0.0012[F]
FLOWFR	Fraction of stream flow available for irrigation	1.0
PND_FR	Fraction of subbasin which drains into pond	0.25
PND_PSA	Surface area of pond when filled to principle spillway (ha)	5[A] 10[B] 15[C]
PND_PVOL	Volume of pond when filled to principle spillway (10^4 m^3)	25[A] 50[B] 75[C]
PND_ESA	Surface area of pond when filled to emergency spillway (ha)	8[A] 16[B] 24[C]
PND_EVOL	Volume of pond when filled to emergency spillway (10^4 m^3)	40[A] 80[B] 120[C]
PND_VOL	Initial volume of pond (10^4 m^3)	10
PND_K	Hydraulic conductivity of the bottom of the pond (mm/hr)	360

A, B, C, D, E, or F denotes the corresponding action related to the variation of the respective parameter. For Action A to be modeled, all variables labeled A, along with the constant parameters were used.

All PND parameters are located in the .pnd files (one for each subbasin). To enable the model to yield results that show only the impacts of increasing ponds in Subbasin 6 (see Figure 1), values such as

PND_FR, PND_VOL, and PND_K were set to constant values. This enables us to see the changes occurring directly from increased pond areas. While the initial pond volume may seem important, the model was set to run for two warm-up years, so the initial pond volume was insignificant (Arnold et al., 2012). The hydraulic conductivity was set to a constant 360 mm/hr, typical of the soils found in the region.

Results and Discussion

Sector Actions and Impacts

Following the steps outlined in the Methods section, the impacts resulting from each impacts on each sector were determined for each individual action. The impacts of each decision are represented in Figure 2 (below). The far left column defines each individual action, and the acting sector. The remaining three columns represent the impact on each individual sector resulting from each action, respectively. The grey dashed line represents a zero change (everything above the grey line marked green represents a positive impact, and blow marked red represents a negative impact).

Looking at actions A-C (taken by the Water Sector) we see that there is a direct, positive correlation between aquifer recharge and increasing the amount of ponds in the subbasin. We also see that there is no impact on the other two sectors with respect to their defined goals. It should be noted that while these actions do not impact the defined goals of the other two sectors, this does not necessarily mean that they are not impacted. If this study were expanded to include multiple goals from each sector, it very well may be found that these actions impact the other two sectors.

Actions D-F (taken by the Food Sector) yield more interesting results. With actions D-F being taken, we see the interdependencies between the three sectors. That is, we see that an action being taken by the Food Sector is impacting the Energy and Water Sectors. From this figure we see that action E results in a very negative impact on the Energy Sector, while providing very little benefit to the Food Sector (this is due to the action resulting in the river being run completely dry). From this we can essentially eliminate action E from the possible choices, as it provides no real benefit to the Food or Water Sectors, while negatively impacting the Energy Sector.

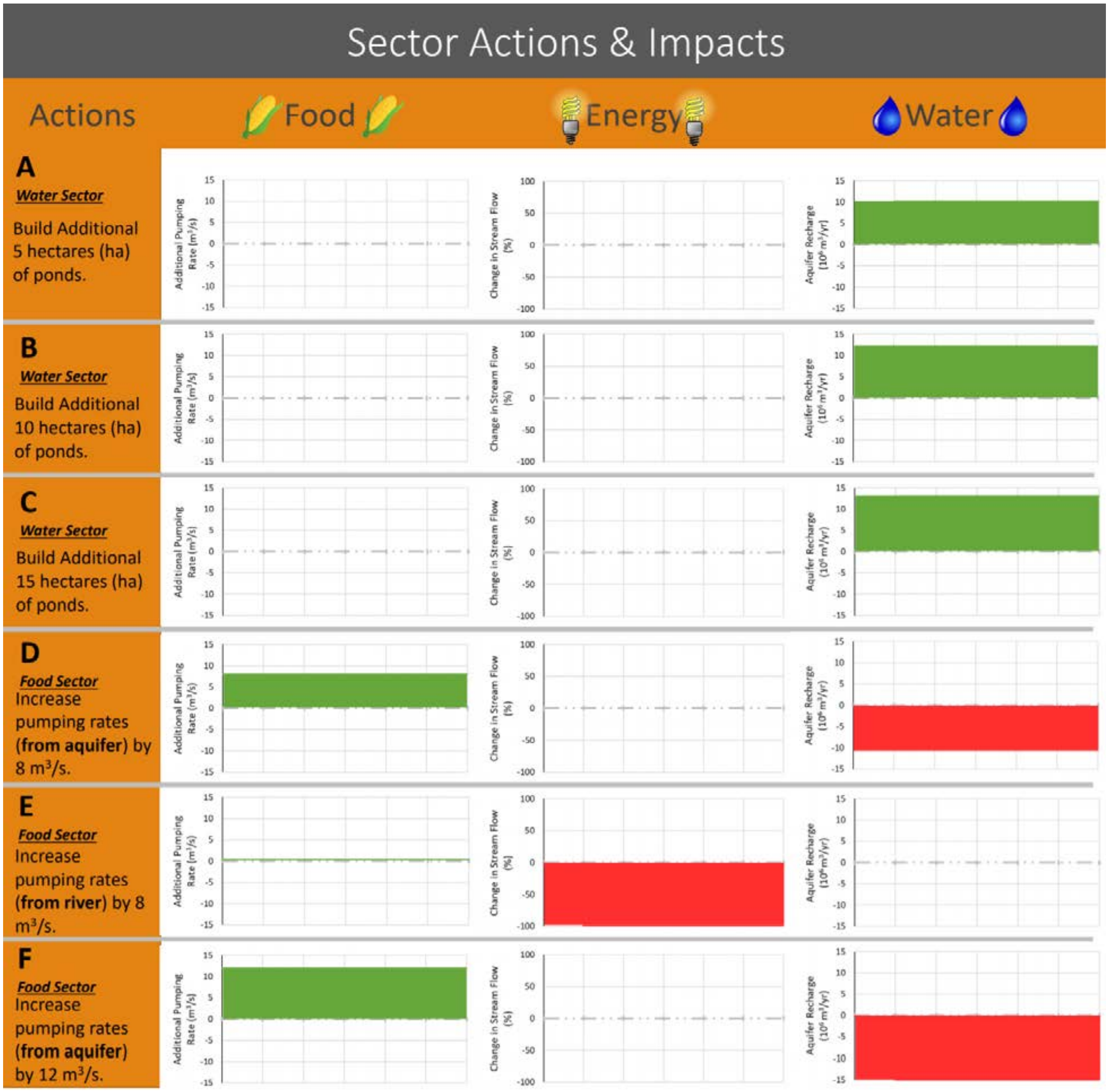

Figure 2: Sector Actions and Impacts

System Pathway Conceptualization and Quantification

Taking the results shown in the System Actors and Impacts Diagrams we can begin to formulate different System Pathways, and their resulting impacts on different sectors. Figure 2 (see next page) depicts two different System Pathways. The heavy, dashed black line represents the resulting impact of the respective sector, due to the chosen actions. The green and red bars represent the resulting impacts shown in Figure 1.

In Pathway 1 we see action A (building 5 hectares of ponds) being taken throughout the 6 year period, while action F (increasing pumping from the aquifer by 12 m^3/s) being taken each year. Looking at the Food sector, we see that it is well above the threshold value set (pumping rates increased by 8 m^3/s). The Energy Sector, is unaffected, as the only action found to impact the Energy Sector was action E. While this pathway exceeds the threshold values for both the Energy and Food Sectors we see that it is significantly below the threshold set by the Water Sector. Looking at the Pathway impact on the Water Sector we see the negative (red) impact outweighing the positive (green) impact. Therefore we find that Pathway 1 fails to meet the needs defined by the Water Sector.

Pathway 2, consists of 4 different actions, two taken by the Water, and two taken by the Food Sector. Initially, action D (increasing pumping by 8 m^3/s) is taken by the Food Sector, while action B (adding 10 hectares of ponds) is taken by the Water Sector. We see that the thresholds of all three sectors are met throughout the first 4 years of this pathway. In the final two years of the pathway we see the final two actions being taken, that is, actions F and A. This represents an increase of pumping rate (up to 12 m^3/s), and an additional 5 hectares of ponds being built. It is important to note that in the final two years (4-6) the Water Sector is taking both action B and A, meaning that the first 10 hectares of ponds were not abandoned. Looking at Figure 2, we now see the Water Sector now having built 15 hectares of ponds, is now able to meet its threshold value, while the Food Sector is able to exceed its threshold value.

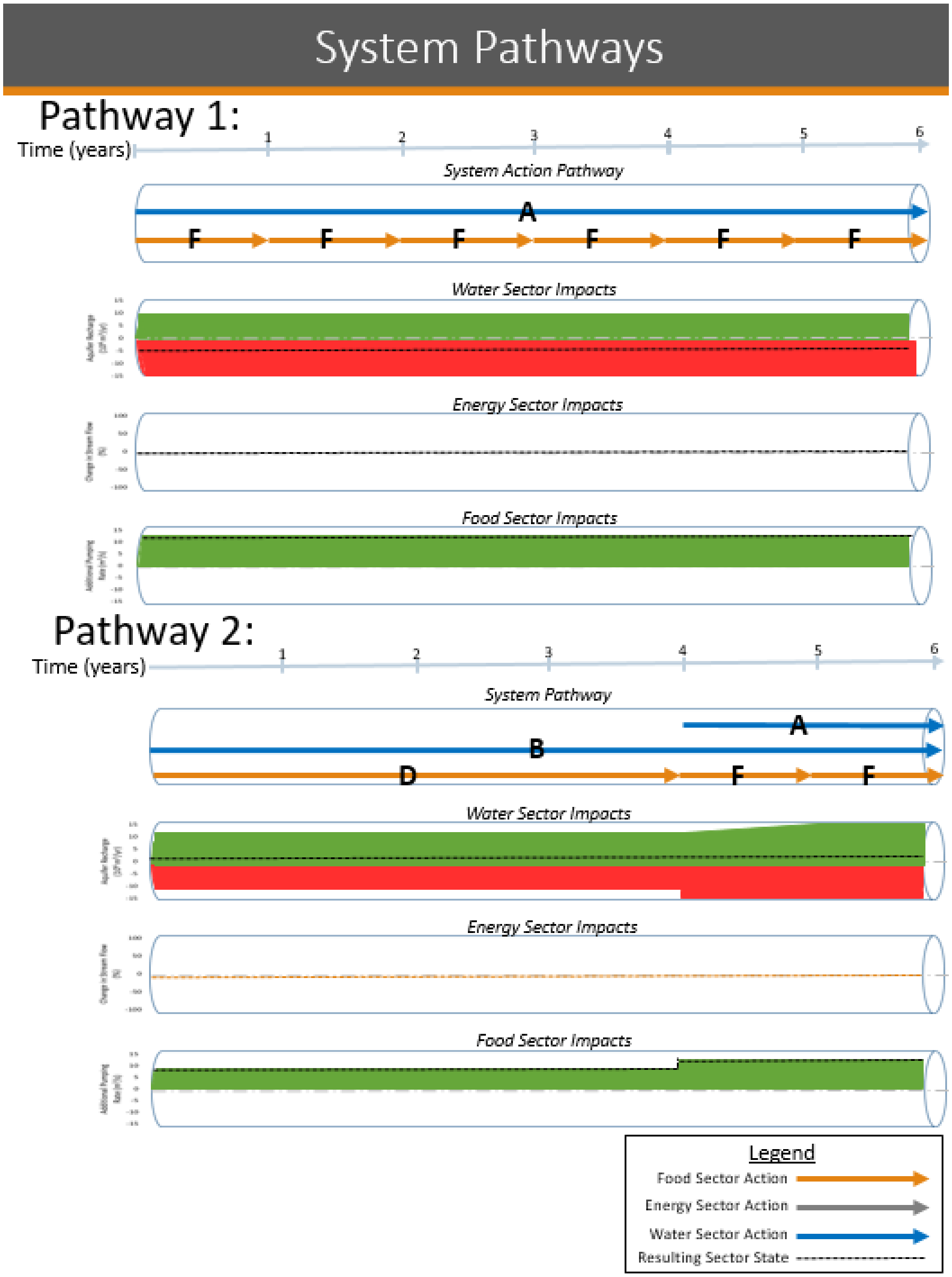

Figure 3: System Pathways

Model Uncertainty

This study found that five of the six decisions did not impact the goal set by the Energy Sector of impacting streamflow. This seems questionable, as fluctuations in aquifer recharge should have some impact on streamflow. This could be due to the inherent inaccuracy in groundwater flows which SWAT does not model to a high degree of accuracy (Sawyer, 2010).

Conclusions

This study applies a course SWAT model to a region with sizeable Food, Energy, and Water Sectors. By setting goals and threshold values for each individual sector, an Action and Impact diagram was formed, yielding a System Pathway diagram. The System Pathway diagram provides a conceptual and quantifiable way of representing actions being taken within a FEW nexus, and the resulting impacts on each sector. This methodology, can be applied to help formulate integrated, adaptive decision making pathways within a FEW nexus. It was speculated that the course model neglected to accurately model the impacts of groundwater fluctuations on streamflow. That being said, they key takeaways found during this study are:

- The System Action and Impact, and System Pathway diagrams provide an integrated approach to adaptive decision making within a FEW nexus
- The System Action and Impact, and System Pathway diagrams can, and should be applied to several different goals for each sector
- The SWAT model used should be integrated with a MODFLOW model to better model groundwater fluctuations

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