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Developing a learning environment for the Edwards Aquifer with a base in systems thinking and dynamics

James Everette Simon III
James Madison University

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Developing a Learning Environment for the Edwards Aquifer with a Base in Systems Thinking and Dynamics

James E. Simon III

A Thesis submitted to the Graduate Faculty of
JAMES MADISON UNIVERSITY

In
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Abstract

The purpose of this project was to create a learning environment that fostered an interest in conservation and preservation of the Edwards Aquifer in children by using the endangered and threatened species that live in the aquifer and depend on it to survive. This game was based on the system dynamics of the Edwards Aquifer that were put into a causal loop diagram.

In order to gather the data I needed for this project, I spent a great deal of time in San Marcos, Texas, at Texas State University’s Albert B. Alkek Library. The library contained hardcopies of information that I would not have otherwise been able to attain. Extensive research was also done online through many state and federal agencies, as well as other universities. The data was put together into a final causal loop diagram and children’s learning environment.

It was determined by the end of research and development of the learning environment that a fun, and interactive game could be created based on Systems Thinking ideas and the system dynamics of the Edwards Aquifer.

Recommendations for further work on this project include expanding the current causal loop diagram into a stock and flow diagrams, and testing the learning environment with children and educators.
Developing a Learning Environment for the Edwards Aquifer with a Base in Systems Thinking and Dynamics

Chapter 1: Problem Statement and Context

Throughout our program in Sustainable Environmental Resource Management (SERM), we defined the idea of sustainable development in just about every class. We came to describe it as a general concept that met the needs of the present human population without hindering future generations' ability to rely on and use those resources as necessary. My goal is to create a learning environment that could get children excited about the conservation and preservation of the Edwards Aquifer (Figure 1) by using the endangered species that live in and depend on the aquifer to pique their interest.

Figure 1, The Edwards Aquifer – source: Edwards Aquifer Website, http://www.edwardsaquifer.net/index.html.
History of the Edwards Aquifer

The United States Geological Survey refers to the Edwards Aquifer’s subterranean aquifer ecosystem as, “… perhaps the most diverse groundwater ecosystem in the world. Increased knowledge about the complex hydrologic processes that control water availability in the Edwards aquifer is imperative for optimal resource management (USGS, 2012).”

The reason for the complexity of the aquifer is because of its history. Approximately 100,000,000 years ago in the Mesozoic era, Texas was covered by a shallow sea habitat consisting of prehistoric marine animals, most all of them with skeletons and shells made of calcium carbonate. When those animals died and sunk to the bottom they formed many different layers on the seafloor, which over the years were compacted together, under the pressure of the weight of the new layers forming and the weight of the water above, to create limestone. Around 70 million years ago the Rocky Mountains were being created by tectonic activity. Sediment created from the mountain formations were deposited across Texas, and the thickness and weight of them caused faults to form between what would become the Edwards Plateau and the Gulf of Mexico (Save Our Springs, 2011)). 17 million years ago, tectonic uplift caused this limestone, now known as the “Edwards and Associated Limestones” and the “Glen Rose Limestone,” to rise above the level of the shallow sea. The nature of the limestone led to breaking which created fracturing and faulting throughout what is now known as the Balcones Fault Zone in the central Texas Hill Country. The fractures and faults within the limestone gave this new aquifer karst features and are what allowed water to begin seeping in and flowing out to create the Edwards Aquifer of the present. While the aquifer is an important source of water today, we also know that it has been a source of water for people in central Texas for at least the last 12,000 years (EAA, 2013). The Edwards Aquifer website presents a diagram (Figure 2) of this process here:
Present State of the Edwards Aquifer

The Edwards Aquifer is home to six endangered species of animal (Texas Blind Salamander, San Marcos Gambusia, Fountain Darter, Peck’s Cave Amphipod, Comal Springs Riffle Beetle and Comal Springs Dryopid Beetle), one endangered plant (Texas Wild Rice) and one threatened species (San Marcos Salamander) according to the Texas Parks and Wildlife Department (TPWD, 2012). It also is where the city of San Antonio, as well as surrounding smaller cities and towns, including parts of the capital city of Austin, get their water. The total number of people using this resource for drinking, bathing and home use in the area is over 2 million (Eckhardt), but that number does not include all of those who come to use it for recreational purposes, or those who simply commute to work in the region and may use it during the day. Their domestic, recreational, agricultural and industrial uses cause a strain on the water flowing out of the aquifer and poses threats to not just the endangered, but all species which rely on its flow. The aquifer’s artesian springs feed rivers that flow to the Gulf of Mexico and provide
brackish environments needed by myriad other species as well, including another endangered species, the Whooping Crane.

The level of water in the aquifer is measured by the level J-17 index well (Figure 3) found in San Antonio. The depth of the well is based on artesian pressure exerted by water higher up in the Edwards limestone formation that holds the water in the Edwards Aquifer. In essence, the well does not determine the depth of the aquifer, but rather changes in the level of artesian pressure in the aquifer.

My Project

This project proposes a framework for an interactive, hands-on game that will educate young people on the importance of the aquifer and how human activity can either preserve or
endanger the ecosystem services provided by the aquifer. When I worked at Aquarena Center for Texas State University – San Marcos, it was my job to educate people about the aquifer; its water, plants, animals, the human impact on the aquifer, and the science that was being conducted in and around it. What I found was that most people did not understand the problems or the science associated with the aquifer, because the information they got about it were usually just isolated facts told to them by a scientist or some other person on TV or radio. What I have done is propose an outline for an interactive systems learning environment (a game) that young people can use to gain a holistic understanding of the interactions between the aquifer’s hydraulic dynamics, its ecosystem services, and the surrounding biosphere and anthrosphere. In addition to the natural ecology, the proposed game accounts for the impact of agricultural, recreational, industrial activity, and human population dynamics. The game illustrates the impact of human activity on rainwater infiltration into the aquifer, and allows users to explore the impact of changes in rainfall on the system.

Ideally, such a game could provide a hands-on learning environment that could be used by organizations like Aquarena Center and schools to help show young people how to better understand the impact that their day-to-day lives have on the aquifer. The learning environment could potentially be used for different age levels. For the purpose of this thesis, the game is targeted for use by elementary or middle school aged children, but could be adjusted by the user to fit the appropriate age group or education level up through 12th grade.

Justification

I believe this project offers one approach to educating young people whose families depend on the aquifer for water at home and work, those who use it for agriculture and industry, and finally those who depend on it for recreational use during the hot summers in Texas. By educating young people on the problems the aquifer and its inhabitants are facing, we can
increase the awareness, and thereby increase the potential for preserving this critical resource for future generations.

Past Efforts at Modeling the Edwards Aquifer

The field data that give insights about how and why water flows through the aquifer are used by hydrologists to create dynamic models of the aquifer. The Edwards Aquifer website (http://www.edwardsaquifer.net/modeling.html) has a section on modeling the aquifer and gives a nice overview of the systems analysis and modeling process. It discusses the different types of models that have been used on the Edwards Aquifer, from physical models of an aquifer to digital simulation models. The site explains the usefulness of the models in helping to manage the aquifer and predict the impact of various events and scenarios before they happen. This is extremely useful because it allows for more informed management of the aquifer without having to go through a potentially very harmful process of trial and error. The site poses three key questions for modeling, and what kinds of models can best help with these questions:

1) Why does something happen?
   a. A physical or 3D model simulation model may help.

2) What will happen?
   a. Digital simulation models work well here.

3) What is the best way to do something? (Listed as the most difficult question)
   a. A combination of models and other systems analysis methods must be used, including the needs and concerns of the general public.

Further explained is why none of the models of the aquifer have been implemented as management tools on a large scale. This can be because they are very complicated and are not easily understood by those making management and/or policy decisions, the concern that they may not be as accurate as they need to be, a lack of good record keeping from the past leading to
inaccurate results, and the fact that “... all the models that predict springflow tell basically the same story... reductions in pumping can increase springflows but probably won't keep them flowing in an extreme drought.” In spite of these problems, the author goes on to say, “Still, decisions have to be made, and making decisions in the face of uncertainty, based on incomplete information but using the best data you have, is the stuff of systems analysis” (Edwards Aquifer 2013).

The site describes nine models¹ from 1979 through 2005, with overviews of how they were built, calibrated, refined and what conclusions they drew. None of them use classic system dynamics methods, such as causal loop diagrams (CLDs) or stock and flow diagrams (SFDs). The advantage of this methodology is that it provides a visual representation of an otherwise complex system using representations that are more intuitive than models that rely on purely abstract mathematical representations. Hence, this thesis describes a CLD as part of a conceptual model for the hydrologic dynamics in the aquifer. This model in turn serves as the basis for the game described in chapter 6.

Methodological Outline

This project relies on resources from several environmental agencies in Texas, including the Texas Commission on Environmental Quality (TCEQ), Texas Parks and Wildlife Department (TPWD), Guadalupe-Blanco River Authority (GBRA), Edwards Aquifer Research and Data Center (EARD), Edwards Aquifer Authority (EAA), Barton Springs Edwards Aquifer Conservation District (BSEACD) and the River Systems Institute (RSI). Outside of Texas I used information from other governmental agencies including the United States Geological Survey (USGS) and the United States Fish and Wildlife Service (USFWS). Nongovernmental sources included PhD dissertations on sustainable development of the Edwards Aquifer, case studies from

¹ Links are available to all of these models in the Edwards Aquifer website’s modeling section: (http://www.edwardsaquifer.net/modeling.html).
ISEE systems on using system dynamics with children, a teacher’s guide about the Edwards Aquifer, a textbook on systems thinking and modeling, books on modeling groundwater hydrology and how water flows through aquifers, books on water policy in Texas, recovery plans for the endangered species, and items pertaining to agriculture over the Edwards aquifer.

Based on this research, a conceptual system-level model was constructed to define the relationships among variables that impact the health of the Edwards aquifer. Based on this prototype system structure, a hands-on game simulator was developed that can be used to demonstrate the dynamics represented in the CLD. Several endangered species that live in and around the aquifer are used as pedagogical “hooks” to draw players into the game and to stimulate interest in the role of the aquifer to support those species. Playing this game will enable users to learn how human activity impacts the health of the aquifer, and hence, the prospects of the endangered species listed earlier.

Chapter 2 summarizes the relevant literature on the use of games and systems thinking for educating people about environmental problems. Chapter 3 gives a brief overview of the ecosystem services provided by the aquifer and the endangered species. Chapter 4 describes the relevant Texas and U.S. water policies that impact the aquifer and the human activities around the aquifer. Chapter 5 describes the role of human activities that impact the aquifer and outlines the system dynamics of the human/environment interactions within the aquifer region, including the role of population growth, agriculture and climate change. The dependence of these activities on the aquifer and their impact on the long-term viability of the aquifer and its ecosystem services are described. Chapter 6 describes a prototype game that mimics these dynamics. Chapter 7 gives a summary of conclusions and recommendations for further work.
Expected Results

The prototype game described herein provides a pilot learning environment for middle- and high school aged children to “experience” and learn about the interdependencies in the ecosystem surrounding the Edwards aquifer’s and the humans and endangered species that depend on it. Personnel at the Aquarena Center in San Marcos, Texas, have expressed an interest in using the game as part of the Center’s educational efforts. They are: Ron Coley, the director of Aquarena Center; Deborah Lane, the assistant director; and Sonja Mlenar, the Coordinator of Instructional Programs at Aquarena Center.
Chapter 2:  
Systems Thinking and Games as Learning Tools for Environmental Problems Facing the Edwards Aquifer

This chapter outlines the various ways in which Systems Thinking can be used in education and in environmental sciences, as well as how they can be used in educational games. The focus is on children in elementary and middle school (and possibly beyond) who live in and around the Edwards Aquifer in central Texas. This target audience has been chosen because of a previous knowledge of work with educating those very same students about the Edwards Aquifer.

The literature referenced in this chapter shows that a systems-oriented educational approach has great potential to help students grasp the complexities of a given environmental issue. The ideas and concepts behind Systems Thinking offer a holistic approach to learning how the aquifer, the things that the aquifer depends on, and the things that depend on the aquifer, all work together to make the aquifer what it is - a tremendous resource that must be protected and managed carefully.

In my work with students while at Aquarena Center, I realized that most of them did not know much about the aquifer at all, so educating them was basically a ground-up endeavor. We had many games and activities for the students to engage in, but none of them really encompassed the entire aquifer system, but rather only isolated parts of it. The only system-level concepts that we discussed with the students were how the water itself flowed through different parts of the aquifer and therefore connected different geographic locations. We did this to show how
pollution coming from a town or municipality several miles away could affect the region that they were living in.

The use of Systems Thinking offers much promise for giving kids a much better understanding of the aquifer and how the people, the water, the land, and the animals that depend on the aquifer are interconnected. While those of who taught the students understood these interconnections, the education about the aquifer was broken up into many parts, and not much was done to show how those parts interacted. Essentially, what we told them was, “the water underground connects everything,” and left it at that. It was left up to the students to try to figure most of the connections out for themselves, but only if they cared to go above and beyond what we showed them. A Systems-based game can provide a holistic approach to learning about the aquifer by combining visual elements as well as hands-on experience. The rest of this chapter will show how a Systems Thinking approach to environmental education has potential for giving students from kindergarten through 8th grade and beyond a much greater understanding of how the Edwards Aquifer really works.

Using Computers and Visualization to Aid in Education

Computers can help us visualize what we read about in textbooks and hear about in classes. As explained in the 2002 report, Exploring the Role of Visualization and Engagement in Computer Science Education, the authors state that, “Visualization technology can be used to graphically illustrate various concepts in computer science. We argue that such technology, no matter how well it is designed, is of little educational value unless it engages learners in an active learning activity. Drawing on a review of experimental studies of visualization effectiveness, we motivate this position against a backdrop of current attitudes and best practices with respect to
visualization use (Naps, Rößling, et al. 2002).” Systems Thinking does exactly that, it actively engages learners. It does so through the use of causal loop diagrams.

What is "Systems Thinking?"

Systems Thinking allows people to actively and holistically explore a problem by identifying how the elements of a system interact and hence collectively create or solve the problem. Systems Thinking is, “a powerful new perspective, a specialized language, and a set of tools that you can use to address the most stubborn problems in your everyday life and work. Systems Thinking is described as “…a way of understanding reality that emphasizes relationships among a systems parts, rather than the parts themselves” (Pegasus Systems, 2013). The Waters Foundation is an organization that is dedicated to bringing Systems Thinking into schools which focuses on kindergarten through 12th grade education. Their mission statement states that they want to “increase the capacity of educators to deliver student academic and lifetime benefits through the effective application of Systems Thinking concepts, habits and tools in classroom instruction and school improvement.” This is a summation of what they believe Systems Thinking and the principles behind it are (Waters Foundation, 2013):

1. What is Systems Thinking?
   a. A set of tools including causal loop diagrams, stock and flow diagrams and simulation models that help map and explore dynamic complexity. The tools help the user gain a holistic awareness of the problem they are addressing. It also refers to the feedback dynamics of balancing in reinforcing loops, limits, delays, and patterns of behavior over time.

2. What is a systems thinker?
a. This is a person who has developed the habit of learning to see and analyze problems and behavior in terms of the systems out of which those problems or behaviors emerge.

3. What are the system thinking tools?
   a. behavior over time graphs, which are used to show how variables change over time;
   b. causal loop diagrams, which are used to show causal relationships and how they feedback into each other;
   c. stock and flow diagrams, which are similar to causal loop diagrams, but are more complex and are the first step in the fourth tool, which is;
   d. dynamic computer models, which show students how to test their work in a computer simulation.

4. Five Systems Thinking concepts?
   a. mental models, our ideas about how things work, our beliefs and assumptions;
   b. the concept of dynamic behavior over time
   c. understandable patterns that are generated by interconnectedness;
   d. feedback, this describes “circular causality,” which shows that things are not always as simple as a cause and effect relationship; and
   e. leverage, the idea of coming up with viable options to solve complex, interconnected problems.

5. What is dynamic modeling?
   a. Dynamic modeling is a concept that allows the modeler to build his or her mental model. It allows for the development of possible future scenarios that can help to explain what may happen to a particular system in the future.
Therefore, Systems Thinking in the classroom or learning context is an approach to education that encompasses the whole of a problem in order to learn about it and fix it, while teaching how to anticipate probable outcomes and new problems that may be associated with those outcomes.

Benefits of Using Systems Thinking in Education

As previously stated, using Systems Thinking gives us a holistic, big picture understanding of a problem or issue. For example, if a teacher asked a younger student trained in traditional methods where rain comes from, he or she may tell them that “rain comes from clouds.” While there might not be anything wrong with that answer at lower grade levels, a student trained in Systems Thinking may answer with statements about evaporation and the water cycle, because they understand that there is a system behind it, although they may not yet understand exactly how the system works.

Systems Thinking is important because, “… dynamic systems are everywhere, and understanding them will give you a leg up. Systems Thinking can be applied all over the curriculum at every grade level, and consistent success and learning is always reported. Learning is said to be enhanced because students are working on “real” problems. Also, research has shown that student centered, experiential, holistic, and authentic instructional settings optimize learning” (Waters Foundation, 2013). In addition, Systems Thinking, “… encourages you to think about problems and solutions with an eye toward the long view -- for example, how might a particular solution you’re considering play out over the long run? And what unintended consequences might it have” (Pegasus Communications, 2012)? Getting children to think about unintended consequences is an important bonus of Systems Thinking, and one that is very important with regards to the Edwards Aquifer.
Employing Systems Thinking in an educational context also helps students learn to identify patterns. “Systems Thinking should be taught and learned because it can help people make sense of the patterns in how things change over time. By understanding the patterns, it can help to generate more favorable outcomes as well as help to understand how things are interconnected where a connection was not previously seen” (Waters Foundation, 2013). This can lead to more effective efforts to influence and shape the future in positive ways.

“Systems Thinking is a perspective because it helps us see the events and patterns in our lives in a new light—and respond to them in higher leverage ways. For example, suppose a fire breaks out in your town. This is an event. If you respond to it simply by putting the fire out, you're reacting. (That is, you have done nothing to prevent new fires.) If you respond by putting out the fire and studying where fires tend to break out in your town, you'd be paying attention to patterns. For example, you might notice that certain neighborhoods seem to suffer more fires than others. If you locate more fire stations in those areas, you're adapting. (You still haven't done anything to prevent new fires.) Now suppose you look for the systems—such as smoke-detector distribution and building materials used—that influence the patterns of neighborhood-fire outbreaks. If you build new fire-alarm systems and establish fire and safety codes, you're creating change. Finally, you're doing something to prevent new fires!” (Pegasus Communications, 2012)

A Systems Thinking approach adds value to education by giving students a basic problem-solving framework that they can apply in many areas. “Education should provide a foundation that gives students mobility to shift with changing demands and opportunities. System dynamics provides a foundation underlying all subjects. When that foundation is mastered, an individual will have the ability to move from field to field.” In addition, Forrester argues that a systems education should enhance innovative tendencies in children, condition students to look
for the source of their troubles first in their own actions before blaming others, and create a better understanding of the conflicts between short-term and long-term goals (Forrester, 1994).

An earlier start to learning systems thinking concepts will pay off in the long run because as students progress in school, they will have to tackle those more complex problems. It will also make them start to think about those unintended consequences that may emerge as a result of solving those original problems, as well as enhance their innovation, teach them how to find problems, and the issues with the temporal scale of those problems. In other words, already having a base in Systems Thinking will help them to have a better understanding of the problems and how to best solve them, so long as they have been taught properly.

Using Systems Thinking with Education about the Edwards Aquifer

The Waters Foundation has a series of quotes given by educators on how they use Systems Thinking which have been summarized thusly, “Systems Thinking and modeling are used to allow students to explore problems in a more in-depth manner. This helps find patterns and feedback behavior using math and science over many disciplines and how those patterns and feedback affect the overall problem. The entire process is then integrated within the curriculum (Waters Foundation, 2013).” For use with the Edwards Aquifer, this could include finding seasonal patterns in the amount of rainfall over the recharge zone, combining that information with how much water is used in the areas of agriculture and industry during those times (or over the course of several years), and referencing them to index wells on the aquifer to see how the water level fluctuates, for example.

What follows are reviews of five environmental case studies that use systems modeling and systems thinking. All come from the iSee website (iSee, 2013). Following each review is a
brief summary of the connections to the Edwards Aquifer and the project described in this dissertation.


   This is an example involving a college-level course in aquatic biology. The author gives some suggestions on how to create models based on live animals, in particular aquatic animals. The author describes the problems associated with using live animals in experiments and explains how, by creating model simulations, one can avoid things like animal rights issues, the monetary cost of keeping animals alive and equipment running, but still get results. According to the author, one of the big benefits of this experiment is that it “eliminated the distractions of lab confusion, delays and frustration. When students didn’t have to worry about dying fish or malfunctioning equipment, they could focus on the biological principles involved, and on how the findings from the sequence of labs came together to create a synthetic whole. They can apply what was learned in one lab to the next.” The exercise also helped highlight what students still needed to learn and that made it very easy to add new variables to the equation (iSee, 2013).

   The Ecofish project demonstrates the value of Systems Thinking and can enhance learning about environmental and ecological problems and suggests that using Systems Thinking to educate students about the Edwards Aquifer is possible, at least at the college level.

2. “*Systems Thinking and Dynamic Modeling Deliver New Insights into Freshwater Systems* ” (Page, 2009). This case study is also based on an aquatic ecosystem. However, this one takes a different approach and looks at man-made impacts on freshwater ecosystems. It studies changes over time in the ecosystems of 58 separate
lakes in Northwestern Ontario, Canada. With their modeling they study “the watershed, the fish, hydrology, phytoplankton, zooplankton, invertebrates, everything.” Lately they’ve been looking at algal blooms on Lake Winnipeg. Algal blooms can become a problem because they suck up nutrients that would otherwise go to other organisms in the ecosystem that are dependent on them. They used their model to determine that they needed to reduce nitrogen and phosphorus loading in order to return Lake Winnipeg to its 1970 loading conditions by removing nitrogen and phosphorus from point sources to bring them down to target concentrations. What they found was that their system was not perfect because of increased rainfall. Basically, because of an increase in rainfall the added water flow into the lake carried more nutrients, which offset any reductions made within the city of Winnipeg. They also modeled what would happen during drought, because if there was a drought, there was potential that the nutrient load could become so low that the fisheries would actually decline. By adjusting the model, they were able to find out that during periods of heavy rain they could not do very much about the nutrient load, however, during periods of drought that it “might be possible to find a sweet spot in which phosphorus concentrations and algal blooms decrease but not to the extent that fisheries also decrease”

This case study is relevant to the Edwards Aquifer because there are frequent algal blooms in Spring Lake on the San Marcos River (part of the Edwards Aquifer system). The San Marcos River is the home of all of the endangered species of animal in the aquifer, and it sits upstream from the bulk of the endangered Texas Wild Rice population (Eckhardt). The ability to predict, and or stop algal blooms could be very important to maintaining what little remains of the Texas Wild Rice by helping to discourage growth of exotic or highly aggressive, invasive plants, like the
Hydrilla. Most importantly, though, this case study illustrates the roll of many variables, including weather variables in an aquatic ecosystem, and provides some insight as to how they could be incorporated into a learning environment for students.

3. “ALCES Landscape Model Informs Land Use Policies” (The Connector, 2009). This is one of the largest models ever created and is currently being used in Canada, the United States and Paraguay. It started out as a landscape model looking at how the landscape in northern Alberta, Canada, was being changed by oil exploration and the spread of agriculture. The model takes into account for history, energy, agriculture, tourism, mining, livestock grazing and residential land uses; and it shows how the land changes over time based on changes to the previously mentioned variables. It is a very important model because it helps show what will likely happen in the future. According to the model developer (Brad Stelfox), “…it forces everyone to understand that there is no win-win situation,” and that “moving forward, everyone is going to have to make adjustments to preserve the province as a whole.” This suggests that the holistic approach from a system-based analysis can lead to better solutions – solutions that recognize the inherent trade-offs and compromises that complex systems present.

The ALCES model is relevant to the Edwards Aquifer because it shows how an environmental scientist may be able to combine multiple land uses over the Edwards Aquifer. In turn, this tells us how we can use a model to show people what the impact of what they are doing may well be on the environment in the future. While the model for this project is not as complicated as the ALCES model, the ideas behind the variables that he has put into his models have been very helpful. Not only was his model helpful in showing everyone in Alberta what was happening, but as his model
grew, it was actually used in creating new policy for a plan that covers the next 100 years in Alberta. The factors that his model includes are population growth, species preservation, air and water quality, agricultural land use, forest history, wildlife, fire risk and management, transportation, residential development, and business development. All of those items are elements that could be included in an educational learning environment.

4. “STELLA for Environmental Sciences: a case study on depletion of the ozone layer” (iSee, 2013) describes a pollution modeling case study at Northwestern University. The model simulation was designed to show how the pollutants (chlorofluorocarbons and ozone) flowed through the atmosphere. Through this model, students were able to see how there can be up to a 15-25 year delay before the pollutant can be purged from the system.

Such delays and are important in the case of the Edwards Aquifer, where changes in land use can lead to pollution whose impact on the aquifer may take years of recovery. This particular case study helped to show how delays in the system are involved, and how to incorporate them into a learning environment so that it can be passed on to those who are trying to learn. Delays in the system are a very important aspect that people need to understand, because it shows them that there may not always be in immediate solution to everything. By educating people on possible delays in the systems, this can help to avoid some serious problems in the future by helping to eliminate potentially hazardous and/or dangerous quick fixes to environmental policy problems that require a much deeper approach than is often taken in the political realm. The study is also important because it deals with the problem of climate change. Losing the ozone layer and heating the planet could
potentially cause shifts in weather patterns. For the aquifer this could be potentially good or bad, as a shift in weather patterns could mean more rain over the recharge zone, or less rain. It could also be both good and bad at the same time, as more rain would mean more water (good), but an unintended consequence of the warmer weather is that it could potentially raise the temperature of the water inside the aquifer, which could have devastating consequences (bad) to the delicate balance required inside the aquifer to keep the endangered species alive that will be discussed in the next chapter.

5. “US-China Project Focuses International Student Teams on Real World Problems” (iSee, 2013) involved younger students in both the United States and China, and focused on how younger students were able to deal with Systems Thinking and modeling. Specifically, it was children from grades seven through 12 working together in teams on four problems. Those four problems included how climate change can affect Vermont’s maple sugar production, the impact of urban development on indicator species, the stages of a successful rocket launch, and improving the water quality of a pond in Nanjing, China. The students worked with each other throughout the year through email and video chats, and at the end of the school year the Chinese students came to the United States to present their models at Champlain College and Worcester Polytechnic Institute in Worcester, Massachusetts (iSee, 2013).

This case study demonstrates that younger children, at least middle school aged, can understand and use Systems Thinking, to explore environmental issues, and the sometimes complicated processes that go along with them. Along with showing that Systems Thinking can be done with younger groups of students, it also showed that
an international component could also be used with Systems Thinking as a common language in education. The international component is important in regards to the Edwards Aquifer because there is a large population of Mexican nationals in central Texas; not to mention the Rio Grande River that forms the entire border between Texas and Mexico which has many of its own problems with water conservation, protection, and policy.

Collectively, these case studies give examples of how Systems Thinking can be incorporated into environmental education. Many of the problems discussed in the case studies can be directly applied to the Edwards Aquifer: from modeling live animals, to man-made impacts on freshwater ecosystems, to land-use models, to climate change, to improving water quality, to conquering cultural and language barriers.

Are Games an Effective Learning Environment?

The Aquarena Center makes extensive use of games in its educational programs. The use of games has been shown to be a powerful learning tool among adults. There has been a “resurgence of interest in ‘management games’ and ‘management flight simulations’ work” among systems modeling practitioners. Lane (1995) argues that “Simulations implemented as IT-based artificial environments can be used advantageously by participants to experiment with different options and make mistakes in order to develop skills, and by observers to coach and assess those participants. It is clearly important to look for well-grounded advantages for using them. What is plain is that the prime inspiration of most business games and simulations is the promotion of learning amongst participants.” In other words, simulations (and games) can be effective because they give players options and the ability to be wrong without causing any real problems.
However, simply because the learning environment is a game or simulation does not necessarily mean that it will be helpful. “We are witnessing a mad rush to pour educational content into games in an ad hoc manner and hopes that player/learners are motivated simply because the content is housed inside a game. The failure to base educational game design on well-established learning and instructional theories increases the risk of the game failing to meet its intended educational goals, and yielding students who are entertained but you have not acquired in the academic skills or knowledge” (Gunter, et al, 2008).

Examples of Learning Environments that Use Systems Thinking

One of the goals of this project was to create a conceptual learning environment that uses systems thinking concepts to allow students to explore the interdependencies of the Edwards Aquifer. Using the following games as examples for inspiration, a potentially effective prototype learning environment for younger students has been created.

The Waters Foundation has several games for students on its website. One of them is an environmental, science, social studies, and economics game based on systems thinking that is called *The Tree Game* (Figure 4). The idea behind the game is that students learn what happens as trees are planted and harvested over the course of several years. The foundation describes how it works like this, “The game is set up so that the company’s stock of trees increases at a constant rate: the forester plants the same number of new trees each year. However, the trees are harvested at an increasing rate: the forester doubles his cutting rate each year. In addition to giving students an intuitive understanding of linear and exponential change, the game illustrates the difficulties of supplying a natural resource product in
an environment with rapidly growing demand (Quaden, et al., 2013).” In using this game as inspiration, a systems thinking learning environment for the Edwards Aquifer would replace the “forest” stock from the Waters Foundation game with a water stock. The planting of trees would be replaced with a recharge rate for the aquifer (based on rainfall and other groundwater dynamics), and the harvesters would be replaced with actors like ranchers, farmers and industries who take the water from the aquifer. With more advanced students, the game could be made increasingly complex by adding variables such as the endangered species, tourism, and changing weather patterns due to climate change.

Another game used by the Waters Foundation is one in which the student plays the role of a wildlife manager. The students manage a herd of elk to sustain a stable population. In order to do this, “they can issue hunting permits and/or natural predators (wolves) into the ecosystem… This game uses the Systems Thinking concepts of balancing feedback, S-shaped growth, reinforcing feedback, exponential growth, overshoot and collapse, and loop dominance” (Waters Foundation, 2013). Translating this game to the Edwards Aquifer, one could use the endangered species in the role of elk, hunting permits would be replaced by water permits, and predators would be represented by the natural predators arty present within the aquifer, or invasive species that are encroaching.

The Creative Learning Exchange (http://www.clexchange.org/) has developed a game called The Mammoth Game and it studies the population dynamics of a herd of mammoths that goes extinct. This game is a little more complex, in that it involves more changing variables and probabilities. It works with dice: the students roll the dice to change the variables and probabilities to help students “explore theories of extinction, and speculate about the factors that contributed to the woolly mammoths’ demise” (Creative Learning Exchange, 2013). This game would take more adaptation to relate to the Edwards Aquifer, but the endangered species of the aquifer (either as a whole, or as individual species) would represent the mammoths, and the
changing variables would be the same as the ones in the aforementioned games with the possibility of adding more based on the educational level of the students involved.

Best Practices

Based on the research done on the role of Systems Thinking and games for this project, the potential benefits for teaching with a Systems Thinking approach towards the Edwards Aquifer, and a learning environment based in Systems Thinking, is something with real potential. Because Systems Thinking enables a holistic perspective of a problem, students would learn how to deal with subjects and issues from a big picture perspective; they would learn to understand the temporal aspects of the problem, as well as how to adjust as the problems, and solutions, change.

When designing how the learning environment works, one has to take into account what the best practices would be.

1. The facilitator. This person would help students play the game and facilitate the discussion and reflections during and after play. This needs to be someone with prior knowledge of the aquifer and who practices and understands the system approach.

2. The game design. This must mimic in some way the important elements and interactions that make up the system. In the case of the Edwards Aquifer, this means that the game must help students understand where the water comes from, how it moves through the aquifer, how it both affects and depends on the broader ecosystem, and how humans can impact all of these things.

3. Lastly, the learning environment must be something that is interactive and fun.
Chapter 3

Ecosystem Services and Endangered Species: Creating an Age Appropriate Storyline for Young People

Educating young people about the aquifer is not an easy task. As previously noted, the United States Geological Survey describes the Edwards Aquifer as one of the most diverse groundwater ecosystems in the world. The challenge is to find a better way to educate children about this complex ecosystem.

Not only is it difficult to understand how the aquifer ecosystem works, but it is also hard to get people interested in something that does not always seem to directly affect them. Farmers and ranchers may certainly appreciate the aquifer’s importance. They are among the first to be subjected to restrictions in times of drought. Children, however, likely do not understand where the water comes from, and they simply may not care. They need something that will get them interested in preservation and conservation. That is where the endangered species of the Edwards Aquifer come in.

Using the endangered species as a pedagogical hook, it is hoped that children will become interested in the aquifer. As this chapter will show, not only do the endangered species rely on the springs of the Edwards Aquifer to survive, but they can also be an indicator of the health of the aquifer, as they are very susceptible to changes in the water quality, and amount of water coming through the aquifer.

This chapter begins by outlining the ecosystem services provided by the aquifer, and then turns to a description of the endangered species. Throughout this chapter and on through chapters
4 and 5 we introduce elements of the qualitative systems model that serves as the conceptual backbone of the game that is briefly described in chapter 6. This chapter concludes with a summary of how these ecosystems services and endangered species can be woven together into a gaming storyline for young people to learn about the aquifer and its importance.

Ecosystem Services

What are Ecosystem Services?

Ecosystem services are essential to our everyday lives, even though we may not even know it. According to the Ecological Society of America (ESA), “Ecosystem services are the processes by which the environment produces resources that we often take for granted such as clean water, timber, and habitat for fisheries, and pollination of native and agricultural plants… Natural ecosystems in the plants and animals with them provide humans services that would be very difficult to duplicate.” The ESA goes on to list some services that an ecosystem provides: moderation of weather extremes in their impacts, dispersal of seeds, mitigation of drought and floods, protection from the sun’s ultraviolet rays, the cycling and moving of nutrients, protection of stream and river channels and coastal shores from erosion, detoxification and decomposition of wastes, control of agricultural pests, maintaining a level of biodiversity, generation and preservation of soils and renewed fertility, contribution to climate stability, purification of the air and water, regulation of disease carrying organisms, pollination of crops and natural vegetation (ESA, 2013).

The United States Department of Agriculture describes ecosystem services as, “goods and services that are traditionally viewed as free benefits to society, or ’public goods’… Lacking a formal market, these natural assets are traditionally absent from society’s balance sheet; their critical contributions are often overlooked in public, corporate, and individual decision-making” (USDA, 2013). Similarly, the World Resources Institute (WRI) states that, “Most of us don’t
even think about, or don’t even realize, the vast array of services nature provides us every day. We call this myriad of nature’s benefits in which we fundamentally depend, ecosystem services (WRI, 2013).”

Value of Ecosystem Services

However, just because these benefits may be viewed as free, that does not mean that they do not have a worth. It is estimated that, on a global scale, these services are “…are worth many trillions of dollars…”

Ecosystems services are being lost around the world. “Aquatic species extinctions and population declines associated with water development have been well documented in the United States and many other developed countries, a story that is likely to be repeated in less-developed countries undergoing rapid changes in land and water use in association with growing populations. As freshwater species and ecosystems are degraded, human society is losing a wealth of ecosystem services provided by healthy freshwater and estuarine ecosystems worldwide” (Fitzhugh and Richter, 2004). Therefore, ecosystem services must be protected.

Edwards Aquifer Ecosystem Services

The Edwards aquifer holds a lot of water, estimates of how much water range from 175,000,000 acre-feet to 25-55,000,000 acre-feet. The estimates vary widely because the aquifer is very complex and not all of the water is available for consumption, or is even accessible (Eckhardt). Based on the currently allowed 572,000 acre-feet per year withdrawal there is enough water in the Edwards Aquifer to last 90-100 years without any recharge at all. The 572,000 acre-feet limit was imposed by Texas Senate Bill 3 from the 2007 Texas legislature.

\[\text{The reason spring discharge is not taken into account here is because the springs will cease to flow after 5-10 years of no recharge, as explained in the first section of the "Endangered Species" section of this chapter.}\]
However, unless it completely stops raining over the Edwards Aquifer for the next 96 years, the water should last much longer than that, so long as the allowed withdrawal is not increased.

In addition to housing many endangered species, the Edwards Aquifer provides many services to those who live in the region. The withdrawal limit of 572,000 acre-feet per year represents at least part of those services. The next several sections highlight some of the more important of those services.

Drought and Flood Mitigation

The Edwards Aquifer helps to soften the impact of drought and flooding in the central Texas region by storing water from seasonal rainfall underground. In a 2008 article about safeguarding freshwater ecosystems, Sandra Postel refers to aquatic ecosystems as “ecological infrastructure.” This infrastructure helps us during times of drought. “When functioning well, this ‘eco-infrastructure’ stores seasonal floodwaters, helping to lessen flood damages. It recharges groundwater supplies, which can ensure that water is available during dry spells” (Postel, 2008).

Cycling and Moving of Nutrients

The cycling and moving of nutrients throughout a freshwater ecosystem, or from a freshwater ecosystem to a saltwater ecosystem, is important for both plants and animals. Without this flow of nutrients, the species in the region would not survive, and those with the ability to move would have to do so. In this role, the Edward Aquifer ecosystem “… filters pollutants, purifies drinking water and delivers nutrients to coastal fisheries. Perhaps most importantly, it provides the myriad habitats that support the diversity of plants and animals that performed so much of this work” (Postel, 2008).

Waste Removal and Water Purification

In addition to providing habitat for flora and fauna, wetlands, such as those located on the Edwards Aquifer, act as a sort of natural filter for waste removal and water purification.
“Wetlands reduce the amount of these harmful substances that enter a stream, river, pond, or lake by acting like a strainer that filters out the bad stuff. When these substances enter a wetland, before reaching the water body, wetland plants will take many of the harmful substances into the roots. They change the harmful substances into less harmful ones before they are released into the water body. Harmful substances may also be buried in wetland soil, where bacteria and other microorganisms break the substances down so they are no longer harmful” (Michigan Tech, 2013). In fact, according to the Texas Commission on Environmental Quality, wetlands are so good at this that artificial wetlands are now being constructed to aid in waste removal and water purification because, “constructed wetlands provide physical, chemical, and biological water quality treatment” (Barrett, 2005). See Figure 5. The only problem seems to be that wetlands perform this filtering service comparatively slowly in relation to conventional wastewater treatment technology (Shutes, 2001).
Biodiversity

Biodiversity refers to the extent to which an ecosystem exhibits a diverse range or variety of life. Biodiversity can include both genetic and ecological diversity. Genetic biodiversity is what gives us different variations of the same species, like the difference between a Chihuahua and a Great Dane. Ecological diversity refers to the diversity of ecosystems, natural communities and habitats. Biodiversity is important because it allows for ecosystems to adjust to disturbances. For instance, if a reptile species goes extinct, a forest with 20 other reptiles is likely to adapt better than a forest with only one reptile. Genetic diversity also helps prevent disease from spreading easily from one species to another (NWF, 2013). The loss of the endangered species in the Edwards Aquifer will lessen the biodiversity of the region.

Pollination

The Texas Wild Rice, one of the endangered species that relies on the springflow out of the Edwards Aquifer, can only be pollinated by flowing water. A study by the University of Texas at Austin, found that “… the pollen of Texas Wild Rice can only travel about 30 inches away from a parent plant. If pollen doesn’t land on a receptive female flower within that distance, no seeds will be produced. No seeds means no plants to replenish population faces other survival threats” (U of Texas, 2013). Therefore, if the ecosystem service that pollinates the Texas Wild Rice stops, the rice will be gone forever.

Fisheries Habitat

The rivers, streams, and lakes of the Edwards Aquifer provide habitat for myriad fish species. There are several types of bass and sunfish, as well as catfish, Gambusia, Gar and many others (TPWD, 2013). Unfortunately, it also provides habitat for exotic species that have been introduced via the trade in aquatic pets for aquariums; it is not uncommon to see African, South American, and Central American cichlids, carp, Pacu, suckermouth catfish, tilapia, mollies and exotic catfish (Bowles, et al., 2001). The fisheries habitat provided by the Edwards Aquifer does not include only the Edwards Aquifer region. The habitat also extends all of the way to the Gulf of Mexico by providing water to the San Marcos, Comal, and Guadalupe rivers, which in turn provide the fresh water needed to keep the fisheries and shrimping industry of the San Antonio Bay system of the Gulf Coast alive (Powell, et al., 1994).

Recreation and Tourism

The San Marcos, Comal, and Guadalupe rivers are quite popular recreational resources in Texas, especially in the summer. Recreational users of the water coming out of the Edwards Aquifer use it for many of the same reasons waters are used recreationally around the world:

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3 San Antonio Bay’s estuaries happen to house another, far more well-known endangered species, the Whooping Crane.
fishing, tubing, canoeing, boating, and swimming. The ecosystem service of recreation also serves the dual purpose of generating revenue for the cities of New Braunfels and San Marcos by the use of the Comal and San Marcos rivers, which are fed almost solely by the springs (Sharp, 2013).

There are also agencies and companies that rely on the ecosystem services provided by the aquifer for use in creating tourism dollars. In addition to educating, Aquarena Center also brings in tourists from around the state to ride its glass bottom boats over Spring Lake (Figure 6). Wonder World Park, in San Marcos, is a company that takes people on guided tours of a massive cave that was formed by water flowing through the aquifer, as well as earthquakes (Wonder World, 2010).

Education

Many educational agencies use the Edwards Aquifer to inform people in the central Texas area about the importance of the Edwards Aquifer. Many of which have been cited throughout this paper, and still more which have been left out. There are schools like Texas State University, the University of Texas, and Texas A&M University; there are agencies like the Edwards Aquifer Authority, the Texas Commission on Environmental Quality, the United States Fish and Wildlife Service and the Texas Parks and Wildlife Department; and there are also places like Aquarena Center, which serve to educate people and instruct them on how the Edwards Aquifer works and why it is important.
Modeling Ecosystem Services

Systems Modeling Concepts and Notation

This chapter will shortly begin to introduce the first building blocks in the qualitative systems model that was developed for this dissertation and that provides the framework for the learning game described in chapter 6. This model is represented as a causal loop diagram (CLD) that shows important variables (or characteristics) of the Edwards Aquifer ecosystem (including the role of humans), how those variables interact, and how those interactions create feedback dynamics that drive the overall health of the system. In order to understand the logic behind the first building blocks in the model, a few basic concepts are necessary: variables, delays, causal links, and link polarity. Other concepts will be introduced later as they are needed. For more details, the reader is referred to Sterman (2000).

Variables

In causal loop diagrams, variables represent time-varying quantities that correspond to characteristics of the real-life system. Their role in a CLD is to identify those characteristics that are most relevant to the system behavior that is of interest. Variables can be both endogenous (variables that are themselves affected by other elements of the system) and exogenous (variables that are not affected by other elements of the system).

The variables in the ecosystem services are the aquifer water level, spring discharge/J 17 depth, natural filtration rate, pollution levels, pollination rates, and nutrient flow (Figure 7). The other ecosystem services are not represented in this figure, as they will be introduced later in other portions of model. The aquifer water level represents the volume of water that is currently in the aquifer and is dependent on recharge from rainfall. The causal link (arrow) pointing from
that water level into the Spring Discharge/J-17 Depth indicates that the water level determines the discharge rate at the San Marcos spring, as well as the depth reading at the J-17 well.

**Delays**

Delays are often an important source of counterintuitive behavior of dynamically complex systems. A delay exists when a change in a causal variable does not yield an immediate response from the affected variable. "Delays give systems inertia, can create oscillations, and are often responsible for trade-offs between the short- and long-run effects of policies" (Sterman, 2000). The example of a delay within the ecosystem services model is with recharge. When it rains, or water flows over the recharge zone, the effects of that are not immediately felt in spring discharge or well depth because it takes a certain amount of time for the water to flow through the aquifer. The time from entrance to exit is the delay in the system. This delay is represented with a “Delay” label on the causal link from the Aquifer Water Level to the spring discharge/J-17 depth.

**Causal Links and Link Polarity**

The causal link between two variables shows the direction of causal flow, pointing from the “causal” variable to the “affected” variable. Each link is assigned a *polarity*. Polarities can be either positive (S) or negative (O). A positive (S) polarity indicates that, “...if the cause increases, the effect increases above what it would otherwise have been, if the cause decreases, the effect decreases below what it otherwise would have been” (Sterman, 2000). That is, the “S” stands for “SAME”...the affected variable moves in the SAME direction as the causal variable.
Negative (“O”) polarity indicates that, “if the cause increases, the effect decreases below what it otherwise would have been, and if the cause decreases, the effect increases above what it otherwise would have been” (Sterman, 2000). In other words, “O” polarity means that the effect moves in the OPPOSITE direction as the cause. The example of this in ecosystem services would be, as rainfall over the recharge zone increases, the aquifer’s water level increases, which causes spring discharge to increase, in turn, spring discharge feeds natural filtration, pollution, and nutrient flow; while an example for a negative link would be, as the spring discharge increases and bumps up the level of natural filtration, the level of pollution in the aquifer decreases.

In other words, to give a basic overview on how to read this portion of the model, as the water level the aquifer increases, it causes spring discharge to move in the SAME direction (“S” polarity), which in turn causes nutrient flow, pollination, and natural filtration to increase (“S” polarity); however, as natural filtration increases, pollution decreases (opposite direction, or “O” polarity).

The Endangered Species of the Edwards Aquifer

As stated in the previous section of this chapter, we may have nearly 100 years to solve a problem of water shortages associated with the Edwards Aquifer, so it might not seem like an urgent issue. By then, weather patterns may have changed due to climate change to provide more rain⁴, technologies to increase an area’s rainfall may have been perfected, or water may even be brought into the region via pipelines from other water-rich regions. Hence, the purpose of the learning environment proposed herein is not to convince students that the health of the aquifer is

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⁴ The potential benefits of climate change are something one does not seem to hear about often, but oddly enough, the amount of water in the Edwards Aquifer is something that could actually be increased by climate change. In a paper titled Climate Change and Groundwater by Hugo Loáiciga, at the Department of Geography at the University of California, Santa Barbara, he found that “… results indicate, therefore, that the primary threat to ground-water use in the Edwards Aquifer comes from the rise in ground-water use associated with predicted growth, not from climate change. The latter, in fact, would increase spring flow in the study area” (Loáiciga 2003).
in immediate danger. Instead, the purpose is to help young people understand how important the aquifer is to the broader ecosystem and the people who are part of that ecosystem. In order to do that, and in order to make an appealing connection to the intended audience, the learning environment will use the endangered species in the aquifer as a pedagogical “hook” to create a meaningful and ecologically valid storyline for the young people that we intend to reach.

This storyline is meaningful and creates a more immediately accessible reason to maintain a healthy aquifer. The endangered species in the aquifer live either in the Comal or San Marcos rivers or the springs that feed those rivers. If the aquifer falls below 90-95% capacity, these springs may cease to flow, and the species will be placed in jeopardy. Hence these endangered species as both a pedagogical hook and as an early warning indicator of the health of the aquifer.

This in fact happened in 1956. Up until the summer of 1956, the endangered fountain darter could be found naturally in two springs in central Texas, Comal Springs and San Marcos Springs. However, 1956 was the worst year of what is known as the “drought of record,” named as such because it is the worst record in drought in the history of central Texas. According to the National Oceanic and Atmospheric Administration, “Texas rainfall dropped by 40% between 1949-1951 and by 1953, 75% of Texas recorded below normal rainfall amounts” (NOAA, 2003). In 1956, the drought was so bad that the water in Comal Springs nearly ceased flowing, with a minimum recorded springflow of 41 gallons per second. According to the San Antonio Water System (SAWS) and their J-17 index well, a well that is used to measure the water level in the aquifer (Eckhardt), the water reached its lowest recorded depth ever, with a reading of 612.5 feet on August 17, 1956, compared to a maximum level of 703.3 feet on June 14, 1992 (SAWS, 2013). When the well drops to a level of 620 feet, springflow Comal Springs becomes intermittent, and at 618 feet it nearly stops completely. At 612.5 feet, the Comal River had been
reduced to shallow pools of water. This minimal flow was not enough to allow the fountain darter to survive in Comal Springs (Edwards Aquifer 2012).

Today, the fountain darter can be found in Comal Springs because, “In 1975, biologists from Texas State University - San Marcos used fountain darters taken from the San Marcos River to successfully reintroduce the species to the Comal aquatic ecosystem” (Aquarena, 2013). However, current models show that if a repeat of the drought of record happened again, given the current level of pumping from the aquifer, Comal Springs would actually go dry for years (Eckhardt). What this means is, instead of 100 years to fix the problem, we would only have 5 to 10 years to fix the problem if we were to save the endangered species in the event of a major drought.

In 1973 the United States Congress enacted the Endangered Species Act. They did this because, in their own words, “various species of fish, wildlife, and plants in the United States have been rendered extinct as a consequence of economic growth and development untempered by adequate concern and conservation; other species of fish, wildlife, and plants have been so depleted and numbers that they are in danger of or threatened with extinction; these species of fish, wildlife, and plants are of aesthetic, ecological, educational, historical, recreational, and scientific value to the nation and its people; the United States has pledged itself as a sovereign state in the international community to conserve to the extent practicable the various species of fish or wildlife and plants facing extinction” (USFWS, 1973). The Endangered Species Act covers not only the species, but the ecosystems in which they live, as stated in Section 1 of the Act, “the purposes of this act are to provide a means whereby the ecosystems upon which endangered species and threatened species depend may be conserved” (USFWS, 1973).

As of 2013, the United States Fish and Wildlife Service (FWS), “…has listed 2054 species worldwide as endangered or threatened, of which 1436 occur in the United States”
The Edwards Aquifer is known to contain over 40 species of highly adapted, aquatic, subterranean species, and out of these 40 species, seven of them are listed as endangered and one of them is listed as threatened. The seven endangered species are the Texas Wild Rice, Texas Blind Salamander, Dryopid Beetle, Comal Riffle Beetle, San Marcos Gambusia, Fountain Darter and Peck’s Cave Amphipod. The one threatened species is the San Marcos Salamander. All of these are found only in the Edward Aquifer (Eckhardt). The rest of this chapter summarizes the issues associated with each of these species and adds variables and causal links to the causal loop diagram introduced earlier to show their dependence on the aquifer for survival.

The most prevalent threats to the endangered and threatened species today are: excessive withdrawals from the aquifer due to agricultural and industrial practices; climate change; population growth; impervious land cover; recreational use of rivers dependent on spring flow from the aquifer; habitat loss; and finally the introduction of, and competition with, invasive species within the aquatic environment (Eckhardt). Some of these issues are more linked to each other than others, for instance: habitat loss is primarily caused by the encroachment of invasive species and less by climate change, agricultural practices or industrial practices. In addition, some of these threats have a greater impact on certain species but not others. For example, recreation will have a huge impact on the Texas Wild Rice because it grows near the headwaters of the recreationally popular San Marcos River; while it has almost no direct impact on the Texas Blind Salamander because it lives entirely underground.

Texas Wild Rice (*Zizania texana*)

Texas Wild Rice (Figure 8) was first “listed as federally endangered on April 26, 1978 and state endangered on April 29, 1993. It was the first Texas plant to be placed on the endangered species list”, so the plant has been protected for the last 34 years. It is usually submerged until it flowers between the months of April and November, when it can extend above the surface of the water up to 40 inches to produce its seeds, although seedlings are becoming
more and more rare in the wild.
The species requires a very particular habitat in order to survive; it needs “fast flowing water of high quality and constant year-round temperatures as provided by adequate springflows. Silting, disturbance of the bottom, or stagnant water will kill off plants.” Today, Texas Wild Rice is currently found only in the upper four miles of the San Marcos River, although in the 1930s it was said that “it was so abundant that a local irrigation company considered it a difficult task to keep plants from clogging its ditches” (Eckhardt).

Recreational activities and population growth along the San Marcos River are the most visible problems facing Texas Wild Rice, “This plant is endangered because the river water is being impacted by the growth of the city of San Marcos and increasing numbers of people swimming, canoeing and tubing the river.” In addition, “…because more people are using water, less underground water is flowing from the springs,” (TPWD, 2012) which only serves to compound the problem. This is a complex problem because pumping water out of the aquifer does not just lower the water level of the aquifer; it also decreases the width and depth of the river. This, in turn, “exposes the shallows where Texas Wild Rice typically would grow.” (Eckhardt)
“River dredging and damming, riverside construction, and bottomland cultivation have destroyed plants, altered stream flows and temperature, or increased siltation” (Eckhardt). There was even an attempt to harvest the seeds, which also diminished chances for survival. A threat that is perhaps less visible, is that of the invasive species of water rat, known as the Nutria (Myocaster coypus, Figure 9), that has come to live in the San Marcos River. “Nutria, a non-native rodent that lives in wetland areas, is also a threat because it eats the wild rice” (TPWD, 2012).

Another invasive species is Hydrilla verticillata (Figure 10). This plant was first introduced to the United States in the 1950s for use in aquariums in Florida, and has since spread throughout the contiguous 48 states. According to the USGS, “once established, hydrilla results in an array of ecosystem disruptions. Changes often begin with its invasion of deep, dark waters were most plants cannot grow. Hydrilla grows aggressively and competitively, spreading to shallower areas in forming thick mats in surface waters that block sunlight penetration to native plants below. In the southeast, hydrilla effectively displaces beneficial native vegetation.” Hydrilla has also been shown to change the physical and chemical makeup of lakes, decrease the weight of sport fish, stratify the water column, decrease oxygen levels, and cause fish kills. Because this invasive species grows so thick, it reduces water flows in streams creating backwater habitats, as well as obstructing boating swimming and fishing and blocking water withdrawal for power generation and agricultural irrigation (USGS, 2012).
There have been attempts to save the plant using various methods; however none of them have been successful. “In the 1970s, botanists attempted to establish a new population in Salado Creek with cultivated plants, but recreational activities continually disturbed transplanted clones. From 1976 to 1982, nursery plants were transplanted to various sites in central Texas. No new populations resulted (Eckhardt).”

**Texas Blind Salamander (Eurycea rathbuni)**

The Texas Blind Salamander (Figure 11) lives underground within the Edwards Aquifer, and as the name suggests, it cannot see. It is a, “sightless, cave-dwelling salamander that reaches a mature length of about 13 centimeters (5 inches). It is a slender, frail-legged amphibian, white or pinkish in color with a fringe of blood-red, external gills. The head and snout are flattened. Two small black eyespots mark the location of vestigial eyes.” Because this creature lives under ground, it is very difficult to study in its natural habitat and therefore little is known about its behavior, other than what it eats, which are insects and other small invertebrates that also live within the aquifer (Eckhardt). The blind salamander’s range is limited to the “Edwards Aquifer’s artesian and recharge zones in the vicinity of San Marcos, Hays County, Texas. It is subterranean but individuals may reach the surface via springs (USFWS, 2012).” It is noted, however, “that other populations may exist in unexplored underground caverns” (Eckhardt).

The blind salamander is very sensitive to changes in water quality and susceptible to groundwater pollutants, so the biggest issue it faces is pollution from agricultural and industrial runoff, as well as the spread of human population and growing impervious cover on or around the recharge zones of the aquifer. Human encroachment onto the recharge zone is a problem because
it essentially shrinks the area available for water to replenish the aquifer. Removing too much water from the aquifer is also a danger. However, this is a species that does not depend on the water that leaves the aquifer, but rather the water that is in it, so the danger is different. “Unless we start mining the resource by using more than goes in on a long-term basis, we will always be able to get plenty of good water for critical uses like eating and bathing. We have never seen the aquifer less than 90-95% full… We sometimes do run out of water in the top 5-10% of the Edwards formation, and that is when the spring stops flowing” (Eckhardt). The aforementioned danger results from the blind salamander requiring clean water that can only be provided by an aquifer that is continuously flowing, so as to prevent stagnation. The aquifer will become more polluted due to the lack of outflow, but this is a long-term more than a short-term worry.

In order to keep the Texas Blind Salamander around, clean water must continue flowing into the aquifer, and eventually out of it. “Survival of the salamander depends on the stability and continued purity of the Edwards Aquifer springflows. As with the other endangered species in the Edwards region, threats are from diminished springflows and pollution of groundwater and runoff caused by increasing demand for water and burgeoning development over recharge areas” (Eckhardt).

Climate change will also have an effect on the salamander, whether it is from increased drought, flooding from increased rainfall, or an increase in temperature all around causing an increase in the temperature of the water within the aquifer itself.

Comal Springs Dryopid Beetle (*Stygoparnus comalensis*)
The Comal Springs Dryopid Beetle (Figure 12) is another blind species that lives in the Edwards Aquifer. "The beetle is a subterranean insect with vestigial eyes. The species has been found in drift net collections from many artesian and pumped wells flowing out of the Edwards Aquifer" (Eckhardt). “It has been found in two spring systems, Comal Springs and Fern Bank Springs, that are located in Comal and Hays counties respectively” (USFWS, 2007). Despite living underground for the entirety of its life, this beetle does not swim and therefore may have a very small range within the Edwards aquifer; in addition it is very difficult to get into the aquifer to try to ascertain what its actual range might be. Its historic range is also not very well documented as the species were not collected until 1987. Because all other members of this particular family of beetle are terrestrial, it is also believed that these beetles may actually live in small air pockets within the aquifer (Eckhardt).

The threats facing this beetle (as well as the riffle beetle and cave amphipod) are habitat loss from a decrease in springflow from an increased take of the Edwards Aquifer and the possibility of drought; flooding, which could carry them far from their natural habitat and away from food sources or towards a new predators; and an increased aquatic environment temperature from climate change or a change in the chemical composition of the aquifer due to increased urban runoff from agriculture, industry and urban sprawl. In addition to man-made threats, there is also an invasive species threat. There are three species of exotic snail that inhabit the springs, they are: *Thiara granifera* and *Thiara tuberculat*; and the Giant Ramshorn snail, (*Marisa cornuarietis*). These snails all eat the vegetation around the springs and may compete for food (Eckhardt).
Efforts to save the Dryopid beetle (as well as the riffle beetle and cave amphipod) are coming mostly from federal law. The most recent being a “Proposed Revision of Critical Habitat for the Comal Springs Dryopid beetle, Comal Springs Riffle Beetle, and Peck’s Cave Amphipod” (USFWS 2012) from October 19th of 2012.

Comal Springs Riffle Beetle (*Heterelmis comalensis*)

The Comal Springs Riffle Beetle (Figure 13), is a small (growing only to 1/8 of an inch), flightless (although it does have wings) beetle that lives in shallow water within gravel substrate and shallow riffles usually about 1 to 4 inches deep; it is also the only invertebrate of the three endangered species that is not subterranean (Eckhardt).

The range of this beetle consists of two spring systems flowing out of the Edwards aquifer one is Comal Springs in New Braunfels and the other is San Marcos Springs, however, only a single specimen has ever been collected from San Marcos Springs. The previous range of the beetle is unknown because it was discovered in 1976 after many other springs in the area had gone dry, such as San Pedro Springs and the San Antonio Springs (Eckhardt). Because the species’ wings do not function and its need for water, it is likely that its range was not much greater than it is today.

Peck’s Cave Amphipod (*Stygobromus pecki*)

The Peck’s Cave Amphipod (Figure 14) is a subterranean, aquatic crustacean without eyes or pigment first discovered in 1965. It is similar to the blind salamander and the Dryopid
beetle with some of these characteristics. The amphipod lives primarily underground, but can be pushed out by springflow and when this happens it hides in crevices and rock and gravel near spring openings (Eckhardt). Because they are blind, when they are pushed out of the springs they become easy prey, so it is important that they find is crevices and gravel to hide in.

It is believed that it only resides in the Comal Springs and Hueco Springs, as “despite extensive collecting efforts, no specimens have been found in other areas of the Edwards aquifer, indicating that its primary habitat is in the zone of permanent darkness in the underground aquifer feeding the springs” (Eckhardt). For the same reasons as the other invertebrates, where this species may have extended to in the past is not well known, nor is the depth to which it lives within the aquifer.

San Marcos Gambusia (*Gambusia georgei*)

The San Marcos Gambusia (Figure 15), sadly, is believed to be already extinct, as it has not been seen since 1983 (TPWD, 2012). The Gambusia was a small fish that bore live young and fed on insect larva and other invertebrates in shaded, slow-moving water (Eckhardt).

The Gambusia was found only in the upper San Marcos River and its headwaters in Spring Lake, San Marcos, Texas (TPWD, 2012). This was a perfect place for the fish because it required “clean and clear water of a constant
temperature. Temperatures in the river vary by only a few degrees throughout the year, averaging about 73°F” (Eckhardt).

This fish faced many problems before its surmised extinction in 1983, including “reduced flow of water from the springs and water pollution from the growth of nearby cities… Introduction of non-native species is also a threat because they may destroy aquatic vegetation, prey on endangered animals or compete with them for food” (TPWD, 2012). The *Gambusia affinis* was is thought to be the primary invasive species that led to its downfall, as interbreeding took place and the *Gambusia georgei* was slowly bred out of existence; “in 1978 and 79 biologists netted more than 20,000 Gambusia specimens but counted only 18 San Marcos Gambusia among them” (Eckhardt).

This species’ recovery did not have much of a chance, “as it was apparently extremely sensitive to any alteration of its habitat. Changes in water turbidity caused by runoff from land clearing and construction, an increase in water temperatures caused by lowered water flows, and pumping of groundwater from the Edwards aquifer could have easily eliminated the species. Even if additional specimens are found, recovery of the San Marcos Gambusia is considered a remote possibility without the cooperation of all state and local agencies that manager use of the aquifer (Eckhardt).

**Fountain Darter (Etheostoma fonticola)**

The fountain darter (Figure 16) “prefers clear quiet backwaters with a profuse bottom growth of aquatic plants and added algae. It is found in the San Marcos and Comal Rivers” (Eckhardt).

Today the fountain darter can be found only
in the San Marcos and Comal River headwaters in Hays and Comal counties, Texas (TPWD, 2012). The population in the Comal River was actually completely eliminated by drought in the 1950s, but the river was restocked with 457 darters taken from the San Marcos River; the Comal River population is now believed to exceed that of the San Marcos River population (Eckhardt).

The problems the fountain darter faces do not stem from only less water flowing from the springs. “Human population growth and increased use of groundwater in the area have caused decreased flow from the springs, especially in years of low rainfall” (TPWD, 2012). Additionally, “swimmers and divers disturb the algae mats used by the darter for spawning;” and again the ram’s horn snail’s introduction in around 1983 has cost habitat loss with competition for food. It is also noted that should the springs stay “dry for a longer period of time there may be changes in water quality that could limit another successful reintroduction,” if it were to become necessary (Eckhardt).

San Marcos Salamander (*Eurycea nana*)

The San Marcos Salamander (Figure 17) was listed as threatened species on July 14, 1980. It is a “dark reddish brown salamander about 1 to 2 inches long… occurs only in Spring Lake and an adjacent downstream portion of the upper San Marcos River… algae provide hiding places for the salamanders and habitat for small animals that serve as their food… (the salamanders) do not occur where the bottom is muddy or bear… eggs are attached to plants or under rocks (TPWD, 2012).” This particular species a salamander does not have lungs, so it must live underwater. They are thought to reproduce year-round and live for at least four
years in captivity. Like the Texas Blind Salamander, which lacks eyes, the San Marcos Salamander also lacks a sensory organ, ears (Eckhardt).

Clean, clear, flowing water of constant temperature is required for suitable habitat (TPWD, 2012). It requires a constant temperature of around 72°F, which is what is found in the San Marcos River where it resides (USFWS, 2012), and which also appears to be the only place it has ever lived historically (Eckhardt). “The San Marcos Salamander is found in shallow alkaline springs carved of limestone with sand and gravel substrates. Pools and streambeds are often punctuated with large limestone boulders. Aquatic vegetation is profuse, and the pool services are covered with moss and thick mats of course, blue-green algae.” Two population estimates have been done, one in 1976 and one in 1993 that estimate there are about 50,000 salamanders remaining, with 5200 of them living below Spring Lake (Eckhardt), meaning that they appear to be okay living in a subterranean environment as well, similar to the Texas Blind Salamander.

The San Marcos Salamander faces similar problems to those of the endangered species, even though the population “appears relatively stable (Eckhardt)” for the time being. Those problems include water quality degradation, habitat loss (USFWS, 2012), reduced springflow resulting from population growth and silt accumulation, the introduction of non-native species (TPWD, 2012), and increased water demand from agricultural development which could potentially cause the springs to become dry (Eckhardt).

Modeling the Endangered Species of the Edwards Aquifer

The endangered species portion of the model (Figure 18) expands on the previous CLD showing how spring discharge and ecosystem services affect the endangered species habitat and population. There are also more delays in the system here. An increase in spring discharge will increase the available habitat in the region for endangered species; however it takes time for the endangered species to populate that available habitat. As spring discharge increases pollination
and nutrient flow, over time this will increase the population of endangered species by increasing the chances for the Texas Wild Rice to reproduce through pollination, and increasing the nutrient load which brings the endangered species more food. As natural filtration increases, this will slowly filter pollution out of the aquifer, which will allow for the endangered species populations to grow further.

All of the endangered species mentioned in this chapter are protected by the Endangered Species Act, as well as the San Marcos River and Comal Springs and Associated Aquatic Ecosystems Recovery Plan (which also covers the San Marcos Salamander). The recovery plan “…delineate(s) reasonable actions that are believed to be required to recover and/or protect listed species. Plans are published by the US Fish and Wildlife Service, sometimes repaired with the assistance of recovery teams, contractors, state agencies and others… Approved recovery plans are subject to modification as dictated by new findings, changes in species status, and the completion of recovery tasks” (USFWS, 1985) According to the recovery plan, “delisting is considered unattainable in the near future” for the Fountain Darter, the San Marcos Gambusia, the Texas Blind Salamander, the Texas Wild Rice, and the San Marcos Salamander. However, “down-listing is considered feasible for the fountain darter, Texas Wild Rice, and Texas Blind Salamander” (USFWS, 1985) farther into the future.

The amount of water that is in the aquifer for our personal use suddenly becomes very limited when the health of the endangered species is taken into account. This is because water
volumes in the Aquifer below 95% of capacity will impact spring discharge levels and the endangered species that are downstream of that discharge. Hence, the 100 years of water supply in the aquifer cannot be consumed without consequences very early on. All of the ecosystem services that are enjoyed by people must now be enjoyed in moderation. Agricultural and household use must be curbed by water use restrictions; we also cannot enjoy our time in the water tubing, swimming, fishing, or boating like we want to for fear of disrupting the delicate aquatic habitats that those endangered species (and even species that are thriving) depend on. Using that water irresponsibly means that the Texas Wild Rice does not get pollinated, the nutrient cycle stops and the endangered animal species do not get the food they need, the water is not naturally cleaned and the endangered species may die from polluted water, and last biodiversity decreases due to the loss of aquatic habitat.

The educational benefit of the aquifer that is enjoyed by Texas schools and organizations also hangs in the balance. Without sufficient water flows through the aquifer, students, along with everyone else, will not be able to get hands-on learning experience. If the water ever stops flowing from the aquifer, we lose it all, at least temporarily, but some of it will never come back; and that is the main point that children need to take away from being educated with regards to the Edwards Aquifer.
Chapter 4

Texas Water Policy and Its Impact on the Edwards Aquifer

The Edwards Aquifer requires its own unique protections and water management policy that is unique to the rest of the state. This is because it covers an area of over 4,350 square miles in parts of 11 counties and is counted on by over 2 million people. In addition, the aquifer has a unique, highly permeable, honeycomb limestone structure (Figure 19) which allows water to flow into and out of it very quickly and over long distances. Hence, it is highly susceptible to contamination by human activity on its surface (TCEQ, 2012). As quoted earlier, “The subterranean aquifer ecosystem of the Edwards aquifer is perhaps the most diverse groundwater ecosystem in the world. Increased knowledge about the complex hydrologic processes that control water availability in the Edwards aquifer is imperative for optimal resource management.” (USGS, 2012)

In addition to the more than 2 million people who live around the aquifer and get their water directly from it, there are also those downstream and on the coast who rely on it for freshwater inflow to bays and estuaries to support industries such as shrimping, as well as habitats for endangered species like the Whooping Crane (figures 20 & 21). Many of these people live
outside the jurisdiction of the Edwards Aquifer Authority, so they do not have as much say in the policymaking over the aquifer.

Water law in Texas is a very complicated matter\(^5\), stemming from the facts that its laws come from many different areas and eras; and they are constantly changing. Two European nations, France and Spain have both laid claim to various parts of Texas over the

\(^5\) Policy will be incorporated into the learning environment, however, it will not be nearly as complicated as it is in reality simply because students in grades K-12 would most likely not have much background Texas water policy.
years, followed by Mexico, then the Republic of Texas, the state of Texas, and even the
government of the Confederate States of America during the United States’ Civil War, before
once again falling under the rules of the state of Texas and the US federal government.

From 1600 to 1821, Spanish civil law governed the water in Texas; from 1821 to 1835, it
was Mexican civil law; from 1836 to 1839 the civil law of the Republic of Texas (after
transitioning to English common law) governed the waters; from 1840 to 1845 it was riparian law
of the Republic of Texas. From 1845 to the present, it has been governed by the laws of the state
of Texas which have varied from riparian law from 1845 to 1888, to prior appropriation in West
Texas, that riparian law in the rest of the state from 1899 to 1912, to mixed prior appropriation
and riparian law from 1913 to 1966; and finally prior appropriation statewide from 1967 to the
present. The Texas State Historical Association sums up water policy in Texas thusly, “The
complexity of the Texas law of water rights stems from its combination of Hispanic elements
with traditional English common law, as well as from its legal fragmentation of the hydrologic
cycle. Water-rights law determines who is entitled to the available water supply, in what
quantities, and for what purposes, and often specifies when and where the water may be used…
Texas courts divide water into unrelated legal classes with different rules of law governing the
ownership and use of each class. Several classes of underground and surface water are
recognized, and recent attempts to modify the weather bring yet another class, atmospheric
moisture, into consideration. Texas law pertaining to surface-water resources is voluminous,
while groundwater law is relatively sparse; as might be expected, law pertaining to atmospheric
moisture is even less developed” (Historical Association, 2013).

History of Texas Water Policy on the Edwards Aquifer

The first real attempt to protect the Edwards Aquifer was in 1959 when the Texas
Legislature created the Edwards Underground Water District. The purpose of the district was to
create maps of the area and assist with the licensing of water permits. The Underground Water
District was not particularly concerned with water quality until 1970, when regulations created by the Texas Water Quality Board were put into effect. In the beginning only six of the eleven counties were affected by the regulations (Kinney, Uvalde, Medina, Bexar, Comal and Hays), and those regulations only covered things like underground storage tanks, aboveground storage tanks and sewer lines. By 1984, regulations covered the residential, commercial and industrial development and required geologic assessments to go along with them. In 1988, the state began to charge fees for the assessment of developments to cover reviews of protection plans and inspections. The recharge zone had new rules in 1999 that covered anything that had the potential for polluting surface streams that flow to cross the recharge zone. Today, large developments now have a 30 day public comment period for review of applications for development (TCEQ, 2013).

Texas Water Laws
Prior Appropriation

The system of prior appropriation is complicated and follows several key principles. In Texas, the most important principle is seniority rule, which states that whoever asks for and is granted a permit for the water first gets it first. The second principle is quantified amount of water, which means that a permit holder has a right to a certain amount of water; however the quantity of water is not absolutely guaranteed, but is limited to the amount of water beneficially used, which brings us to the next principle of beneficial use. Texas considers beneficial use to be domestic, municipal, agricultural, industrial, recreation, parks, game reserves, and environmental flow to be beneficial uses. The next principle of appropriation is transferability, this principle allows for the transfer of a water permit from party to party, or the direct selling of one’s water. The cancellation and loss of water rights is another key element, which follows the “use it or lose it” principle; this means that water rights may be revoked after a 10 year period of disuse or abandonment. Interbasin transfers and the Junior writes rule allow for the transporting of water outside of the water basin it originally came from, however this rule is tricky because once water
is sold to another party outside of the basin, that water is no longer protected under the *seniority rule*, so in times of drought this helps keep water where it should be. (Sowar et al., 2011)

In order for any of the above principles to take effect, an interested party must first acquire a water right. To acquire a water right six conditions must be met:

1. unappropriated water is available
2. water will be beneficially used
3. existing water rights will not be impaired
4. the proposed use is not detrimental to the public welfare
5. the proposed use is consistent with a water supply need in the regional water plan
6. reasonable diligence will be used to avoid waste and achieve conservation

Even after these conditions are met, the Texas Commission on Environmental Quality has a list of items that may be affected downstream that must be assessed in order for water permit to finally be awarded. (Sowar et al., 2011)

**Groundwater Law and the Rule of Capture**

Groundwater law follows different rules than surface water, which is governed under prior appropriation principles. In Texas, “whereas surface water is state-owned, groundwater is the private property of the landowner” (Sowar et al., 2011). Because groundwater is the private property of the landowner that means that it falls under *the rule of capture*. The rule of capture comes from English common law and states that “absent malice or willful waste, landowners have the right to take all the water they can capture under their land and do with it what they please, and they will not be liable to neighboring landowners even if in doing so they deprive their neighbors the waters use.” Obviously this rule is quite unfair and so it has been modified over the years to combat three things: willful waste, malicious harm to a neighbor, and
subsidence (Potter, 2013). Thankfully, the Edwards Aquifer is no longer subject to the rule of capture due to Texas Senate Bill 1477.

Texas Senate Bill 1477

Texas Senate Bill 1477 (SB 1477), also known as the Edwards Aquifer Authority Enabling Act, was signed into law by Texas legislature on May 30, 1993, under the threat of federal action in regards to the Endangered Species Act, to create the Edwards Aquifer Authority (SB 1477, 1993). The act “created a conservation and reclamation District, named the Edwards Aquifer Authority… The Edwards Aquifer Authority was charged with regulating groundwater withdrawals pursuant to the conservation amendment and the Texas Constitution… replacing the rule of capture in five counties and portions of three others with a permit system” (Sowar et al., 2011).

The institution of this law created quite an uproar over private property rights because, as stated earlier, people living in Texas could take water whenever they needed it up until that point. In fact, the Travis County District Court “found that the rules of the Edwards Aquifer authority which limit withdrawals, as well as the Edwards Aquifer Authority’s Critical Management Plan rules, were invalid because their adoption did not adhere to the administrative procedures act.” Because of rulings like this and others, SB 1477 was not found to be fully within the law until a full 10 years after its signing into law (Votteler, 2000).

In essence, by the time SB 1477 became fully compliant, it helped prevent what ecologist Garrett Hardin coined as a “tragedy of the commons.” People could no longer extract water from the Edwards Aquifer at will, regardless of adverse effects on others (human, plant and animal) dependent on the resource. Unfortunately, on May 28, 2007, the Texas legislature passed Senate Bill 3 which raised the Edwards Aquifer’s pumping cap from 400,000 acre-feet per year to 572,000 acre-feet per year.
The Endangered Species Act

While all of the above laws can stand on their own merit, they also must adhere to the Endangered Species Act where applicable. As per Section 2 of the Act, “It is further declared to be the policy of Congress that all Federal departments and agencies shall seek to conserve endangered species and threatened species and shall utilize their authorities in furtherance of the purposes of this act. It is further declared to be the policy of Congress that Federal agencies shall cooperate with state and local agencies to resolve water resource issues in concert with conservation of endangered species” (USFWS, 1973).

The Texas State Water Plan

The Texas State Water Plan is redone every five years, with the most recent being done in 2012. Planning starts at the regional level with 16 regional water planning groups. To complicate matters, parts of the Edwards Aquifer fall under seven of those regions: D, F, G, J, K, L, and O. The primary function of the plan is “to meet the state’s needs for water during times of drought… to ensure that our state cities, rural communities, farms, ranches, businesses, and industries will have enough water to meet their needs during a repeat” of the drought of record. The 2012 plan mainly focuses on Texas’ expected 82% increase in population over the next 50 years, from just over 25 million people to just over 46 million people and just how much water it will require to sustain a population of that size. The plan includes potential scenarios involving failures to address water shortages, prolonged drought, proposed new reservoirs. It also covers 562 strategies to increase water supplies for Texas (Callahan, et al., 2012).

Water Agencies in Texas

As mentioned earlier, not only is water divided into different classes all over the state, but there are federal and state agencies that aim to have a hand in creating and controlling water policy in Texas. The Edwards Aquifer has its own set of rules, courtesy of Senate Bill 1477, and this complicates matters further.
US Army Corps of Engineers

The Corps of Engineers is in charge of major navigation, flood control, water supply, recreation and wetland regulatory presence in the state. The Corps manages locks and dams on most of the 15 major rivers in the state, including some that travel across the Edwards Aquifer. They are also in charge of 40% of the state’s water supply sitting in reservoirs. The US Bureau of reclamation also has a presence in Texas; however it does not have a presence or jurisdiction over the Edwards Aquifer. (Sowar et al., 2011)

Texas Water Development Board (TWDB)

The Texas Water Development Board’s mission is as follows, “to provide leadership, planning, financial assistance, information, and education for the conservation and responsible development of water for Texas.” Created in 1957 as a response to the drought of record, the board runs many financial assistance programs funded by state bonds and federal grants. The board is authorized to issue up to $10.93 billion in financial aid for water or wastewater related projects (TWDB, 2012). The duties of the board are as follows:

1. coordinate and fund regional planning groups and regional plans
2. consolidate regional plans into a state water plan
3. collect and maintain water data
4. administer loan and grant programs to local governments for water supply and water quality purposes
5. develop groundwater availability models and projections for the state’s major and minor aquifers
6. administer the environmental water trust
7. assist in financing state and local water projects (Sowar et al., 2011)
Texas Commission on Environmental Quality (TCEQ)

The Texas Commission on Environmental Quality “is the Environmental Protection Agency for Texas. The agency has broad regulatory powers over water, air, and waste pollution programs established under both state and federal legislation… establishes policy into supervisory responsibility over programs assigned to the TCEQ” (Sowar et al., 2011). The mission of the TCEQ is “to strive to protect our state’s public health and natural resources consistent with sustainable economic development. Our goal is clean air, clean water and the safe management of waste (TCEQ, 2013). The TCEQ’s responsibilities are as follows:

1. administer and allocate surface-water rights under the prior appropriation doctrine
2. administer the state’s water quality program
3. regulate public drinking-water systems
4. regulate dam construction, maintenance, and removal
5. administer the oil and hazardous spill program in license hazardous waste disposal facilities
6. regulate water well drillers
7. administer the National Flood Insurance Program
8. certify wastewater treatment operators
9. regulate water and sewer rates
10. define priority groundwater management areas (Sowar, et al., 2011)

Texas Parks and Wildlife Department

The Texas Parks and Wildlife Department develops and protects water-based recreation and wildlife, and enforces safety and efficient game laws. The TPWD also has a say in any changes made to water right applications and modifications with regards to the protection of aquatic and riparian ecosystems; and acquires water rights to protect instream flows and
freshwater inflows to Texas bays and estuaries (Sowar et al., 2011). The mission of the TPWD is “to manage and conserve the natural and cultural resources of Texas and to provide hunting, fishing and outdoor recreation opportunities for the use and enjoyment of present and future generations.” Some of the stated goals of the TPWD are to be a national leader and effective conservation and outdoor recreation programs; serve the people of Texas; use the best available science and making decisions; and responsibly manage finances and appropriations (TPWD, 2012).

Texas Railroad Commission

The Texas Railroad Commission protects groundwater and surface water from pollution generated by oil and gas production. The commission also regulates surface mining of coal and lignite, and uranium and water resources associated with that mining activity (Sowar et al., 2012). The commission is the oldest regulatory agency in the state of Texas and actually no longer is in charge of railroads in the state. Their website has an entire section devoted to educating children about mining, energy and the environment, as well as games for the kids to help them learn (Railroad Commission, 2013).

The Edwards Aquifer Authority (EAA)

SB 1477 brought the Edwards Aquifer Authority into existence in 1993 in order to ensure that the San Marcos and Comal Springs flows never dropped below the minimum required gallons per minute in order to protect the endangered species that live in and depend on the springs coming out of the aquifer. Their mission statement is quite simple into the point: “manage, enhance, and protect the Edwards aquifer system” (EAA, 2013). “The EAA has four primary tasks. The first is to adopt a critical management plan for restricting withdrawals during periods when the aquifer level in spring discharge rates are approaching levels adversely affecting endangered species. The second is to issue permits for groundwater pumping based on historical use. The third is to limit total pumping from the aquifer… The continuous minimum springflows
of the Comal Springs and of the San Marcos Springs are to be maintained to protect endangered and threatened species to the extent required by federal law. The fourth is to manage the aquifer through to the development and implementation of a groundwater management plan and the assessment of pumping fees to finance the operation of the EAA” (Sowar et al., 2011).
The Edwards Aquifer authority is also in charge of implementing water restrictions (Figure 22). There are five stages of water restrictions involving two major pools of water in the aquifer, the San Antonio pool and the Uvalde pool, and they are triggered when, “in the San Antonio pool when the 10 day average of the rate of springflow at either the Comal or San Marcos Springs, or aquifer reading at the J-17 index well in Bexar County drops below the Stage I trigger level. Likewise, a more restrictive stage of Critical Period is activated by any one of these triggers. However, the declaration of a less restrictive stage of Critical Period requires the

Figure 22, critical period drought stages and triggers – source: http://data.edwardsaquifer.org/files/CPM_Triggers.pdf.
10 day averages of all three trigger levels to be above the activation thresholds of the particular stage in effect at the time… San Antonio pool only: in order to enter Critical Period Stage V, the applicable springflow trigger is either less than 45 CSS based on a 10 day rolling average or less than 40 CFS based on a three day rolling average.Expiration of critical period stage V is based on a 10 day rolling average of 45 CFS or greater.” The Uvalde pool has no Stage I and “enters Critical Period at Stage II based on the 10 day average of aquifer level readings at the J 27 index well in Uvalde County” (EAA, 2013)

River Authorities

River authorities (Figure 23) are special districts in Texas that have control over surface waters in their river basin. They currently own and operate 22 major water supply reservoirs, with a combined storage capacity of more than 10,000,000 acre-feet. This comes out to an estimated 43% of the surface water in the state and they have the right to sell this water to public and private entities. The authorities cannot tax, but they can do these six things:

1. operate dams and reservoirs
2. supply raw untreated and treated water to municipal, industrial, and other customers
3. operate wastewater facilities
4. control drainage and floods
5. supply water for irrigation and maintain irrigation channels
6. provide hydroelectric power (Sowar et al., 2011)
There are two such major authorities operating within the Edwards Aquifer, they are the Lower Colorado River Authority (LCRA), and the Guadalupe-Blanco River Authority (GBRA). The LCRA is the largest river authority in Texas, with more than 1800 employees, and controlling more than 4,000,000 acre-feet of water, the only authority exceeding 4 million.

“LCRA owns and operates six dams… along a 600 mile stretch of the Texas Colorado River… in 11 counties and more than 30 communities, including the city of Austin. It also operates 20 regional and local wastewater treatment facilities and an environmental laboratory… It owns 16,000 acres of recreational lands along the Colorado River, operating more than 40 parks, a natural science Center, and nature preserves. They attract more than 1 million visitors a year” (Sowar et al., 2011).

Figure 23, River Authorities – source: Water for Texas: 2012 Texas State Water Plan
Representing Water Policy in the Systems Model

In order to incorporate a high-level view of Texas water policy into the model, Figure 24 adds four variables to the causal loop diagram: Agricultural/domestic water use, Water restrictions, Artificial water storage and Drought. This introduces two balancing feedback loops, indicated with the numbered labels B2: Ag/Dom Cycle and B3: Policy Delay.

Balancing vs. Reinforcing Feedback

A feedback loop is a circular causal structure within a causal loop or stock and flow diagram involving a closed-chain of causal connections. In other words, you can follow the causal links in a feedback loop to eventually end up at the place where you started. Feedback loops are very important because they, together with the stock and flow structure, delays, and nonlinearities, determine the dynamics of the system (Sterman, 2000). An important characteristic of dynamically complex systems is that their behavior is largely dictated by multiple, sometimes competing, feedback loops. Just like causal links, loops also have a polarity that is either positive or negative. A positive feedback loop is one that is reinforcing and accelerates growth (or collapse), while a negative feedback loop is balancing and counteracts change to seek a steady state. This model has no positive feedback loops.

Water Restrictions and Artificial Water Storage

The balancing feedback loop B2: Ag/Dom Cycle (B2), represents how the levels of agricultural and domestic water use are determined in part by the spring discharge and J-17 levels. They in turn affect the water level in the aquifer, which in can eventually reduce the discharge and J-17 levels. If the reduction in discharge is great enough, it will curb agricultural and domestic use, completing the loop. This is a balancing loop because it counteracts change. Increases in agricultural and domestic use set in motion changes that eventually work to curb use.
The causal link from Water Restrictions to Agricultural/Domestic Water Use demonstrates how enacting policy has the immediate effect of changing the amount of water used. Water restrictions are used (in response to drought or excess water use) to curb agricultural and domestic consumption, thereby maintaining a balance between supply and consumption.

The Policy Delay loop (B3) is another balancing feedback loop because the original increase (or decrease) in the aquifer’s water level is counteracted by the dynamics of the loop. As the aquifer’s water level increases causing the J-17 depth to increase, agricultural and domestic water use increases because of the extra water in the aquifer. Over time the water will be depleted which causes the water restrictions to be enacted. As the water restrictions begin to kick in, over time this will augment the aquifer’s water level and allow it to begin rising again.

Figure 24, Policy
Policies to Protect Endangered Species

Figure 25 adds the role of the Water Discharge, Education and Water restrictions in affecting the health of the endangered species populations.

The feedback loop **B4: Endangered Requirements**, represents the dynamic whereby reductions in spring discharge effectively reduce the available habitat for the endangered species, leading to a decline in those species. This in turn leads to further water restrictions (as per the Endangered Species Act) with the intent of restoring things to a desirable level. When the aquifer’s water level is up and spring discharge is high, the available habitat and species populations approach desired levels, which will eventually lead to a relaxing of water restrictions.

The three balancing loops **B5: Filtration/Pollution**, **B6: Wild Rice**, and **B7: Nutrient Cycle** all represent the balancing interplay between the health of the aquifer, the vitality of its ecosystems services, the well-being of the endangered species, and water restrictions aimed at restoring spring flows and habitat.

The **B8: Education** balancing loop has perhaps one of the longest delays in the model because the delay is the amount of time it takes students to grow into decision-makers. Education reflects efforts to give hands-on education to young people about the Edwards Aquifer and its importance to the broader ecosystem. If the aquifer level is high, or increasing, (or low, or decreasing) then the possibilities for education will increase (or decrease). As the students age, the education they received about the aquifer will go back into how they use the water in the aquifer. This will affect the amount of habitat available for the endangered species, as well as future water restrictions on agricultural and domestic water use throughout the Edwards Aquifer region.
The Edwards Aquifer - Policy/Endangered

Figure 25, Policy/Endangered
Chapter 5
Rainfall, Hydrology and Human Interactions in the Edwards Aquifer Region

Overview of Water Flow through the Aquifer

This chapter describes how water flows through the aquifer. This description provides a basis for the system dynamics that round out the systems model developed in the previous chapter.

Scientists have used several methods to study the hydrology of the Edwards Aquifer: computer models (Eckhardt), some tracking of eco-friendly dyes through the aquifer into wells and spring outlets (Beery, et al. 2005), and the use of dissolved helium to determine the location of the freshwater/saline water boundary in the Edwards Aquifer (Hunt, et al. 2010).

The aquifer is classified as a Karst Aquifer. The United States Geological Survey classifies Karst as, “…a terrain with distinctive landforms and hydrology created from the dissolution of soluble rocks, principally limestone and dolomite. Karst terrain is characterized by springs, caves, sinkholes, and a unique hydrogeology that results in aquifers that are highly productive but extremely vulnerable to contamination… Hydrology is typified by a network of interconnected fissures, fractures and conduits and placed in a relatively low-permeability rock matrix. Most of the groundwater flow and transport occurs through the network of openings, while most of the groundwater storage occurs in the matrix” (USGS, 2013) as shown in figure 26. In other words, water flows rather easily through the aquifer. In some cases this water reaches open underground reservoirs. Hence, the Edwards Aquifer is similar to a series of underground cisterns, surrounded by sponges, connected via pipes. Eckardt (2013) describes the rock matrix (shown in Figure 26) as a “honeycomb rock matrix that stores 95% of the water in the aquifer. To
move long distances, water leaves the matrix and enters a well-defined conduit, where water may be transmitted very far rather quickly.”

Figure 26, Water movement through the aquifer – source: Edwards aquifer website, http://www.edwardsaquifer.net/geology.html.

The water does not necessarily have an easy time moving from place to place inside the aquifer, however. There are many fault lines (Figure 27) running through the Edwards Aquifer recharge and artesian zone regions of this area, and as we will see, these faults are one of the

primary reasons for the aquifer’s existence.

The conduits of water flowing through the aquifer are often broken up by these faults and fractures, which can separate them into various units throughout the aquifer. These faults cause the water to change direction, or even stop flowing altogether as shown in figure 28. “Some of the faults have caused enough lateral displacement so that the Edwards limestones are not connected. These are called barrier faults” (Eckhardt), which can also be seen in figure 28 along with the freshwater/saline water barrier. “Large faults act as barriers or partial barriers to groundwater; while smaller faults and associated joints form local and regional groundwater conduits” (Eckhardt).
A more complete cross-section of the aquifer, from its westernmost tip in Brackettville, in an easterly direction under San Antonio, to its easternmost point in Hays County, is shown in figure 29, along with the changes in elevation of the land, the aquifer, and lower limestones down to 1400 feet below sea level.

With the water having flowed through the limestone for millions of years, and because of numerous earthquakes in the region, the aquifer includes large cave systems (Figure 30). Several of these caves have turned from discharging springs into recharging sinkholes over the millennia as the climate has become drier (Eckhardt). Some of the caves have even turned into tourist attractions.

Perhaps the most impressive cave system in the region is Robber Baron Cave. It was a tourist attraction in the 20s and 30s, and one of its caverns actually was a speakeasy during the prohibition era in the United States (Eckhardt).
All of these sinkholes, conduits, and caves mean that the aquifer can be recharged fairly quickly, given enough rainfall; the problem is the aquifer is not always able to hold all of that rainfall.

Again, according to Eckardt (2013), “water enters the aquifer easily through the recharge zone, but the subsurface drainage is generally inadequate to hold all of the water that falls in large rain events. Recharge conduits and sinkholes quickly become filled up with water… Compared to other types of aquifers such as those composed of sand, the Edwards is not an especially good storage aquifer where water can be placed in and expected to stay in storage for use later. Transmissivity is high enough that as long as enough hydraulic pressure exists to force the water up to the level of springs, significant amount of water will flow out. We can artificially increase recharge to the aquifer when water is available and it might help us through a short-term drought of one or two years.” In other words, while the aquifer can recharge very quickly, it can also discharge very quickly because the springs in the aquifer are artesian⁶, and the storage areas above spring level simply do not hold water very well. Complicating recharge matters further is the fluctuation in rainfall (Figure 31).

⁶ Artesian pressure is when, “... groundwater aquifers between poorly permeable rock, such as clay or shale, may be confined under pressure. If such a confined aquifer is tapped by a well (or spring, such as the case with the Edwards Aquifer), water will rise above the top of the aquifer” (USGS, 2013).
The solution to this is artificial water storage, but while it is effective, it can be incredibly expensive. In June of 2004 the San Antonio Water System (SAWS) brought its Twin Oaks Water Plant online. Planning had started in 1996, and in July of 2002 SAWS approved $110 million to build the plant and 29 miles of pipelines and pumps to deliver the water. In less than a year and a half, the facility had successfully stored over 20,000 acre-feet of water. The plant was used during droughts in 2006, 2008, and 2011, while recharging in the years between and since. By the end of 2012 (Figure 32), there was almost 95,000 acre-feet in storage (Eckhardt).
Groundwater Dye Tracing

In 2005 Joseph Beery, Brian Hunt, and Dr. Brian Smith were commissioned by the Barton Springs/Edwards Aquifer Conservation District to study the dye tracing technique for the Edwards Aquifer. Their book, *Summary of 2005 Groundwater Dye Tracing*, outlined why it is done and how it works. Groundwater dye tracing is done in the Edwards Aquifer in order to determine how water flows underground in both speed and direction, while also looking for its ultimate outflow destination. The summary of this experiment demonstrated how, “the introduction of non-toxic, organic dyes (Eosine) into the subsurface via injection points, such as caves, sinkholes, and wells, and analyzing charcoal receptors and water samples taken from discharge points such as wells and springs,” water could move through the aquifer at anywhere from “2.3 to 7.4 miles per day.” It was acknowledged that the conditions of the aquifer flow rates were well above average for the month of May in 2005 for this experiment. Nevertheless, the experiment showed that the water was moving nearly 30 miles underground (not including meanders) in a south by southwesterly direction. The book also mentions to concurrent dye
tracing activities within the San Antonio segment of the Edwards Aquifer. One of the activities, done by the Edwards Aquifer Authority, showed that dye (Fluorescein) placed in a cave south of the San Marcos Springs was later detected in the San Marcos Springs, which meant that water was also flowing to the north underground and coming out in the same discharge (Beery, 2006).

However, not all water in the aquifer flows in a south and southwesterly direction; nor does it always flow quickly. The majority of the water in the aquifer actually flows slightly south, then east and northeast based on the locations of barrier faults; and some water may move only a few feet a day, and may actually remain underground for several hundred years before it comes out at a well or a spring (Eckhardt). Figure 33 shows a general map of how the water flows throughout the aquifer before emerging from Comal and San Marcos Springs.

As discussed earlier, the complexity of Texas water law affecting the Edwards Aquifer is partly a result of the flow patterns from these studies. These studies show that water policy cannot
be determined on localize basis, because water coming out of springs does not necessarily come from the local area. These studies and resulting maps of flow patterns show that water flows to the San Marcos Springs, from many directions, and over great distances. In other words, the health of the San Marcos Springs provides a kind of “barometer” of the health of the entire aquifer. In addition, since these springs are the only single location where all of the endangered species can be found this has significant implications for those species.

Helium Analyses of the Freshwater/Saline-Water Transition Zone

Another important phenomenon indicating the health of the aquifer is the freshwater/saline water boundary, which signifies the line of saltwater encroachment into the usable water of the Edwards Aquifer. The problem with saltwater is that it cannot be used for drinking by humans, livestock, or crops unless it is treated first, nor can the endangered species of the aquifer live in it. So, the problem with saltwater intrusion is that the greater the intrusion, the less usable water there is for homes, businesses, farms and ranches, and endangered species.

Hunt, Lambert, and Fahlquist (2002) reported on study of how salt-water intrusion may become a greater problem for the aquifer. Dissolved noble gases (helium-3 and helium-4) were dissolved into water to be collected by the US Geological Survey as a smaller part of a larger study. In total 69 dissolved gas samples from 19 monitoring wells spread along the fresh/saline-water boundary were retrieved. The monitoring wells were drilled between 1972 and 2001 by government agencies at the Federal, State and Local levels. They are categorized as fresh, transitional and saline based on dissolved solid concentrations taken from well sampling or from fluid profile logging of the wells. The wells extend down into the upper 20 feet of the Edwards Aquifer and are spaced across the aquifer from Uvalde to Hays County (Figure 34). Samples are collected using stainless steel casks lowered into the well in the event that the well does not have a sampling spigot. Once the samples have been retrieved, they are poured through copper tubing into Tygon tubing. Once the sample has settled and air bubbles have been purged, the Tygon
tubing is crimped on both ends and sealed with refrigeration clamps while avoiding contact with the atmosphere. The samples were sent to the Denver Noble Gas Laboratory in Denver, Colorado for testing. The lab separated the gases from the water using an ultra-high vacuum extraction system, measuring pressure of the gases. A mass spectrometer was then used to determine the concentrations of gases. Finally, a cryogenic cold trap was used to further separate the helium and neon and a MAP-215-50 mass spectrometer obtained the absolute ratios of helium in the samples.

The authors state that helium-4 concentrations generally increase as salinity increases, and that larger concentrations of helium-4 represent older water (water that has been in the aquifer longer) because of exposure to crustal or mantle sources of helium-4. Tracking the concentration of helium-4 across the aquifer therefore showed that the water moved in a northeasterly direction from the southeast based on an increase in helium-4 concentrations. This information also helped to confirm that helium-4 in the aquifer came from mostly terrestrial sources, rather than atmospheric sources. The data further suggested that the saline water was coming from deep within the crustal rocks through faults and fractures and contained other noble gases such as neon and argon which indicate oil and gas hydrocarbons, meaning there is the potential for commercial drilling for oil and natural gas, which could further endanger the aquifer if it was pursued. Lastly, the data showed that there is a connection between the Trinity aquifer (north, west and partly beneath the Edwards) that allows water flow from the Trinity through the transition zone of the Edwards.

This paper gives a good indication of how water flows through the aquifer and shows how water can flow from one aquifer to another. Salt water intrusion into the aquifer is going to become a larger and larger problem as the population of Texas grows and the water level of the aquifer becomes depleted. Showing evidence of oil or gas below the aquifer shows another potential threat from the same study in that drilling through the aquifer could cause major
problems, not just from spills and leaks in pipes and wells, but also from equipment used above the aquifer.
Figure 34, Helium Analysis – source: USGS, Sources of Groundwater Based on Helium Analyses in and near the Freshwater/Saline-Water Transition Zone of the San Antonio Segment of the Edwards Aquifer, South-Central Texas, 2002–03.
Hi-Level Model of Edwards Aquifer Hydrology

This basic model of the hydrology within the Edwards Aquifer is in Figure 35. The balancing loop B1: Basic Aquifer Cycle represents the balance between the water volume in the aquifer (Aquifer water level) and the discharge. The balancing force of this loop is driven by the rainfall and recharge rates over the aquifer’s recharge zone.

As discussed earlier in this paper, rainfall can also be affected by climate change. As the climate gradually changes and rainfall increases, the aquifer is expected to recharge at higher rates. Without interference, the water level in the aquifer will gradually rise, causing spring discharge to increase; and as the spring discharge increases the water level will decrease, which balances the loop.

With an increase in rainfall also comes an increase in flooding. The flooding could be caused by massive amounts of rain all at once resulting in flash floods. Alternatively, it could be caused by the aquifer already being full, which would mean that the rainfall would have nowhere to seep into the aquifer and the resulting excess grain would simply turn into storm water runoff.

If climate change did not bring about an increase in rainfall, drought could set in. With a decrease in rainfall, drought conditions would increase and natural recharge of the aquifer would be lessened. If natural recharge decreased, then the water level the aquifer would also decrease and spring discharge along with it.
Figure 36 adds the Artificial Storage variable from previous diagrams to show how the artificial storage of water can help offset drought conditions and keep flows in the aquifer to desirable levels through artificial recharge. This requires adequate rainfall in order to build up a sufficient store of excess water.

Using the Full Model to Tell the Story: Humans, Species, and Hydrology

Figure 37 brings into one diagram all of the previously described dynamics. What follows in this section is a brief description of this full model.
The Edwards Aquifer

Figure 37, The Full Model
A basic knowledge of all 8 feedback loops is necessary if the one is going to use the model to describe the dynamics of this highly complex ecosystem. Each loop can certainly be discussed individually, but in order to get the desired holistic Systems Thinking approach this project is based on, the entire model must be considered.

When discussing the full model, the educator should start with the Climate Change variable and work their way through the 8 loops from there. As climate change potentially increases the amount of rainfall over the Edwards Aquifer over time the variables of recharge, flooding, drought, and artificial water storage are directly affected. In turn, each of these has an effect on variables deeper into the cycle.

Natural recharge will increase the aquifer’s water level, having a beneficial impact on each of the subsequent feedback loops. It will increase water available for human consumption, endangered species habitat, filtration, pollination, and nutrient flow; as well as improve the ability of educators to teach their students. One of the added benefits is an increase in biodiversity as time goes on because of an increase in spring flow and natural habitat, although the increase in biodiversity does not necessarily loop back in to the model; it can stand on its own. With increasing water levels and spring discharge, there will also be a more robust recreation and tourism industry in the region. This benefits the local economy by having both local people and visitors using the lakes, rivers, and streams for activities like fishing, boating, and floating. More feedback loops could be built into this model based on how the increased revenue from recreation and tourism is spent, as well. The money could go towards education, habitat improvement, drought and flood mitigation, or improvements in the way people use their water to reduce take from the aquifer.

While an increase in rainfall escalates the threat of flood danger that has an adverse effect on recreation and tourism, that same rainfall can go towards artificial water storage. Artificial
water storage directly impacts the amount of artificial recharge and the agricultural and domestic use of water from the Edwards Aquifer. It could also help to mitigate flood danger by storing some of the water that would otherwise be the storm water runoff that causes flooding. Increasing artificial water storage with rainfall to raise the aquifer’s water level with artificial recharge benefits the aquifer in the same way natural recharge does.

Ideally, there would always be enough rainfall to keep the aquifer’s water level high enough for to support the ecosystem services that people and endangered species. If water levels fall, then water restrictions would be implemented.

Combining an understanding of the Edwards Aquifer’s hydrology with models such as this is needed because these models can be used by educators and policymakers to help educate people about the problems facing the aquifer in order to stop, or at least combat, the damage that can be caused by human interference with the Edwards Aquifer. Taking a holistic approach, such as the one offered by using a Systems Thinking approach to the problem, can help the aquifer and the endangered species dependent on it thrive well into the future, just as they have in the past.
Chapter 6

The Edwards Aquifer Prototype Learning Environment

This chapter provides a description of the learning environment for students I have created for the Edwards Aquifer. The learning environment itself will look and act very similar to the popular children’s game “Chutes and Ladders,” from Hasbro, but with several key additions and changes made by myself.

Chutes and Ladders – A Framework for Water Flow

Hasbro describes the game as a “game of rewards and consequences. As kids travel along the game path, they encounter situations that reward them for good deeds by letting them climb the ladders or punish them for misbehaving by sending them down chutes. All the while, they are learning to recognize numbers and count to 100.”

Figure 38, Chutes and Ladders – source: http://bottlefedparents.blogspot.com/2012/10/chutes-and-ladders-devils-game.html.
In Hasbro’s version of the game (Figure 38), there can be up to eight players, each represented by a token which travels across 100 squares from the bottom left of the board to the top left. They move by spinning an arrow on top of a board labeled with the numbers one through six. For each player’s turn, they spin the arrow and move the appropriate number of places the arrow points indicates. If their spin gets them to the bottom of the ladder, they climb it; if their spin gets them to the top of the chute, they slide down it. Any time a player spins the arrow and lands on a square that is not the bottom of the ladder or the top of the chute, their turn is over.

The object of the game is to get to the top of the board before the other players. In the Hasbro game players must land exactly on square 100 in order to win. If their spin takes them past square 100, they do not get to move and must wait for their next turn. Players can also get to square 100 by landing on square 80, which is a ladder that takes them directly to square 100, thus ending the game.

Throughout the game board, at the tops and bottoms of each chute and ladder, there are pictures. These pictures depict good or bad things, depending on whether or not they are associated with a chute or a ladder. For example, square 1 depicts a little girl planting a garden. If a player starts the game by spinning a “one,” they climb that ladder to square 38 and find that at the top of the ladder is that same girl harvesting fruit from the plants she put in her garden. This makes the kids associate things like gardening and patience with getting ahead. However, on the flip side of this concept is square 87. Square 87 is the top of a chute and has a picture of a little boy climbing up on the kitchen counter and trying to sneak cookies out of the cookie jar. If a player lands on that square, they slide all the way back down to square 24, which has a picture of the boy sitting on the floor after having fallen off the counter and breaking the cookie jar. This
particular association shows kids that doing something they should not do will set them back, and sometimes way back.

So the original game of chutes and ladders teaches children and lessons about patience and doing the right thing, versus doing the wrong thing, by using a fun, interactive learning environment. The idea behind my game is the same, just about the Edwards Aquifer, with some changed and added features.

Description of the Learning Environment

Much like Hasbro’s game, my learning environment (figure 39) involves rewards and consequences. While students travel across my board they will come upon good situations and bad situations, which will send them either downstream, back upstream, pollute them, or eliminate them. With the younger students, or those without any background knowledge of the Edwards Aquifer, the educator in charge will describe what happens and why each time a player lands on a designated square. When played by older students, or with students who already have background knowledge of the aquifer, the students themselves will explain what happens and why on the square have landed on.

The players will be represented by a token on the board that is one of the endangered or threatened species in the aquifer. They will also have a cup of blue marbles to start the game that represent clean rainwater, the number of which will be determined at random using a double spin of the spinner, and these marbles will be kept to the side during the game. Players will move across the board and into the aquifer from top left and try to reach the bottom left, in a simulated downhill fashion as though they were running water. Players will move their pieces in the same way, using the spinning arrow. After their spin, if they land on a square with an ecosystem services feature, they will slide downstream closer to their goal. Another option is landing on a pollution square; when this happens the player gives up one of their blue marbles and gets a black
one, representing polluted water. A player may exchange a black marble for a blue marble when they cross over the wetland ecosystem service that cleans water, the distance determined by a total after a double-spin. There is the possibility of landing on a square such as agriculture, which uses water; when landing on this square, the player gives up a blue marble and move back the same way as if they had landed on a drought square. Landing on the livestock square results in losing a blue marble, gaining a black marble and spinning again to determine how many spaces
they move back. Finally, if a player lands on an artificial recharge feature square, they will be rewarded with an extra blue marble.

In an effort to more fully incorporate rainfall into the game, players may randomly land on rainfall squares to determine whether or not they get more blue marbles. The amount of marbles will be determined by using the spinner.

The object of this game is to get to the bottom of the board and flow out of the aquifer via the springs and make it down river, into the Gulf of Mexico. However, getting there first does not mean the player wins. Once a player reaches the bottom of the board, they go back to the beginning (if time allows) and start over with a new spin as though they are falling rain, starting the water cycle again. Because we want the kids to learn that the aquifer is a system dependent on all of the water in it, the game is not over until everyone gets to the bottom of the board at least once (although with more available time, the number of times players must reach the end could be increased). Once everyone has reached the bottom of the board, they will then count their blue marbles against their black marbles. The more blue marbles the players successfully get to the bottom, the cleaner the water and the better the chance that the endangered species in the aquifer survived. However, each time a player comes out with a black marble, or a certain number of black marbles, a member of an endangered species dies.

A player not having to land directly on square 100 to finish the game is an added benefit that makes the players think about how the movement of water is a cycle that never really ends. Because water moves through our planet's ecosystems in a cyclical fashion, we do not want the children to think of water reaching the ocean as the definitive end of that water's journey. Given extra time, the player could reenter the game at the beginning, or a designated point somewhere in the middle of the board, after their water has gone through the evaporation and rain segments of the water cycle through as many turns as time allows.
This Edwards Aquifer prototype learning environment could be very helpful to schools and agencies in the Edwards Aquifer region that are doing things to help educate children about the water they depend on every single day. It could even be modified to represent other water systems all over the United States, or the world. The people working for those schools or agencies would still need to follow the best practices laid out in Chapter 2, which require a presenter with prior knowledge and a desire to teach about the aquifer; an understanding and the ability to apply a holistic approach to explaining how the player and their water “flow” through the game; and finally, they must keep all of the participants involved. If all of this is done correctly and by the right people, this learning environment would be a very effective tool for teaching children about the Edwards Aquifer.
Chapter 7

Conclusions

Summary – Revisiting the Project Goals

The goal for this project was to create a learning environment for the Edwards Aquifer based on Systems Thinking and dynamics, and a model of the aquifer to go along with it. The belief was that a learning environment such as this would be a wonderful tool for educators to help children in central Texas learn about the aquifer they depend on for their water needs every single day.

In order to get children interested in such a learning environment, eight species that resided within the Edwards Aquifer were chosen as a pedagogical hook to draw them in. Six of the species were listed as endangered animals, one was an endangered plant, and one was listed as a threatened animal. To make the students to think about the aquifer and the problems that it faces in a holistic way, the endangered species were woven into the water issues of the over 2 million people who use the aquifer for domestic, recreational, educational and agricultural purposes across central Texas.

The learning environment idea is a way to get young people interested and educate them about the importance of the aquifer and how we as humans can either help or harm the ecosystem services that the aquifer provides for us and the region as a whole. A learning environment that they can interact with is a new way to increase awareness about (and more importantly, increase the potential to conserve) the aquifer, rather than just hearing about well depths, spring discharges, and water restrictions on TV or radio mixed in with all of the other media they may be consuming.
Using several different national and state agencies, as well as nongovernmental sources such as textbooks, books on water policy, teachers’ guides, and case studies; a model and a learning environment or developed. The model and learning environment concepts are based on the use of games and systems thinking in education, ecosystem services and endangered species, water policy, and human activities and their impacts on the system dynamics of the aquifer. It is expected that this prototype will be used and refined by the Aquarena Center at Texas State University in San Marcos, Texas as part of their educational efforts towards the Edwards Aquifer.

Outstanding Issues and Challenges

Developing and engaging learning environment for children that will effectively educate them about the issues facing the Edwards Aquifer is a challenging task. The biggest problem with this project was the sheer abundance of information on the aquifer. Trying to sift through it all and decide what was best, or most relevant to today, when developing the learning environment was a major issue.

A lack of relevant research pertaining to Systems Thinking and games was part of the challenge. There seems to be only a few select agencies and organizations that focus on Systems Thinking in education. Pegasus Systems, The Waters Foundation, The Creative Learning Exchange and the Massachusetts Institute of Technology seem to be the only thorough sources of information on the subject. Defining the benefits of using Systems Thinking in games and games for education is also difficult, as most of the information found about it simply states that it is beneficial, but neglects to explain why. Thankfully, applying Systems Thinking to education about the Edwards Aquifer was not nearly as difficult.

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7 Recently Texas State University received a $1 million donation for its River Systems Institute, under which the Aquarena Center resides, from The Meadows Foundation. The Institute and the Center are currently in the process of changing their names and falling under the single heading of "The Meadows Center for Water and the Environment at Texas State University." (http://www.meadowscenter.txstate.edu/)
Incorporating the ecosystem services and endangered species into a learning environment is not as difficult as deciding what to actually put into the learning environment. Using the Chutes and Ladders game as a starting point seemed like the best way to do this because of the way a player's token flows through the game, much like the way water flows through the aquifer.

The issues with including water policy in the learning environment mirrored the problem of there being just too much information about the aquifer. There are a great many water policy laws regarding the Edwards Aquifer, which are enforced by several agencies. Federal and state law both have jurisdiction, although state law is more prominent. The end result in the paper was simply choosing the biggest laws with the most impact and historical value that governed, or were specially made for, the Edwards Aquifer, but ignored the rest of Texas for the most part. However, for the learning environment there was no way to fit everything in, so policy had to be inserted into individual squares that demonstrated the consequences of water policy.

The modeling chapter was the difficult to write, but not challenging to add into the learning environment. Describing the hydrology of any aquifer is difficult, but when the USGS says that the Edwards Aquifer might be the most complex karst aquifer in the world, it is not easy to deal with, let alone blend into a children’s game. From describing what a karst aquifer is, to how the water is able to make its way into and move through rock (in both easy and difficult ways) because of millions of years of geological force, to how we know how the water moves using dyes and helium to map water flow, and finally how we can artificially recharge the aquifer, is difficult to describe, but easy to draw. Adding rain squares throughout the board; along with “chutes” depicted as water flowing through the aquifer, rivers, and wetlands solved that problem.

Once the learning environment was designed and developed, two other problems arose. The first issue was whether or not the game would actually work. Once the problem of what sort of game would work the best was figured out by using a chutes and ladders type of the game, it
was just a matter of applying the aquifer dynamics, ecosystem services, and the endangered species to the template. The issue with the game was the lack of being able to test it on some actual students who are trying to learn this material, which ties into the recommendations for people who would like to expand on this idea. The second problem was making the game adjustable for age groups. This problem was solved by allowing the instructors to teach the younger students about the dynamics throughout the game, while making the older students and explain the dynamics to the instructor as they came across them.

Recommendations

The most important recommendation is that the learning environment be tested on children who are trying to learn about the Edwards Aquifer, and also tested on teachers or educational agencies which are trying to teach these same children about the aquifer. Being able to watch people interact with each other while playing the game, and get their recommendations and criticisms on how to make the learning environment better is a crucial next step for anyone who would like to take this idea and expand on it in the future.

Expanding not only on the learning environment, but also on the model would be incredibly beneficial. One possible way to expand on the model would be to incorporate stocks and flows into it. A stock and flow diagram (SFD) is simply a CLD that has explicitly identified the stocks (reservoirs, sinks, or sources of memory and inertia) in the system, along with flows (processes and rates by which the stocks vary over time). A stock and flow diagram serves as the basis for a running simulation model (Sterman, 2000). Because the model may be the only causal loop diagram that has been created using the Edwards Aquifer as the centerpiece, it is possible that someone with a PhD in Hydrology, Environmental Geography, or even Biology or Geology, could take this model, or parts of it, and do some really great things with it to help further the knowledge and understanding of the Edwards Aquifer. Even politicians who understood the
concepts behind the model could use it in the future to help with the development of new policy to help protect the aquifer's ecosystems and the ecosystem services that it provides.

If someone took the model and/or learning environment from this project and used it to help further the education of children in the Edwards Aquifer region, as well as use it to help make policymaking more efficient, I believe that would be outstanding for the future of the Edwards Aquifer and Systems Thinking in education.
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