Integrated Engineering and Landscape Architecture Approaches To Address Groundwater Declines in the High Plains Aquifer

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Summary

The High Plains Aquifer, which overlies eight states in the central United States, supplies water for 30% of the nation's irrigated agriculture and provides the primary source of potable water to the region. Society is currently wrestling with how to adapt to declining groundwater elevation throughout much of this region. Case studies of this issue are examined by students in engineering and landscape architecture with a goal of preparing future leaders to understand this water resources system and effectively communicate modeling results to decision makers. The GIS (Geographic Information System) data required for these studies is readily available online from a variety of sources documented here. Technical competencies necessary to utilize these data in models of the system are presented to students, and teams of students are given the task of evaluating proposed methods of managing and utilizing groundwater in selected study areas in the region. A description of the approaches adopted by engineers and landscape architects to address this issue is presented. Recommendations are offered to integrate engineering and landscape architectural approaches to better understand water resources systems.

Keywords: Groundwater, Analytic Element Method, GIS, geospatial technology

Context and Logistics

The issue of groundwater declines is being addressed by students in related engineering and landscape architecture courses. One course is offered through Civil Engineering, CE 654: Design of Groundwater Flow

Systems. This 3-credit course is aimed at seniors and first year graduate students with participants from Agronomy, Biological & Agricultural Engineering, Chemical Engineering and Civil Engineering. A general understanding of fluid mechanics is prerequisite. This course introduces students to: 1) groundwater concepts and the framework of study, 2) field methodology, 3) GIS technology, and 4) groundwater modeling.

The second course is offered through Landscape Architecture, LAR 758: Land Resources Information Systems. This 3 credit course is also aimed at seniors and first year graduate students with participation from Landscape Architecture, Regional & Community Planning. Advanced undergraduate or graduate standing are prerequisite. This course is organized in four sections: 1) GIS science, 2) defining land resource systems, 3) geospatial analysis of systems, and 4) land-use suitability modeling.

Case studies are conducted in both courses by teams of two to four students to address a water resources topic of importance in the Kansas region. Data is collected from existing GIS repositories and supplemented by field visits to the study region. This data is utilized within modern geospatial and modeling tools to quantify and understand the system. Complementary goals of investigation are: learning to 1) design solutions for groundwater flow application, and 2) develop information useful for planning and design.

Introduction

This manuscript documents approaches adopted by engineering and landscape architecture students to develop understanding of water resources systems. The particular system examined here is the High Plains Aquifer, which resides under the eight states of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. Regionally, short-term consumption of groundwater in the High Plains Aquifer provides for a dynamic bio-socio-economic system through irrigated agriculture. Long term transition to sustainable usage matching natural recharge rates will impact economies, demographics, ecologies, and the landscape. The groundwater use in this region reflects global trends; "Presently, irrigation accounts for 70% of all water withdrawals … [increasing] by 14% in the next 30 years" (UNESCO, 2003).

Case studies are used by students to learn how to use modeling tools to understand this system. Engineering students are tasked with evaluating proposed method of managing the groundwater resources. These proposed methods are developed in cooperation with the managers of local groundwater districts. Landscape architecture students are tasked with defining existing land-use practices and suggesting opportunities and constraints for decision-making about use of the landscape. Object oriented approaches and geospatial technology are utilized in both courses.

This manuscript is organized as follows. First, the data utilized by both engineering and landscape architecture courses are identified and described. Next, questions and instructions specified for case studies in Spring 2005 courses are presented. The object oriented methods of analysis are presented for engineering students and landscape architecture students, and the results of analysis are described. Assessment of student learning is then presented, and recommendations for others interested in applying these techniques are offered.

Supporting Information

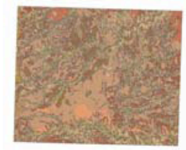
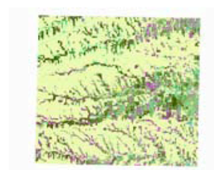
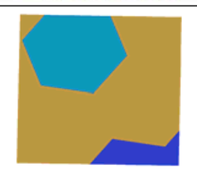
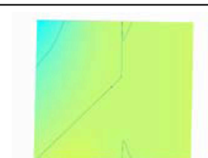
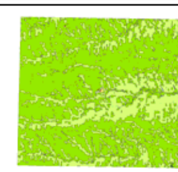
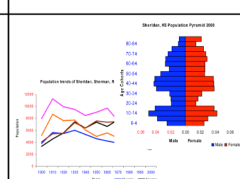
The data used for case studies is illustrated in Table 1. Engineering students primarily use natural system data related to geology, physiography, hydrology and hydrography. Landscape architecture students used all data sources to examine the interactions between natural and social systems. Both the types of data and the data sources are identified in this table. A significant portion of each course is devoted to understanding and interpreting these data.

Questions

The case studies each address issues of water use and sustainability in the High Plains region. Engineers developed groundwater models using current and projected water use with the goal of understanding the impacts of proposed management strategies on groundwater storage and fluxes. Landscape architecture students developed land-use suitability models to quantify the carrying capacity of the landscape if environmental land-use planning had been implemented prior to the Public Land Survey System.

Engineers met with groundwater managers to discuss proposed groundwater management strategies. These discussions led the students to define the problem statement, *"How do wells, recharge, and alternative schemes for water use and economic benefit produce trends and oscillations in groundwater elevation?"* Students developed written reports that identified the characteristics of the study region, described the modeling approach, presented modeling results, and discussed the impacts of proposed management strategies over a 40 year time horizon.

Table 1. Data in engineering and architecture case studies.

Data	Data Clearinghouses	Data Samples
Geology	www.nationalmap.usgs.gov www.ngdc.noaa.gov/index.html http://gisdasc.kgs.ku.edu http://kgs.ku.edu	
Soils	http://soils.usda.gov http://soildatamart.nrcs.usda.gov http://gisdasc.kgs.ku.edu	
Physiography	www.nationalmap.gov www.seamless.usgs.gov http://gisdasc.kgs.ku.edu	
Hydrography and Hydrology	http://nhd.usgs.gov http://water.usgs.gov www.epa.gov/ebtpages/water.html http://gisdasc.kgs.ku.edu www.kgs.ku.edu/hydro/hydroindex.html www.kdhe.state.ksu.us/water/index.html	
Vegetation	http://biology.usgs.gov/npsveg/index.html http://gapanalysis.nbii.gov	
Wildlife	www.fws.gov http://water.usgs.gov/nawqa www.gisdasc.kgs.ku.edu www.kdwp.state.ks.us	
Climate	www.unidata.ucar.edu www.ncdc.noaa.gov www.oznet.ksu.edu/wdl/	
Land Use/ Land Cover	www.nationalmap.usgs.gov http://landcover.usgs.gov/natllandcover.asp http://seamless.usgs.gov http://gisdasc.kgs.ku.edu	
Demographics and Economics	www.nationalatlas.gov www.census.gov www.census.gov/epcd/www/naics.html www.usda.gov/nass	

Landscape architects examined four aspects of the land resource system: 1) introduction, 2) definition, 3) analysis and evaluation, and 4) carrying capacity. The final aspect synthesized team findings to generate a series of alternative land management scenarios and plans. Students developed written reports summarizing the systems, describing the model method, and evaluating the environmental land resource model. Students also orally presented findings to a panel of faculty evaluators from landscape architecture, engineering and economics.

Analysis

Engineering Students

Groundwater modeling is based upon an object oriented approach called the Analytic Element Method (AEM). This method was pioneered by Strack (1989), and integrated with GIS geodatabase models by Steward & Bernard (2006), Steward et al. (2005) and Bernard et al. (2005). The essential elements necessary for modeling and application on a computer for the case study are presented next.

There are two fundamental equations and one assumption commonly used to model groundwater flow. The first equation, Darcy's Law, provides a constitutive relationship between the specific discharge vector, $\mathbf{q}$, and head, ϕ,

$$\mathbf{q} = -k\nabla\phi \tag{1}$$

where k is the hydraulic conductivity. The Dupuit assumption that head does not vary in the vertical direction provides a means of vertically integrating (1) over the saturated thickness and relates the specific discharge to the discharge per unit width, $\mathbf{Q}$. This relationship may be expressed as $\mathbf{Q} = \mathbf{q}(\phi - B)$ for unconfined conditions when $(\phi - B) < H$ and $\mathbf{Q} = \mathbf{q}H$ for confined conditions when $(\phi - B) \geq H$, where B is the aquifer base elevation and H is the aquifer thickness. Vertically integrating (1) gives

$$\mathbf{Q} = -\nabla\Phi \quad ; \quad \Phi = \begin{cases} \dfrac{k(\phi - B)^2}{2} & (\phi - B) < H \\ kH(\phi - B) - \dfrac{kH^2}{2} & (\phi - B) \geq H \end{cases} \tag{2}$$

where Φ is the potential for $\mathbf{Q}$, assuming B, H, and k are piecewise constant. The second fundamental equation, continuity of flow (conservation of mass), gives

$$\nabla \cdot \mathbf{Q} = R - S_y \frac{\partial \phi}{\partial t} \tag{3}$$

where R is the rate of recharge and S_y is the specific yield. Combining the vertically integrated Darcy's Law, (2), and continuity of flow, (3), gives

$$\nabla^2 \Phi = -R + \frac{1}{\alpha} \frac{\partial \Phi}{\partial t} \tag{4}$$

where α is the aquifer diffusivity ($k\bar{\phi} / S_y$ for unconfined flow and kH / S_y for confined flow).

In the Analytic Element Method, analytic elements are created with three distinct features: 1) specified geometry, 2) mathematical representation that exactly satisfies equation (4), and 3) boundary conditions. All analytic elements may be superimposed to model flow in a groundwater aquifer and the resulting expressions for potential Φ may be evaluated at any point to provide groundwater head ϕ and flow $\mathbf{Q}$ using equation (2).

The analytic elements used in this case study are those associated with wells, recharge and regional flow. Wells are modeled using the Theis (1935) solution with geometry of a point, boundary condition of specified pumping rate and mathematical representation of

$$\Phi = -\frac{Q}{4\pi} \mathrm{E}_1(u) \quad , \quad u = \frac{r^2}{4\alpha(t - t_0)} \tag{5}$$

where Q is the pumping rate of a well that turns on at time t_0, r is the horizontal distance from the well, and E_1 is the exponential integral. Recharge and regional flow are modeled over an area of infinite extent using boundary conditions of specified flux and head and mathematical representation

$$\Phi = R\alpha t - U_x x - U_y y + C \tag{6}$$

where U_x and U_y are the discharge of uniform flow in the x- and y-directions, and C is a constant chosen to match a specified value of head at a reference location.

This groundwater model was implemented in Scilab, an open source computer application with capabilities similar to MatLab®, which is freely available at www.scilab.org. A sample script is found in Figure 1 along with graphical results generated by this script within Scilab.

```
clear;
// Setup window size
xlimit=[0:3:100];   ylimit=[-50:3:50]';
x=xlimit(ones(ylimit),:);
y=ylimit(:,ones(xlimit));
plottime=10;

// Aquifer properties
k=10;  Sy=0.15;  H=50;  B=780;  headaverage=40;
alpha=k*headaverage/Sy;

// Functions
deff('[potential]=head_to_potential(head,k,H,B)',...
    'potential=(0.5*k*(head-B).^2)      .*((head-B)<=H)...
            +(k*H*(head-B)-0.5*k*H^2) .*((head-B)>H)');
deff('[head]=potential_to_head(potential,k,H,B)',...
    'head=B+sqrt(2*potential/k)       .*(potential<=0.5*k*H
          +((potential/(k*H))+0.5*H).*(potential>0.5*k*H^2)
deff('[out]=expint(z)',...
   ['c0=-0.57721566;c1=0.99999193;c2=-0.24991055;c3=0.05519968;c4=-0.00976004;c5=0.00107857;',...
    'a1=8.57332897401;a2=18.0590169730;a3=8.6347608925;a4=0.2677737343;',...
    'b1=9.5733223454;b2=25.6329561486;b3=21.0996330827;b4=3.9584969228;',...
    'out=(-log(z)+c0+c1*z+c2*z.^2+c3*z.^3+c4*z.^4+c5*z.^5).*(abs(z)<=1)...
        +((z.^4+a1*z.^3+a2*z.^2+a3*z+a4)./((z.*exp(z)).*(z.^4+b1*z.^3+b2*z.^2+b3*z+b4))).*(abs(z)>1)']);

// Recharge, uniform flow, constant
R=0.0001;  Qx0=1.7;  Qy0=0;  C=head_to_potential(820,k,H,B);
potential=C*ones(x);
potential=potential+R*alpha*plottime-Qx0*(x-mean(xlimit))-Qy0*(y-mean(ylimit));

// Well
Q=1000;   xw=mean(xlimit);  yw=mean(ylimit);   t0=0;
u=((x-xw).^2+(y-yw).^2)/(4*alpha*(plottime-t0));
potential=potential-(Q/(4*%pi))*expint(u);

// Plot head
head=potential_to_head(potential,k,H,B);
xbasc();
plot3d(xlimit,ylimit',head');
```

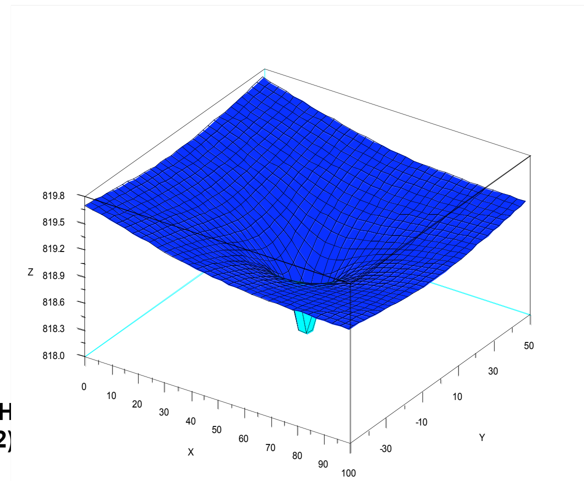


Figure 1. Scilab script for groundwater model and sample results of head near a well.

Student learning for this case study progressed from:

1. Introduction to parameters and fundamental equations.
2. Development of analytic elements.
3. Implementation of equations in Scilab during class in a computer laboratory.
4. Gathering data from GIS sources and field investigations.
5. Development of groundwater models for the case study region and interpretation of results.

Landscape Architecture & Planning Students

Landscape architecture and planning students engage in an iterative problem solving process to address the environmental planning challenges for the water dependent region. Student teams first focus on analysis of individual natural or social systems with the goal of understanding trends and applying a variety of available models to specific system data for forecast or analysis purposes. For example, students analyzing population utilize census data to understand historic trends then input the data into population estimate models such as the Gompertz Regression Model. Students analyzing soils analyze spatial patterns and distribution of specific characteristics (e.g. engineering/physical or chemical) as well as implement models such as Land Evaluation and Site Assessment (LESA) (USDA SCS, 1983) to determine suitability of soil to remain in agricultural production or be committed to community development.

Student teams make presentations, create reports, and GIS maps illustrating historic trend and existing condition analyses as well as model results for following systems: geology, soils, physiography, hydrography, hydrology, climate, vegetation, wildlife, ecosystems, transportation, land use/land cover, demographics, and economics. While individual natural and social system analyses and model results provide excellent insight as to opportunities and constraints, or capacities of individual systems for specific purposes, they individually can not provide the nexus for a comprehensive plan. Rather these system analyses and model results serve as inputs to more comprehensive land use suitability models which are developed by the class using a group consensus building technique called Delphi.

In this process the students' modeling and analysis results are combined via a weighted overlay analysis where inputs and weights are determined via the Delphi method of consensus building. The Delphi method typically involves the use of a selected diverse group of experts or stakeholders with differing or opposing opinions and systematically attempts to determine consensus or divergence of their opinions (Strauss & Zeigler, 1975).

The Delphi Method was developed by the RAND Corporation in the 1940s and 1950s for forecasting future events by Olaf Helmer and Norman Dalkey (Dalkey and Helmer, 1963) and has proven to be an effective method for forecasting procedures for complex issues with variable alternatives (Dunn, 1994). The Delphi method implementation goal is to describe alternatives to an issue in a forum that allows some level of accountability and measure of consensus among participants. "The policy Delphi method's unique strength is that it incorporates education and consensus building into the multistage process of data collection, thus enabling description of agreement about specific policy options among key players in the policy decision process. Taking part in the Delphi process can be a highly motivating experience for participants." (Raynes & Hahn, 2000).

The Delphi Method typically involves 2-5 stages (Critcher & Gladstone, 1998). The first stage is aimed at determining the range of opinions and is typically a survey or interview instrument (phone, email, web, paper, personal or group interview) developed by the researcher, stakeholders or a combination of inputs. The survey/interview instrument typically has questions from four categories: 1) Forecast, 2) Issue, 3) Goal and 4) Options (Dunn, 1994). Responses are typically rated on Likert-type scales.

Forecast questions ask participants to judge the reliability of information based on a provided statistic or estimate of a future event. Typical responses range from certainly reliable to unreliable. Issue questions ask respondents to rank issues in terms of importance relative to others. Typical responses range from certainly very important to unimportant. The goal category survey questions are to determine participant opinion about the desirability of certain policy goals. Typical responses range from very desirable to very undesirable. Finally respondents are asked questions regarding options to identify the likelihood that specific options might be feasible. Typical responses range from definitely feasible to definitely unfeasible.

Results of the first stage survey/interview are tallied and statistically analyzed to determine the similarities and differences of opinions among the group. Mean rankings and standard deviations are calculated and typically a standard deviation close to 1 indicates consensus. The second stage of the process removes items determined to have consensus from the first survey or interview and a new instrument or interview process started with only questions that had significant variation in response. A decrease in standard deviation between stages indicates an increase in agreement

(Hakim & Weinblatt, 1993; Jairath & Weinstein, 1994). The analyzed results are then reported to the respondents for discussion. This process is repeated until consensus is reached typically 2-5 total stages.

Alternatively, investigators ask panels of experts to prioritize ideas by assigning a rank score, and then analyze the responses using qualitative methods (Cookson, 1986; Jairath & Weinstein, 1994). Techniques for this type of survey include simple graphical analysis such as "vote the dots" or graphs, while others use interquartile deviation (IQD) to determine consensus—a Chi Square approach with a McNemar test. Again a trend which has declining values would indicate movement toward consensus and a values approaching 1.00 generally indicate consensus.

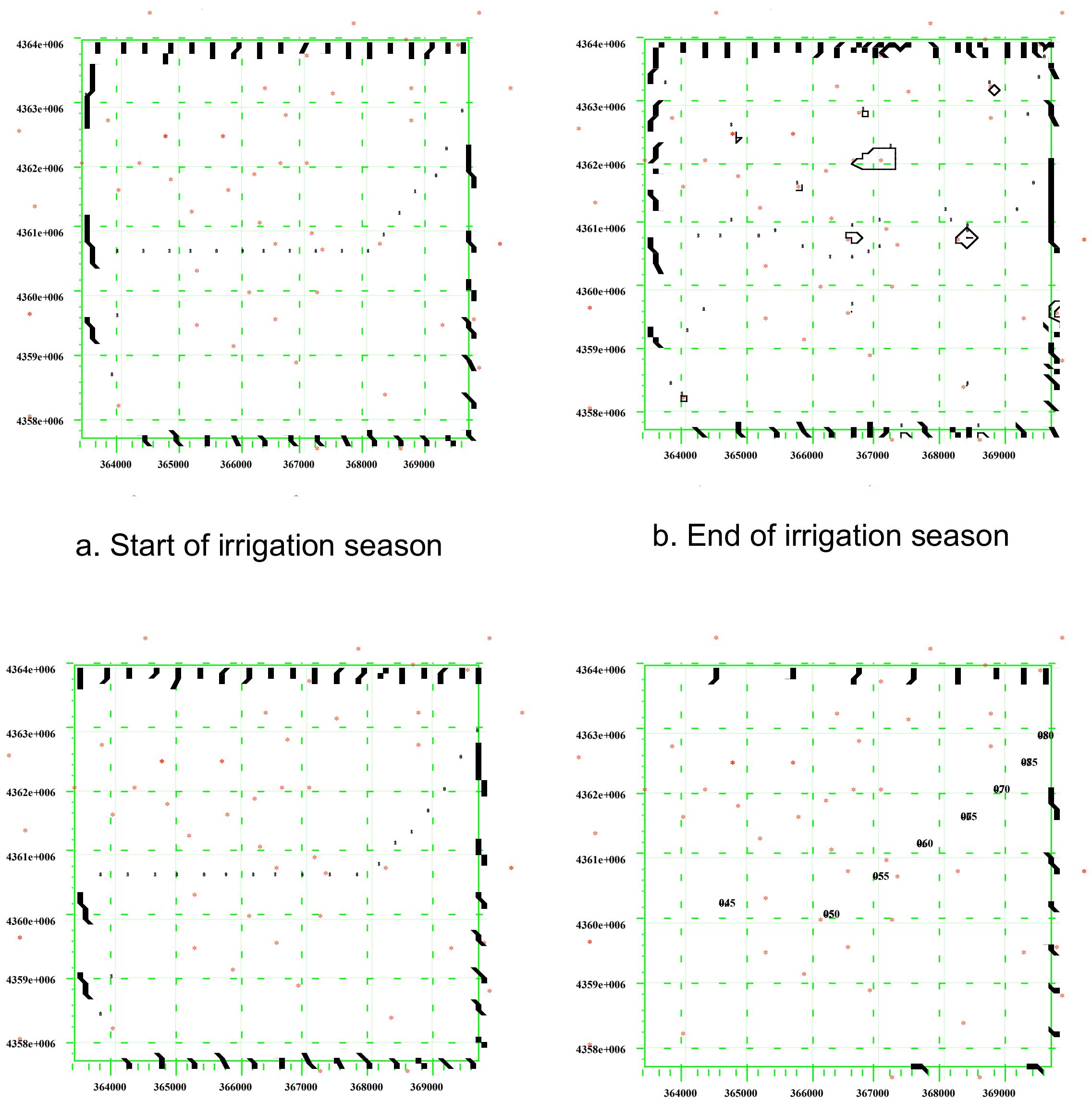
Landscape architecture and planning students created the Delphi survey to determine variables of natural and social systems required in making decisions about land use for environmental/ecological, economic or community development and the weights those factors should have in weighted overlay model run in ArcGIS.

Results and Outcomes

Engineering students worked in teams to utilize the approaches described above in developing groundwater models. An example of these model results is found in Figure 2, which illustrates the groundwater elevation in a 6400m by 6400m (4 mile) region at three different times in an irrigation season, as well as the net yearly decline. Each red dot represents a well, and head is contoured at 1m intervals. A net decline of approximately 0.5m per year closely matches field observations.

Students exercised these models over intervals of 1, 10, 20 and 40 years to quantify the changes in groundwater which will occur given current water-use practices. The models were also exercised using changes in water-use being considered in groundwater management districts. Specific management strategies in four districts included: water banking, artificial recharge, water buy-back programs, and aquifer sub-unit identification. By comparing projected modeling results using current and proposed water-use, students were able to quantify the impact of management strategies on water storage and fluxes.

Landscape architecture students where organized into three groups and each group goal was to develop and run one of three alternative weighted overlay models to assess the capacity of natural and social systems for: 1) environmental/ecological opportunities 2) economic development, and 3) community development. Each team used the Delphi method to



a. Start of irrigation season

b. End of irrigation season

c. Start of next year's irrigation season

d. Yearly groundwater decline

Figure 2. Modeling results from groundwater case study, illustrating changes in groundwater elevation over a yearly pumping cycle and net yearly groundwater declines.

determine variables from individual natural and social system analyses presentations and data. Delphi analysis also determined the magnitude of influence for each variable to be used in the group weighted overlay model, as illustrated in Figure 3. The sum of influence for all group consensus variables equals 100 percent.

Students from each group used the consensus variables and weights to develop a Model Builder weighted overlay model in ArcGIS 9 software, which is also shown in Figure 3. While Delphi methods are readily adaptable to courses in engineering and landscape architecture, utilization of the GIS infrastructure to support both groundwater models and Model Builder require extensive expertise and training.

Each team developed their model to determine the spatial locations most to least suitable capable of environmental/ecological, economic development, or community development opportunities. The results of each of these weighted overlay models were then combined via a second Delphi process where all groups participate to determine the weight each model should have in the final capacity model. The results of this consensus building process determine the weight each of the three models should have in the final weighted overlay model determining which land areas are most suitable for environmental/ecological, economic or community development.

Comprehensive Learning

Communities throughout the High Plains Aquifer region will continue to face planning challenges as the aquifer resource continues to decline. Engaging engineering and landscape architecture students in related case-studies provides understanding of the magnitude and complexity of the issue and teaches complementary critical skills in land-use planning and engineering design. Integration of student understanding across these courses provides an opportunity for students to work together, share results, and develop understanding of disciplinary water resources processes within cross disciplinary land-use planning. The comprehensive goal of this collaborative learning is to inspire teams of leaders in their respective fields to work together to develop scientific understanding of such critical problems in academia and carry that experience forward professionally.

Economic Group Voting Matrix

H: High
M: Medium
L: Low

	Vote#1	Vote#2	Layer Used	Agriculture	%	Industry	%
Hydrology							
Hydraulic Conductivity							
Saturated Thickness	x		x	M	3	L	1
Specific Yeild %	x		x	H	6.64	L	1
Ground Water Availability	x		x	H	6.64	L	1
Impared Streams		x	x	L	1	M	3
Climate							
Average Annual Temperature		x	x	M	3	L	1
Average Annual Precipitation	x						
Average Annual Snowfall			x	M	3	L	1
Vegetation							
Matrix – Small Patch		x	x	H	6.64	L	1
Crops	x		x	H	6.64	L	1
Riparian – High Order							
Riparian – Low Order							
Prairie		x	x	H	6.64	L	1
Geology							
Depth to Bedrock	x		x	M	3	H	6.64
Cost of Drilling	x		x	H	6.64	H	6.64
Wildlife							
Riparian Zones		x	x	H	6.64	H	6.64
Playa Lakes		x	x	H	6.64	H	6.64
Soils							
Particle Size		x	x	L	1	H	6.64
Prime Farmland	x		x	H	6.64	H	6.64
Drainage		x	x	M	3	M	3
Flooding Frequency	x		x	H	6.64	L	1
Runoff		x	x	L	1	L	1
Grassland Habitat		x	x	M	3	L	1
Wetland Habitat		x	x	H	6.64	H	6.64
Herbaceous Habitat		x	x	M	3	L	1
Physiography							
Slope	x		x	H	6.64	H	6.64
Aspect	x		x	M	3	H	6.64

Figure 3. Partial view of weighted overlay model and voting matrix for economic development team

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