Figure 11. Rain event. Notice no ponding/runoff in the pervious concrete gutter.

Figure 12. Pervious concrete parking lot, private business, during rain event. Note no ponding of rainfall.

Figure 13. Installation of porous asphalt parking lot at the City's new Airport Park, south parking lot.

Figure 14. Rain event. Airport Park's porous asphalt south parking lot.

Table 1. Water Quality Changes – Bacteria

Date	Dry or Wet	Influent or Effluent	Well Depth	Coliform total	Coliform fecal	Fecal Enterococci
02/05/2010	W	I		90,000	500	1,153
02/06/2010	W	E	Shallow	16,000	2,400	5,616
% Change				82%	-380%	-387%
02/06/2010	W	E	Deep	16,000	800	2,304
% Change				82%	-60%	-100%
02/09/2010	W	I		24,000	1,400	26,000
02/10/2010	W	E	Shallow	50,000	240	700
% Change				-108%	83%	97%
02/10/2010	W	E	Deep	160,000	1300	1417
% Change				-567%	7%	95%
02/27/2010	W	I		9000	30	1389
02/27/2010	W	E	Shallow	90000	24000	4176
% Change				-900%	-79900%	-201%
02/27/2010	W	E	Deep	160000	24000	4464
% Change				-1678%	-79900%	-221%
10/30/2010	W	I		9000	500	54
10/30/2010	W	E	Shallow	160000	5000	4320
% Change				-1678%	-900%	-7900%
10/30/2010	W	E	Deep	160000	13000	7920
% Change				-1678%	-2500%	-14567%

Table 2. Water Quality Changes – General Minerals

Date	Dry or Wet	Influent or Effluent	Well Depth	Conductivity	Hardness	pH	TDS	TSS
02/05/2010	W	I		80	31	6.28	50	14
02/06/2010	W	E	Shallow	320	111	6.28	280	40
% Change				-300%	-258%	0%	-460%	-186%
02/06/2010	W	E	Deep	820	293	6.31	510	82
% Change				-925%	-845%	0%	-920%	-486%
02/09/2010	W	I		70	13	7.93	40	51
02/10/2010	W	E	Shallow	840	272	7.17	530	56
% Change				-1100%	-1992%	10%	-1225%	-10%
02/10/2010	W	E	Deep	820	292	6.99	620	32
% Change				-1071%	-2146%	12%	-1450%	37%
02/27/2010	W	I		210	50	7.06	192	36
02/27/2010	W	E	Shallow	183	52.3	6.64	123	81
% Change				13%	-5%	6%	36%	-125%
02/27/2010	W	E	Deep	125	29	7.01	73	86
% Change				40%	42%	1%	62%	-139%
10/30/2010	W	I		78	16	5.27	52	54
10/30/2010	W	E	Shallow	200	37	5.93	114	35
% Change				-156%	-131%	-13%	-119%	35%
10/30/2010	W	E	Deep	268	73	5.9	144	47
% Change				-244%	-356%	-12%	-177%	13%

Table 3. Water Quality Changes – Metals

Date	Dry or Wet	Influent or Effluent	Well Depth	Cadmium (dissolved)	Chromium (dissolved)	Copper (dissolved)	Lead (dissolved)	Mercury (dissolved)	Nickel (dissolved)	Zinc (dissolved)
02/05/2010	W	I		ND	ND	0.026	ND	ND	ND	0.147
02/06/2010	W	E	Shallow	ND	ND	0.005	ND	ND	ND	ND
% Change						81%				100%
02/06/2010	W	E	Deep	ND	ND	0.005	ND	ND	ND	ND
% Change						81%				100%
02/09/2010	W	I		ND	ND	0.012	ND	ND	ND	0.11
02/10/2010	W	E	Shallow	ND	ND	ND	ND	ND	ND	0.013
% Change						100%				88%
02/10/2010	W	E	Deep	ND	ND	ND	ND	ND	ND	0.01
% Change						100%				91%
02/27/2010	W	I		ND	ND	0.05	ND	ND	0.006	0.271
02/27/2010	W	E	Shallow	ND	ND	0.011	ND	ND	ND	0.071
% Change						78%			100%	74%
02/27/2010	W	E	Deep	ND	ND	0.009	ND	ND	ND	0.07
% Change						82%			100%	74%
10/30/2010	W	I		ND	ND	0.013	ND	ND	ND	0.138
10/30/2010	W	E	Shallow	ND	ND	0.011	ND	ND	ND	0.068
% Change						15%				51%
10/30/2010	W	E	Deep	ND	ND	0.01	ND	ND	ND	0.049
% Change						23%				64%

Table 4. Water Quality Changes – Miscellaneous

Date	Dry or Wet	Influent or Effluent	Well Depth	Turbidity	COD	BOD	Oil Grease
02/05/2010	W	I		31.9	57	9	ND
02/06/2010	W	E	Shallow	120	28	3	ND
% Change				-276%	51%	67%	
02/06/2010	W	E	Deep	42.6	23	3	ND
% Change				-34%	60%	67%	
02/09/2010	W	I		22.1	47	9	ND
02/10/2010	W	E	Shallow	68	8	ND	ND
% Change				-208%	83%	100%	
02/10/2010	W	E	Deep	109	15	ND	ND
% Change				-393%	68%	100%	
02/27/2010	W	I		32.7	140	27	ND
02/27/2010	W	E	Shallow	83.8	72	11	ND
% Change				-156%	49%	59%	
02/27/2010	W	E	Deep	62.8	50	13	ND
% Change				-92%	64%	52%	
10/30/2010	W	I		22.8	116	33	8
10/30/2010	W	E	Shallow	25	82	37	ND
% Change				-10%	29%	-12%	100%
10/30/2010	W	E	Deep	27	98	40	ND
% Change				-18%	16%	-21%	100%

Table 5. Water Quality Changes – Nitrogen, Phosphorous

Date	Dry or Wet	Influent or Effluent	Well Depth	Nitrate	Nitrite	Ammonia	Ortho-phosphate
02/05/2010	W	I		3.45	ND	0.72	0.14
02/06/2010	W	E	Shallow	0.56	0.03	ND	0.27
% Change				84%	100%	100%	-93%
02/06/2010	W	E	Deep	1.37	0.03	ND	0.16
% Change				60%	100%	100%	-14%
02/09/2010	W	I		0.93	ND	0.51	0.05
02/10/2010	W	E	Shallow	7.05	0.04	0.19	0.15
% Change				-658%	-100%	63%	-200%
02/10/2010	W	E	Deep	4.02	0.041	0.17	0.16
% Change				-332%	-100%	67%	-220%
02/27/2010	W	I		6.98	ND	1.75	0.18
02/27/2010	W	E	Shallow	2.61	ND	0.27	0.19
% Change				63%		85%	-6%
02/27/2010	W	E	Deep	2.69	ND	0.46	0.19
% Change				61%		74%	-6%
10/30/2010	W	I		0.14	ND	0.97	0.25
10/30/2010	W	E	Shallow	0.69	ND	0.56	0.59
% Change				-393%		42%	-136%
10/30/2010	W	E	Deep	0.54	0.04	0.43	0.48
% Change				-286%	-100%	56%	-92%

A Decision Support System for Sustainable Urban Water Supply

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Abstract

Under rapidly growing water demand and the potential prolonged drought due to climate changes, a long-term sustainable water supply must be assured. This study develops a generally applicable decision support system (DSS) tool as an aid in the planning of long-term water supply. The model incorporates multiple water sources (ex, ground water, surface water, natural and artificial recharge), users (ex, municipal, agricultural, industrial, and natural evapotranspiration), and water qualities (ex, raw water from sources, treated potable and reclaimed water). In addition, sustainability indicators are developed and applied in general water system to quantify future water supply sustainability based on multiple scenarios (representing future conditions of water supply and demand) utilizing the developed DSS model. The DSS model and sustainability quantification indices will support the public and stakeholders in decision making process through the scenario analysis representing potential future water conditions. The application of the DSS model will be demonstrated through a case study on the regional water supply system in Tucson, AZ.

INTRODUCTION

Southern Arizona is faced with a water shortage problem due to its finite ground water sources and rapidly growing communities. Long-term water availability is a concern for water utilities and communities. To aid in improving locations with high demand for potable water and a high dependency on groundwater, the state of Arizona has set-up five active management areas (AMAs). Having no water overdraft is the main goal of the AMAs, allowing them to preserve limited groundwater for sustainable water future. Overdraft, or groundwater mining, is then defined by having a larger withdrawal, pumping, than the recharge amount, artificial or natural recharge. However, less ground water mining is not enough to show the systems overall direction. Different parameters and indices must be formulated to be able to understand and evaluate the AMA's long term water supply sustainability. The sustainability indicators for water supplies can predict overages and shortages in the different water sources, allowing for decisions to be made pertaining to groundwater and surface water yields. These indices can then help with the planning for future changing conditions including community growth and climate related changes.

This study focuses on Tucson Active Management Area (TAMA), one of the five Arizona AMAs, and looks at sustainability of both users and sources. Previous studies have only focused on one side presenting indicators for either the demand or the supply (Hashimoto et al. 1982a; Cai et al. 2002). The index parameters used here are similar to those from Hasimoto et al. (1982a), but have been modified to fit and adapt to a large scale water supply system for both user and sources. Apart from this, the indicators can be seen as a time series and certain periods of time can be compared, rather than having a single variable representing the completed simulation. This model also examines "safe-yield" at a certain time period by restricting groundwater mining that is missing in previous studies. Kang and Lansey (2010) did not propose the use of safe-yield but instead allowed for groundwater mining to be infinite.

METHODOLOGY

To further understand and quantitatively evaluate system's water availability, various indices have been defined. These indices can be used to see current and future abilities of systems for sustainable water supply. Different parameters are defined for the two different sides, supply and demand. The supply side is then defined as the source. It can be a ground water or surface water. The demand side refers to the user, such as municipal, industrial, and agricultural which require a certain amount of supply. The TAMA system is considered to be operating in a satisfactory state for the supply when the amount of water that is being replenished, naturally or artificially, meets or exceeds the amount of water that is being withdrawn for the year in question; and is satisfactory for the demand, the users, when the users demand is fully met. Ideally both the supply and demand would remain in satisfactory terms.

Reliability

Reliability is defined as the probability for a system to be in a satisfactory state. For the user's side, a satisfactory state is achieved when the total user demand is met. Reliability for an individual user is defined as;

$$\frac{\sum Years\ demand\ is\ met}{\sum Years}. (1)$$

Each year is checked to determine that the years demand has been met. If it has been met, the year is given a value of 1, otherwise the year is given a value of 0. These values are then summed and divided by the total amount of years to date. Since reliability is done yearly, it can be checked as a reliability to date. As a reliability for all users, the same equation is seen, however two separate equations are used, one which showing an overall reliability and the other the magnitude of reliability. For all users, the reliability equation is given by;

$$\frac{\sum Years\ all\ users\ demand\ is\ met}{\sum Years}. (2)$$

Equation 2 shows that all the users must have their demand met in order for the denominator to receive a value of 1. This equation is an extreme case and fails to show the magnitude of failure. The second reliability equation for all users shows the magnitude of the reliability as;

$$\frac{\sum Demand\ met}{\sum Total\ demand}. (3)$$

Equation 3 is used yearly. In this case the sum of the demand met is the demand met for the year in question of all users divided by the sum of the total demand for that year. Both equations should be read differently; for example, a value for equation 2 at year 20 will show the reliability over the twenty years, while in equation 3, a value at year 20 will show the reliability for all users in that year.

For the source, reliability follows the equation,

$$\frac{\sum Replenished\ Years}{\sum Years}. (4)$$

As with the user, a replenished year will be given a value of 1 and a mined year will be given a value of 0. The replenished years are summed to the year in question and then divided by sum of the year to date to determine the reliability to that year. A year that has no mined nor replenished water is considered satisfactory and given a value of 1.

Resilience

Resilience is defined as the quickness of a system to recover from failure once it has failed. Resilience for the users follows the equation,

$$\frac{\sum Number\ of\ Incidents}{\sum Years\ users\ demand\ is\ not\ met}. (5)$$

For an individual user, an incident is defined as not meeting the user's demand. While in a failure state, a string of consecutive years will be defined as in the same incident. It is not until the user reaches a satisfactory year that the incident will end and a new failure will then dictate the second incident. The inverse of the resilience equation will give the average years it will take the individual user to return from a failure. For all of the users, the equation is similar and consists of an extreme and conservative value. The conservative equation is

$$\frac{\sum Number\ of\ Incidents}{\sum Years\ a\ single\ user\ fails}. (6)$$

In this case an incident is defined in the same way as it is for an individual user; however an incident will occur when any of the user fails and the incident will continue until all of the users reach a satisfactory state. In this case it is possible for one user to begin the incident and another user to fail and prolong it. In an extreme resilience, the equation is

$$\frac{\sum Number\ of\ Incidents}{\sum Years\ all\ users\ fail}. (7)$$

In equation 7 an incident will not begin until all of the users are in a failure state and continue until any one of the users reaches a satisfactory state. The inverse of the extreme resilience will then depict the average years it will take system to return from a failure state where all of its users have experienced failure.
In the source, resilience is calculated by the equation,

$$\frac{\sum Number\ of\ Incidents}{\sum Number\ of\ years\ failed}. (8)$$

For the source, an incident is defined as a year with mined water. This incident will continue as long as the failure occurs and can only be ended by a satisfactory year. All of the values for resilience are normalized and can have a range of values between 1 and 0 with higher values being favored. In resilience, a value of 0 can only be obtained if the system fails every year of the simulation and a value of 1 will be achieved by having no failures or a single year failure followed by a recovery next year.

Vulnerability

Vulnerability is defined as the magnitude of failure. The vulnerability of the system is calculated on a yearly basis. For the individual users, vulnerability follows the equations as;

$$1-\frac{Demand\ not\ met}{Users\ demand}.\ (9)$$

For this equation the demand not met refers to the amount of the user demand that has not been met for the year in question. It is normalized by dividing the demand not met by the user's total demand for the year. To make value of 1 be favored, it is subtracted from 1 thus the vulnerability ranges from 0 to 1 with higher value being favored, which is consistent with other indicators. Vulnerability is compared yearly to the previous year for a minimum. Due to this, once the user's total demand has not been met, it will reach a vulnerability of 0. For all users, vulnerability follows the equation as;

$$1-\frac{All\ users\ demand\ not\ met}{Total\ users\ demand}.\ (10)$$

The sum of demand not met is calculated for the year in question of all the users and is normalized by dividing it by the sum of all users demand for the year. Same as the individual users, vulnerability is checked yearly and only takes the minimum value to date, thus it is not able to increase. For the source side, vulnerability is calculated by the equation as;

$$1-\frac{|Deficit|}{Years\ Demand}.\ (11)$$

For the groundwater source, a deficit is defined as ground water mining. Ground water mining occurs when the ground water pumping exceed that years recharge. The years demand is then used to normalize the vulnerability between a value of 0 to 1 with the value of 1 depiction zero ground water mining and no vulnerability of the source.

Sustainability

Sustainability is then referred to as the long-term system ability of achieving a satisfactory state. Sustainability for the user is then calculated as;

$$1-\frac{\sum_t Demand\ not\ met}{\sum_t Users\ Demand}.\ (12)$$

The sustainability of the user is an accumulation of the demand not met over time divided by the sum of the user total demand over time. Sustainability, therefore, differs from all of the other index parameters since it accumulates its value over time and is not based annually. The sustainability of all the users can be defined as

$$1-\frac{\sum_t Total\ demand\ not\ met}{\sum_t Total\ demand}.\ (13)$$

The sustainability of all the users is the defined as the accumulation of all of the user demand not met. The accumulated total demand of the users is the use to normalize sustainability. Sustainability is then normalized between 1 and 0 where 1 is preferred indicating that the total demand is met. For the source, the sustainability is defined by;

$$1 - \frac{\sum|Deficit|}{\sum Recharge}. (14)$$

The deficit in the equation refers to the amount of water that has been excessively withdrawn from the aquifer. The range of the sources sustainability is from 1 to -∞. A value of 0 indicates that to date the amount of water over mined is equal to the total amount of water recharged. If there is no deficit, the value is then 1 and preferred. The sustainability of the source shows a trend rather than an amount and the increasing sustainability shows a system that is improving over time even if there is still a deficit.

Decision Support System (DSS) Model

These metrics are then calculated by the use of a decision support system (DSS) model developed using Microsoft Excel; Figure 1 shows an excerpt page of the model where the several input parameters may be added to the DSS model. Different inputs for the DSS include names for the users with different variables for each user aiding the model in predicting future conditions. Each users demand can be calculated by either an initial population or quantity to find its demand. If an initial population is chosen, a population growth rate and per-capita-use for the initial year as well as target values can be added at year 50 and year 100 after the initial year.

If population determined user, what is the growth rate and GPCD				
	Growth Rate (%)	Growth Rate (%) @ +50	Growth Rate (%) @ +100	Uncertainty
Municipal	1.50%	1.50%	1.50%	10%
Agricultural	-	-	-	-
Industrial	-	-	-	-

If population determined user, what is the growth rate and GPCD				
	GPCD	Projected GPCD @ +50	Projected GPCD @ +100	Uncertainty
Municipal	172	172	172	10%
Agricultural	-	-	-	-
Industrial	-	-	-	-

If Supply determined what is the yearly increase in quantity or percent			
	Amount (AF)	Percent Increase (%)	Uncertainty
Municipal	-	-	-
Agricultural	-	-3%	10%
Industrial	250	-	10%

Figure 1. DSS model sample page where user input may be added

Input parameters also have the option of including an uncertainty value (random deviation). If this is chosen, a normal distribution random number generator will add the error depending on that year value (mean) and user choice of uncertainty level (%). Here a standard deviation of 10% of the mean value ($CV=\sigma/\mu=0.1$) is used to represent parameter uncertainty. However if the initial demand amount is chosen instead of a population, a yearly increase or decrease can be chosen for the user; this yearly change can be in the form of value, a set amount, or percent of the previous year's demand. The yearly increase and decrease amount can then have an uncertainty associated to each value. On the supply side, each ground water and surface water source can then be selected. Different recharge, evapotranspiration and