MANAGING WATER USE AND MUSSELS POPULATIONS IN A SOUTHEASTERN US RIVER

Jane Q. Student

MANAGEMENT PROBLEM

Streamflow regulation and land conversion are the dominant problems facing natural resource managers and planners in the southeastern US (Richter et al. 1997). In recent years, the rapidly growing human population has led to large scale urban development and increased water demands from agriculture, industry, and municipalities. These anthropogenic alterations have likely had unintended negative impacts on aquatic biota. Freshwater mussels throughout the Southeast have experienced substantial population declines in recent decades that have been attributed to a variety of factors ranging from naturally occurring disturbances (e.g., periodic drought) to disturbances resulting from water resource development activities and land use conversion (Williams et al. 2008). Despite the wide range of attributed factors, their relative contribution to observed mussel population declines remains unclear (Strayer 2008; Williams et al. 2008). The underlying ecological mechanisms responsible for population declines (e.g., reproductive failure, low survival) also are poorly understood for many species (Haag and Warren 2008). Hence, it is difficult for biologists and managers to develop informed and effective management and conservation strategies for imperiled mussels.

The challenges in developing effective mussel conservation strategies are typified in the Spring Creek located in southwest Georgia. It contains five federally listed mussel species: Shinyrayed pocketbook (Hamiota subangulata), Oval pigtoe (Pleurobema pyriforme), Purple bankclimber (Elliptoideus sloatianus), Gulf moccasinshell (Medionidus penicillatus), and Fat threeridge (Amblema neislerii). The Basin is surrounded by one of the most highly productive agricultural regions in the Southeast with a substantial portion of the agricultural lands irrigated from aquifers and surface waters. Previous research indicated that water use within the basin caused a 17% - 39% reduction in fish species distribution and was negatively related to mussel presence. Currently, state water managers have a backlog of applications for water withdrawal in the basin and the need to decide if additional water can be withdrawn without harm to existing mussel populations. To aid in the decision-making process, we use a structured decision making approach to identify management objectives and developed a model to evaluate the relative benefit of alternative management actions on the objectives of stakeholders.

Spatial and temporal dimensions

The scope of this decision is Spring Creek tributary of the Apalachicola River located southwestern GA. This stream is a Coastal Plain stream with large meanders, very low gradient, and minimal channel entrenchment. The watershed is contained in the Dougherty Plain physiographic district and characterized by karst hydrologic systems where the creek receives substantial amounts of groundwater from the underlying Floridan aquifer. The streambed is composed primarily of sand, with small patches of gravel and cobble in areas that have down cut into the Ocala limestone. Land use within the Spring Creek watershed is primarily a mixture of irrigated row crop agriculture and industrial forest with heavily forested riparian zones. Riparian buffers are generally wide and stream banks are gently sloping and very stable. The spatial extent of the decision is section of area potentially affected by water withdrawal, the lower 47 km. One of the fundamental objectives was the long term persistence of all mussel species (listed below). Thus, the temporal horizon or the decision was 100 years.

Legal, regulatory, and institutional constraints

The management of natural resources within the state of Georgia is the responsibility of the Georgia Department of Natural Resources (GADNR). The broad responsibility lies in establishing streamflow and best management practices standards, permitting water withdrawal, and setting wildlife conservation laws. Management of the Federally-listed mussels within the basin is the responsibility of the US Fish and Wildlife Service (USFWS) under the framework of the endangered species act.

Ecological context

Freshwater mussels are long-lived organisms, with maximum age varying among species but generally ranging from tens to one hundred years or more (Bauer 1992, Bogan 1993, Bauer and Wachtler 2001). The potentially slow response time of mussel species to disturbance causes additional uncertainty surrounding the factors responsible for population declines (Strayer 2008). Similarly, mussel populations are potentially slow to respond to management and conservation efforts, resulting in additional uncertainty surrounding their effectiveness for protecting at-risk species. Freshwater mussels also require host fishes to reproduce and quite often potential hosts include a small number of species. Thus, any factor affecting host fishes also can affect freshwater mussels.

Mussel population declines in the southeastern US have been attributed to a variety of factors, including excessive erosion and sedimentation (Bogan 1996, Brim Box and Mossa 1999), stream impoundment and channelization (Vaughn and Taylor 1999, Layzer and Scott 2006), habitat fragmentation (Watters 1999), water quality degradation (Augspurger et al. 2003); drought (Lake 2003, Golladay et al. 2004, Haag and Warren 2008), reductions in host fish populations (Smith 1985, Haag and Warren 2003), and invasive species introductions (Ricciardi and Rasmussen 1999, Strayer and Malcolm 2006). Despite the wide range of attributed factors, their relative influence on observed mussel population declines remains unclear (Strayer et al. 2004, Strayer 2008, Williams et al. 2008, Downing et al. 2010), and the underlying mechanisms responsible for population declines, such as reproductive failure and low adult survival, are poorly understood for many species (Bogan 1993, Strayer et al. 2004). Much of this uncertainty stems from the long life span, complex life history, and cryptic behavior of mussels, all of which contribute challenges to research and management.

STAKEHOLDERS

Stakeholders for the decision included the two decision-makers, the GADNR and USFWS, local landowners (farmers), and a conservation group, the Spring Creek Watershed Association.

OBJECTIVES

The stakeholders met and identified objectives and developed the means objectives network shown in Figure 1. The fundamental objective was to maximize the socioeconomic value to the local community. To achieve this objective, the stakeholders needed to maximize the persistence of mussels (i.e., to avoid the costs mussel of additional recovery actions) and maximize the local economic gain. To achieve the latter of these, the stakeholders believed that they could increase agricultural and forest industry outputs. There were several other means objectives identified. However, many of these were outside of the purview of the decision context: water withdrawal from the Spring Creek Basin. Thus, the final management objectives included the fundamental objective: maximize the socioeconomic value and two sub-objectives (1) maximize the persistence of mussels and (2) maximize water available for irrigation.

DECISION ALTERNATIVES

The decision alternatives were limited to those permitting decisions that could be made by the GADNR, increase water withdrawal, maintain current levels of water use, or decrease water withdrawal. The USFWS had no direct authority to permit water withdrawal. However, the service could declare jeopardy to the listed species if they believed that the decision was likely to cause in adverse effects to the mussels and their habitats. The jeopardy determination would prevent GADNR from issuing the permits.

VALUATION OF OUTCOMES

The stakeholder group ranked value of the outcomes of each sub-objective as 1 (least desirable outcome) to 3 (most desirable outcome). These values were then summed to estimate the socioeconomic gain (Table 1).

DECISION MODEL OVERVIEW

The water management is a stochastic model that estimates the probability of mussels (*Hamiota subangulata*) persisting in Spring Creek in response to water management decision. It is composed of environmental factors (e.g., future weather, water temperature and dissolved oxygen levels in the summer), population dynamics, and anthropogenic components. The spatial extent of the model is the lower 47 km of Spring Creek.

The model is graphically represented as an influence diagram that consists of model components, referred to as nodes with each node consisting of environmental states that are mutually exclusive and collectively exhaustive. The directed arcs indicate casual relationships between model components with parent nodes influencing (pointing into) child nodes. For instance, future habitat (a child node) is influenced by current sea otter population status (a parent node) and current habitat (also a parent node). The relationships among components using probabilistic (conditional) dependencies were parameterized using expert opinion (summarized in Table 2). Below we identify and describe the model components, their associated states, and the sources of information that were used to parameterize the node and conditional dependencies.

Future weather

An unconditional representing the probability that weather during the summer in any given year during the next 100 years is one of five states. States were defined relative to observed 1950-2000 weather data. Unconditional probabilities were estimated using expert opinion (Table 3).

States: Dry hot- precipitation below the 25 percentile and temperatures above the 75 percentile
Wet hot - precipitation above the 75 percentile and temperatures above the 75 percentile
Normal – all other years
Dry cool- precipitation below the 25 percentile and temperatures below the 25 percentile
Wet cool- precipitation below the 75 percentile and temperatures below the 25 percentile

Streamflow conditions

The model component represents the streamflow conditions during any given summer and is represented by three states that were defined relative to long term flow records in Spring Creek basin, 1950-2000. The model component depends on the water withdrawal decision and future weather and was parameterized using expert opinion (Table 4).

States: Low- flows below the 25 percentile
Normal – all other years
High- flows above the 75 percentile

Summer water temperature

The model component represents the average water temperature during any given summer and is represented by five states. The model component depends on future weather and was parameterized using expert opinion (Table 5).

States: Five equally spaced discretized values that ranged from 24-34^{o} C

Dissolved oxygen

The model component represents the average dissolved oxygen during any given summer and is represented by three states. The value of the component depends on streamflow conditions and summer temperature and was parameterized using expert opinion (Table 6).

States: Three equally spaced discretized values that ranged from 0-9 mg/L

Adult mussel survival

The model component represents the annual survival of adult mussels during any given year and is represented by two states. The value of the annual survival component depends on dissolved oxygen and temperature during the summer and was parameterized using expert opinion (Table 7).

States: Normal – annual survival greater than 70%
Below average - annual survival less than 70%

Initial adult abundance

Unconditional component represents the initial abundance of adult mussels (at time = 0) and is represented by two states. States and unconditional probabilities were based on expert opinion (Table 7).

States: Low- less than 1000 adults present at t=0
High- more than 1000 adults present at t=0

Host fish abundance

The model component represents the abundance of mussel host fishes during any given summer and is represented by two states. The value of the component depends on streamflow conditions and dissolved oxygen and was parameterized using expert opinion (Table 9).

States: Abundant- more than 5000 host fishes present
Rare- fewer than 5000 host fishes present

Successful reproduction

The model component estimates the probability that mussels will successfully reproduce in any given year and is represented by two states. The probability that mussels will successfully reproduce depends on host fish abundance and streamflow conditions and was parameterized using expert opinion (Table 10).

States: Yes- the mussels reproduce
No- the mussels do not reproduce

Probability of persistence in 100 years

The model component estimates the probability that mussels will persist to 100 years in Spring Creek and it is represented by three states. The probability that mussels will persist depends on successful reproduction, adult survival, and initial adult abundance. The effect of these components was parameterized using expert opinion (Table 11).

States: < 25 years-mussels will persist less than 25 years from present
25-75 years-mussels will persist from 25 to 75 years from present
>75 years-mussels will persist more than 75 years from present

I performed a one-way sensitivity analysis to determine how the changes in the aforementioned components would affect the socioeconomic value of the decision. A tornado diagram was then constructed to graphically display the results of the sensitivity analysis.

DISCUSSION

The optimal decision was to increase water withdrawal from Spring Creek with an expected socioeconomic value of 5.28. Given the decision to increase water withdrawal, I estimate a 48.6% probability that the mussel species will persist more than 75 years. One way sensitivity analysis indicated that the expected value of the decision was most sensitive to model was most sensitive to successful reproduction and initial adult abundance and least sensitive to summer water temperatures. These two key uncertainties would be high priorities for future research or monitoring efforts.

Value of the SDM process

Using the SDM process to evaluate water withdrawal was an important step in furthering transparency in decision making, evaluating assumptions concerning the effect of water withdrawal on mussel populations, and refining monitoring and research needs focused on improving decision making. My experience developing an influence diagram also highlights the struggle among biologists to continually to incorporate higher levels of ecological and population dynamics assumptions and processes. The initial diagram contained dozens of nodes and was very complicated and confusing. The focus on parameterizing explicit nodes and their relations forced me to recognize the importance of narrowing the processes influencing mussel populations, while acknowledging the many of the process and dynamics driving mussel populations are outside the scope of the water withdrawal decision.

Future steps

I was concerned that the probability of persisting at least 75 years was unacceptably low. In fact, the estimated probability of persisting more than 75 years increased slightly to 49.7% when the decision was decrease water withdrawal. Additional analysis indicated that the estimate of persistence was most sensitive to initial adult abundance and the probability of successful reproduction and was insensitive to adult mussel survival. I believe that this was counter-intuitive and that the model in its current form was inadequate. Thus, I decided that future efforts should ask technical experts to create a new model for estimate mussel persistence that relied on empirical data and models rather than expert opinion.

LITERATURE CITED

Brim Box, J., and J. D. Williams. 2000. Unionid mollusks of the Apalachicola Basin in Alabama, Florida, and Georgia. Bulletin 21 of the Alabama Natural History Survey. Alabama Natural History Survey, Tuscaloosa, Alabama.

Campbell, D. C., J. M. Serb, J. E. Buhay, K. J. Roe, R. L. Minton, and C. Lydeard. 2005. Phylogeny of North American amblemines (Bivalvia, Unionoida): prodigious polyphyly proves pervasive across genera. Invertebrate Biology 124:131–164.

Golladay, S. W., P. Gagnon, M. Kearns, J. M. Battle, and D. W. Hicks. 2004. Response of freshwater mussel assemblages (Bivalvia: Unionidae) to a record drought in the Gulf Coastal Plain of southwestern Georgia. Journal of the North American Benthological Society 23:494–506.

Haag, W. R. 2010. A hierarchical classification of freshwater mussel diversity in North America. Journal of Biogeography 37:12–26.

Hornbach, D. J., V. J. Kurth, and M. C. Hove. 2010. Variation in mussel shell sculpture and shape along a river gradient. American Midland Naturalist 164:22–36.

Howard, J. K., and K. M. Cuffey. 2003. Freshwater mussels in a California North Coast Range river: occurrence, distribution, and controls. Journal of the North American Benthological Society 22:63–77.

Johnson, R. I. 1970. The systematics and zoogeography of the Unionidae (Mollusca: Bivalvia) of the southern Atlantic Slope Region. Bulletin of the Museum of Comparative Zoology 140:263–449.

Layzer, J. B., and L. M. Madison. 1995. Microhabitat use by freshwater mussels and recommendations for determining their instream flow needs. Regulated Rivers: Research and Management 10:329–345.

Morris, T. J., and L. D. Corkum. 1999. Unionid growth patterns in rivers of differing riparian vegetation. Freshwater Biology 42:59–68.

Mulvey, M., C. Lydeard, D. L. Pyer, K. M. Hicks, J. Brim Box, J. D. Williams, and R. S. Butler. 1997. Conservation genetics of North American freshwater mussels *Amblema* and *Megalonaias*. Conservation Biology 11:868–878.

Strayer, D. L. 1993. Macrohabitats of freshwater mussels (Bivalvia: Unionacea) in the streams of the northern Atlantic Slope. Journal of the North American Benthological Society

12:236–246.

Williams, B. K., J. D. Nichols, and M. J. Conroy. 2002. Analysis and management of animal populations: modeling, estimation, and decision making. Academic Press, San Diego, California.

Williams, J. D., A. C. Bogan, and J. T. Garner. 2008. Freshwater mussels of Alabama and the Mobile basin in Georgia, Mississippi, and Tennessee. University of Alabama Press, Tuscaloosa, Alabama.

Williams, J. D., and M. Mulvey. 1994. Recognition of freshwater mussel taxa: a conservation challenge. Pages 57–58 *in* G. K. Meffe, and C. R. Carroll (editors). Principles of conservation biology. Sinauer Associates, Sunderland, Massachusetts.

Table 1. Ranks of outcomes for Spring Creek water withdrawal decision.

Probability of persistence		Economic valuation of water use outcome		Socioeconomic value
Outcome	**Rank**	**Outcome**	**Rank**	
<25 years	1	Increase 10%	3	4
25-75 years	2	Increase 10%	3	5
>75 years	3	Increase 10%	3	6
<25 years	1	No change	2	3
25-75 years	2	No change	2	4
>75 years	3	No change	2	5
<25 years	1	Decrease 10%	1	2
25-75 years	2	Decrease 10%	1	3
>75 years	3	Decrease 10%	1	4

Table 2. Summary of influence diagram components included in the Spring Creek water withdrawal decision.

Model component	**Definition and Source**	**Component State**
Future weather	The future weather affecting the Spring Creek Basin within the next 100 years. Probabilities reflect annual probabilities of each state. (Expert opinion)	Dry hot Wet hot Normal Dry cool Wet cool
Streamflow conditions	Summer flow conditions for Spring Creek. (Expert opinion).	Low Normal High
Summer water temperature	The average summer temperature for Spring Creek. (Expert opinion).	Discretized values from 24-34 C
Dissolved oxygen	The average dissolve oxygen reported for Spring Creek. (Expert opinion).	Discretized values from 0-9 mg/L
Host fish abundance	The abundance of host fish for *H. subangulata.* (Expert opinion)	Abundant Rare
Initial adult abundance	Initial population sizes. (Expert opinion)	<1000 >1000
Adult mussel survival	The natural survival of *H. subangulata* ages 2-20. (Expert opinion)	Normal Below average
Successful reproduction	Annual reproductive success of *H. subangulata*. (Expert opinion)	Yes No

Table 3. Unconditional state probabilities for future weather node.

State	Probability
Dry hot	0.25
Wet hot	0.25
Normal	0.35
Dry cool	0.05
Wet cool	0.1

Table 4. Conditional probabilities for streamflow based on expert opinion.

Water withdrawal decision	Future weather	Streamflow		
		Low	Normal	High
Increase	Dry hot	0.71	0.24	0.05
Increase	Wet hot	0.05	0.24	0.71
Increase	Normal	0.47	0.41	0.12
Increase	Dry cool	0.71	0.24	0.05
Increase	Wet cool	0.05	0.24	0.71
Status quo	Dry hot	0.63	0.31	0.06
Status quo	Wet hot	0.06	0.31	0.63
Status quo	Normal	0.25	0.50	0.25
Status quo	Dry cool	0.63	0.31	0.06
Status quo	Wet cool	0.06	0.31	0.63
Decrease	Dry hot	0.50	0.25	0.25
Decrease	Wet hot	0.06	0.28	0.67
Decrease	Normal	0.21	0.37	0.42
Decrease	Dry cool	0.50	0.25	0.25
Decrease	Wet cool	0.06	0.28	0.67

Table 5. Conditional probabilities for average summer temperature based on expert opinion.

Future weather	Average stream temperature 24-26	26-28	28-30	30-32	32-34
Dry hot	0.08	0.14	0.19	0.32	0.28
Wet hot	0.08	0.14	0.19	0.32	0.28
Normal	0.09	0.17	0.24	0.27	0.23
Dry cool	0.13	0.23	0.21	0.23	0.20
Wet cool	0.13	0.23	0.21	0.23	0.20

Table 6. Conditional probabilities for summer dissolved oxygen based on expert opinion.

		Dissolved oxygen		
Streamflow	**Temperature**	**0-3**	**3-6**	**6-9**
Low	24-26	0.47	0.47	0.06
Low	26-28	0.68	0.32	0.01
Low	28-30	0.13	0.57	0.29
Low	30-32	0.26	0.58	0.17
Low	32-34	0.26	0.58	0.17
Normal	24-26	0.63	0.36	0.01
Normal	26-28	0.86	0.14	0.00
Normal	28-30	0.17	0.54	0.29
Normal	30-32	0.15	0.45	0.40
Normal	32-34	0.28	0.57	0.15
High	24-26	0.66	0.33	0.01
High	26-28	0.08	0.54	0.38
High	28-30	0.20	0.52	0.29
High	30-32	0.16	0.52	0.32
High	32-34	0.41	0.46	0.13

Table 7. Conditional probabilities for adult survival node based on expert opinion.

Summer temperature	Dissolved oxygen	Adult survival: Normal	Adult survival: Below average
24-26	0-3	0.07	0.93
24-26	3-6	0.96	0.04
24-26	6-9	1.00	0.00
26-28	0-3	0.03	0.97
26-28	3-6	0.91	0.09
26-28	6-9	1.00	0.00
28-30	0-3	0.01	0.99
28-30	3-6	0.81	0.19
28-30	6-9	1.00	0.00
30-32	0-3	0.00	1.00
30-32	3-6	0.63	0.37
30-32	6-9	1.00	0.00
32-34	0-3	0.00	1.00
32-34	3-6	0.41	0.59
32-34	6-9	1.00	0.00

Table 8. Unconditional probabilities for adult abundance based on expert opinion.

Adult Abundance	Probability
>1000	0.25
<1000	0.75

Table 9. Conditional probabilities for host abundance based on expert opinion.

Stream flow	DO	Host abundance Abundant	Rare
Low	0 to 3	0.10	0.90
Low	3 to 6	0.20	0.80
Low	6 to 9	0.30	0.70
Normal	0 to 3	0.35	0.65
Normal	3 to 6	0.50	0.50
Normal	6 to 9	0.50	0.50
High	0 to 3	0.40	0.60
High	3 to 6	0.45	0.55
High	6 to 9	0.45	0.55

Table 10. Conditional probabilities for successful reproduction based on expert opinion.

		Successful reproduction	
Flow	**Host fish**	**No**	**Yes**
Low	Abundant	0.60	0.40
Low	Rare	0.75	0.25
Normal	Abundant	0.35	0.65
Normal	Rare	0.75	0.25
High	Abundant	0.40	0.60
High	Rare	0.80	0.20

Table 11. Conditional probabilities for population persistence at 100 years.

Successful reproduction	**Adult Abundance**	**Probability of persistence to 100 yr.**		
		< 25 years	**25-75 years**	**>75 years**
No	<1000	0.55	0.35	0.10
No	>1000	0.20	0.45	0.35
Yes	<1000	0.10	0.20	0.70
Yes	>1000	0.02	0.08	0.90

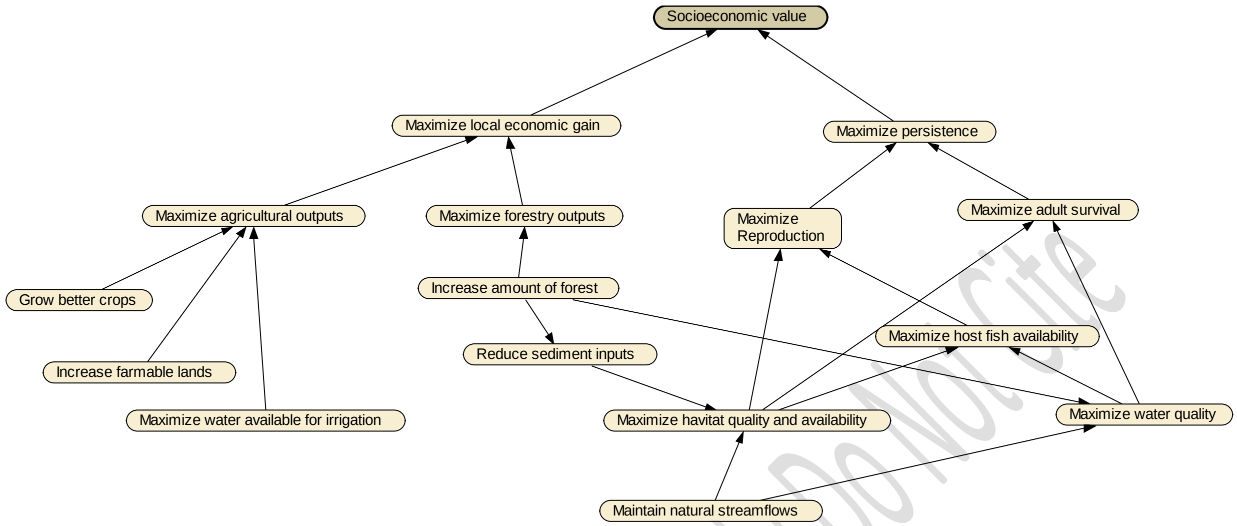

Figure 1. Means objectives network for the spring creek water withdrawal decision.

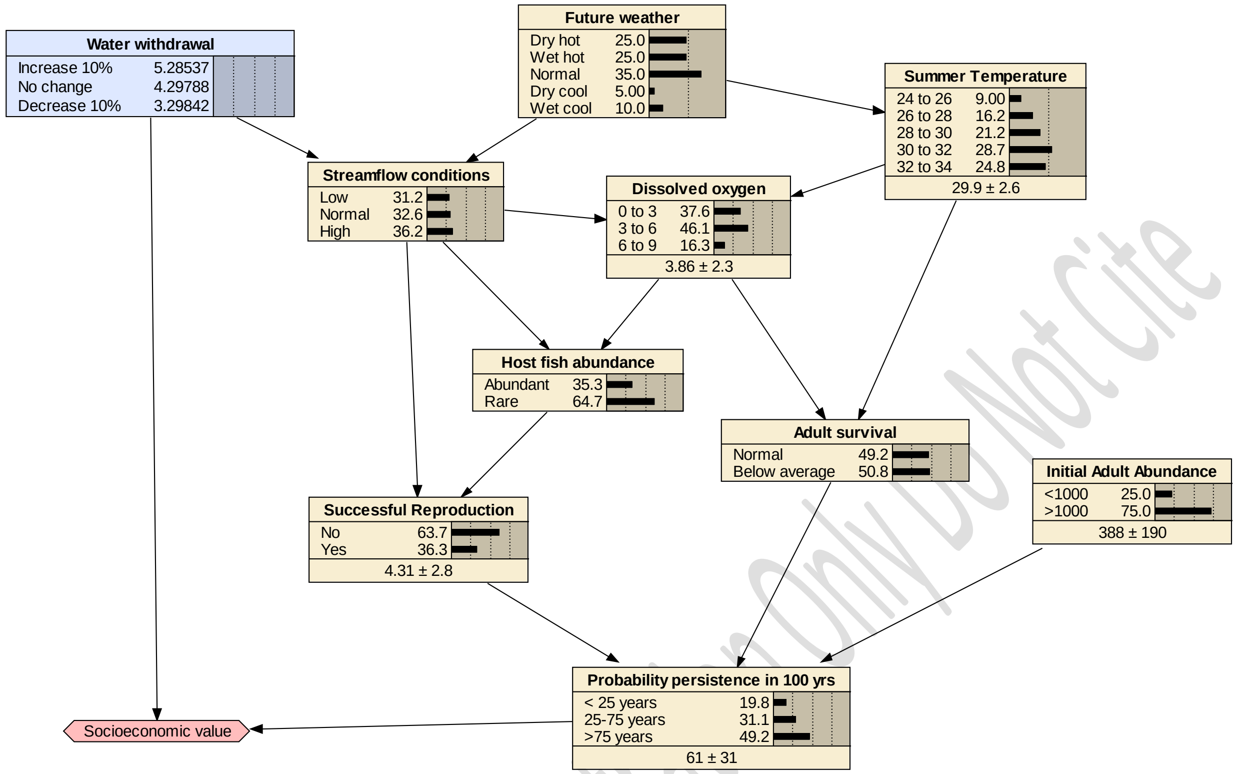

Figure 2: Influence diagram used to evaluate the optimal water management decision in Spring Creek, GA.

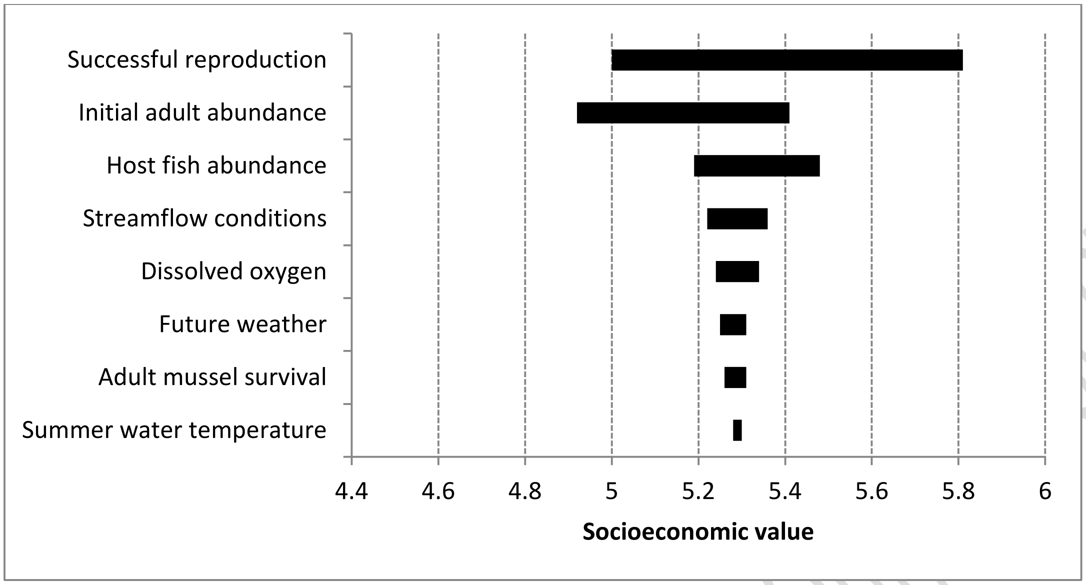

Figure 3. Tornado diagram for one-way sensitivity analysis of Spring Creek water management decision.