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A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada

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Abstract

Water managers increasingly are faced with the challenge of building public or stakeholder support for resource management strategies. Building support requires raising stakeholder awareness of resource problems and understanding about the consequences of different policy options. One approach that can help managers communicate with stakeholders is system dynamics modeling. Used interactively in a public forum, a system dynamics model can be used to explain the resource system and illustrate the effects of strategies proposed by managers or suggested by forum participants. This article illustrates the process of building a strategic-level system dynamics model using the case of water management in Las Vegas, Nevada. The purpose of the model was to increase public understanding of the value of water conservation in Las Vegas. The effects of policies on water supply and demand in the system are not straightforward because of the structure of the system. Multiple feedback relationships lead to the somewhat counterintuitive result that reducing residential outdoor water use has a much greater effect on water demand than reducing indoor water use by the same amount. The model output shows this effect clearly. This paper describes the use of the model in research workshops and discusses the potential of this kind of interactive model to stimulate stakeholder interest in the structure of the system, engage participant interest more deeply, and build stakeholder understanding of the basis for management decisions.

Keywords: System dynamics; Water conservation; Las Vegas, NV; Public participation; Stakeholder involvement; Simulation modeling

1. Introduction

The primary tasks faced by water resource managers and policy-makers are to identify and evaluate effective strategies for achieving resource management objectives. A secondary, but increasingly important challenge is to develop stakeholder support for those strategies. Policy-makers rarely can make and implement decisions in isolation from stakeholders. At a minimum, management decisions generally require stakeholder support of funding initiatives or legislative changes. In some cases resource management policies require stakeholders to change their behavior. Successfully implementing some kinds of water conservation programs, for example, depends on convincing water users to reduce the amount they use. While some success can be achieved through economic incentives and regulations, stakeholders are more likely to fully support policies if they understand the causes of the problem and consequences of policy decisions. Even conservation programs that include non-voluntary measures consider public education about the system a critical component (e.g. Platt and Delforge, 2001). Hale (1993) divides public involvement into three categories: public awareness, which he defines as raising knowledge that a problem or issue exists; public education, which is providing information so the public can understand government policies and actions; and public participation, in which the public has an opportunity to assist in decision-making. Building support for environmental management decisions involves at least the first two levels: raising public awareness of the issue and developing understanding of the connections between potential solutions and system consequences.

Communicating the complexity of a resource system to a broad stakeholder audience can be difficult, however, because of the dynamics of the system, differences in technical expertise of the audience, and potentially conflicting perspectives among stakeholders. Resource supplies and demands may vary over time and in response to other variations in the system. Changes in one part of

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the system can feed back to cause unexpected changes in other parts of the system. Interventions often have non-linear, indirect, or synergistic effects. A given outcome can have multiple causes and delays between actions and effects can make it difficult to identify policy options. Understanding the way resource systems work also requires a certain amount of technical knowledge, which may not be shared by all members of the audience. Finally, stakeholders in a resource management system may hold conflicting mental models about the way a system works, the causes of resource problems and acceptable solutions.

System dynamics modeling is one approach that can help managers meet the challenges of communicating with stakeholders. A system dynamics model represents the key feedback structures in the system. Simulating the model shows the effect of the system structure on policy interventions. Although such computer-based simulation tools are often used to help decision-makers evaluate policy options, their potential for public communication could be exploited more fully. In particular, system dynamics models can help managers communicate information about the structure of the system and show stakeholders, visually and with a minimum of technical jargon, the consequences of different actions. Using a model in an interactive forum can engage participants in discussions that foster a common understanding about the system and consensus about management actions. The purpose of this paper is to illustrate how a resource manager would create a simple system dynamics model for public communication and what benefits she or he might expect. The paper describes the steps followed to develop a model for improving public understanding of water management options in Las Vegas, Nevada and discusses its use in public workshops.

System dynamics is a problem evaluation approach based on the premise that the structure of a system, that is, the way essential system components are connected, generates its behavior (Richardson and Pugh, 1989; Sterman, 2000). If dynamic behavior arises from feedback within the system, finding effective policy interventions requires understanding system structure. System dynamics is well suited to analysis of problems whose behavior is governed by feedback relationships and that have a long-term time horizon (Vennix, 1996). It is not well suited to one-time decisions, such as facility siting decisions. The process of creating a simulation model helps clarify the resource management problem and makes modelers assumptions about the way the system works explicit. Once a model is built, it can be used to simulate the effect of proposed actions on the problem and the system as a whole. As Forrester (1987) notes, this kind of tool is necessary because, while people are good at observing the local structure of a system, they are not good at predicting how complex, interdependent systems will behave.

A system dynamics analysis proceeds through several major steps, shown below (e.g. Ford, 1999; Richardson and Pugh, 1989). These are the same steps followed in any problem solving process. In a system dynamics context they are applied to problems where the issue can be represented as a problematic trend over time. As with any problem solving process, this is an iterative process. Results at any stage can feed back to previous steps. For example, step 4, Build confidence in the model, may require many iterations back to step 2, to refine the system description. Building a model for decision support within an organization may use only the first five steps. Using the model for public communication includes step 6.

1. Define the problem
2. Describe the system
3. Develop the model
4. Build confidence in the model
5. Use the model for policy analysis
6. Use the model for public outreach

Resource managers can involve stakeholders in the modeling process at different stages. At the least participatory level, Hale's (1993) category of raising public awareness, managers can use a completed model to demonstrate the effects of alternative policies to stakeholders. A more participatory scenario would allow participants to suggest their own strategies to be tested. Depending on the way the discussion is facilitated, this approach can greatly enhance participant understanding of the resource system and effects of alternative management decisions. At the most participatory level, stakeholders can help develop the simulation model that represents system structure. Costanza and Ruth (1998) describe three cases in which system dynamics models were used in the problem definition step for scoping resource management problems. Van den Belt (2000) describes the use of system dynamics for "mediated modeling" with stakeholder groups, an example of involving stakeholders in step 2, system conceptualization. Vennix (1996) describes several cases of stakeholder participation in model building, steps 1–4 above. Guo et al. (2001) describe the use of a system dynamics approach for policy analysis (step 5), in environmental planning in China.

In a previous paper (Stave, 2002), I described a case in which system dynamics was used to help a stakeholder advisory group make policy recommendations about transportation and air quality problems in Las Vegas, Nevada. In that case, system dynamics was used to structure the advisory group's discussions from beginning to end — from their initial definition of the problem to their identification and evaluation of policy alternatives. They used the modeling process and model as a decision-support system and stakeholders were involved in all steps of the model development process. In this paper, I describe a model that was developed as a stakeholder learning-support system (LSS), (Ford, 1996). Stakeholders were not involved in model development, but were given the opportunity to use the model in a facilitated forum as step 6. The following sections explain and illustrate the application of each of the model development steps.

1.1. Define the problem

The first step is to identify one or more key variables whose behavior over time defines the problem. The graph of these indicator variables is used as a reference graph in step 4 to test whether the model adequately represents the system generating the problem.

Fig. 1 shows the problem definition graph for the Las Vegas, Nevada water management case. Las Vegas is one of the fastest growing metropolitan areas in the US, located in one of the country's most arid regions. The population in 2000 was over 1.4 million people (CCA, 2000), and has been increasing by 5000 to 7000 people per month for the past decade (LVCVA, 2000). Fig. 1, the Southern Nevada Water Authority's 1999 projection of water supply and demand (Southern Nevada Water Authority (SNWA), 2000), represents the management problem graphically. Water resources fluctuate, then settle around a level of approximately 8.02×10^8 m^3 (650,000 acre-feet) per year. Demand increases steadily with population growth until it exceeds supply in approximately 2025. The critical management question is how to extend the point at which demand exceeds supply further into the future.

Management options fall into two basic categories: increase supply or reduce demand. The Southern Nevada Water Authority (SNWA) is pursuing a wide variety of options. However, because increasing supply is politically and economically expensive, the SNWA considers conservation a critical component of its water planning efforts (SNWA, 2002). SNWA expects it will be able to achieve a 26.5% reduction in use over their projection of demand without conservation by 2020 through a combination of changes in water pricing and conservation education. Convincing users of the importance and effectiveness of conservation is key to meeting this goal.

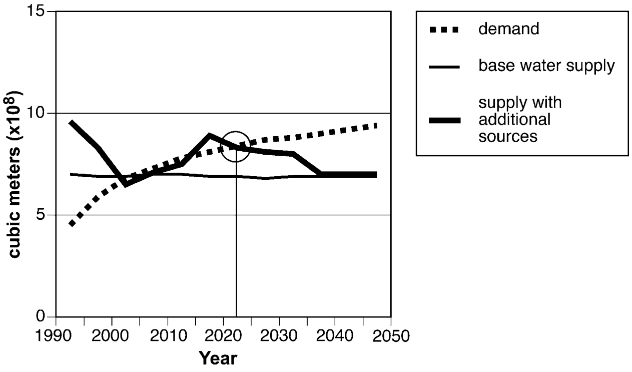


Fig. 1. Las Vegas, Nevada metropolitan area water supply and demand. (Source: SNWA (1997, 2000)).

1.2. Describe the system

Describing the system means identifying the system structure that appears to be generating the problematic trend. This involves extracting the essential elements and connections from the real system that produces the observed or anticipated behavior. The final representation of key variables and causal links is called the dynamic hypothesis, that is, the structure that is thought to explain the dynamic behavior in question. This structure serves as the basis for creating the simulation model.

Fig. 2 shows the hydrologic context of the system. The Las Vegas metropolitan area is contained within a 411,000 ha (1586 square mile) drainage basin that extends approximately 65 km (40 miles) from the Spring Mountains in the west to Lake Mead in the southeast. Fig. 3 shows the path of water in the Las Vegas system. Most (88%) of the area's water supply is drawn from Lake Mead; the rest is drawn from groundwater in the basin (SNWA, 2001). After treatment, water is distributed throughout the valley. Water used indoors is sent to one of three wastewater treatment plants, all of which discharge their treated effluent to the Las Vegas Wash, the primary outflow from the basin. Water used outdoors, for irrigating lawns, landscaping and golf courses, for example, either returns to the atmosphere through evapotranspiration, contributes to shallow subsurface soil moisture, or flows overland through street drains and flood control channels to the Las Vegas Wash. Dry weather flows in the Wash are sustained primarily by effluent from the three sewage treatment plants in the valley, which discharged an average 0.52×10^6 m^3 (138 million gallons) per day in 1997 (LVWCC, 2000). Additional flow in the Wash comes from resurfacing shallow groundwater, excess irrigation water, and stormflow. Las Vegas Wash discharges into Lake Mead 6 miles upstream from the city's drinking water intake. Water taken from Lake Mead for the Las Vegas metropolitan area's water supply returns to the Las Vegas Valley upstream from the Wash, creating a physical loop in the metropolitan area's water system.

Water supply is affected by the circular nature of the system. Since Lake Mead is part of the Colorado River system, Las Vegas' water withdrawals are limited by laws governing the Colorado River to a maximum consumptive use of 3.7×10^8 m^3 (300,000 acre-feet) per year (LVWCC, 2000). However, the city receives "credit" for the amount of treated water it returns to Lake Mead from wastewater treatment plants, providing water quality standards are met. With the "return flow credits" Las Vegas is permitted to withdraw from Lake Mead the allocated amount plus the amount of return flow credited. The total supply varies, therefore, with the amount used. In 2000, return-flow credit was approximately 1.85×10^8 m^3 (150,000 acre-feet), increasing the total water supply to 5.55×10^8 m^3 (450,000 acre-feet) (SNWA, 2000).

Water demand is driven largely by residential use. As shown in Fig. 4, 65% of municipal water is used by

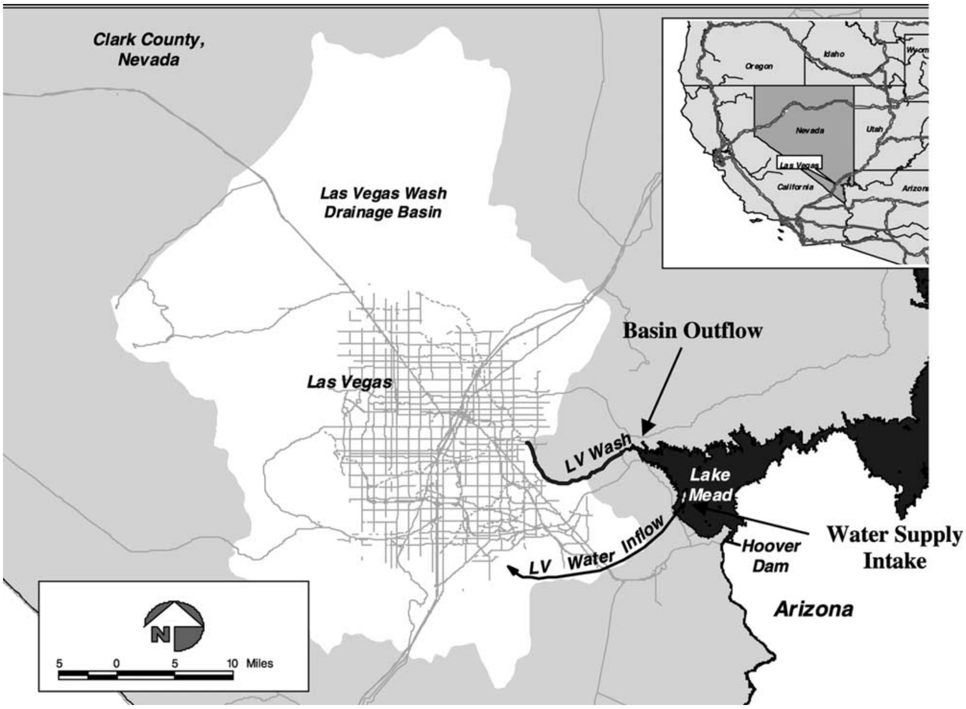


Fig. 2. Las Vegas Valley drainage basin showing water supply intake and Las Vegas Wash drainage.

residential customers. Of that, about 40% is used indoors and 60% is used outdoors. In spite of the salience of water quantity and quality issues in the arid Las Vegas environment, there is little understanding among residents of the metropolitan area about sources and uses of water in this system. Per capita water use is among the highest in the US. Most residents are relatively recent arrivals from other parts of the US, many from more humid climates with

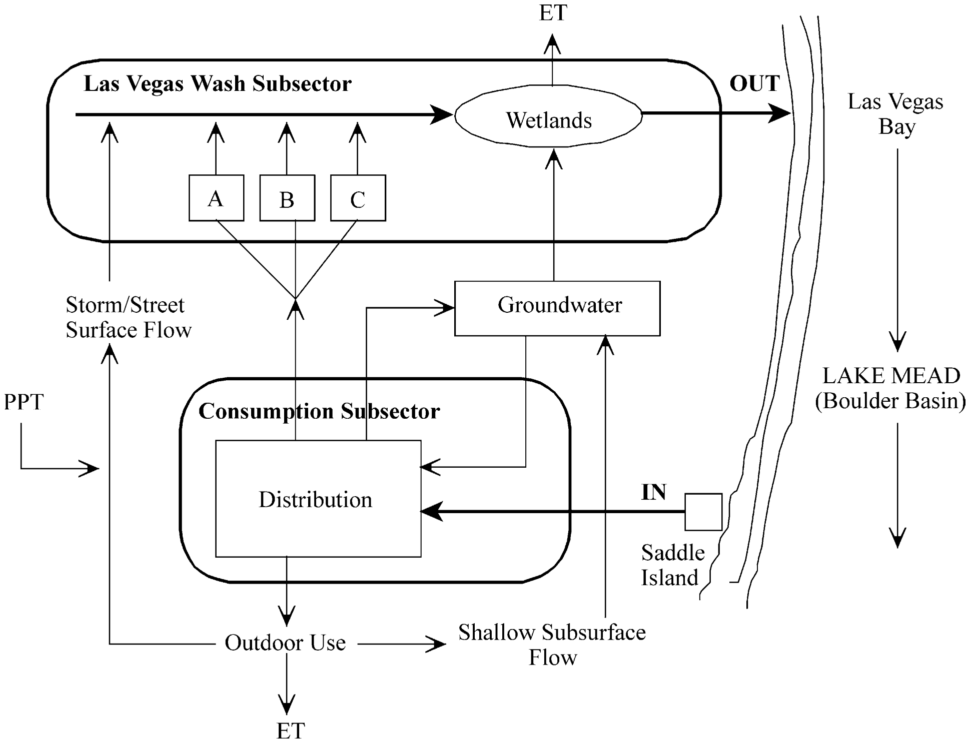


Fig. 3. Schematic diagram of the Las Vegas water system. ET represents evapotranspiration, PPT represents precipitation, and A, B, and C indicate the three wastewater treatment plants that serve the Las Vegas metropolitan area.

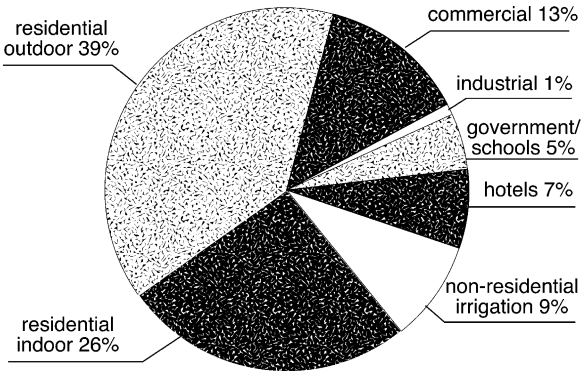


Fig. 4. Distribution of water use in Las Vegas by category. (Source: SNWA (1997)).

greater annual precipitation. They tend to prefer landscapes that include green lawns and lush vegetation, perhaps representing landscapes where they came from, rather than native desert vegetation. Hence, 39% of all water used in Las Vegas is used for residential irrigation, mostly for watering lawns.

1.2.1. Dynamic hypothesis

The problem being modeled is the relationship between supply and demand in the Las Vegas water system. Based on the fundamental systems premise that a system's structure generates its behavior, the next step was to identify the supply and demand structure of the Las Vegas water system. The supply side of the system consists of the physical flows of water; the demand side of the system focuses on the resident population and the distribution of water use. The model boundary includes the primary source of water supply, the Colorado River at Lake Mead and the primary pathways of flow within the Las Vegas Valley. It also includes the Las Vegas resident population. Fig. 5 shows the major variables affecting supply and demand and their connections. The feedback loop shown represents the return flow credit mechanism. This structure represents the dynamic hypothesis, or preliminary explanation of the structural relationships that lead to changes over time in supply and demand. Supply changes in response to external sources, but also in response to changes in water use, through the mechanism of return flow credit. Demand increases as population increases. When water use increases, treated wastewater flow increases. Return flow credit also increases, increasing supply. But when demand increases faster than supply, demand eventually equals, then exceeds supply.

1.3. Develop the model

In the model development stage, the dynamic hypothesis is represented as a set of stocks and information flows. Figs. 2, 3, 5, and 6 show progressively more abstract representations of the Las Vegas Water System. While they all represent the path of water flow in the Las Vegas Water System, Fig. 6 distinguishes between stock variables, or places water accumulates in the system, and flow variables that regulate the rate at which water moves from one stock to another. In all representations, water is withdrawn from

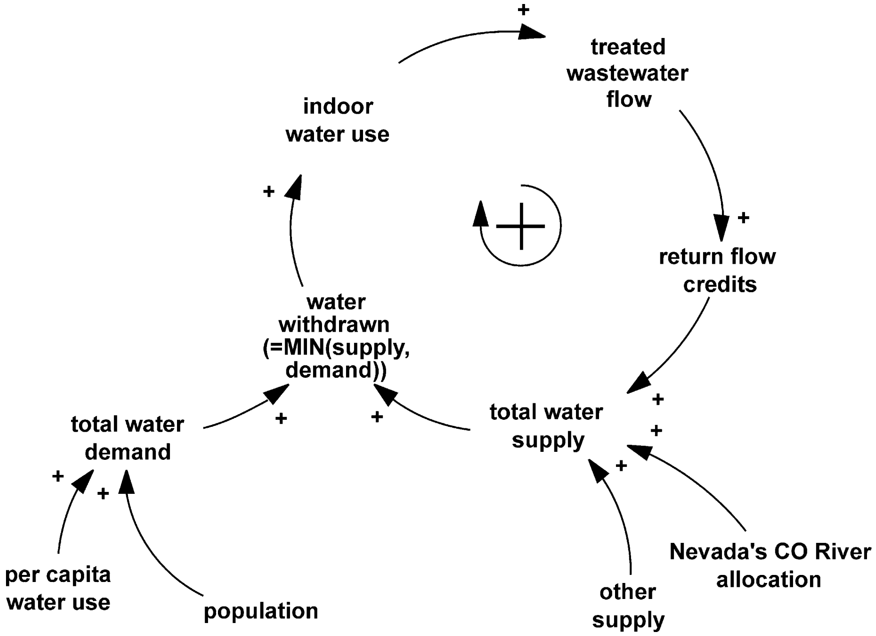


Fig. 5. Las Vegas water system causal loop diagram showing the effect of residential indoor water use on supply. (A " + " on the arrow connecting two variables indicates the variable at the tail of the arrow causes a change in the variable at the head of the arrow in the same direction. A " − " would indicate a change in the opposite direction. E.g., the diagram proposes that as indoor water use increases, it will cause treated wastewater flow to increase. The sign at the center of the loop indicates it is a positive feedback loop, in which a change in one variable feeds back to reinforce the initial change.)

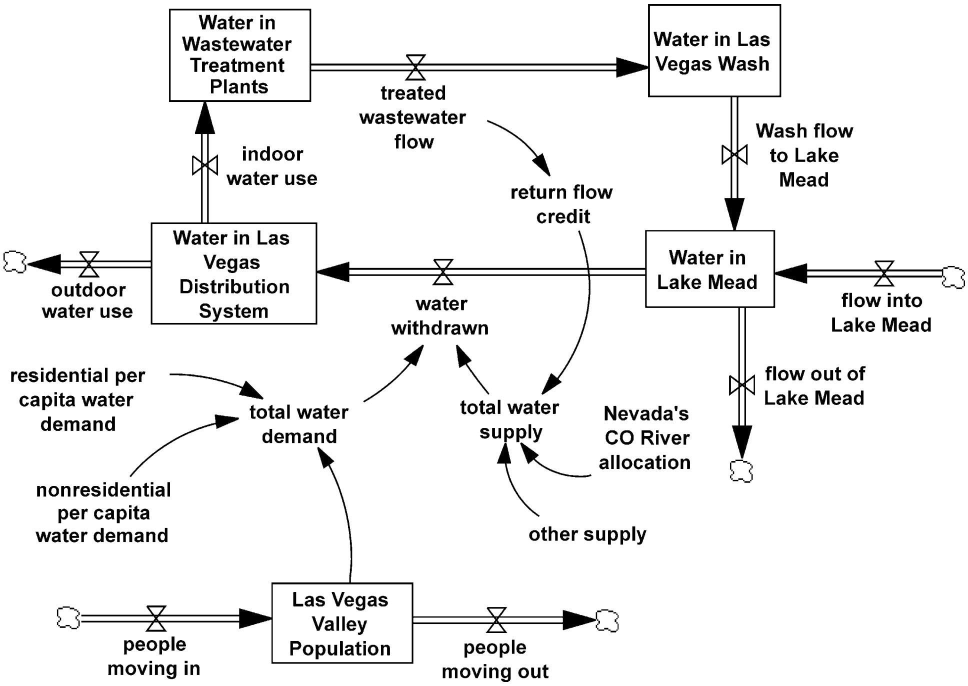


Fig. 6. Las Vegas water system model structure. Boxes represent stocks, or accumulations in the system. Double arrows represent material flow which is regulated by rate variables.

Lake Mead and distributed among customers based on water demand. Some is treated at municipal wastewater treatment plants, and then discharged into the Wash, which eventually returns it to Lake Mead. Water treated in the wastewater treatment plants becomes part of water supply, through the mechanism of return flow credits. Residence time in the distribution system, wastewater treatment plants and the Las Vegas Wash is set at approximately 1 week. Residence time in the distribution system is set at 1 month. Water demand is based on population and per capita water demand. The model was developed using Vensim PLE version 3.0 software (Ventana Systems Inc., 1998).

1.3.1. Assumptions in the model

The model contains several simplifying assumptions. For example, the model assumes water supplies will remain as projected by the SNWA, the return-flow credit mechanism will not change, and the Colorado River will remain the principal source of water for Las Vegas. Initial values are based on SNWA (1997) estimates of total per capita water use of approximately 1.1 m^3 (290 gallons) per capita per day (calculated as total water used divided by total residential population), and 0.7 m^3 (190 gallons) residential use per capita per day (calculated as water used by residential customers divided by residential population). The distribution of water demand is assumed to remain constant for each simulation run. Water losses in the system are assumed to be negligible.

When demand exceeds supply, the model only allows the amount of water available to be withdrawn. At this point, the water stocks are in equilibrium, although population continues to increase. Although the specific equilibrium values depend on the model parameters in a given run, the amount of water in the treatment plants and the Las Vegas Wash is the same at equilibrium and there is approximately twice as much water in the distribution system. The model apportions the available water equally among residential and non-residential uses, and assumes it is distributed in the same proportions to indoor and outdoor uses. Therefore, although population continues to increase after water demand exceeds supply, return flow credit reaches a maximum value as soon as demand exceeds supply. Potential return flow credit increases are offset by decreases in per capita water available and, thus, use. Total water supply, therefore, reaches a maximum constant value as soon as demand equals supply. Since the purpose of this model is to demonstrate the relative effects of the range of management options, it includes only resources that have already been secured. The 2002 SNWA Water Resources Plan (SNWA, 2002) lists 13 resource options for meeting future demand. These range from uncertain resources such as interim surplus flow on the Colorado River to very expensive resources such as seawater desalination exchanges with California and stormwater recapture. While SNWA expects that it will be able to meet projected future demand using some combination of resources, it is placing a strong emphasis on reducing demand through conservation. Model users have the option of adding new supplies as well as implementing conservation measures.

The model assumes that the most significant factors affecting the change in population are immigration and outmigration. The model does not account for births and deaths. This assumption has been reasonable throughout the development of the metropolitan area. The model uses population growth projections made by the Nevada State Demographer (NDWP, 2000).

1.4. Build confidence in the model

Before using the model to identify and test policy options, it must be validated against the observed or anticipated trend. If the model reproduces the problematic trend, and represents the system as stakeholders understand the real system actually works, we assume the model contains the critical elements generating the problem. If it does not reproduce the reference graph, the modelers must go back to the second step to revise the dynamic hypothesis or model structure. Fig. 7 shows the base case output of the model. To determine demand, the model uses the per capita water use assumptions described above multiplied by the population projections of the Nevada State Demographer. Supply is the sum of the two fixed sources of supply (groundwater and allocation from the Colorado River) plus the amount of return-flow credit. Comparing Fig. 7 to Fig. 1 shows the model reproduces the general trends that define the water management problem. Demand in Fig. 7 follows the shape of the projected curve in Fig. 1, reaching approximately 10×10^8 m^3 in 2050. Supply levels off just above 8×10^8 m^3 and demand exceeds supply in approximately 2025. This indicates the model captures the essential structure of the system and can be used for policy testing.

1.5. Use the model for policy analysis

When the model structure has been validated, it can be used to test the effect of policy interventions on the problem. This includes studying the model structure to identify policy levers, then simulating the effect of those changes.

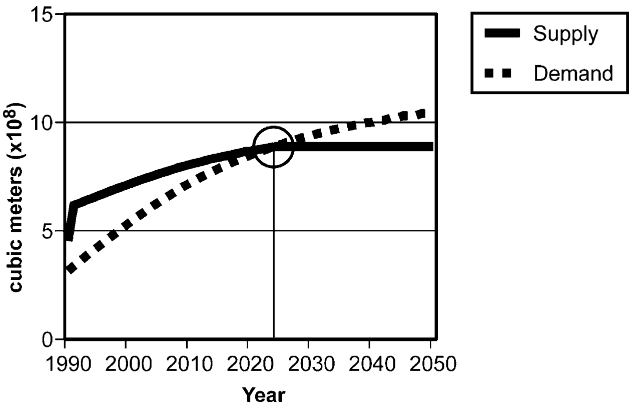


Fig. 7. Base case model output.

1.6. Use the model for public outreach

Several authors have discussed the benefits of group model-building or involving stakeholders in model development (e.g. Vennix, 1996; Andersen and Richardson, 1997; Van den Belt, 2000; Costanza and Ruth, 1998; Stave, 2002). But even when stakeholders are not involved in the model development process, a completed model can be an effective public outreach tool. The water model described above was used in three pilot workshops and seven research workshops to test the effectiveness of using a completed system dynamics model for engaging stakeholders in discussions about resource management. We recruited a total of 83 Las Vegas community members to join in a discussion of Las Vegas water management issues. Workshop participants, ranging in age from 18 to 65 years old, included teachers, students, environmental professionals, and retired citizens. None of the participants had any previous experience with system dynamics models. The workshops lasted approximately two and a half hours. Participants were given a brief introduction to the problem using Fig. 1 above and an overview of the water system structure using Figs. 2 and 4. After the introduction, we spent about 45 min in a facilitated discussion of what might be done to extend the time at which demand would exceed supply. We took 5–10 min to introduce the concept of a model, describing it as an abstraction of reality for a given purpose, and stepped through Figs. 2, 3, and 6 to show how we progressively abstracted from the map of the watershed to create the model. The key to this transition was showing the same pathway of flow—from Lake Mead, into the distribution system, to the treatment plants, into the Wash, and back to Lake Mead—in each diagram. We explained that the purpose of this model was to help evaluate the relative merits of different policy options for addressing the problem of water demand exceeding supply in the near future. We then used the model to simulate the effects of policy and management ideas participants had proposed in the earlier discussion, and used the model output to continue the discussion of potential policy and management options. A future publication will discuss the workshops and research results in more detail.

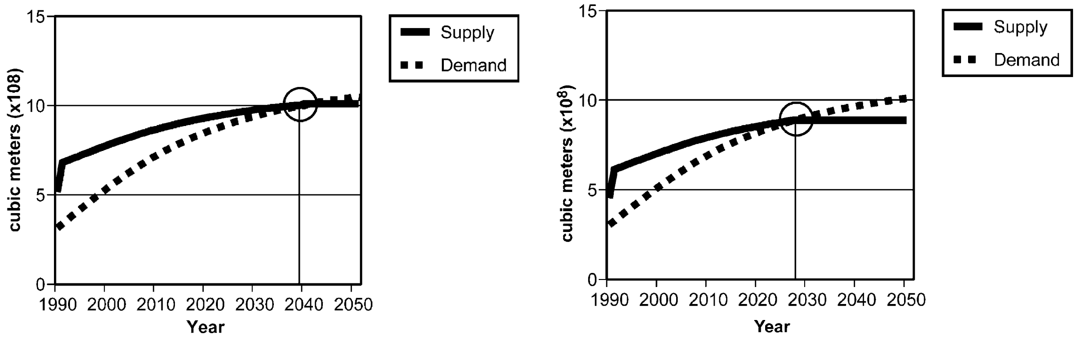
1.6.1. Policy alternatives and model results

Participants in all workshops suggested the following similar set of management strategies for extending the time it takes for water demand to exceed supply. Fig. 8a–f show representative model output from each of the policy tests, holding all other parameters constant. Each group proposed somewhat different parameter values for each run. Some groups explored a range of values for different parameters. The values used to generate these figures are those workshop participants felt would represent politically, economically or socially reasonable possibilities.

a.*Increase supply*. Even though participants felt it would be expensive to find new sources of supply, they thought that

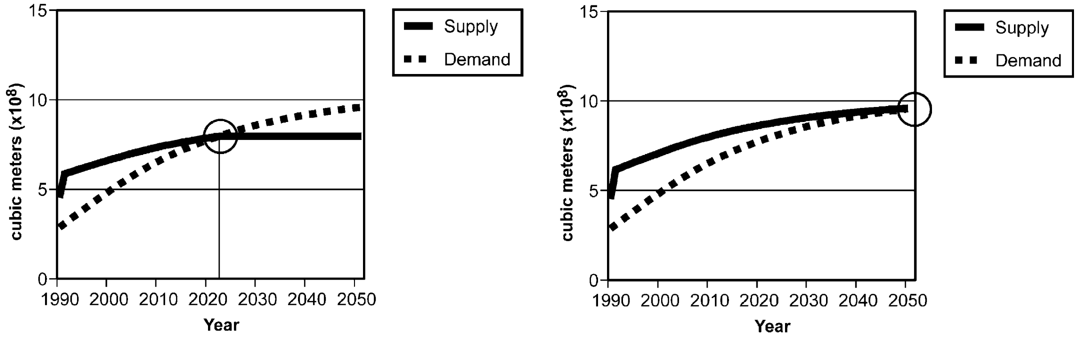
a. Increased Supply

b. Decrease hotel use



c. Decrease indoor residential use

d. Decrease outdoor residential use



e. Decrease inmigration

f. Combination of policies

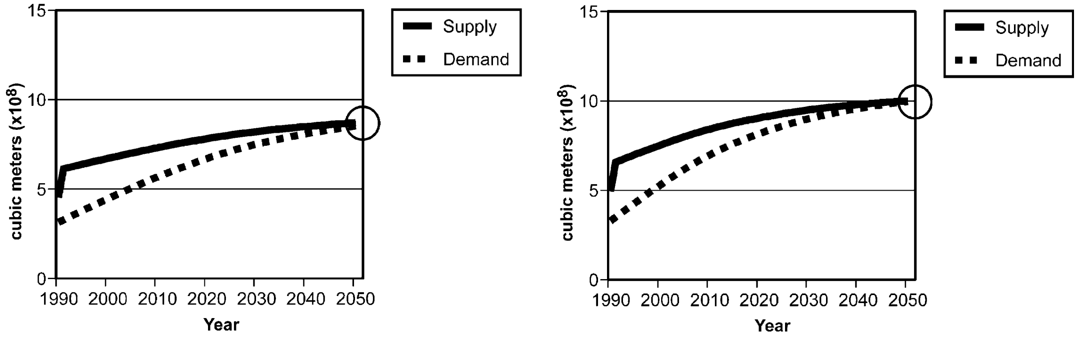


Fig. 8. Results of model simulations for policy tests.

increasing supply would eventually be necessary. Discussion centered around what level of increase might be reasonable. Fig. 8(a) shows the effect of raising the total supply from the current 3.7×10^8 m^3 (300,000 acre-feet) per year by 0.62×10^8 m^3 (50,000 acre-feet), approximately 17%.

b. *Make hotels/casinos conserve*. The hotel/casino industry is a central economic focus in Las Vegas. Many hotels appear to use water extravagantly because they have lush landscaping and many fountains and pools. Although the hotel industry uses only 7% of the municipal water supply, the perception among visitors and residents is that they use much more. Workshop participants wanted to test the effect of reducing hotel water use. Fig. 8(b) shows the effect of cutting hotel water use in half, from approximately 7% of total water use to 3.5%.

c. *Reduce residential indoor water use*. Reductions in residential indoor use could be achieved through the use of low-flow showerheads, more water-efficient appliances, low-flush toilets, or price-based incentives to decrease personal water use. Fig. 8(c) shows the effect of reducing residential indoor water use by 0.09 m^3 (25 gallons) per capita per day, from the current estimate of 0.29 m^3 (76 gallons) to 0.19 m^3 (51 gallons) per capita per day.

d. *Reduce residential outdoor water use*. Residential outdoor use could be reduced through landscape conversion, from lawns to xeriscape, for example. Fig. 8(d) shows the effect of reducing residential water use by 0.09 m^3 (25 gallons) per capita per day outdoors (from 0.43 m^3 (114 gallons) to 0.34 m^3 (89 gallons) per capita per day).

e. *Decrease population (or slow growth)*. There was much debate about whether or not this would be a politically feasible option. Some participants felt that population growth would begin to decrease without deliberate action as problems such as traffic congestion and air pollution worsen, making Las Vegas less attractive as a place to live. Fig. 8(e) shows the effect of reducing immigration from an initial 7000 people per month to 5000 people per month.

f. *Combination strategies*. Most of the workshop groups felt that no single policy would solve the problem, and so suggested several combination strategies. Fig. 8(f) represents a combination of increasing supply by $0.31 \times 10^8\ \mathrm{m}^3$ (25,000 acre-feet) per year (a 9% increase) and decreasing residential outdoor water use by $0.08\ \mathrm{m}^3$ (20 gallons) per capita per day (an 18% reduction).

All options except reducing indoor water use move the point at which demand exceeds supply beyond 2025, but some options appear to be more effective than others. Reducing hotel use by 50%, for example, would only buy a few more years, even if that dramatic level of reduction were possible. Increasing supply by 17% extends the crossing point by about 12 years. Reducing population growth and reducing residential outdoor water consumption by the suggested amounts both keep supply above demand for the planning horizon. Combining a relatively small increase in supply with a modest reduction in residential outdoor water use yields the same effect as reducing population growth.

2. Discussion

The challenge resource managers face in communicating with resource stakeholders about a complex and dynamic resource system is to reduce the complexity of the system but still explain the key elements that govern the system's response to policy interventions. They also need to engage the interests of stakeholders who may have different levels of technical expertise. In our workshops, we found the model greatly enhanced participant discussions about the system. The use of the model shifted the discussion from who was to blame for the water problem (hotels and golf courses) and how to solve it (get more water or make the water wasters use less) to how the system works and why it responds to policy changes as it does. The model output graphs, generated from participant suggestions, served as a "hook" that engaged participant interest and led to further questions about the system.

In discussions before the model was introduced participants offered solutions to the Las Vegas water management problem based on a variety of different mental models about how the system works. Their ideas were largely based on their experiences with water issues elsewhere or their personal observations of water misuse in Las Vegas. Most of the participants first suggested increasing supply. Their ideas for reducing demand focused on hotels and golf courses, which they believed were using most of the water. Those who thought we should reduce per capita use focused on reducing indoor use. They described programs from other parts of the US that subsidized low water use appliances or where water was offered in restaurants only by request. In the first part of the discussion, we recorded participant suggestions, and grouped them in the five general policy categories (a through e) above.

When we used the model to simulate participant suggestions in the second part of the workshop, the discussion shifted from a focus on solutions to questions about why different options had different effects. After soliciting suggestions for specific parameter values for each policy option, we ran the model, then asked participants to describe what they saw in the graph and how it compared with previous graphs. After a few simulations, participants began volunteering suggestions for the next simulation as soon as they saw the graph. Because we introduced the problem graphically (explaining that the goal was to move the crossing point further out into the future) and presented the model output in the same form, participants could judge easily whether their suggestion had the desired effect and how it compared to other suggestions. At first, participants focused on the crossing point, but then began to notice that different options had different effects on the supply and demand lines. They began asking questions about what caused the lines to change.

The liveliest discussions were stimulated by counter-intuitive results. Participants were surprised to see that small changes in per capita use could be as effective as larger increases in supply and that reducing outdoor use was more effective than reducing indoor use. Many expected increasing supply to be the most effective policy lever and indoor water conservation to be the best conservation policy. Model simulations show instead that reducing outdoor water use has a greater effect than reducing indoor use, and that reducing outdoor use is a more powerful policy lever than increasing supply. Even without considering the costs involved, the model shows that supply would have to be increased substantially to make a difference. By contrast, a small decrease in per capita consumption has a considerable effect. In addition, the system appears straightforward but is dynamically complex because of the return-flow credit mechanism. Supply *increases* with increased *indoor*water use, because indoor water is sent to the wastewater treatment plants and is counted for return-flow credit. Decreasing indoor water use therefore decreases supply at the same time it decreases demand, and thus does not produce the expected effect on the supply–demand crossing point. Decreasing outdoor water use, however, has a great effect because it decreases demand and does not reduce supply. The model output graphs showed these effects clearly. In both cases, the surprise was generated by comparing the model output from different policies.

Several things helped make this model effective for communicating with the public. We framed the presentation around a specific management question, tied the model introduction to a map with which everyone was familiar, and kept the model small. Instead of a general information session on the water system, we described the problem graphically, then started the discussion by asking: how do you think we could move the crossing point out later than 2025? Participants seemed to feel more comfortable with a specific management question posed in this way than when the discussion was presented as a general exploration of water management issues. After experimenting with several ways of introducing the water system, we found that the map of the drainage basin worked best. Participants could identify major streets and landscape features on the map. We anchored the next two levels of abstraction, the schematic diagram of the water system (Fig. 3), and the system diagram (Fig. 6) to map features (Lake Mead and the Las Vegas Wash) and at each level described the physical pathway of water flow (from the Lake, to users, to the Wash, and back to the Lake). It helped that the model was small enough to fit on one display screen, and that we could lay out the model to mimic the layout of the real system. This allowed us to draw the connection between the basin diagram and the model structure.

We also found users do not need to know anything about systems modeling to be able to gain system insights. We experimented in the pilot water model workshops with different amounts of introduction to systems concepts and found that users were able to follow the model with almost no introduction to models, modeling, or systems thinking. This supports Ford's (1996) experience with an LSS for the Snake River system. He found that it was possible to bring participants quickly to a level of understanding about the model that they could work with easily.

This case study demonstrated several benefits of system dynamics for public communication about resource management. The ability to run model simulations in an interactive forum allows stakeholders to participate in the evaluation and comparison of different policies. Model simulation provides immediate feedback to participants about their ideas. Model output graphs provide a powerful visual way to compare the results of different policy tests. Seeing unexpected results generated in response to participant suggestions engages their interest and provides opportunities for educating participants about the system in response to their questions. The use of the model not only helps participants better understand the basis for management decisions, but also stimulates discussion among group members and can help build the consensus and support resource managers need to implement their decisions.

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