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SYSTEM DYNAMICS TO SUSTAINABLE WATER RESOURCES MANAGEMENT IN THE EASTERN SNAKE PLAIN AQUIFER UNDER WATER SUPPLY UNCERTAINTY[1]

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ABSTRACT: Water supply uncertainty continues to threaten the reliability of regional water resources in the western United States. Climate variability and water dispute potentials induce water managers to develop proactive adaptive management strategies to mitigate future hydroclimate impacts. The Eastern Snake Plain Aquifer in the state of Idaho is also facing these challenges in the sense that population growth and economic development strongly depend on reliable water resources from underground storage. Drought and subsequent water conflict often drive scientific research and political agendas because water resources availability and aquifer management for a sustainable rural economy are of great interest. In this study, a system dynamics approach is applied to address dynamically complex problems with management of the aquifer and associated surface-water and groundwater interactions. Recharge and discharge dynamics within the aquifer system are coded in an environmental modeling framework to identify long-term behavior of aquifer responses to uncertain future hydrological variability. The research shows that the system dynamics approach is a promising modeling tool to develop sustainable water resources planning and management in a collaborative decision-making framework and also to provide useful insights and alternative opportunities for operational management, policy support, and participatory strategic planning to mitigate future hydroclimate impacts in human dimensions.

(KEY TERMS: water supply uncertainty; system dynamics; multidisciplinary research; human dimension; sustainable water resources; sustainable water resources planning; water resources planning; sustainable water management; groundwater/surface-water interaction; climate change; climate variability.)

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INTRODUCTION

To maintain reliable and sustainable water resources systems in the face of uncertain climatic and hydrologic conditions, it is imperative that systems should be in place to address impacts of future water supply and demand on water systems in a changing environment. The Eastern Snake Plain Aquifer (ESPA) is the largest and the single-most important aquifer in the state of Idaho in that it underlies the largest irrigated agricultural area in the Pacific Northwest, which produces a majority of Idaho's agricultural commodities. Thus, much of

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Idaho's agricultural production relies on this critical water resource. Therefore, alternative management strategies over the next few decades are of great interest to federal, state, and local agencies that are responsible for supplying affordable water, sustaining the continuum of system reliability, and increasing annual water revenues under an uncertain future water supply.

However, developing effective adaptive management strategies for coping with global change in a complex, highly managed water system such as the ESPA is challenging. Careful consideration and investigation are required to obtain the predefined goals through the inherent feedback processes dynamically obtained within the system. Additionally, implementing effective management strategies into real-world problems often requires intense scientific efforts not only because the fundamental mechanism governing the structure of a problem relies on nonlinear dynamics, but there are also communication challenges between model developers, water resource managers, and stakeholders in describing the complex relationship between the water resources and the human systems that rely on this resource.

Over the past few decades, numerous studies using a computer modeling framework have been investigated to better understand water resources systems and enhance system reliability associated with them. Simulation models, in particular, are widely used and have become the most commonly used method for monitoring, planning, and managing water systems (Fisher and Palmer, 1997; Palmer *et al.*, 2002). The complexity and versatility within the mathematical simulation framework often make it the most commonly used method for evaluating alternative water management options (Sigvaldason, 1976; Palmer and Holmes, 1988; Ryu *et al.*, 2009). Such a versatile modeling environment facilitates the rapid generation and evaluation of new alternatives and provides user-friendly graphical interfaces. As a result, simulation models are commonly applied to assist water resources planners in monitoring systems and to evaluate operational policies and alternatives to those policies.

System dynamics (SD) is a computer simulation technique designed to provide a flexible avenue with which to identify problems and to obtain alternative solutions by enhancing our capacity to extrapolate and interpolate in a meaningful manner in a broader context (Winz *et al.*, 2009). As the concept of SD has been introduced by J.W. Forrester (Forrester, 1969), various applications have been implemented in many disciplines, including the insurance industry (Cavaleri and Sterman, 1997), urban planning (Forrester, 1970), global resource dynamics (Meadows *et al.*, 1972), environmental policy (Vennix, 1996), the K-12 education (Chandler and Boutilier, 1992; Mandinach and Cline, 1994), and water resources planning and management (Gao and Liu, 1997; Simonovic and Fahmy, 1999; Ahmad and Simonovic, 2000; Guo *et al.*, 2001; Stave, 2003; Tidwell *et al.*, 2004; Li *et al.*, 2010). A major advantage of SD as compared with other modeling approaches is that the relationship between "cause" and "effect" can be easily visible as a matter of stocks and flows processes. Conceptually, SD can deal with a high degree of nonlinear problems, which are the most likely to exist in highly managed environmental systems. Furthermore, it can be used as a qualifier relating to conceptual uncertainties and limited number of variables created to replicate limited historical targets in calibration. An SD model allows complex environmental problems to be converted into a more manageable modeling description. For that reason, the SD-modeling approach has become known as an effective tool for providing a means for testing the effectiveness of training and decision aids used to improve systems thinking skills (Sweeney and Sterman, 2000).

Computer simulation models associated with SD concepts have continually evolved in water resources planning and management studies. By the 1980s, the U.S. Army Corps of Engineers' Hydrologic Engineering Center (HEC) developed the HEC-3 and HEC-5 models, and applied the models to conservation storage and flood control systems (Yeh, 1985). During the 1990s, Palmer (1993) introduced the "Shared Vision Planning" (SVP) concept as a procedure that allows interested participants to achieve consensus by forming a shared vision of a system or process. This concept was also defined by National Drought Studies (Werick and Whipple, 1994). SVP does not necessarily result in consensus, but increases the chance of that happening by reducing cognitive conflict, so participants can focus on inherent interest and values conflicts. Thus, the advantages of this concept are to (1) provide insights into questions and concerns that generate conflicts, (2) include information that represent the interest and perspectives of all participants, (3) obtain equitable benefits for all participants, and (4) provide the opportunity for a high level of involvement by all stakeholders. The modeling environment includes software packages such as the STELLA (ISEE, 1985), PowerSim (Powersim Solutions, 1993), MODSIM-DSS (MODSIM-DSS, 2010), RiverWare (RiverWare, 2010), SIMULAB (The Math Works, 1991), and Vensim (Vensim, 2007). The SD embodied in the STELLA framework, in particular, has been widely applied to water resources planning and management nationally and internationally. A benefit of this modeling environment is interactive use in a group setting to support joint fact-finding, policy dialogue, and alternative evaluation. More recently, Stave (2003) applied this modeling system to communicate the complexity of a resource system to a broad stakeholder audience by building support for environmental management decisions and policy making. Li *et al.* (2010) also demonstrate the potential impacts of future climate change on streamflow and reservoir operation in a northern American prairie using the SD.

Based on previous research results and literature review, SD in the STELLA framework is applied in this effort to pursue developing sustainable water resources management in the ESPA, especially by coupling with adaptive management options against abrupt uncertain future hydrologic conditions. The goal of this article is to develop a computer model using SD concepts to aid decision making by providing useful insights for resource planners, system managers, and policy makers concerning water supply uncertainty, water conflicts, and water resources planning and management in a changing global environment. Ultimately, both improving adaptation capability and enhancing water systems will provide many economic benefits in this region, and further it will leverage human decisions in the complex human-nature systems present in many states.

The remainder of the article is organized as follows. First, a brief and selective review of water issues in the study area is presented. This is followed by the details of the SD model developed and the data used. Model results are then presented and discussed in the subsequent section. Finally, conclusions and future work are discussed.

WATER ISSUES IN THE STUDY AREA

The Snake River Basin extends in a crescent shape across most of southern Idaho and into eastern Oregon. The eastern portion of it hosts the ESPA as shown in Figure 1. The ESPA is 27,971 km^2 with a main stem length of 274 km. Annual mean precipitation on the surface of the plain ranges from about 20 to 25 cm/yr and is uniformly distributed between winter and summer, whereas annual mean precipitation on higher mountains within the Snake Basin exceeds 150 cm/yr, with about 80% occurring in the winter. As shown in Figure 1, the elevation varies across the plain from about 750 m above sea level near King Hill on the west to more than 1,410 m in the northeastern part of the plain near Idaho Falls. The mountains rise to 4,200 m near the state boundary between Idaho and Wyoming (Garabedian, 1992). The quantity of precipitation as snowfall that occurs during the winter season contributes the majority of water resources for aquifer recharge, as snow melting processes in the early summer sustain streamflows and irrigation diversions. The highly permeable geologic formation is comprised of numerous basalt flows

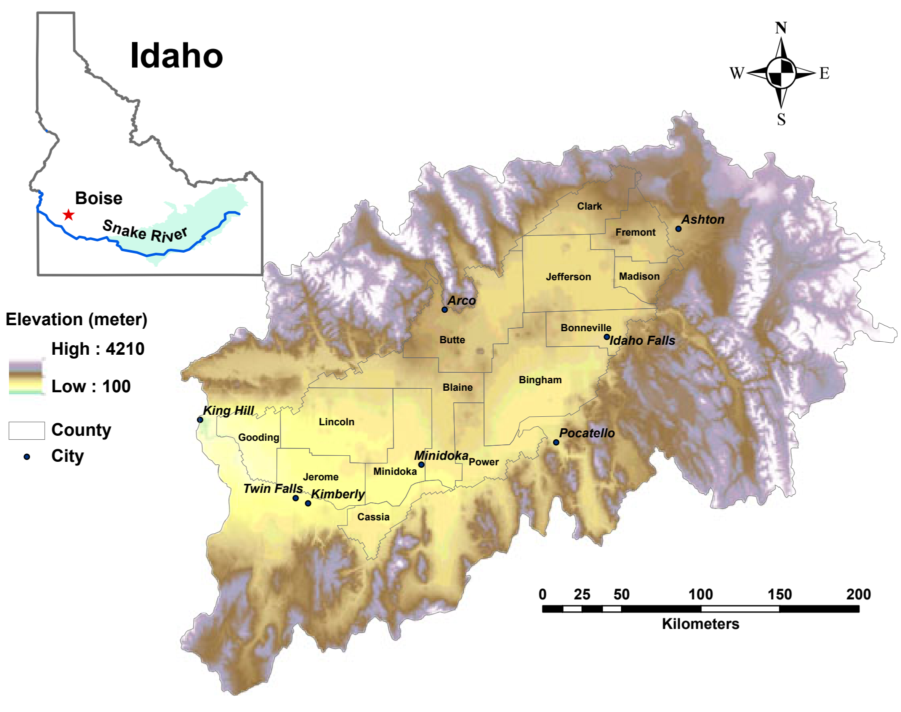

FIGURE 1. Schematic of the Eastern Snake Plain Aquifer and Tributaries, Idaho.

with some sedimentary interbeds within the ESPA (Cosgrove and Johnson, 2005).

The ESPA is the economic life-blood of Idaho; many people rely on its water resources to produce Idaho's agricultural products, including potatoes, wheat, barley, and other grains, along with dairies, feedlots, and aquaculture (State of Idaho, 2005). The volume of water stored in the aquifer is estimated to have increased by about 18.5 billion cubic meters between 1915 and 1955 due to excess irrigation water recharging the aquifer after diversions of water from the Snake River began in 1910. In the mid-1950s, farming in the ESPA began to change due to increased water application efficiency through advances in irrigation technology, including conversion from surface irrigation to sprinkler irrigation. This increase in water application efficiency led to decreased groundwater recharge that has contributed, along with increased groundwater pumping (GP) for expanded irrigated areas, to the decline of groundwater levels and spring discharges in the downstream portions of the basin near Thousand Springs (Johnson *et al.*, 1999). Recharge and discharge mechanisms of the aquifer are very dynamic in the sense that the aquifer itself and the surface-water streams and canals comprise a coupled natural and human system. Although recharge processes into the aquifer include natural hydrological connections primarily through tributary inflows (12%) and precipitation (10%), the majority of aquifer input is recharge by irrigation percolation (66%), which is a secondary hydrological process incidental to highly managed surface-water irrigation. Therefore, surface-water and groundwater resources should be, and are, managed as a single resource in this region (Winter *et al.*, 1998). Groundwater discharge from the aquifer is also a complicated process. Natural discharge to springs and the Snake River are the primary sources of aquifer water loss. Groundwater irrigation, which is a human-induced water activity, also contributes significantly to aquifer discharge, especially since the mid-1950s when many groundwater irrigated lands have been brought into agricultural production in this region.

This has brought management challenges to the state of Idaho because water rights administration in Idaho employs the doctrine of Prior Appropriation (known also as "first in time-first in right"). In times of shortage, an earlier user has a right to take water from the source in preference to later appropriators, which can force later appropriators to cease the use of water. Water right tensions arise between senior right holders (usually surface irrigators and aquaculture fed by springs) who assert injury as a result of groundwater pumping (generally by junior right holders) that affects spring flow and surface-water depletion. Consequently, the State of Idaho has declared a moratorium on new groundwater appropriations and adopted conjunctive groundwater/surface-water administration within a common priority system where surface-water and groundwater are hydrologically connected.

The concept of Prior Appropriation administration evolved in surface-water-only systems where the hydraulic interconnections among surface-water users are readily apparent, and benefits provided by administrative action are essentially instantaneous. Neither of these facts, however, applies to the relationship between groundwater use and surface-water use due to sometimes long lag times between groundwater pumping and spring discharge. The Idaho Department of Water Resources (IDWR) is the agency responsible for water allocation in the ESPA, charged with administrating surface-water and groundwater rights jointly. In order to facilitate this joint administration in a context of great factual uncertainty, IDWR has put significant resources into modeling efforts to develop and update a groundwater flow model known as the Eastern Snake Plain Aquifer Model (ESPAM), which is developed using the MODFLOW modeling framework (Harbaugh *et al.*, 2000). The ESPAM is evolving in consultation with the Eastern Snake Hydrologic Modeling Committee (ESHMC) chaired by the IDWR. The current version of the model is version 1.1 (Cosgrove *et al.*, 2006), with expected release of stable version ESPAM2.0 in May 2012. Membership in the ESHMC includes federal, state, and local agencies as well as private consultants on behalf of water users. Those include U.S. Bureau of Reclamation, U.S. Geological Survey, U.S. Fish and Wildlife Service, Idaho Power, Idaho Ground Water Appropriators, The Surface Water Coalition, the Idaho Water Resources Research Institute, the University of Idaho, and others. The magnitude of this effort underscores that developing sustainable water resources planning and management strategies against uncertain future hydrologic conditions is unequivocally an important priority in this region. These perspectives evolve through a continuous series of modeling adjustment and feedback that serve to develop a more user-friendly decision support tool, facilitating communication among stakeholders and incorporating many different policy-driven management options within the system. The system dynamic model presented here basically utilizes output data from the ESPAM model as inputs to leverage social and political stability in complex aquifer management in a timely fashion, which, to date, have typically been limited to the combined data-intensive and physically based model, such as ESPAM. Therefore, this model will ultimately strengthen local capacity to adjudicate and renegotiate an agreement that allows all parties to decrease their harm equally until they reach acceptable alternatives. The modeling component, such as a rich graphical user interface for participatory (stakeholder), structured deliberation (water right), and solutions (negotiation) is critical to better incorporate regional considerations, constraints, and objectives into decision making through SD.

DATA

To formulate an SD model, an aquifer water budget analysis based on seven inflow and outflow components from ESPAM has been conducted for the ESPA. Water components from ESPAM were then utilized as inputs for the SD model. Major recharge components consist of five water fluxes, including (1) surface-water irrigation, (2) tributary inflow, (3) precipitation, (4) stream and non-Snake River losses, and (5) canal losses. The two primary discharge components are (1) groundwater pumping and (2) spring discharges and Snake River gains. Aquifer recharge occurs mainly in the north and east portion of the plain through percolation from surface-water irrigation, made possible by many dams and diversion structures. Flow from the plain's geographic boundary and tributaries also comprise primary sources of natural recharge to the ESPA. Significant recharge results from canal leakage because major canals are not completely lined. In general, canal losses are estimated to be as much as 40% of their flow, based on water year 1980 evaluations (Kjelstrom, 1986). Another recharge component is rainfall falling directly on the plain and percolating into the aquifer, but its contribution is relatively minimal. Figure 2 illustrates dynamics of fluxes to and from the Snake River in the ESPA.

The SD modeling proceeded in parallel with the development of ESPAM2.0 and relied upon preliminary data from that process. Each process is dependent on the output of the ESPAM process and is encapsulated in a data flow mechanism, which is supported by the STELLA architecture. Using the preliminary ESPAM2.0 data, aquifer recharge and discharge components were defined for the past three decades. As shown in Figure 3, percolation from surface-water irrigation and groundwater irrigation as pumpage is by far the largest anthropogenic aquifer recharge and discharge component, respectively.

In the ESPAM2.0 data, monthly stress periods are defined from May 1980 through October 2008. A stress period is the length of time during which aquifer recharge and discharge (aquifer stresses) are held constant, and typically the irrigation season stress

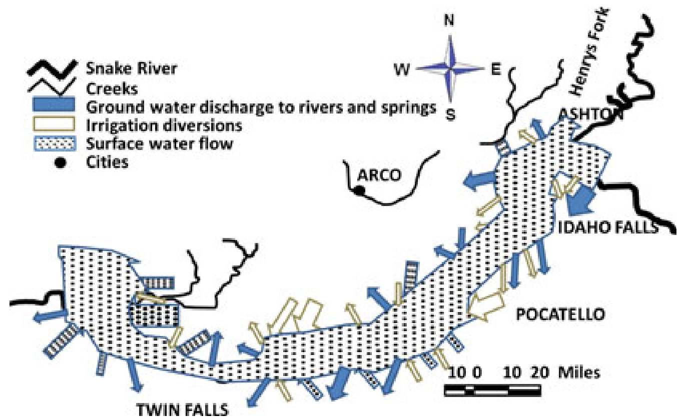

FIGURE 2. Flow in the Snake River Is Strongly Affected by Irrigation Diversions and by Inflow from Downstream Springs (after Kjelstrom, 1986). Note that the blue arrows represent direct flux into the Snake River via river gains, irrigation returns, or discharge from adjacent springs. The brown arrows represent surface-water diversions, which contribute significant recharge incidental to irrigation.

period starts on May 1 and ends on October 31. Recharge and discharge are calculated for individual irrigation water entities, including surface-water and groundwater irrigation parcels (Figure 4). Surface-water irrigation entities are mapped based on Geographic Information System (GIS) data of company service areas, provided by IDWR. Groundwater irrigation entities are defined by depth to water and local irrigation practices. Individual water-budget data routed into the SD model are provided by IDWR from preliminary ESPAM2.0 data. Individual water budget components are described as follows.

Precipitation (P)

Annual average precipitation on the plain is approximately 8.1 billion cubic meters, with 80% of this falling on nonirrigated lands. It is estimated that precipitation on nonirrigated lands contributes aquifer recharge of about 0.8 billion cubic meters per year, which is equivalent in magnitude to almost 20% of net extraction for groundwater irrigation (Garabedian, 1992). Precipitation on the other minor-area land uses, including dry farms, cities, and wetlands, contributes to the water budget about 0.24 billion cubic meters per year (Goodell, 1988).

On irrigated lands, precipitation is included in the calculation of surface-water irrigation recharge (component SW below) and groundwater irrigation discharge (component GP below).

To compute recharge from precipitation on nonirrigated lands, precipitation depths from the Parameter-elevation Regressions on Independent Slopes

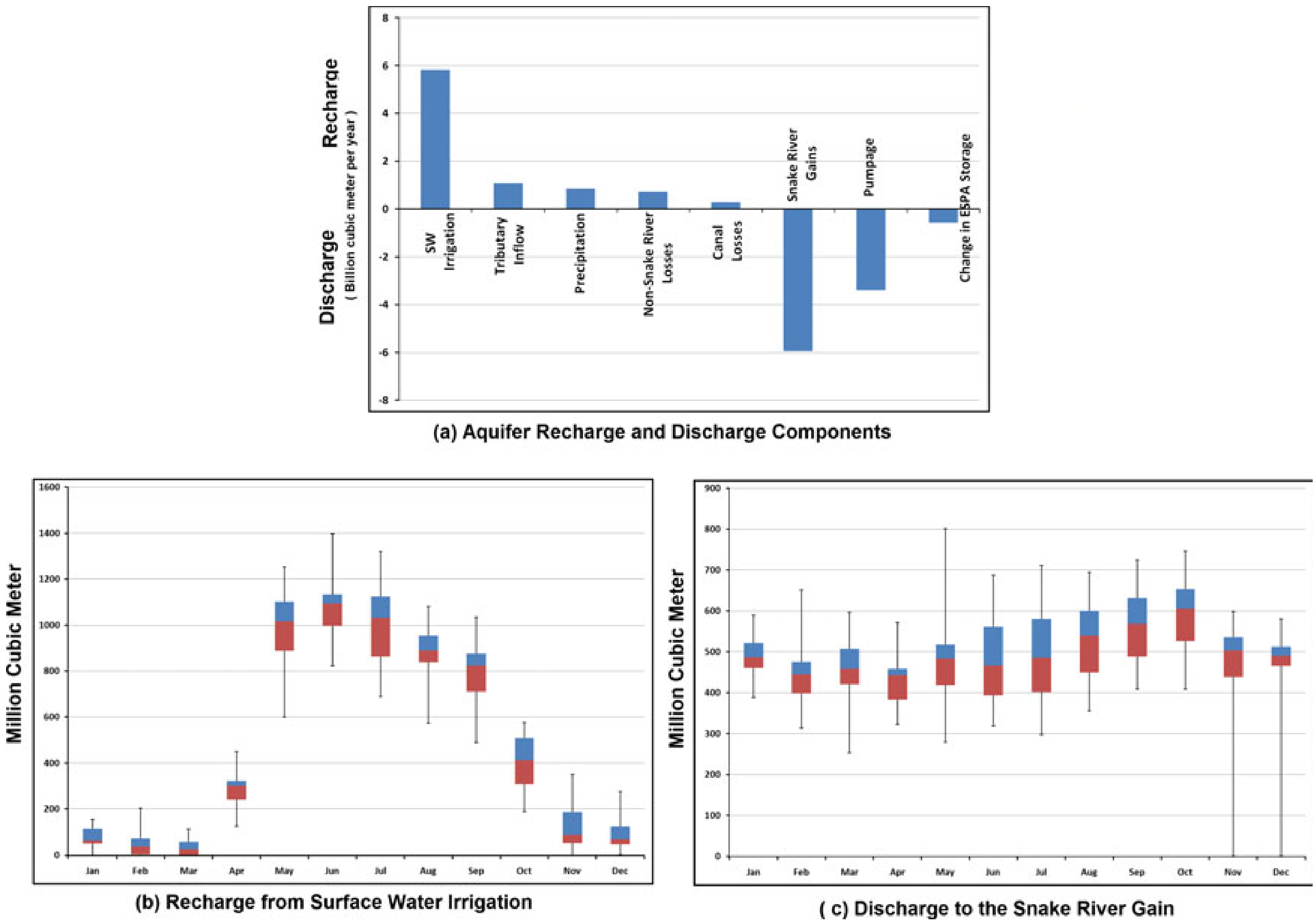

FIGURE 3. (a) Aquifer Recharge and Discharge Components, (b) Monthly Average Recharge from Surface-Water Irrigation, and (c) Discharge to the Snake River. Note that these data from the Eastern Snake Plain Aquifer Model (ESPAM) and evapotranspiration (ET) are incorporated into surface-water irrigation (SW) through crop-consumptive irrigation requirements (Garabedian, 1992).

Model (PRISM) climate-mapping system (Daly and Taylor, 2001) and generalized soil maps (Mundorff *et al.*, 1964; Garabedian, 1992) were used. Excluding minor-area land parcels, such as dry farms, cities, and wetlands, all the areas of the plain are subdivided based on GIS polygon layers, which include both irrigated and nonirrigated lands. The outcome was a single GIS grid map for each stress period, representing the depth of recharge from precipitation on nonirrigated lands, calculated using a nonlinear algorithm from ESPAM1.1 (Contor, 2004). Conceptually, total recharge from precipitation (TP) can be denoted as the sum of precipitation on minor-area land use (MP), irrigated-land use (IP), and nonirrigated land use (NP). However, note that the recharge component from precipitation shown in Figure 3a is derived from NP, whereas IP is implicit in the surface-water irrigation and pumpage components in the same figure.

Evapotranspiration (ET)

Evapotranspiration (ET) is a critical element in water budget analysis. Typically, potential evapotranspiration (PET) is used to estimate the amount of water that could evaporate and transpire from a vegetated landscape without restrictions other than the atmospheric demand (Thornthwaite, 1948; Penman, 1956; Priestley and Taylor, 1972). Traditional ET estimates are the product of reference ET (ETr) and a crop coefficient (Kc). ETr defines the evaporative power of the atmosphere and Kc defines the crop-specific response, including variety, growing season, percent cover, etc. Crop-type data are obtained on a county-wide basis from National Agricultural Statistical Service Data and applied to ET_{Idaho} ET depths for nearby weather stations.

Although PET can be measured directly by lysimeters, these provide point estimates at a single geo-

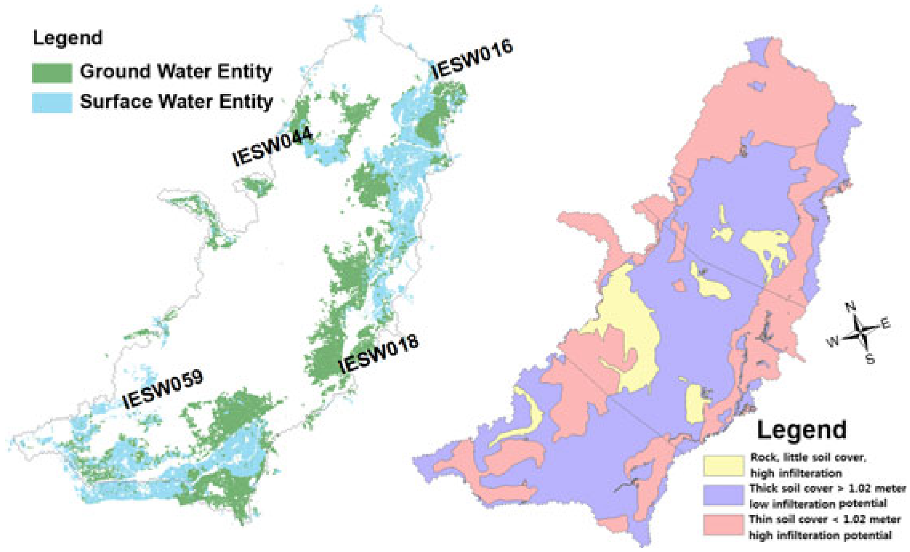

FIGURE 4. Surface-Water and Groundwater Irrigation Entities (left) and General Soil Classification (Mundorff *et al.*, 1964; Garabedian, 1992) in the ESPA (right). Note that reservoir and diversion canal facility are not shown in irrigation entities.

graphic location, and for only the vegetative cover present in the lysimeter. In this work, Mapping Evapotranspiration with high Resolution and Internalized Calibration (METRIC) is used to represent Actual Evapotranspiration (AET) across areas of wide spatial extent. The METRIC is an image-processing model based on the evaluation of the energy balance at the earth's surface (Allen *et al.*, 2007a,b). Application of the METRIC energy balance essentially produces a rasterized 30×30 m map of Fraction of Reference Evapotranspiration (ETrF) and AET using a special combination of both short- and long-wave bands and several intermediate files during data assimilation processes. The final ETrF and AET maps after reprocessing (e.g., data conversion from binary to text format) as needed are provided by the University of Idaho Remote Sensing team at Kimberly, Idaho. In this study, traditionally calculated ET estimates (ET_{Idaho}, 2009) are used as primary data because of the spatial and temporal extent of data availability. Remote-sensing ET estimates are used to calibrate ET adjustment factors, which refine the traditional ET estimates for nonstandard conditions, including any chronic water-supply limitations or deficit-irrigation conditions.

Canal Losses (RC)

Incidental recharge by means of canal seepage contributes to the elevated water table and increased flows of springs discharging to the Snake River. Canal systems in the ESPA supply water to support the approximately 61 cm (2 feet) per year of crop consumptive use serving approximately 3,642 km^2 (900,000 acres) of surface-water-irrigated land (Garabedian, 1986; Kjelstrom, 1986). Leakage from these canals results in significant recharge to the groundwater table (Johnson *et al.*, 1999). To compute recharge from canal seepage, the recharge tool developed by IDWR (Cosgrove *et al.*, 2006) was utilized by adjusting changes in groundwater use on irrigated lands. Seepage was considered as a percentage of diversions, with calculations performed for every month. Recharge from canal leakage for each stress period, for each ESPAM model cell (1.6 km^2), was calculated using the following equation (Contor, 2008):

$$\mathrm{RC} = (1/C) \times D \times F \times M, \tag{1}$$

where RC is the recharge from canal seepage for the individual ESPAM model cell (cubic meters); C is the number of model cells intercepted by the canal; D is the diversion volume for the entity served for the stress period (cubic meters); F is the constant seepage fraction for the stress period; and M is the multiplier for automated calibration (default 1.0). Note that regardless of the multiplier used, the product of M and F ($M \times F$) ranges from 0 to 1.

Non-Snake River Losses (SEEP)

Losses from other streams are treated as specified flux boundaries in the ESPAM model input. Note that gains to the Snake River are described in later sections. The flux is estimated from a simple mass-balance of inflows and outflows to the stream reach, using the following equation:

$$\mathrm{SEEP} = Q_{\mathrm{in}} - Q_{\mathrm{out}}, \tag{2}$$

where SEEP is the rate of storage change at a given time, Q_{in} and Q_{out} are inflow and outflow within the subreach, respectively. For gain and loss calculation at any specific subreach, the basic equation can be further extended associated with the measured recharge and discharge in the river at the upstream and the downstream river segments. For details, the reader is referred to Taylor and Moore (2009).

Tributary Underflow (TU)

Underflow from tributary basins into the aquifer is also an important component of the water balance for the ESPA. A previous study reported that underflow estimates from tributary drainage basins is about 8% of the annual inflow to the aquifer (Kjelstrom, 1986; Garabedian, 1992). It is acknowledged that water use in the tributary basins directly affect water supply in the ESPA, but estimating tributary underflow (TU) is challenging in hydrologic modeling efforts because of uncertainty and data limitations. However, modeling and calibration efforts to improve data and methods continue in progress to enhance the model's performance as up-to-date data become available. Additional detail is provided by Cosgrove *et al.* (2006).

Surface-Water Irrigation (SW)

The basic equation for net impact of surface-water irrigation used in the SD model can be defined as:

$$\mathrm{SW} = D - R + \mathrm{IP} - \mathrm{ET} \times K - \mathrm{RC}, \tag{3}$$

where the net impact of SW is the surface-water irrigation (cubic meters) in a given month; when SW is positive, recharge to the aquifer occurs; otherwise, discharge from the aquifer is indicated. D is the diversion (cubic meters); R is the return to surface-water source (cubic meters); IP is the precipitation on the irrigated parcels (cubic meters); ET is the evapotranspiration (cubic meters); K is the adjustment factor of ET (fraction); and RC is the canal losses (cubic meters).

The surface-water-irrigated areas of the study area are divided into irrigation entities, comprised of groups of individual canal companies, irrigation districts, and private surface-water irrigation rights that share similar water right characteristics, irrigation practices, and return-flow patterns and locations. To facilitate the calculation of canal losses (which were not accommodated in the groundwater irrigation algorithms discussed below in Groundwater Pumping), Irrigation Entity IESW044 was labeled as a surface-water entity, even though its source is water pumped from wells, but conveyed via canal to distant irrigated lands.

Note that three implications can be made when surface-water irrigation (SW) is negative. First, mixed-source lands (lands that have both a surface-water right and a supplemental groundwater right) exist throughout the study area. When surface-water supplies are inadequate to support crop requirements, the expectation is that irrigators will use supplemental wells, and the negative value of SW will correctly represent this additional pumping as an aquifer extraction in our calculations. Second, negative values of SW could result from a water-stress condition where supplemental pumping is either not available or not used. In this case, actual ET will indicate pumping that may not exist. Details of ET and adjustment factors are available in Taylor and Contor (2011). Finally, negative values of SW could result from temporal imprecision in diversion and ET data. In this case, our algorithms will result in a temporal imprecision of too much recharge in one period, offset by too much discharge in another, with the net annual water balance being approximately correct.

Groundwater Pumping (GP)

In contrast to surface-water irrigation, groundwater irrigation estimation is a relatively simple procedure. Groundwater irrigation is denoted as:

$$\mathrm{GP} = \mathrm{IP} - \mathrm{ET}, \tag{4}$$

where GP is the groundwater irrigation by pumping; when GP (cubic meters) is positive, recharge to the aquifer occurs; otherwise, discharge from the aquifer occurs; IP is the precipitation (cubic meters); and ET is the evapotranspiration (cubic meters).

Recharge to the aquifer from precipitation on groundwater-irrigated lands typically occurs during winter months, whereas discharge is generally seen in summer months. If discharge occurs in winter months, it is likely related to an overestimate of wintertime ET due to water storage in the soil profile or the snowpack rather than precipitation. GP is calculated as the net effect of pumping; it assumes that all groundwater pumping for irrigation that does not satisfy ET percolates back to the aquifer. The offsite groundwater pumping described above for Entity

IESW044, along with supplemental pumping for one offsite well in IESW016, is added (as a negative value) to GP in the calculations.

Snake River Gain (SG)

Previous studies have noted that significant amounts of water from the aquifer discharge to the Snake River along the reach from Milner to King Hill (Kjelstrom, 1986; Garabedian, 1992). Between Milner and King Hill, the deeply incised Snake River Canyon truncates the aquifer across zones of transmissive pillow basalts and basaltic sands. A second region of large spring discharge is in the Ferry Butte area upstream of American Falls Reservoir (Cosgrove *et al.*, 2006).

Because the primary purpose of the model is to represent interaction between the aquifer and the Snake River and its tributary springs, Snake River gains and major spring discharges are calculated by the model as head-dependent boundary fluxes. Gauge data from IDWR and the U.S. Geological Survey were primarily used. Additional refinement and understanding were provided by detailed Snake River gains studies by Hortness and Vidmar (2004).

METHODOLOGY

Model Development

The SD-modeling approach is applied to aid understanding of how future hydrologic conditions will affect storage, recharge, and discharge behavior of the ESPA over the next few decades until 2100. Based on water budget analysis done by the ESPAM, the water components to connect the ESPAM to the SD model include surface-water irrigation (SW), tributary underflow (TU), precipitation on nonirrigated land parcels (NP), non-Snake River losses (NL), and canal losses (CL) as recharge components. Groundwater pumping (GP) and Snake River gain (SG) are employed as discharge in the analysis. All elements are interconnected directly and indirectly via hydrologic "cause and effect" relationships. For example, the decreased precipitation can be the primary cause of decreasing surface flow. Consequently, surface-water irrigators will be experiencing water shortage conditions, reducing incidental recharge from SW. Simultaneously, groundwater irrigators will pump additional water from the aquifer to offset the reduction of precipitation in the calculation of GP. Both responses affect spring flow depletion, resulting in impacts of commercial fish production, hydropower generation, municipal and industrial (M&I), and domestic water uses. In response, senior water right holders could trigger "water delivery calls," resulting in groundwater pumping curtailment. As such, the goal of the SD model is to improve the understanding of recharge and discharge dynamics associated with surface-water and groundwater interaction in this context. A simplified representation of the model is shown in Figure 5. Recall that, respectively, recharge component and discharge component consist of five and two water fluxes described in the data section. Arrows in Figure 5 do not necessarily indicate the direction of water fluxes, but it represents functional relationships of each water component connecting to the aquifer water budget.

Implication of Water Supply Uncertainty on System Dynamics

To better understand the consequences of water supply uncertainty in the ESPA, a causal loop diagram defining the relationships between "cause" and "effect" is necessary. Figure 6 lays out the important components and relationships needed to describe a series of hydrological sequences driven by uncertain hydroclimate conditions. For example, reduced rainfall and increased temperatures as a result of climate variability could increase surface-water depletion so that surface-water irrigators likely experience water shortage. Simultaneously, under drought conditions, additional groundwater withdrawals would be made by groundwater irrigators, precipitating a "water delivery call" initiated by surface-water irrigators. The same climatic drivers (reduced precipitation and

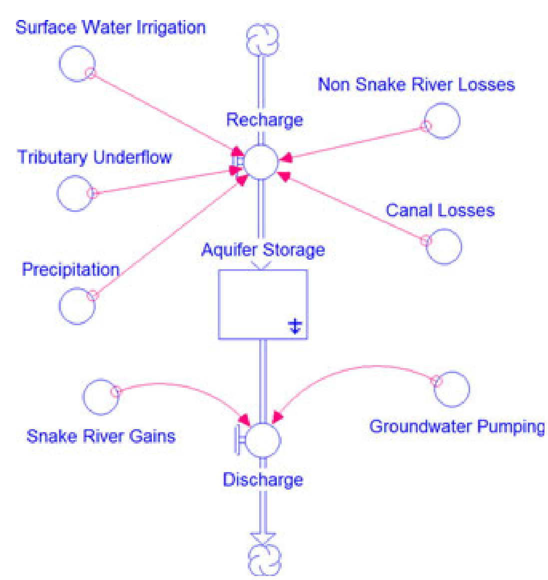

FIGURE 5. Simplified Representation of Recharge and Discharge Dynamics in the ESPA.

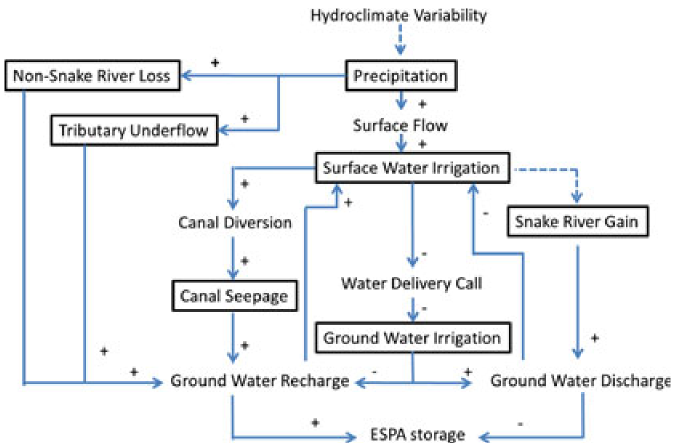

FIGURE 6. Consequences of Climate Change on Surface and Groundwater Interaction in System Dynamics for the ESPA. Note that "+" and "−" represent positive and negative relations, respectively. Water components used in system dynamics are boxed.

increased temperatures) could also contribute to decreasing tributary interflow and recharge on nonirrigated lands. All these could contribute to reducing Snake River gains, which in turn can cause reductions in surface-water deliveries and recharge from surface-water irrigation, ultimately decreasing the rate of aquifer recharge.

In Figure 6, each arrow indicates an influence of one element on another, and "+" and "−" represent positive and negative relations, respectively. Thus, the condition of the previous case can be interpreted as follows. As the decreased precipitation causes decreasing surface flow, a "+" symbol is assigned, whereas a "−" symbol is assigned to represent the relationship between groundwater irrigation and groundwater discharge, which is subsequently reversed.

The time horizon of this SD model extends from May 1980 to October 2008, the period used for calibration purposes in ESPAM, and the model operates on a monthly time step. The calibration of ESPAM was accomplished using version 9.0 of a nonlinear parameter estimation program (PEST) (Doherty, 2004) for data interpretation, model calibration, and predictive analysis. No additional calibration effort has been made in the SD model because the aquifer storage simulation, one of the calibration targets, agrees well with that from ESPAM (comparisons not shown in the article). Detailed calibration processes are well documented in the ESPAM final report (Cosgrove *et al.*, 2006).

Base-Case Scenario

To evaluate how the ESPA responds to future hydroclimate variability, it is necessary to develop a base-case scenario. The base-case scenario defines the future condition of the ESPA system if it continues operating in its present condition. To develop a base-case scenario, historic water data, including surface-water irrigation, tributary underflow, precipitation, non-Snake River losses, canal losses, Snake River gains, and groundwater pumpage, are examined to identify how historic water activities affect the aquifer storage. After initial runs, it appeared that aquifer water levels in the ESPA system decrease gradually over time. This parallels historically observed trends, and one implication is that water use from and recharge to the aquifer are not in balance.

However, the time series includes significant droughts at the end of the time series (1999 through 2008) and a nearly three-decade period during which practices and water use patterns continued to evolve. Continued indications of declines may also be because one or more discharge inputs are overestimated, or one or more recharge inputs are underestimated.

Thus, to avoid confounding results of water supply uncertainty with the implications of current conditions and practices, the model was adjusted to produce a baseline scenario with no long-term decline or increase implicit of groundwater level in the data. Based on examination of historic water data, and Snake River gains data for seven different reach segments, it appears that gains to the river (which are discharges from the aquifer) are likely overestimated during dry months when the surface-water flow regime is highly dominated by base flow. This may affect indications of aquifer depletion over time. Therefore, a minor adjustment to Snake gains has been made to stabilize the ESPA system, creating a base-case scenario free from implicit increases or declines, which is an ideal condition as designed without trends. This provides a basis against which all system performances associated with future supply and demand scenarios are evaluated.

System Performance Measurement

To evaluate a system's performance under uncertain water supply conditions, a variety of measurement techniques can be incorporated, especially by focusing on system reliability, water quality, economic efficiency, and financial security (Cai *et al.*, 2002; Jaffe and Al-Jayyousi, 2002). System reliability, in particular, is commonly used in sustainable water resources planning and management when it is used as an indicator to evaluate a system's performance (Ryu *et al.*, 2009). System reliability can be defined by the frequency or probability that a system is in a satisfactory state (Hashimoto *et al.*, 1982). The system reliability used in this study can be defined as:

$$\alpha = 1 - \frac{\sum_{t=1}^{n} F_t}{N}, \tag{5}$$

where N is the number of monthly time steps over historic water records and F is the state of failure ($F = 0$ when the system meets demand target, which is a threshold defining satisfactory system conditions; otherwise $F = 1$ in a nonsatisfactory condition).

In this study, 97% of system reliability is adopted as a criterion, which means that we allow 3 failures out of 100 operations to meet demand targets. In our case, the 97% system reliability criterion is a quantity of water adequate to meet all demand targets from the ESPA system with only one failure over the 29 years (1980-2008) of historic water records. Perhaps, 97% system reliability here is a too rigorous threshold in the sense that, in reality, farmers will still take on a farming operation even with lower reliability. For example, they might work with 90% reliability, especially if the 10% of nonreliability still provides "partial" water supply during those short months. However, the concept of reliability here does not necessarily specify water availability to meet specific water demand targets, such as surface-water irrigators, groundwater irrigators, canal companies, or other system requirements. Rather, 97% reliability is the lumped value to evaluate system-wide performance.

A scenario baseline, assumed to reflect current conditions, was first investigated to provide information to water managers and planners regarding the *status quo* condition, and to provide context for assessing future risks. This condition defines the expected future condition of the ESPA system if it were to continue operating in its present business-as-usual condition, that is, if future irrigation practices and hydroclimatic conditions are defined by 2008 conditions.

Identification of Interrelationships Among Water Components

From a water resources management perspective, water supply uncertainty is often denoted as "a problematic situation" because the consequences of hydroclimate variability would have potential impacts on water availability for regional water demands, including M&I, hydropower, ecology, water quality, irrigation, and other consumptive and nonconsumptive uses.

To incorporate the impact of hydroclimate variability on the ESPA in an SD framework, a series of supply and demand scenarios are developed. Although coupling the output from global circulation models into a regional hydrologic model as inputs in a hydroclimate model is one of typical approaches to simulate long-term runoff for the watershed level, there are significant challenges to overcome uncertainty issues embedded in climate models, along with socioeconomic complexity intertwined in human dimensions. Therefore, for this study, the future impacts of hydroclimate variability on the ESPA are characterized by perturbing water supplies available to surface-water irrigation because a direct model input was used rather than a product of model behavior, assuming that surface-water irrigation activities directly correspond to surface-water depletion driven by uncertain hydrologic conditions. Note that this perturbed surface-water irrigation can be a placeholder for refined estimates of changes in hydrologic drivers, based on the results of coupled climate-hydrologic modeling when such models become available.

The base-case scenario and five water management alternatives (described later) were investigated to identify how the ESPA system responds to the perturbed surface irrigation driven by the reduced runoff that may result from climate change. Each water budget component, therefore, is represented as a function of linear and nonlinear relationships with surface irrigation in the SD. For example, canal losses can be represented by a linear relationship with surface-water irrigation shown in Figure 7 and the rate of canal losses can be derived from surface irrigation. Other functional relationships between SW and others are listed in Table 1. Once relationships are identified, variability of all water components can be explained by surface-water irrigation as the primary indicator and recipient of future hydrologic conditions potentially driven by hydroclimate variability.

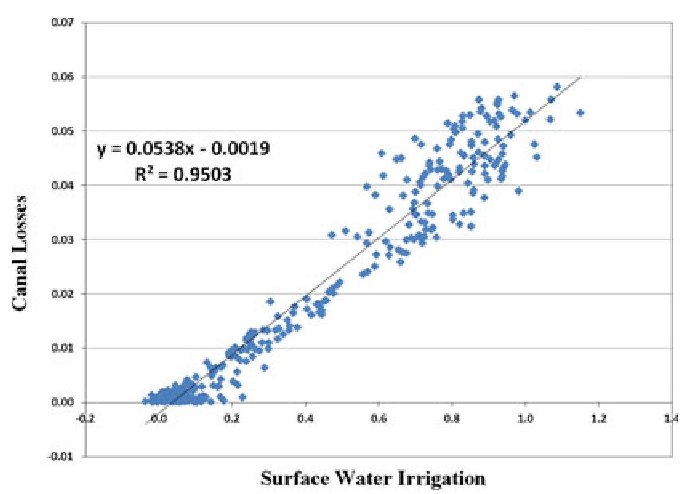

FIGURE 7. Linear Relationship Between Canal Losses and Surface Irrigation in the ESPA over Stress Periods.

TABLE 1. Functional Relationship Between Surface-Water Irrigation (SW) and Other Water Activities.

Relationships Between X (SW) and Y	Equation	R^2
Canal losses	$Y = 0.0538X - 0.0019$	0.9503
Groundwater pumping	$Y = -0.2488X^2 - 0.3076X - 0.0414$	0.7641
Snake gain and loss	$Y = -0.1463X - 0.382$*	0.1619

Notes: X and Y represent SW and its counterpart, respectively.
*Although relationship between SW and Snake gain/loss in the present study is evaluated using a linear equation, this relationship will be updated by a nonlinear equation, such as response function (Cosgrove and Johnson, 2005) to increase R^2.

Management Options

The first step in the development of alternatives is to identify management options suggested by the water budget adjustment mechanisms in the comprehensive aquifer management plan (CAMP) approved by the Idaho Water Resources Board (Idaho Water Resources Board, 2009). For this study, a total of four management options are considered, including (1) a conservation plan for groundwater and surface water (denoted as CON hereafter); (2) managed aquifer recharge (MAR) to maximize outcomes for fish and wildlife, surface and groundwater quality, hydropower, and recreation; (3) demand reduction through irrigation efficiency and groundwater curtailment during drought (GWC); and (4) weather modification program (WMO) to increase winter snowpack and augment surface-water flows.

Each management option can be applied individually to the SD model using the control panel illustrated in Figure 8, and results obtained. For instance, a broad water conservation program (option CON), including conservation opportunities in several irrigation districts (e.g., Minidoka Irrigation District, Southwest Irrigation District, A&B Canal Company) and surface water transfer to achieve streamflow restoration on flow-limited streams, is estimated to reduce demand of surface flow by 5-8% and groundwater flow by 3-5%. Note that mixed benefits and negative impacts on groundwater recharge through demand reduction for the long term have not been incorporated into this estimation.

Managed aquifer recharge along the Snake River (option MAR) including both fall and spring recharge efforts and development of long-term contracts with canal companies to deliver recharge water when IDWR's permit is in priority is estimated to increase surface water supply 2-5% and groundwater supply 2-3% based on information gained from the functional nonlinear relationship between surface and groundwater irrigation (see Table 1). We assumed that demand reduction through groundwater curtailment administrated by IDWR (GWC) would result in

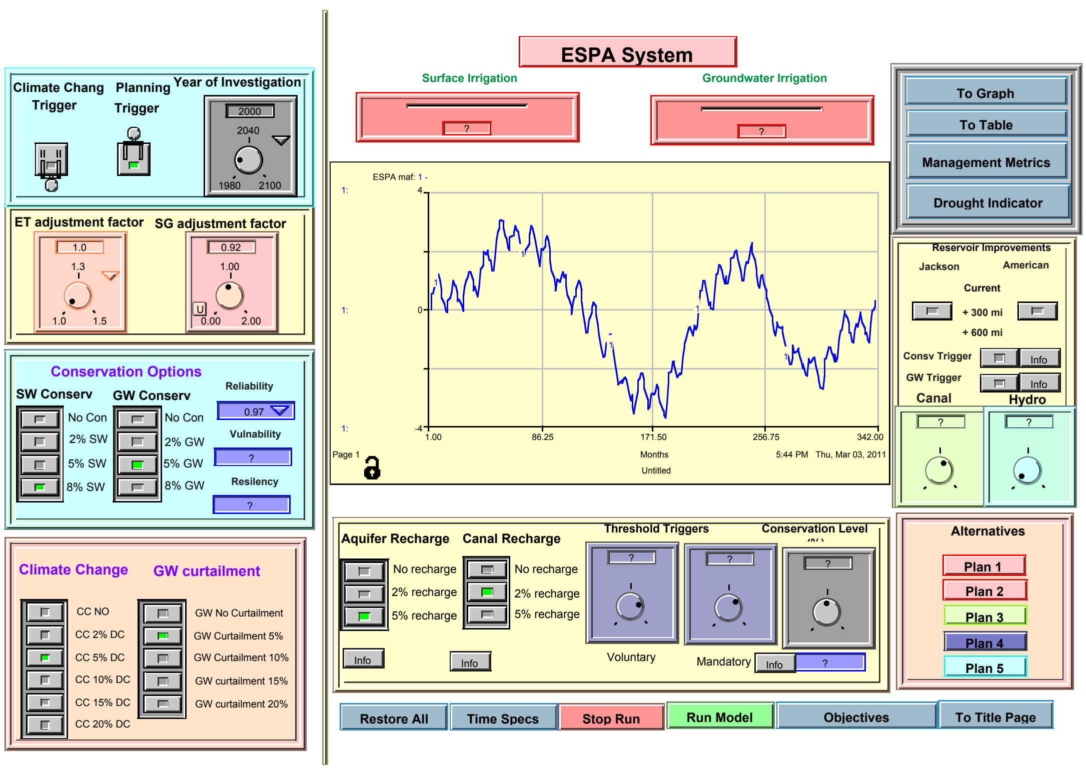

FIGURE 8. Control Panel for Management Options Selections in the System Dynamics.

groundwater demand reduction of up to 15% during a typical drought.

The effects of WMO are estimated based on a cooperative weather modification project initiated by the Idaho Power Company. It is considered to be able to increase winter snowpack in the Upper Snake River Basin and is estimated to promote streamflow augmentation up to 3% through increased precipitation and tributary inflows, but this activity will be avoided to prevent the risk of flooding, to protect public safety during heavy precipitation (Idaho Water Resources Board, 2009).

These management options for promoting sustainable water management over the next few decades in the aquifer were combined to create five alternatives to evaluate the system reliability for the years beyond the CAMP planning horizon of year 2030.

RESULTS

A set of variables are proposed for assessing the sustainability of the ESPA system over a 100-year time horizon against uncertain future hydrologic conditions. Simply put, the past 30 years of data have been extended over a 100-year time horizon using a time-dependent relationship derived from the historical time series through trend analysis modeling. Next, the five possible reduced streamflow scenarios, including 2, 5, 10, 15, and 20% of surface flow perturbation, were tested by means of possible depletion made by uncertain future hydrologic conditions. Thus, impacts of hydroclimate variability on the water supply side have been evaluated, corresponding to surface-water changes from year 2000 to 2100 as shown in Table 2. The differences of system reliability during a 100-year planning horizon are then computed to determine what percentage of surface reduction is a potential starting point to develop sustainable aquifer management under an uncertain future hydrologic condition. As shown in Table 2, system reliability is minimally changed over the time when 10% or more of surface-water reduction is applied. This implies that 10% of reduction threshold due to hydroclimate variability may affect system performances of the aquifer significantly in the sense that the system is not resilient to the increased water demand over time. Rigorous adaptive management strategies, therefore, should be in place to mitigate water shortage driven by surface flow reduction.

TABLE 2. System Reliability Corresponding to Surface Flow Reduction over the Planning Horizon.

Flow Reduction	Years of Implementation					
	2000	2020	2040	2060	2080	2100
2% reduction	0.89	0.83	0.78	0.74	0.59	0.42
5% reduction	0.50	0.38	0.35	0.28	0.24	*0.23*
10% reduction	0.20	*0.20*	*0.19*	*0.18*	*0.17*	*0.17*
15% reduction	0.15	*0.13*	*0.13*	*0.13*	*0.13*	*0.12*
20% reduction	0.10	*0.10*	*0.09*	*0.09*	*0.09*	*0.09*

Note: System reliability in italic represents the change of system reliability is <0.02 at every 20-year interval for a 100-year planning horizon.

As 10% or more of surface-water reduction affects the system reliability of the aquifer significantly, it is necessary to develop sustainable aquifer management alternatives, considering multiple management options. The SD model was constructed with a user interface allowing the operator to manipulate the implementation of various management alternatives, while selecting different assumptions about the level of hydrologic impact. If a selected alternative cannot meet the system reliability of 97% at any time, additional management options must be added to increase reliability to meet the target criterion, if possible.

Each alternative except Alternative 3 contains at least two management options, such as a water-conservation program combined with managed aquifer recharge or groundwater curtailment and weather modification. The results indicate that no single management option guarantees a system reliability of 97% suggested by this study through the year 2030 planning horizon of CAMP hydrologic goals (Idaho Water Resources Board, 2009).

Table 3 compares alternatives composed of different management options. Alternative 1 includes a water conservation program (CON), and a conservation program linked with managed aquifer recharge (MAR). The management options of the CON alone cannot meet system reliability of 97% until 2020, when the MAR option would be introduced. The combination of CON and MAR results in meeting system reliability of 97% for another 20 years, but unable to meet demand targets beyond 2040 (Table 3).

Similar to Alternative 1, Alternative 2 evaluates conservation (CON); conservation plus managed recharge (CON and MAR); and conservation, managed recharge, and a weather modification program (CON, MAR, and WMO). Weather modification is introduced in 2060 when additional water resources are required to meet system targets.

Unlike Alternative 1 and Alternative 2, Alternative 3 solely depends on groundwater curtailment options to achieve system targets. A total of 15% GWC is initially applied to reduce demand until 2020, when additional reduction of GWC up to 20% is introduced to meet system reliability of 97% through 2060 (Table 3). No more than 20% GWC is considered in this study, based on expectations of political and economic constraints.

TABLE 3. System Reliability of Five Alternatives Over Next Few Decades Until 2100.

Alternatives	Management Options	Years of Implementation					
		2000	2020	2040	2060	2080	2100
Alt. 1	CON	1.00	0.99	0.96	0.89	0.83	0.78
	CON + MAR	1.00	0.99	0.99	0.96	0.90	0.83
Alt. 2	CON	1.00	1.00	0.96	0.89	0.83	0.78
	CON + MAR	1.00	1.00	0.99	0.96	0.90	0.86
	CON + MAR + WMO	1.00	1.00	1.00	0.99	0.96	0.91
Alt. 3	GWC(15)	0.97	0.89	0.83	0.78	0.74	0.59
	GWC(15) + GWC(20)	0.97	1.00	1.00	0.99	0.92	0.91
Alt. 4	GWC(20)	1.00	1.00	1.00	0.99	0.96	0.91
	GWC(20) + WMO	1.00	1.00	1.00	0.99	1.00	0.97
Alt. 5	CON	1.00	0.99	0.96	0.89	0.83	0.78
	CON + MAR	1.00	0.99	0.99	0.96	0.90	0.83
	CON + MAR + WMO	1.00	0.99	0.99	0.99	0.96	0.91
	CON + MAR + WMO + GWC(5)	1.00	0.99	0.99	0.99	1.00	1.00

Notes: Additional management options in the column of management options are implemented when current options are unable to meet the system reliability of 97% in the ESPA (e.g., only CON was applied in Alt. 1 until 2020, and MAR in addition to CON was applied to meet the target, which is the system reliability of 97%). The shaded areas indicate system reliability that is higher than 97% (0.97), which has been defined as an acceptable level.

Alternative 4 implements groundwater curtailment (GWC) along with a weather modification program (WMO) starting in year 2080.

Alternative 5 avoids water conflicts possibly embedded in GWC by seeking a combination of management options that may be achieved on a voluntarily basis. The CON is initially introduced to increase surface-water availability by executing conversions during the spring and fall shoulder seasons as well as during the irrigation season as storage capacity allows (Idaho Water Resources Board, 2009). Additional management options MAR (managed aquifer recharge) and WMO (weather modification) are introduced sequentially when the system begins to fail to meet demand targets in the period 2040 through 2060. These options may help to achieve the system reliability target until 2060 without being a burden to groundwater irrigators. Minor GWC (5%) is implemented to meet system targets starting in 2080. Water management and planning exercises associated with alternatives and management options presented here can be demonstrated in the SD environment through a graphical user interface shown in Figure 8. These exercises are extremely important for stakeholder groups to reach ultimate water conflict resolution and/or conjunctive aquifer management in a “shared vision modeling” framework, especially during drought periods.

CONCLUSION AND FUTURE WORK

This study provides an example of how SD can be used to guide management of the ESPA associated with uncertain future hydrologic conditions potentially influenced by climate change and variability. SD, applicable to large water systems, has advanced greatly in the number of water resources applications over the past few decades. As contrasted with other conventional modeling approaches, this approach is distinguished by (1) explicit representation of the system, (2) transparent modeling building blocks, and (3) management potential to resolve water conflicts among stakeholder groups.

This study shows that the ESPA is sensitive to future hydroclimate variability. Four perturbed surface flows, ranging from 2 to 20% with reasonable increments are generated to mimic future streamflow realization due to uncertain hydroclimate conditions. The results show that perturbed hydrologic conditions affect aquifer dynamics, resulting in significant impacts on annual water yield (presented by the metric of system reliability) in the ESPA so that adaptive management options and planning alternatives are needed to maintain reliable water resources to cope with hydroclimate variability over the next few decades until 2100. Five alternatives were identified as a function of the system reliability and then evaluated. Although five alternatives meet the criterion of system reliability of 97% until 2030 (the Comprehensive Aquifer Management Plan or CAMP planning horizon), only Alternatives 3 and 5 meet system targets through 2100. However, Alternative 3 appears that it is not likely to be implementable because significant groundwater curtailment (20% reduction) would harm groundwater irrigators through 2060. Alternative 5 is attractive in that a wide range of management options have been implemented initially, assuming that such could be achieved on a voluntarily basis. Only later is a more rigorous management portfolio adopted, when additional demand reduction is necessary to meet the targets.

Although this research demonstrates a general framework of SD for sustainable water resources planning and management in the ESPA, there are significant challenges. First, the possibility that the *status quo* implies an imbalance between aquifer recharge and discharge may mean that even absent climate change and hydrologic variability, some management actions may be required to maintain system reliability. Second, future hydrologic conditions associated with climate change remain uncertain. Balancing the results of SD modeling with social and economic costs of implementation of alternatives will remain extremely challenging as long as the changes are future and uncertain, whereas costs are immediate and concrete. Third, future technology improvements in irrigation application and changes in cropping patterns have not been incorporated in this study. Fourth, the driving climate-change modeling itself is sometimes questioned; economists often claim that all climate scenarios currently available do not consider the effects that future technology improvement may have upon bringing greenhouse gases into equilibrium (Ray Supalla retired from Department of Agricultural Economics, University of Nebraska-Lincoln, personal communication). Similarly, it is extremely difficult to integrate economic concepts into sustainable water management both to define and evaluate individual alternatives. Finally, the management options implemented in the alternatives may exceed what practically can actually occur. Alternative 4, for instance, implies demand reduction of 20% through groundwater curtailment. From a policy and social cost standpoint, this perhaps is unlikely.

Quantifying the uncertainty embedded in these issues would be critical to better develop and refine sustainable water resources planning associated with water supply uncertainty in the ESPA. Refining the input data is vital, particularly to better understand whether present (2008) recharge and discharge are in equilibrium. The work could be expanded to consider both timing and quantity impacts on demand for water, in conjunction with the supply considerations examined here. As hydrologic modeling improves our understanding of the impact of hydroclimate variability upon surface-water flows, the broad-brush reductions considered here may be inserted into the analysis to refine understanding.

Finally, although a general framework of SD is proposed in this study to manage a water system undergoing changing hydrologic conditions, a study on global environmental change is not an easy task and no universal solution exists. It requires all levels of inter-, multi-, and intradisciplinary efforts to establish sound planning alternatives to respond to an uncertain future hydroclimate. Stakeholder-driven modeling frameworks and participatory approaches within local communities are highly recommended to assess the physical and socioeconomic effects of simulated climate- and management-induced scenarios on sustainable water resources management in a changing climate. Such collaborative efforts equipped with SD modeling, such as that used in this study, will encourage decision makers to focus on the appropriate management options while they consider the ubiquitous political concerns often compromising planning alternatives.

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