DISSERTATION

MODELS FOR MANAGEMENT OF WATER CONFLICTS:

A CASE STUDY OF THE SAN-JOAQUIN WATERSHED, CALIFORNIA

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ABSTRACT

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Competition for use of water is increasing and leads to many conflicts among competing interests with complex goals in water management systems. To deal with the complex competing and conflicting situations, a variety of changes in management policies are required. Technical system models are essential to create performance and other decision information, but models to simulate views of the competing parties are also needed to help resolve or mitigate conflicts. These models can be used as helpful tools to designate effective strategies and water resources management policies that encourage parties to cooperate by accurately simulating the stakeholders' behavior and interactions. In this study a new approach to agent-based modeling (ABM) was introduced to simulate the behavior and interactions of the parties participating in a conflict scenario, which was modeled as a game. Water issues of California's San Joaquin River watershed were used as an example of a long-standing situation. The ABM explained the interactions among the parties and how they could be encouraged to cooperate in the game to work toward a solution. It was confirmed that this model can be used to manage conflicts in complex water resources systems as a powerful tool to establish rules based on the timing of flows, water demands, environmental concerns, and legislative resources. It provides a clear description of human-organizational interactions and a better understanding of complex interactive systems by simplifying the complexity of views and interactions of competing parties. Using this proposed conflict management model, decision-makers will have more reliable support for their decision-making processes.

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

Water is a unique and vital resource for all living creatures. Unlike other consumable resources, it is important for almost everything from biology to economy to aesthetics to spiritual practice (Wolf, 2008). There is no substitute for water. However, the fact that it is unevenly distributed in space and time has provided significant challenges in managing water resources. There is no water management for a single purpose alone and it is always managed in regards with competing interests such as: agricultural, industrial and domestic uses, hydropower generation, recreation and environmental protection. Therefore, the management of water resources inherently involves conflicts among competing users who seek to exploit the water for different purposes.

Although many of the conflicts are purely political, there is broad agreement in the scientific community that the best path to wise water management is a shared governance approach based on comprehensive analysis and facilitated stakeholder involvement. The fundamental concept in the shared governance approach is that the views and concerns of all system operators, stakeholders, and agencies being affected by water resource decisions should be considered in all stages of decision making process.

Most of the major systems in the United States have gone through a period of conflict over their operations in the last decades. Some examples are: 1) The Missouri River system, with conflicts between navigation versus hydropower and recreation purposes in downstream and upstream, respectively; 2) The Columbia River system, with conflicts between protecting aquatic life and hydropower; and 3) The

Apalachicola-Chattahoochee-Flint (ACF) system, with conflicts between upstream urban water supply, downstream estuarine environment, and middle-reach navigation (Lund and Palmer, 1997). The conflicts over water management in California have been going on for decades. The main subject of conflicts in California has been the limited supply of water for agricultural water diversions and urban water demands. Enacting new environmental regulations, in order to protect the ecology of the region, created more limitations on the water supply.

The largest source of California's water is the Sacramento-San Joaquin Delta (the Delta). At least a portion of water demand for approximately two-thirds of all Californians, including even San Diego County residents, is supplied from the Delta and its headwaters in the Sacramento and San Joaquin Rivers. These water resources supply agricultural water demands of the Central Valley, where the majority of productive agricultural efforts in California take place. The Central Valley consists of the Sacramento Valley and San Joaquin Valley. Almost half of the nation's fruits and vegetables are produced by the agricultural activities in this region.

However, agricultural activities in the Central Valley have increased the level of some water quality constituents in the Sacramento and San Joaquin Rivers and in the Delta. The quality of water in the Delta is currently unable to meet objectives for many constituents. Between the two main headwaters of the Delta, the Sacramento watershed receives enough rainfall to dilute the contaminants to an acceptable level, but since the San Joaquin watershed is generally drier, the water quality conditions are more critical in this watershed. As a result, water quality management in the San Joaquin watershed is more important and challenging because of its own environmental health and its impact on the Delta's water quality condition. The main sources of water contaminants in the San Joaquin watershed are agricultural return flows and naturally occurring constituents. These sources of contaminants have caused higher concentrations of salinity, pesticides, nutrients, and some other important contaminants in water bodies of the region.

Of all the water quality constituents, the key water quality issue affecting agricultural activities in the region is salinity (Peterson et al., 1996; Pitzer, 2009). Salinity is important because increasing it can cause serious impacts on agricultural production as well as domestic use of water. High levels of salinity in soil water content decrease plant available water, cause plant stress and ultimately result in reduction of agricultural productivity. It also has inverse environmental impacts and threatens aquatic life. The focus of the research in this dissertation will be on the San Joaquin watershed, as one of the main salinity drivers in the Delta Region, and salinity will be the parameter of interest.

Agriculture, as one of the main sources of salinity in the region, is the dominant activity and a multibillion dollar industry in Central Valley. However, agricultural water diversions and environmental protection goals have negative externalities on each other. Therefore, intense conflicts have been increasing between the agricultural water users and environmental sectors. Water scarcity has also caused conflicts between different agricultural water users arguing to receive or increase their water rights. The conflicts in the region used to be over how water is managed and allocated to water diversions due to the water shortage. In other words, the conflicts were mostly over the amount of water allocated to water users. However, new environmental concerns and new regulations to allocate enough water to the environmental sectors in order to save aquatic life have created more limitations on the water resources and exacerbated the conflicting situations (Sheikh and Cody, 2005).

Numerous efforts have been made to solve the conflicting situations in the region. Out of these efforts, it can be claimed that California Bay-Delta Program (CALFED) has been the most comprehensive and effective effort. Nonetheless, one and a half decades after the formation of CALFED, there are some serious criticisms on its effectiveness regarding performance in resolving conflicts. One of these criticisms is that it has not been able to eliminate the zero-sum nature of the game, where increasing the benefit to one party causes a reduction in the benefit to the other party, through collaborations. It has also failed in adoption of new science in decision making processes (Hanemann and Dyckman, 2009).

It can be claimed that one of the circumstances discouraging the parties to cooperate is the unreliable future of the Delta. Without major changes in policy, the collapse of the Delta is expected (Lund et al., 2007; 2010). Although decline or collapse of the current system in the Delta could impose drastic costs to stakeholders, the expectation of state or federal aid in case of failure is one of the main causes that prevent stakeholder cooperation.

1.2 GENERAL OBJECTIVE

A main objective in water resources management is conflict management and its aim is to come up with consensus solutions that, to some extent, satisfy the goals of all stakeholders in a system. Several forms of conflict resolution approaches have been introduced. These approaches generally emphasize the need of communication, understanding, and negotiation among different parties or stakeholders (Raiffa 1982). To develop an effective and applicable conflict management plan, these communications and negotiations must be mathematically formulated and simulated. These simulations can be used as tools to evaluate the impact of different management scenarios.

In this dissertation, the main objective is to reduce conflicts over water quality management in the San Joaquin watershed through development of a conflict management model, which simulates the water users'/stakeholders' behaviors and interactions, and evaluating some predefined management scenarios. For this purpose, the main parties in conflict in the region are considered to be agricultural diversions and environmental protection agencies. The State is also considered as a mediator party. The management scenarios are mostly defined to encourage agricultural water users to cooperate in the game.

1.3 RESEARCH QUESTION

Major Question: Theories exist that although science and engineering are essential, conflicts like the ones in California are resolved ultimately by the legal and political processes and finance is always a big issue. Therefore, it is critical for scientists and engineers to identify and propose feasible solutions that are transparent and coherent, and which can lead to agreement among the competing parties. Therefore, it should be specified whether the conflicts in the San Joaquin watershed can be reduced through management enhancements?

Sub Questions: In case the management enhancements can lead to less conflict, what social enhancements are more feasible and applicable? What are the most effective legislative improvements? To what degree must different social and legislative enhancements be incorporated?

1.4 SOLUTION

Encouraging parties to cooperate could be a key to solve the conflicts in the Delta (Madani and Lund, in review). Perception of the parties about the region's future must be changed in order to encourage them to shift from their self-optimizing attitude. This may be achieved through an exchange of information and a degree of education and social learning by providing more interaction among stakeholders. Changing and enhancing the stakeholders' perceptions about the region's future helps them believe that the status quo, which ultimately could end up with the Delta failure, will result in less benefit since the stakeholders should solve the problem on their own. Meanwhile, the state should also take into account that in case of the Delta failure, the main loser is going to be the state itself. Therefore, the state involvement in solving the region's conflict is required. This involvement can be accomplished by providing some financial incentives to encourage parties to cooperate. These financial incentives might be proportional to the loss imposed to the state from non-cooperation and Delta collapse.

In this dissertation, a variety of management scenarios, which represent educational, social, and political enhancements, are defined. These scenarios are then tested using a behavioral simulation model linked to an optimization model. While the optimization model finds the theoretical best solutions, the behavioral simulation model tests the possibility of implementing these solutions in an actual situation. The scenarios could be defined to evaluate the impact of state involvement through some constitutional amendments as well as provision of some financial incentives to determine the degree at which the state involvement in the game (as a political enhancement) is effective, and to assess the influence of providing some knowledge enhancement and educational programs in different levels (as social improvements). Another scenario may put the stakeholders themselves in charge of solving the problem in case of a collapse. This case can be interpreted as imposing penalties on the stakeholders as a result of non-cooperation. These penalties are generally less net benefit to stakeholders since they should solve the problem on their own. These scenarios may help to shift from the zero-sum aspect of the conflicting situation. The results obtained from implication of different management enhancement are then compared with each other as well as with the status quo to determine the best management scenario.

1.5 HYPOTHESIS

The main hypothesis of this research is that the conflict management model proposed in this study with more reliable simulation of outcomes for the competing and conflicting parties can help to define management scenarios resulting in higher levels of water users'/stakeholders' satisfaction in the conflict resolution process. Using this model helps to reduce the existing conflicts in the study area by incorporating some management enhancements.

The proposed conflict management model simulates the behaviors of all water users/stakeholders with the main objective of reducing the conflicts over water quality management in the San Joaquin watershed. The model is trained to show agents' behaviors due to different management scenarios. Then, a variety of management scenarios are defined to enhance the system. The general framework of this conflict management model is shown in Figure 1.1. Agents in this figure represent different water users or stakeholders in the system. As demonstrated in this figure, a behavioral simulation model is linked to a decision-making optimization model to help determining different levels of water demands due to implementation of different management enhancements.

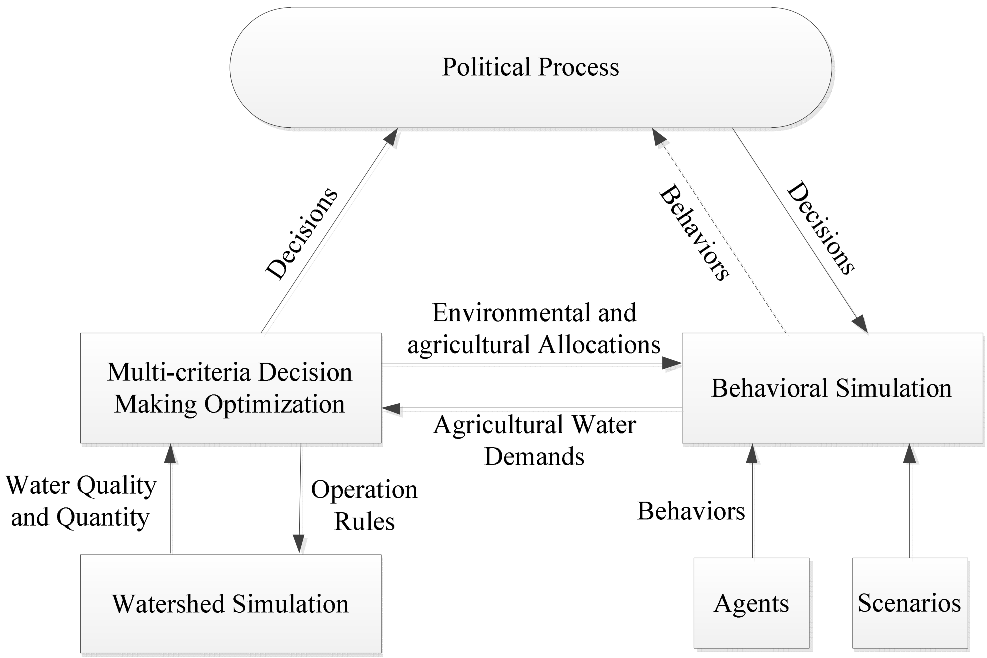

Figure 1.1 The general framework of the proposed conflict management model

1.6 SUMMARY

Fertile soil in the Central Valley of California has created a multibillion dollar agricultural industry in the region. The San Joaquin Valley, which covers almost half of the Central Valley, is of great importance for agricultural activities. However, water shortage has created difficulties in supplying water demands and, in consequence, some conflicts has arisen between different water users expecting to receive at least their water rights. Agricultural activities increase the level of salts in the watershed and result in developing more limitations and negative externalities between agricultural water diversions and environmental protection agencies. In this dissertation, a conflict management model is developed, containing three main models: watershed simulation model, decision-making optimization model, and behavioral simulation model. This model is then used to test the impacts of applying some defined management scenarios on conflict reduction in the region. The effectiveness of these scenarios is tested using the utility functions of different water users/stakeholders to measure their satisfaction. Scenarios resulting in higher satisfaction levels than the status quo are considered as the solutions of the problem.

CHAPTER 2

LITERATURE REVIEW

2.1 CONFLICT RESOLUTION

Conflict is a disagreement among individuals or groups that differ in attitudes, beliefs, values, goals or needs. Because of these differences, the parties are likely to have different perception of the issues in conflict. The key issue in the analysis of conflicting situations is to identify the parties; i.e. individuals, groups, organizations, nations, or other systems, involved in the conflict (Bercovitch, et al. 2009). These parties might disagree about the amount, timing, and quality of their share from a common resource.

In the field of water resources systems, in all phases of analyzing, operating or designing a project, decision makers must ensure that the project is physically, environmentally, financially and economically feasible. They should also check the feasibility of the project due to social and political issues. To reach a socially acceptable compromise, decision-makers should attempt to find an optimal trade-off between conflicting objectives (Raquel et al., 2007). Water resources management is a combined process of sharing water and resolving conflicts among water users and stakeholders. Stakeholders in this context refer to individuals, organizations, or institutions that have stakes in the outcome of decisions related to water or assimilative capacity sharing, because they are either directly affected by the decisions or have the power to influence or block the decisions (Wolf, 2002). Meeting the alternative goals of conflict resolution requires cooperation of all participants and stakeholders. Non-cooperative behavior arises when at least one water user neglects the externalities of his adopted water usage strategies (Loaiciga, 2004).

A proper management scheme must have a multi-objective approach to take into account various interests such as domestic users, agriculturalists, hydropower generators, recreators and environmentalists within the region of interest. When conflicts are developed, negotiations start among the mentioned interests to find an acceptable solution. However, the complexity of finding mutually acceptable solutions increases exponentially as more stakeholders are involved (Wolf, 2008). Wolf claims that there are four different types of negotiation in the process of conflict resolution in water management: rights-based, needs-based, interest-based, and equity-based negotiations. Parties involved in a conflict may have various perceptions of the conflicting issue. Wolf categorized various perceptions into four Worlds: physical, emotional, knowing and spiritual. To clear these types, he considered a glass of water as an example. The glass of water is recognizably on a physical plane (physical perception). If one is thirsty, he perceives it emotionally (emotional perception). It can be intellectualized considering its components and interaction of water with our body (knowing perception). One may also say a blessing over the water and it becomes a source of spiritual nourishment (spiritual perception).

To clarify the impact of having various perceptions of water on conflict resolution processes, Wolf (2008) evaluated an actual conflicting case. In the peace negotiations between Israel and Arabs, each side had different approach to the issue of water. Arabs mostly had physical and emotional sense to the water issue; while for the Israeli side it was mostly intellectual.

Rothman (1991) specified four stages of negotiations as: 1) adversarial, in this stage each side defines its positions or rights 2) reflexive, which addresses the needs of each side that bring them to their positions 3) integrative, in this stage negotiators brainstorm together to address their underlying interests 4) action, in which negotiators work on implementation and re-entry.

For an effective water resources management with conflict resolution purposes, specifying the parties in conflict and determining the type of their perception of water can help to designate the type of negotiations and conduct negotiation processes.

2.1.1 CONFLICT RESOLUTION MODELS

Conflict resolution began to emerge as a specialized field in the 1950’s (Bercovitch, et al. 2009). In the 60's and 70's, theories of conflict resolution found their roots in economics and game theory and soon thereafter it became of interest for many researchers in the field of water resources. Since then, numerous waste-load allocation models have been developed with the intention of resolving or reducing conflicts between water users or adapting to new circumstances for water quality management purposes. These models minimize total effluent treatment costs, while satisfying water quality standards throughout the system. The majority of the classical models incorporate the uncertainties of waste-load allocation problems by choosing particular low flow values, such as 7Q10, and the maximum observed water temperature (Karamouz et al., 2006).

The conflict resolution models are usually complicated, nonlinear, and computationally intensive, especially when different stakeholders, who have their own priorities, are involved (Bazargan-Lari et al., 2008). Clearly, a successful management scheme should take into account the interests of all stakeholders. Loucks (1990) developed a shared vision model which was the common development of a single model or modeling framework by different groups of stakeholders (Theissen and Loucks 1992; Palmer and Keyes 1993; Keyes and Palmer 1993, 1995; Werick and Whipple 1994). In this approach, all parties impacted by water resource decisions (such as system operators, stakeholders, and agencies) are provided the opportunity to participate in model design, development, and evaluation. The goal is to provide these parties with tools that increase understanding of the conflict and the ability to evaluate potential trade- offs (Lund and Palmer, 1997).

Nandalal and Simonovic (2003) developed a simple system dynamics-based bargaining model to resolve a conflicting situation between two water users. They allocated water from a hypothetical river to two water users according to their aspirations and relative weights. Despite the significant results they obtained from their proposed conflict resolution method, their model had been developed for only two water users and it did not consider quality issues. Karamouz et al. (2006) extended the Nandalal and Simonovic model to simulate the bargaining process among multiple players. They incorporated the objectives and preferences of stakeholders and decision-makers of the system in the form of utility functions have the capability of considering both quality and quantity issues. Using this approach they could provide a final agreement among the players. Their model provided optimal water and waste load allocation policies in a river system.

In another study, Karamouz et al. (2010) extended their conflict resolution model further to consider the impacts of an upstream reservoir operations. They resolved the conflicts over the quality and quantity allocations from the downstream river system with regard to the operating rules of the upstream reservoir derived from an optimization model. The optimization model determined the quality and quantity of water released to the river. They compared their model's performance with another conflict resolution model based on the Nash bargaining theory. For this comparison, they used reliability, resiliency and vulnerability criteria. The results showed better performance of the system dynamics model in comparison with the Nash model. They, therefore, claimed that their proposed model could provide an effective tool for water allocation and water quality management in a reservoir-river system.

2.2 CALIFORNIA WATER QUALITY MANAGEMENT

For decades, there have been serious conflicts over how water resources are managed in California. The main subject of conflicts among stakeholders and competing interests in this state has been the limited supply of water (Sheikh and Cody, 2005). Whether and how to transfer water from the Delta region to users elsewhere has been the root cause of the conflicts in California (Hanemann and Dyckman, 2009). Enacting new regulations to prevent the ecosystem and health of the region created more limits to the water supply and new controversies raised among stakeholders over water supply distribution. Water diversions and implementing new regulations to protect the Delta ecosystem create negative externalities on each other and the situation can be seen as a zero-sum game, where increasing the benefit to one party causes a reduction in the benefit to the other party. Some of the main new regulations that exacerbated the conflicting situations in the region are (Sheikh and Cody, 2005):

1) Endangered Species Act (ESA) enacted in 1973 to allocate specific water supplies to natural areas as well as fish and wildlife. This act caused changes to dam operations, water flow, and pumping facilities.

2) Central Valley Project Improvement Act (CVPIA), which changed the priorities for water supply to the CVP by ranking fish and wildlife water needs at the same level as irrigation and domestic water uses.
3) Clean Water Act (CWA), through which mutually acceptable water quality standards were adopted by the state and federal authorities. These authorities concurred to regulate the CVP and SWP operations to meet the standards and also to develop target flows for ESA listed species. The CWA regulates both surface water and groundwater quality and is enforced by the EPA.

To deal with water management competing and conflicting issues in the region, a variety of innovative ideas have been developed. However, the main criticism to them is that they did not have an overall framework. It can be claimed that the most comprehensive effort to resolve water resources conflicts in the region has been the California Bay-Delta Program (CALFED) which was initiated in 1995. There are 23 federal and state agencies in the CALFED Policy Group that are responsible for overseeing the implementation of CALFED, assessing its progress, and reviewing and coordinating CALFED and related programs (Gerlak and Heikkila, 2006).

CALFED designated the "problem area" as the Delta and the "solution area" as all areas hydraulically connected to the Delta or relying on its water supplies, mainly Sacramento and San Joaquin Rivers (CALFED, 2000). Addressing three main problems was the focus of the program: ecosystem health, water quality, and water supply reliability. CALFED intended to respond to the conflicts through a series of agreements and revisions that have involved federal and state legislation, and stakeholder accords (Sheikh and Cody, 2005). Early in the program the CALFED agencies figured out that the program needed to have very active public involvement, particularly from identified interest groups or NGOs. One of the best and earliest achievements of CALFED was public awareness and their participation into water conservation activities (Macaulay, 2001). However, there have been some main concerns in implementation of the CALFED program. These concerns are (Sheikh and Cody, 2005):

- Some agricultural stakeholders have concern over the amount of water they will receive and ask for assurances to receive a certain percentage of their contracted supplies.
- Other agricultural and urban contractors fear their water supplies may be threatened by such assurances.
- Some are concerned that the program is not balanced and the methods of distributing water may disadvantage them.
- Some question the legitimacy of scientific findings for environmental water needs.
- Others are worried if legislative efforts to resolve some of these issues undermine the ability of the CALFED to restore fisheries and the Bay-Delta ecosystem.
- Some environmental groups argue for more flows to support the recovery of endangered plant and animal species.
- Some believe in investing in water conservation, using new technologies, and new pricing strategies to lower demand for Bay-Delta water
- Environmental groups prefer managing existing supplies more efficiently rather than development of new surface storage projects.

Despite the strong scientific fundamentals and comprehensive and adaptive planning for the CALFED program, it can be claimed that it has not been successful after years of implementation. Hanemann and Dyckman (2009) claimed that the CALFED has not been able to eliminate the zero-sum aspect of the game through collaborations, negotiations and collective decision makings by stakeholders. They considered the CALFED program as a continuing failure to adopt new paradigms of governance, to organize adequately, to deal with complex systems, to cope with dynamic ecosystems, to embrace science in decision-making, and to adapt to new knowledge and new ways of knowing. Besides, the significant disagreement about the property rights and the fact that actors prefer to spend their energy fighting to change their property rights rather than accommodating to them has created an intangible situation for the bargaining solution.

Elimination of the strong support from the political leadership in Washington and Sacramento after President Bush was elected caused the situation at CALFED to begin a slow decline (Hanemann and Dyckman, 2009). New leadership that was less supportive of CALFED, creation of the California Bay-Delta Authority (CBDA) without enough authority, and depletion in external funding secured earlier from Congress and the state taxpayers were other reasons for the decline of CALFED (Nawi and Brandt, 2008). All in all, a review by the Little Hoover Commission (2005) found CALFED to be ‘‘costly, underperforming, unfocused and unaccountable’’.

To deal with the conflicting situation in the area and resolve it, some major changes in policy are required to help protect the Delta against being collapsed (Lund et al., 2007; 2010). Madani and Lund (in review) evaluated the nature of the conflicts in the Delta Region. The main conclusions of their study are summarized in the following. For half a century, the nature of the conflicts in the Delta has had a Prisoners' Dilemma game-theoretical structure, when all sides of the conflict prefer not to cooperate and act individually. This behavioral strategy ultimately causes the Pareto optimum solution to be less than even when all parties cooperate. Nowadays, due to the deterioration of the Delta and more environmental, social, and political limitations, some parties have to compromise and cooperate. This situation is called a Chicken game, when a party (especially the one with higher risk aversion) accepts to participate in cooperation and becomes the chicken. In Chicken games, the dominant strategy of the parties is to wait as long as possible to force other parties to deviate from non-cooperative strategies. However, since a collapse can impose significant costs to the state and stakeholders, the sooner the parties cooperate, the lower losses for the parties and state.

2.3 WATER QUALITY SIMULATION MODELS

One of the requirements for water resources development and watershed management is an understanding of hydrological variations due to changes in watershed characteristics over long-term periods (Bhaduri *et al*., 2000). Regarding quality impairments in watersheds, water quality assessment techniques have recently become more into consideration. The current techniques include two methods: (a) water quality field monitoring and (b) computer/mathematical modeling (Parajuli et al. 2009). Field monitoring is the most reliable method but it is expensive. Computer/mathematical models help to save time, reduce costs, and minimize the need for testing management alternatives (Shirmohammadi *et al*., 2006).

The digital computer was brought to the hydrologists as a powerful new tool in the late 1950's (Snyder, 1965). Computer models of water resource systems require a clear and consistent conceptualization of the workings knowledge of these systems (Lord, et al. 1990). In developing water resources systems models, the challenge is to develop a basin-scale model that: (1) is computationally efficient; (2) allows considerable spatial detail; (3) requires readily available inputs; (4) is continuous-time; (5) is capable of simulating land-management scenarios; and (6) gives reasonable results (Arnold et al. 1998).

Numerous watershed models with various capabilities and degrees of complexity are currently available. A number of these models estimate runoff, sediment yield, and phosphorus loads, and many help water quality goal development and implementation (Borah *et al*., 2006). In general, these models are used as tools for developing management strategies to reduce effects of non-point source pollution on water quality (Parajuli et al. 2009).

In developing conceptual models, the Stanford Watershed Model (Crawford and Linsley, 1966) was a first step. It is a simulation model of the hydrologic cycle. The model gets hourly rainfall and daily potential evapotranspiration (as its inputs) and gives hourly stream flow any time the flow is above a preselected base level, mean daily flow, total annual runoff, end-of-month soil moisture and groundwater storages, actual evapotranspiration and other information. However, SWM could not represent the ultimate in precipitation-runoff relationships (Linsley 1967). After SWM, numerous conceptual models and approaches have been developed. Some commonly used conceptual models are:

1. The Streamflow Synthesis and Reservoir Regulation (SSARR) model, which provides mathematical hydrologic simulations for systems analysis to help planning, design, and operation of water resources (Rockwood *et al*., 1972).
2. The HEC-1, originally developed in 1967, considers a river basin as an interconnected system of hydrologic and hydraulic components and simulates the surface runoff response of the basin to precipitation (Hydrologic Engineering Center, 1981). The model provides the computation of streamflow hydrographs at desired locations in the river basin.
3. HYMO, which is a problem-oriented computer language for use in modeling the runoff from watersheds. The name, HYMO, comes from the words “hydrologic model”. HYMO provides simple means of building hydrologic models for the design and evaluation of flood control structures, flood forecasting, or research studies (Williams and Hann, 1973).

The Sacramento model (Burnash *et al*., 1973) and the tank model (Sugawara *et al*., 1976) are other commonly used conceptual models. In all of these models, some processes are described by differential equations based on simplified hydraulic laws, and other processes are expressed by empirical algebraic equations.

Soil moisture replenishment as well as depletion and redistribution for the dynamic variation in areas contributing to direct runoff have been incorporated in more recent conceptual models. For example, the ARNO model (Todini, 1996) uses a probability distribution of soil moisture and TOPMODEL (Beven *et al*., 1987) uses a topographic index. ARNO is a semi-distributed conceptual rainfall-runoff model. The name, ARNO, was derived from Arno River. The areas of application are both in land-surface-atmosphere process research and as an operational flood forecasting tool. ARNO represents the soil moisture balance as well as the transfer of runoff to the outlet of the basin. The concepts of a spatial probability distribution of soil moisture capacity and of dynamically varying saturated contributing areas are incorporated by the model (Todini, 1996).

TOPMODEL is a physically-based computer model of basin hydrology. The name was derived from topography-based hydrological model. The model combines the spatial variability of source areas with the average response of the soil-water storage of the basin to reduce the number of model parameters and the fieldwork required. TOPMODEL subdivides cachments into several hydrologically homogeneous subcatchment units. These units are modeled separately. This model has been designed specifically for unforested catchments with a humid-temperate climate (Beven et al., 1984).

Physically-based, distributed catchment models that have the potential to overcome many of the deficiencies associated with simpler approaches are a new generation of hydrological models. Differential models based on conservation of mass, energy and momentum such as SHE (Abbott *et al*., 1986) and IDHM (Beven *et al*., 1987; Binley *et al*., 1989) can be considered as another class of hydrological models.

The SHE model is a physically-based, distributed model, which simulates water movement in a basin. This simulation is performed with the finite difference solution of the partial differential equations defining the processes of overload and channel flow, unsaturated and saturated subsurface flow, interception, ET and snowmelt. An orthogonal grid network represents the basin to achieve the spatial distribution of catchment parameters. The model incorporates data on topography, vegetation and soil properties and does not require a lengthy hydrometeorological record for its calibration. The SHE is also able to quantify uncertainties by accomplishing sensitivity analyses for realistic ranges of the parameter values (Abbott et al. 1986). However, the data requirements for this model are substantial and the strength of differential models like SHE lies beyond the field of pure rainfall–runoff modeling (Jain *et al*., 1992). Another physically-based catchment model for overland flow, saturated and unsaturated subsurface flow and channel flow is Institute of Hydrology Distributed Model (IHDM) developed by Beven and Calver (1987).

Non-point source modeling was initiated in the early 1970s in regard with the Clean Water Act. Knisel (1980) developed a model called Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model, to simulate the impact of land management on water, sediment, nutrients, and pesticides leaving the edge of a field. This model was later expanded further by Leonard et al. (1987)

to simulate groundwater pesticide loadings (Groundwater Loading Effects on Agricultural Management Systems, GLEAMS) and by Williams et al. (1984) to simulate the impact of erosion on crop production (Erosion–Productivity Impact Calculator, EPIC). However, none of these models considered subsurface flow, ET or plant growth (Arnold et al. 1998).

In order to overcome these shortcomings, in the early 1990s, USDA developed a conceptual, continuous time model to assist water resource managers in assessing the impact of management and climate on water supplies and non-point source pollution in watersheds and large river basins. This model is called SWAT (Soil and Water Assessment Tool). The main objective of developing the SWAT model was to provide a tool to predict the impact of management on water, sediment and agricultural chemical yields in large ungauged basins as well as to assess water supplies and non-point source pollution on large river basins (Arnold and Fohrer 2005).

SWAT is a flexible model that can be applied to watersheds with a wide range of different environmental conditions (Arnold and Fohrer 2005). It incorporates features of several USDA Agricultural Research Service (USDA ARS) models including the Simulator for Water Resources in Rural Basins (SWRRB) model (Williams *et al*., 1985; Arnold *et al*., 1990), CREAMS, GLEAMS, and EPIC. The model SWAT is applicable for integrative river basin management and has the following components: weather, hydrology, erosion/sedimentation, plant growth, nutrients, pesticides, agricultural management, stream routing and pond/reservoir routing.

The models that have been most commonly used by the State and Federal water management agencies in California include DWR's Delta Simulation Model 2 (DSM2), CALSIM-II, and the Resource Management Associates (RMA) Bay-Delta Model (CALFED Bay-Delta Program, 2007).

DSM2 is a one-dimensional mathematical model, which dynamically simulates tidal hydraulics, water quality, and particle tracking in a network of riverine or estuarine channels. There are three modules in DSM2 including: HYDRO (hydrodynamics), QUAL (water quality), and PTM (particle tracking). It can simulate stages, flows, velocities, many mass transport processes (including salts), multiple non-conservative constituents, temperature, and movement of individual particles (USDI, 2008).

The CALSIM model was designed by the California Department of Water Resources to separate the physical and operational criteria from the actual process of determining the allocations of water to competing interests. It evaluates operational alternatives of large, complex river basins (California Department of Water Resources, 2000).

The Resource Management Associates (RMA) model is a two dimensional model, which provides more accurate simulations of the movement of water and solutes in the large channels and flooded islands of the Bay and west Delta. The effects of major changes to Delta geometry such as the breaching of levees can be predicted appropriately using this model (CALFED Bay-Delta Program, 2007).

2.4 AGENT-BASED MODELS

Agent-based modeling is a young yet already widely diffused approach to the analysis, modeling and simulation of complex systems (Bandini et al., 2009). It is a basis for modeling social life as interactions among reconciling agents who influence each other according to the influences they receive (Macy and Willer, 2002). An agent-based model provides a tool to represent a human decision-making process explicitly (Soman et al., 2008).

Galàn et al. (2009) evaluated some studies (Epstein, 1999; Axtell, 2000; Bonabeau, 2002; Bousquet and Le Page, 2004) on agent-based modeling and specified the advantages of this approach over the other modeling paradigms. Based on their study, using agent-based modeling:

1) More natural and transparent descriptions of the systems can be provided.
2) The hypothesis of homogeneity in the population can be relaxed.
3) Explicit representations of geographical environments can be incorporated.
4) Local interactions can be modeled.
5) The bidirectional relation between the individuals and the system can be modeled.
6) The emergent behavior can be captured.
7) The potential criticisms and suggested modifications to the model, made by domain experts and stakeholders, can be easily incorporated.

8) Economic, social, territorial, technological, and every influential dimension can be included in one model.

In agent-based modeling, agents are defined as autonomous entities that have particular knowledge and information (Parker et al., 2003). They can interact with other agents and a common environment. Agents are also goal directed; can act upon the environment; and can react to policy and market conditions (Woolridge and Jennings, 1995). An agent can be any type of independent component (Bonabeau 2002). In simulating social processes using agent-based modeling, agents are considered as people or groups of people, and agent relationships represent processes of social interaction (Gilbert and Troitzsch 1999). The first social agent-based simulation was developed by Thomas Schelling in 1978 to study housing segregation patterns. Agents in this simulation represented people and agent interactions represent a socially relevant process (Schelling 1978).

In the past few years, there has been a significant development of agent- based modeling applications in the water management domain (Galàn, et al. 2009). Izquierdo et al. (2003) developed an agent-based model, called FEARLUS-W, for river basin land use and water management to investigate ways of synthesizing stakeholder priorities. Their model was an extension of an already existing model, FEARLUS, developed by Polhills, et al. (2001). This spatially-explicit agent-based model was built to evaluate the complex interactions among water users upstream and downstream a river. They concluded that their model provided flexibility to address asymmetries due to the flowing nature of river water while interactions between the socio-economic and the ecological aspects of the river basin were also carefully taken into account. According to their conclusion, FEARLUS-W is a tool to increase our understanding of socio-economic interactions between stakeholders in river basin management.

Edwards et al. (2005) assessed the relevance of using an aggregate versus an agent-based (called individual-based in their study) model of water consumption according to the information available on the resource. Their model was the adaptation of Young's (1999) sociologic diffusion model for residential water domains. They consider two kinds of individuals in their study: households and farmers. These individuals had different basic needs in water and different social parameters defined their evolution. Each individual could choose between two types of water consumption behaviors: careful or indifferent. They concluded that these models are highly dependent on the available information on the resource and the type of this information plays a key role not only on the evolution of both individual-based and aggregate models but also on the difference of results between them.

Galàn, et al. (2009) developed an agent-based model for domestic water management in the Valladolid metropolitan area, Spain. They integrated models of urban dynamics, water consumption, and technological and opinion diffusion in an agent-based model linked with a geographic information system. Their opinion diffusion model was formulated based on Edwards et al.'s (2005) work. Using this model, they could simulate and compare various water demand scenarios by evaluating the influence of urban dynamics and other socio-geographic effects in domestic water demand. They concluded that using agent-based modeling can help to overcome some common weaknesses, relative to most traditional methodologies, such as the difficulty to understand the underlying assumptions of the models, the willingness to ignore geographical aspects of the system, and the complexity and failure to integrate diverse socioeconomic aspects in one single model. In general, their model was a tool to obtain complementary insights on the complex issues characterizing water management systems.

Zechman (2007) proposed a multi-agent modeling framework that combined agent-based, mechanistic, and dynamic methods to simulate contamination events. Using this simulation, she analyzed threat management strategies in water distribution systems. The framework was designed to consider the typical issues incorporated in water distribution threat management. This modeling framework enabled her to evaluate management strategies based on simulating more realistic interactions.

Kock (2008) used Agent-Based Modeling in Socio-Hydrological Systems. He developed two agent-based models of society and hydrology for Albacete, Spain, and the Snake River, eastern Idaho, USA, to investigate the societal effects of incorporating an additional institution to the existing water resources management institutions. He integrated essential elements of the regional society (such as real world actors), hydrology, geology; and economic into his models. According to his conclusions, institutional capacity and water conflict dynamics are highly related, however, their direction of influence may vary. Furthermore, in his research, Kock specified critical elements of the design of ground water banking institutions.

Soman et al. (2008) developed a multi-agent based model to capture multiple farmer typology behaviors in making land use decisions that affect the production. They considered agents as landowners, divided into different groups based on their goals, soil crop productivity, and the size of their farm operations. They also analyzed the possible economic and environmental outcome for policy scenarios, such as change in agricultural/environmental policies such as soil conservation, using this agent-based model. Their model helped to understand the interaction and feedback between the agents and their environment associated with different policy initiatives. This model was a tool to predict future land use decisions regarding to various market conditions and policies.

Kennedy et al. (2010) developed an agent-based model to simulate conflicts between herdsmen in east Africa. Using agent-based modeling, they simulated interactions and conflict between herders with different ethnic identities as well as herders and farmers over the utilization of the common grazing land and water resources. Their intention was to figure out if adding wells improves the conflicting conditions. This agent-based simulation model provided them with a tool to evaluate the effect of changing the number of watering holes in reducing conflicts.

2.5 SUMMARY

According to the literature reviewed in this study, conflict is inevitable in water resources management. In California, there have been long lasting and complex conflicts over how the limited water resources are managed and whether or how to transfer water. Raising environmental concerns and enacting new regulations to protect the environment and aquatic life in the region imposed more limits to water supply and exacerbated the conflicting situation. To manage the water resources in California, several innovative ideas have been developed. All of these ideas suffered from the lack of an overall framework. The most comprehensive effort to manage water resources in California was the creation of

CALFED. However, after one and a half decades of implementation of CALFED, its failure has been claimed by some researchers. One of the main criticisms to CALFED is that it has not been successful in encouraging the parties to cooperate and eliminate the zero-sum aspect of the game. However, encouraging the competing parties to cooperate in the game is a key to resolve the conflicts.

In this dissertation, an optimization model which optimizes a multiobjective function is defined to fine the theoretical best solutions for the problem. This model is then linked to a behavioral simulation model, which simulates the parties' behaviors and reactions to different situations to find a more applicable solution for the conflicting problems. Then, a variety of management scenarios are defined and introduced to the behavioral simulation model in order to evaluate the parties' reactions due to these scenarios. Evaluating the performance of implementation of these scenarios, the most effective one(s) in encouraging the parties to cooperate are specified. This process is explained in detail in Chapter 3.

CHAPTER 3

METHODOLOGY

In this chapter, the proposed conflict management model is discussed. This model is a combination of three models including: an optimization model, a watershed simulation model and a behavioral simulation model. The methods to develop these models are explained in detail in the following sections. After developing the conflict management model, it should be confirmed that the proposed model can help to define management scenarios that result in higher levels of water user and stakeholder satisfaction in the conflicting situation. For this purpose, a multi-criteria objective function is defined, which is discussed in the next section. The performance of the proposed model is tested solving this problem. The measures to verify the performance of the model will also be introduced and explained in this chapter.

3.1 SETTING UP THE OBJECTIVES FUNCTIONS

To manage the conflicts in the study area, a multi-criteria objective function is defined as presented in Equation 3.1:

$$\min \{f_1(x), f_2(x), f_3(x)\} \qquad 3.1$$

where, $f_1(x)$, $f_2(x)$, and $f_3(x)$ are the objective functions of the system, which respectively maximize the outflow and minimize salinity load to the Delta, and maximize water diversions. This multi-criteria objective function and all constraints are constructed on a daily basis, which provides the opportunity to consider the timing of flow and allocations. The objective functions of this study are defined as:

1. To maximize the outflow, $\max \hat{f}_1(x)$, to the Delta area for downstream environmental purposes. Since the overall multi-criteria objective function is to be minimized, to maximize this function, its negative value is minimized:

$$f_1(x) = -\hat{f}_1(x) \qquad 3.2$$

2. To minimize the salinity load, $\min f_2(x)$, being transferred to the Delta area for environmental purposes; and
3. To maximize the water allocated to diversions, , $\max \hat{f}_3(x)$. The negative value of this objective function is minimized as explained for the first objective function.

$$f_3(x) = -\hat{f}_3(x) \qquad 3.3$$

To solve this problem, the constraints of the system must also be taken into account. These constraints are:

1. The minimum environmental flow requirements must be considered along the river and its tributaries, i.e. at least the minimum environmental flow requirements must be met after each diversion.
2. Agricultural water users cannot receive more than their maximum water demand. The maximum agricultural water demand for each field is estimated as the difference between the crop water demand in the growing season and the amount of water that each field receives from precipitation or snowmelt.

3.2 SOLVING THE PROBLEM

Reducing conflicts among different stakeholders/water users is the main purpose of solving this multi-criteria objective function. Therefore, a conflict management model, which is a combination of three models, is developed. These models are: 1) optimization model, 2) watershed simulation model, and 3) behavioral simulation model. In the optimization model, the objective function presented in Equation 3.1 will be solved using the Surrogate Worth Trade-off (SWT) method, introduced by Haimes and Hall (1974). This method provides alternative solutions in terms of a Pareto optimal set of solutions. The final optimum solution is then selected from this Pareto optimal set by interacting with decision-makers of the system. In general, the SWT method has four main steps (Debeljak et al., 1986):

1. Generation of non-inferior solutions
2. Generation of associated trade-offs
3. Interaction with the decision-maker(s) to obtain preference or worth information
4. Choice of the best-compromise solution.

These steps will be discussed in detail in Section 3.3. A watershed simulation model (explained in Section 3.4) is linked to the optimization model to determine the variation of flow and salinity in the river as well as the availability of water to be allocated to diversions. The amount of allocations is determined regarding to the water users' demands as well as the constraints of the system. It should be noted that water demands are influenced by the water users' behavioral processes and social networks. In order to simulate these influencing factors, an Agent-Based Model (ABM) is developed and linked to the other models of the conflict management model as the behavioral simulation model.

ABM is a newly developed approach to simulate the actions and interactions of autonomous agents and to assess their effects on the entire system (Macal and North, 2010). This class of simulation has recently become into the consideration of researchers since its computational fundaments have been provided due to the recent computer advances. Details of the ABM approach will be discussed in Section 3.5.

The overall interaction between the watershed simulation, optimization, and behavioral simulation models is illustrated in Figure 3.1. As demonstrated in this figure, the optimized values of diversions as well as outflow and salinity loads being transferred to the Delta are determined by the optimization model which is linked to the watershed simulation model. These values are introduced to the behavioral simulation model. This model simulates the reactions of different agencies to implementing different scenarios. Therefore, it can help to evaluate the effectiveness of management strategies.

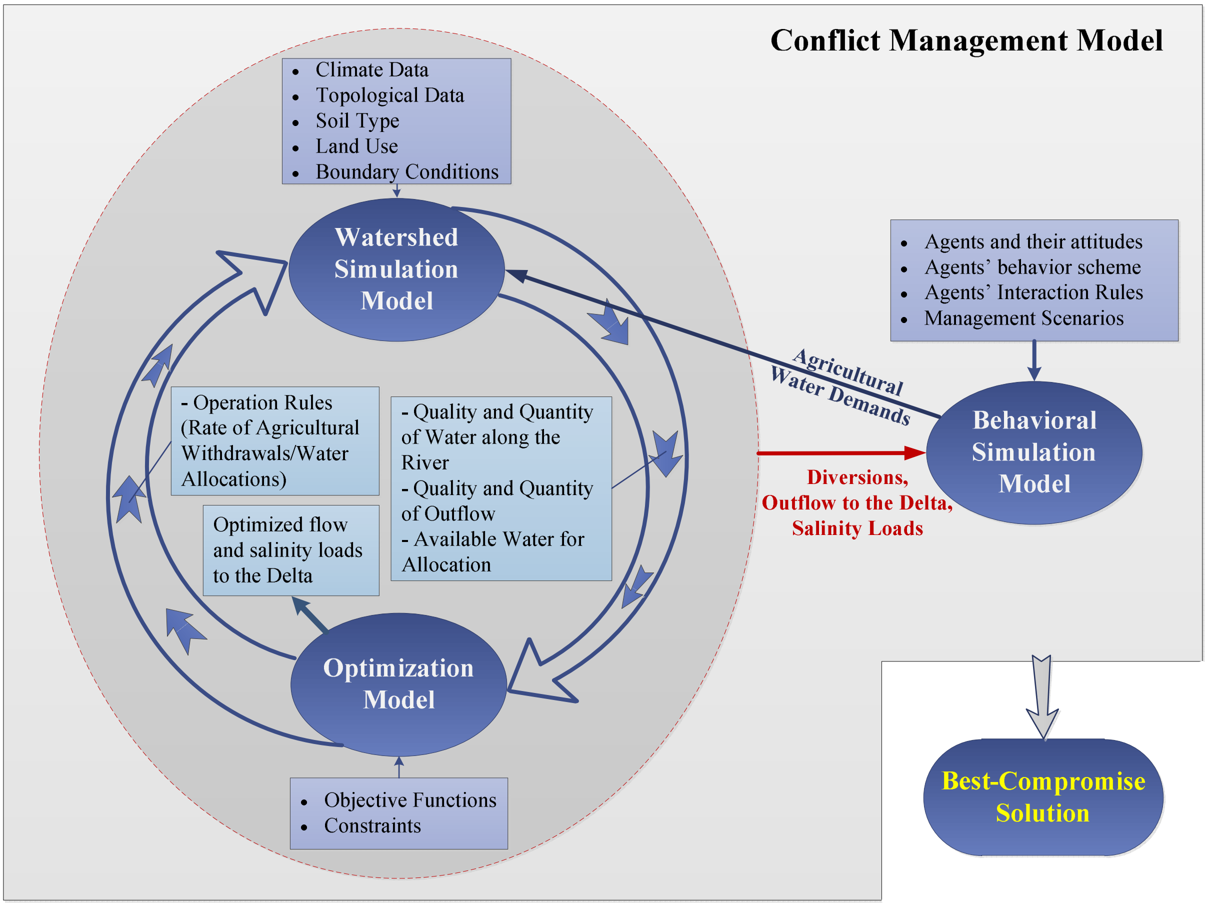

Figure 3.1 The overall interaction between the watershed simulation, optimization, and behavioral simulation models

3.3 SURROGATE WORTH TRADE OFF METHOD

In the Surrogate Worth Trade Off method, introduced by Haims and Hall (1974), a set of Pareto optimal solutions is formed first and the trade-off functions are constructed using the Lagrange Multipliers method. Then, the surrogate worth of each of the Pareto optimum points is specified, interacting with decision-makers. Using these values, the surrogate worth function is constructed. The final optimum solution is selected from the values of surrogate worth function received from decision-makers. The process of constructing the surrogate worth function and selecting the optimum solution will be discussed in Section 3.3.2. To clarify the method, assume the general form of a multi-objective problem with *n* objective functions as shown in Equation 3.4:

$$\min \{f_1(x), f_2(x), \dots, f_n(x)\} \qquad 3.4$$

Subject to

$$g_k(x) \leq 0 \qquad k = 1, 2, \dots, m$$

$$x_j \geq 0 \qquad j = 1, 2, \dots, t$$

where, $f_j(x)$ are the objective functions and $g_k(x)$ are the constraints of the system. To use the Lagrange Multipliers method, one of the objective functions is considered as the primary one and the others are treated as constraints. Then, the Lagrange Equation is generated as follows:

$$L = f_1(x) + \sum_{k=1}^{m} \mu_k \cdot g_k(x) + \sum_{j=2}^{n} \lambda_{1j} \cdot [f_j(x) - \varepsilon_j]; \qquad j = 2, \dots, n \qquad 3.5$$

where, $f_1(x)$ is the primary objective function, μ_k and λ_{1j} are the Lagrange multipliers. The multipliers can be zero or nonzero. A zero Lagrange multiplier corresponds to the inferior set of solutions, whereas a nonzero multiplier shows that particular constraint limits the optimum and corresponds to the non-inferior set of solutions. The Kuhn-Tucker conditions are now defined as:

$$\lambda_{1j} \cdot [f_j(x) - \varepsilon_j] = 0 \qquad j = 1, 2, \ldots, n \tag{3.6}$$

$$\lambda_{1j} \geq 0 \qquad j = 1, 2, \ldots, n \tag{3.7}$$

If either of λ_{1j} or $f_j(x) - \varepsilon_j$ is nonzero, Equation 3.6 can only be valid in case the other one is zero. Hence, the Lagrange multiplier of inactive (not binding) constraints is zero, whereas the value of λ_{1j} for an active (binding) constraint is not necessarily zero. Therefore, the sets of active and inactive constraints are determined using Equation 3.6. The trade-off function is then developed based on the active constraints.

To use the Lagrange Multipliers method, the exact equation of each objective function must be available. However, the objective functions of this study are dependent on a variety of different watershed, meteorological, topological, etc. parameters and each of the objective functions is a combination of multiple physical and hydrological equations. Therefore, it is not practical to use the Lagrange Multipliers method for this study. In order to overcome with this issue, the Pareto optimal set is determined using multi-objective Genetic Algorithm (GA) method, which is discussed in the following section.

3.3.1 Genetic Algorithm

Genetic algorithms have being widely used to find optimal solutions to computationally difficult problems. Holland (1975) developed the genetic algorithm method for solving both constrained and unconstrained optimization problems. This method imitates the process of biological evolution and successively modifies the solutions of a problem. To explain how the genetic algorithm works, first some important terminologies are defined as follows:

Fitness Functions: or objective functions are the functions that must be optimized (minimized or maximized).

Individual/Chromosome: is a set of parameters which result in a proposed solution to the problem.

Gene: each parameter in a chromosome is called a gene.

Score: the value of the fitness function based on an individual/chromosome is the score of that individual.

Populations: an array of individuals is called a population.

Generations: each consecutive population is called a generation.

Parents and Children: in each iteration, certain individuals are selected from the population to create the new generation. These selected individuals are called the parents. The individuals created in the next generation are called children.

Three main types of rules are applied to produce children for the new generation: 1. Mutation, which is referred to as random changes to a single parent, i.e. one or more genes are changed in a parent chromosome; 2. Crossover, which is swapping a part of the genetic information containing in two chromosomes; 3. Elite children. The chromosomes resulting in the best solutions in each iteration are considered as the elite of each population and will directly be transferred to the next generation without any change. Figure 3.2 illustrates the creation process of different types of children. Selecting parents and creating children are two of the main steps of GA. A basic genetic algorithm has four main steps (Goldberg, 1988):

1. Creating the initial population of chromosomes
2. Computing the fitness function(s) based on the population
3. Selecting of parents from the current population to create the next generation. For this purpose, chromosomes that result in better scores are selected as parents.

4. Producing the children for the next generation

After generation of the new population, steps two through four are repeated for a fixed number of generations. Therefore, a population of individual solutions is repeatedly modified over successive generations and the population evolves toward a Pareto optimal front. This successive process continues until one of the stopping conditions is reached. These stopping conditions include: a fix number of generations, time limit, fitness limit, etc.

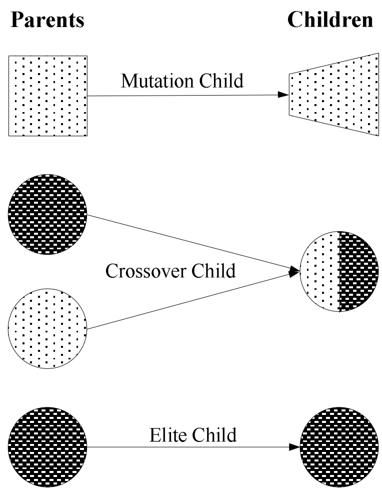

Figure 3.2 Schematic diagram of three types of children being created in a GA optimization process

3.3.2 Construction of the Surrogate Worth Function

After determining the Pareto optimal front, the surrogate worth function must be formed based on the non-inferior solutions in the Pareto front/trade-off function. Interacting with decision makers, a surrogate worth function, $W_{ij}, i \neq j \text{ } and \text{ } i, j = 1, 2, \dots, n$, is defined as a function of each point on the trade-off function between every two objective functions in the scale of -10 to +10. β_{ij} shows the value of each point on the trade-off function between objective functions *i* and *j*. The value of -10 indicates that β_{ij} marginal units of objective *i* is much less than one marginal unit of *j*. Whereas, +10 indicates the opposite.

In this study, to provide decision-makers with more tangible values, the ratio, R_{ij}, between β_{ij} and the status quo is calculated and decision-makers are asked to determine the surrogate worth of these ratios. For example, assume β_{ij} is a point on the trade-off between water diversions and outflow to the Delta and it corresponds to *A* amount of water diversion and *B* amount of outflow to the Delta. The status quo values for diversion and outflow are *A'* and *B'*, respectively. In this case, decision makers are told that *A/A'* decrease or increase in diversions will result in *B/B'* increase or decrease in the outflow and they are asked to determine the surrogate worth corresponding to these ratios. After the surrogate worth of all trade-off points are determined, the solution is where the surrogate worth is equal to 0, $W_{ij} = 0$. This means that the solution belongs to the indifference band. The optimum/best compromise solution is where the surrogate worth is simultaneously equal to zero for all pairs of objectives.

There are three different alternatives to determine the indifference band. In one approach, which considers ordinal scale of the surrogate worth function, the decision maker is asked to determine the corresponding values of W_{ij} to two distinct R_{ij}. Then, the linear function between these two W_{ij} is developed. The value of R_{ij} is equal to $R_{ij}{}^{*}$ where $W_{ij} = 0$ along the linear function (Figure 3.3). After determining all $R_{ij}{}^{*}$, the $R_{ij}(x) = R_{ij}{}^{*}$ relations are solved simultaneously.

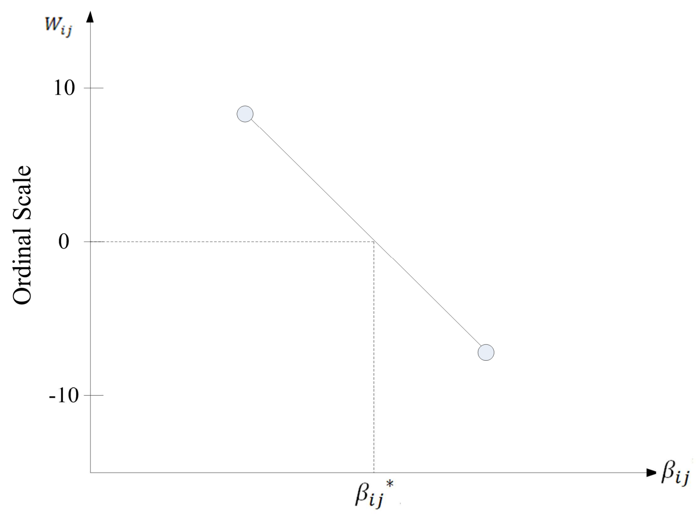

Figure 3.3 Determination of the indifference band at $R_{ij}{}^{*}$ (Haims and Hall, 1974)

In another approach, the surrogate worth function is developed via regression analysis in the function space. In the third approach, which is preferred over the other ones, the corresponding value of ${f_j}^*(x)$ to ${R_{ij}}^*$ is determined. Then, the single objective optimization problem in Equation 3.8 is solved to specify the desired x^*.

$$\min \ f_1(x) \qquad 3.8$$

Subject to

$$f_j(x) \leq {f_j}^*(x) \qquad j \neq i \quad and \quad j = \{1, 2, \dots, n\}$$

$$g_k(x) \leq 0 \qquad k = 1, 2, \dots, m$$

For more details please review Haimes and Hall (1974). Figure 3.4 demonstrates the overall algorithm of the surrogate worth trade-off method in this study.

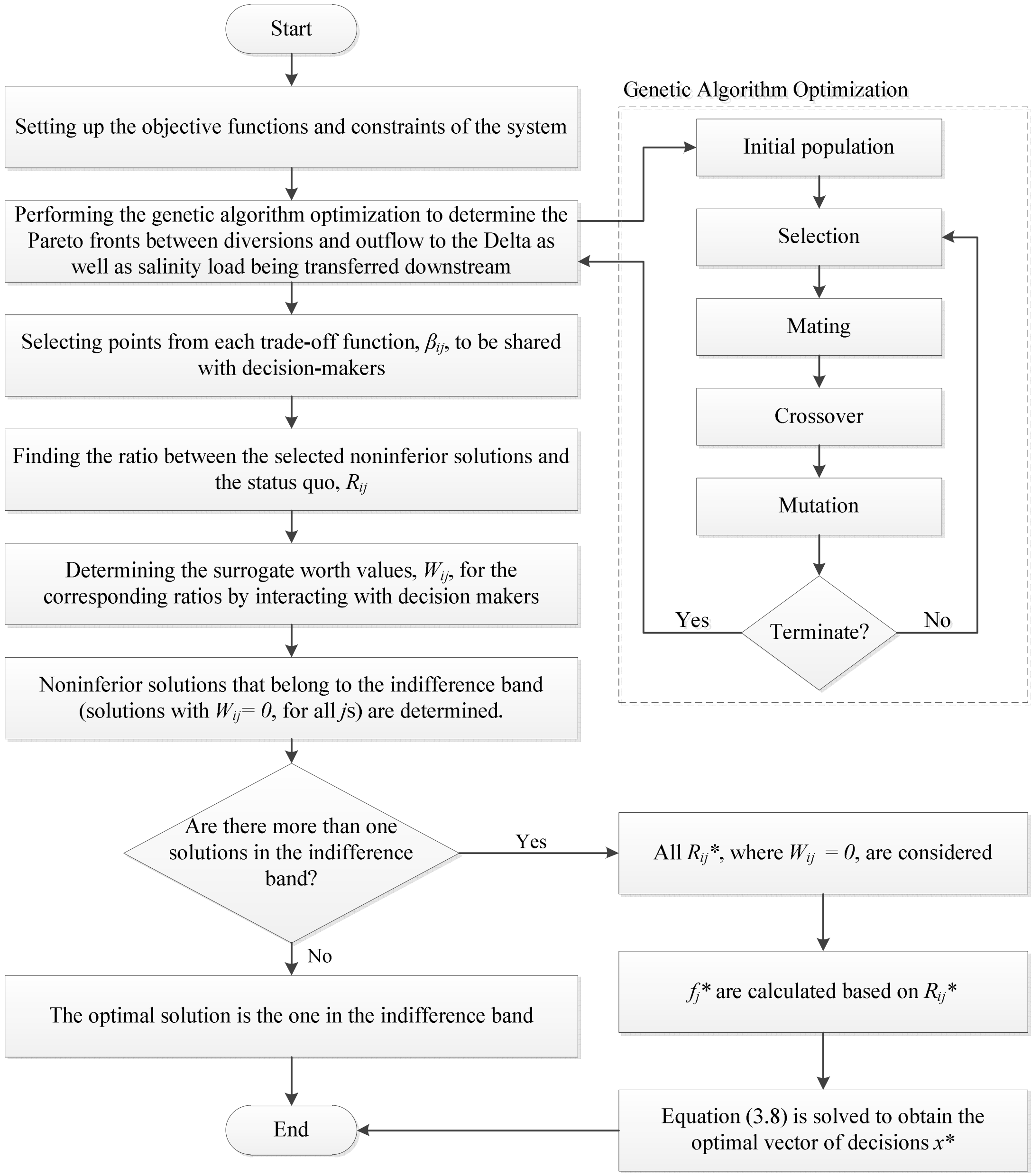

Figure 3.4 The overall algorithm of the surrogate worth trade off method

3.4 WATERSHED SIMULATION MODEL

In this research, the San Joaquin watershed is simulated to assess the variation of flow rate and salinity concentration along the river and at its outflow to the Delta. This simulation model is used as a tool to evaluate the influence of the management scenarios on the quantity and quality of water in the study area. For this purpose, ArcSWAT simulation model is used. The ArcSWAT is a graphical user input interface for the SWAT (Soil and Water Assessment Tool) model (Arnold *et al.*, 1998) which is added to ArcGIS-ArcView as an extension.

SWAT is a continuous time, physically-based river basin, or watershed, scale model. It can be used to evaluate and predict the impact of management practices on water, sediment, and agricultural chemical yields in large, complex watersheds having different soils, land use, and management conditions over long periods of time (for more information please check the ArcSWAT website at swatmodel.tamu.edu/software/arcswat). Unlike most of the simulation models, SWAT does not incorporate regression equations to describe the relationship between input and output variables. Instead, it simulates a number of various physical processes in the watershed to obtain predictions/simulations even where there is not a measured data. SWAT needs specific information about weather, soil properties, topography, vegetation, and land management practices occurring in the watershed (Neitsch *et al.*, 2005). The main input data required to simulate a watershed using ArcSWAT are:

- Digital Elevation Model (*DEM*) files, which are spaced grids of elevation points
- Land cover database (such as NLCD[1], and NASS[2])
- Soil geographic data bases (such as STATSGO[3], SSURGO[4], NATSGO[5], etc.)
- Climate data (temperature and precipitation)
- Point source data (location, flow rate, and quality)

The NLCD land cover database classifies land use as agricultural, urban, open water, etc., but the NASS database specifies the type of crops being planted in each agricultural land. Therefore, to be able to specify the water demand of each agricultural field, the NASS database will be used in this study. For the soil database, STATSGO is used since it is already built in the SWAT model as default. Once the above

[1] National Land Cover Data
[2] National Agricultural Statistics Service
3 State Soil Geographic Database
4 Soil Survey Geographic Database
5 National Soil Geographic Database

mentioned input data are introduced to the model, it delineates the watershed's subbasins and simulates the quality and quantity of water flowing in the river regarding to the inflows, runoff, point and nonpoint sources, etc.

3.4.1 Sensitivity Analysis

After developing a hydrological model, it is important to calibrate it and verify the predictions obtained from the model. However, to calibrate a hydrological model, a significant number of parameters that influence the hydrological system must be considered and optimized. These parameters include climate, hydrologic, water quality, sediment, channel processes parameters, etc. However, the model might not be sensitive to all of these parameters. In order to reduce calibration computation time, it is helpful to perform a sensitivity analysis in advance to specify the parameters to which, the model is sensitive. Therefore, calibration is accomplished using only these parameters.

Sensitivity is a measure of the effect of change in one factor regarding to change in another factor (McCuen, 1973). Sensitivity analysis is a technique that helps to discover whether different values of an independent variable will impact a particular dependent variable under a given set of assumptions and if so, how the impact would be. Sensitivity index (*SI*) can be used as a measure to determine the sensitivity of a dependent variable to an independent variable. *SI* represents the change in simulation results in accordance with the change in a specific model parameter. Sensitivity index for a time series is calculated as:

$$SI_k = \left\{ \sum_{t=1}^{T} \left[\left(\frac{Sim_{k,t} - Sim_{k,t}^0}{Sim_{k,t} + Sim_{k,t}^0} \right) \Big/ \left(\frac{Par_k - Par_k^0}{Par_k + Par_k^0} \right) \right] \right\} \Big/ T \qquad 3.9$$

where, SI_k is the sensitivity index for parameter *k*, Par_k^0 is the default value for parameter *k*, Par_k is the adjusted value for parameter *k*, $Sim_{k,t}^0$ is the simulated value obtained from the model at time *t* while parameter *k* has its default value, $Sim_{k,t}$ is the simulated value obtained from the model at time *t* while parameter k has its adjusted value, and $t = 1, \ldots, T$. Clearly, the model is not sensitive to the parameters that their corresponding *SI* value is equal to zero. The parameters that have a *SI* value other than zero will be considered sensitive and will be used to calibrate the simulation model.

3.4.2 Calibration of the Watershed Simulation Model

The main purpose of calibrating a hydrologic model is to find values of model parameters so that the predictions values have a reasonable match with the observed values. In calibrating hydrologic models, one or more objective functions, which represent the similarity between the observed and simulated values, should be optimized (Zhang et al. 2009). The most commonly used objective functions are sum of squares for error, Coefficient of Determination (R^2), bias, Nash-Sutcliffe Efficiency (NSE), root mean square error, relative error, etc. The optimized model is then used to evaluate the effectiveness of water resources management scenarios.

Different calibration methods have been developed and applied to enhance the reliability of SWAT simulations (Eckhardt and Arnold, 2001, Bekele and Nicklow, 2007; Kannan et al., 2008). Duan et al. (1992) developed a powerful global optimization procedure, entitled the shuffled complex evolution (SCE-UA) method. This method efficiently and effectively identifies the optimal values for the model parameters. Van Griensven et al. (2006) incorporated the shuffled complex evolution algorithm for parameter calibration of SWAT. Muleta and Nicklow (2005) combined Genetic Algorithms (GA) and Generalized Likelihood Uncertainty Estimation (GLUE) methods to conduct parameter calibration and uncertainty analysis of SWAT.

To calibrate the San Joaquin watershed simulation model, five different objective functions were optimized using the shuffled complex evolution algorithm. These objective functions are discussed in Section 3.4.2.1 and the shuffled complex evolution algorithm is explained in Section 3.4.2.2.

3.4.2.1 Statistical criteria for evaluating the performance of hydrologic prediction

The statistical criteria that have been used in this study to evaluate the performance of the San Joaquin watershed simulation model are discussed in this section. These criteria are relative error, PBIAS, coefficient of determination, Nash-Sutcliffe efficiency, and root mean square error.

Relative Error (RE) helps to designate the ratio between absolute error and the observed data values. It is a measure of the uncertainty of simulation in comparison with the measurement and in most cases is expressed as percentage. RE is calculated as:

$$RE = \left[\left(\overline{Obs_t} - \overline{Sim_t}\right)/\overline{Obs_t}\right] \times 100 \qquad 3.10$$

Where, $\overline{Obs_t}$ is the mean of observed data values for the entire time series, $\overline{Sim_t}$ is the mean of simulated data values for the entire time series.

PBIAS demonstrates the average tendency of the simulated data to be larger or smaller than the corresponding observed data (Gupta et al., 1999). Smaller PBIAS values signify a more reliable simulation. Positive values point to overestimations, and negative values indicate underestimations (Gupta et al., 1999). PBIAS can be calculated as:

$$PBIAS = \left[\sum_{t=1}^{T}(Sim_t - Obs_t)/\sum_{t=1}^{T} Obs_t\right] \times 100 \qquad 3.11$$

where Sim_t is the model simulated value at time *t*, Obs_t is the observed data value at time *t*, and $t = 1,2,\ldots, T$.

Coefficient of Determination (R^2) is equivalent to the square of the Pearson's product-moment correlation coefficient (Legates and McCabe, 1999). It expresses the proportion of the total variance in the observed data that can be demonstrated by the model. R^2 ranges between 0.0 and 1.0 and the closer it is to 1.0 the better performance of the model. It can be determined as:

$$R^2 = \left\{\frac{\sum_{t=1}^{T}(Obs_t - \overline{Obs_t})(Sim_t - \overline{Sim_t})}{\left[\sum_{t=1}^{T}(Obs_t - \overline{Obs_t})\right]^{0.5}\left[\sum_{t=1}^{T}(Obs_t - \overline{Obs_t})\right]^{0.5}}\right\}^2 \qquad 3.12$$

Nash-Sutcliffe Efficiency (NSE) is used to evaluate the predictive power of hydrological models. It ranges from $-\infty$ to 1 and reveals how well the plot of the observed data value versus the simulated data value fits the 1:1 line (Nash and Sutcliffe, 1970). The closer the NSE values are to 1.0, the better model performance. Equation 3.13 shows how NSE is formulated.

$$NSE = 1.0 - \sum_{t=1}^{T}(Sim_t - Obs_t)^2 / \sum_{t=1}^{T}\left(Obs_t - \overline{Obs_t}\right)^2 \qquad 3.13$$

Root Mean Square Error (RMSE) is a measure of the difference between the mean of observed data values and the simulated data values. RMSE aggregates these differences into a single measure of predictive power. It is formulated as:

$$RMSE = \left(\frac{\sum_{t=1}^{T}(Obs_t - Sim_t)^2}{T}\right)^{0.5} \qquad 3.14$$

Table 3.1 presents general performance ratings for streamflow, sediment, and nitrogen/ phosphorous for bias and Nash-Sutcliffe for a monthly time step. If the performance ratings of these measurements for the San Joaquin watershed simulation model meet the values shown in Table 3.1, the simulation model can be considered accurate.

Table 3.1 General performance ratings for streamflow for bias and Nash-Sutcliffe for a monthly time step (Moriasi et al., 2007)

Performance Rating	Nash-Sutcliffe	Bias (%)		
		Streamflow	**Sediment**	**N,P**
Very good	0.75 < NSE ≤ 1.00	Bias < ±10	Bias < ±15	Bias < ±25
Good	0.65 < NSE ≤ 0.75	±10 ≤ Bias < ±15	±15 ≤ Bias < ±30	±25 ≤ Bias < ±40
Satisfactory	0.50 < NSE ≤ 0.65	±15 ≤ Bias < ±25	±30 ≤ Bias < ±55	±40 ≤ Bias < ±70
Unsatisfactory	NSE ≤ 0.5	Bias ≥ ±25	Bias ≥ ±55	Bias ≥ ±70

3.4.2.2 Shuffled Complex Evolution

Shuffled complex evolution approach was first introduced by Duan et al. (1993). The method is based on a combination of four concepts that have proved successful for global optimization (Duan et al., 1993):

1. Combination of random and deterministic approaches: the former assists to make the algorithm flexible and robust, and the latter allows the SCE algorithm to effectively use the response surface information to conduct the search.
2. The concept of clustering: helps to focus attention of the search on the most promising of the spaces identified by the initial complex.
3. The concept of a systematic evolution of a complex of points spanning the region toward global improvement. This strategy helps to ensure that the search is relatively robust and is conducted by the structure of the objective function.
4. The concept of competitive evolution, which helps to improve global convergence efficiency

The process of the SCE method can be summarized as follows (Duan et al., 1992): It starts with a population of points randomly selected from the feasible space. The population is then divided into several communities that each of them contains $2n + 1$ points, where n is the dimension of the problem. Each community evolves based on a statistical *reproduction* process. This process uses the *simplex* geometric shape to direct the search in an improvement direction. At fixed intervals in the evolution, the entire population is shuffled and points are reallocated to communities to guarantee information sharing. If the initial population size is sufficiently large, during the search progress, the entire population moves to converge toward the neighborhood of global optimum. The algorithm of SCE is presented in Figure 3.5. For more detail please see Duan et al. (1992 and 1993).

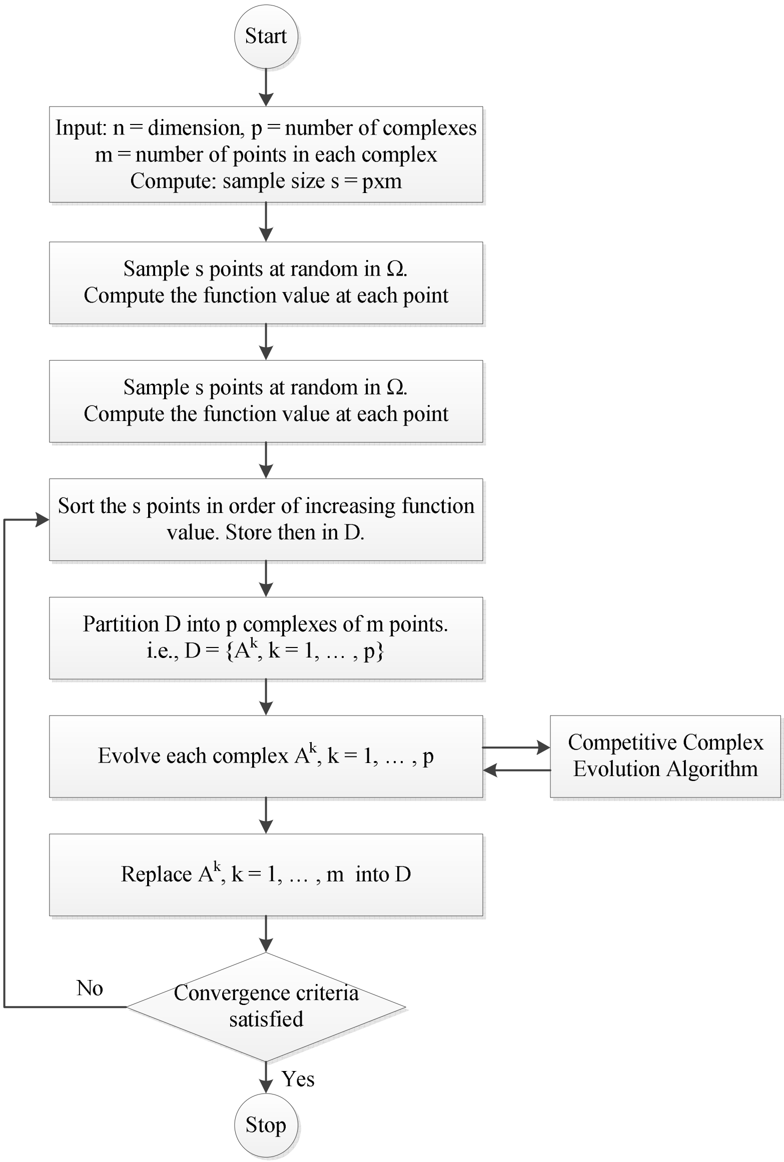

Figure 3.5 Flow chart of the shuffled complex evolution (SCE) method (Duan et al., 1992)

3.5 BEHAVIORAL SIMULATION MODEL

The behavioral simulation model is developed using agent-based modeling, which is a nearly new modeling paradigm. In this approach, the system is formulated from the perspectives of the individual agents, which are modeled as discrete autonomous entities with particular goals and actions (Ng et al., 2010). In comparison with traditional models, agent-based models are flexible, they capture emergent phenomenon, and incorporate real world systems involving complex human decision making (Bonabeau, 2002). The key steps in developing an agent-based model are (Macal and North, 2006a and b):

1. Identifying agents;
2. Accurately specifying their distinct behaviors;
3. Defining the environment the agents live in and interact with;
4. Identifying the agents relationships and get a theory of their interaction with each other and with the environment;
5. Getting the essential agent-related data;
6. Appropriately representing agent-to-agent interactions as well as environment-agent interactions;
7. Validating the agent behavior model.

3.5.1 Definitions

Agents: Macal and North (2006a) defined agents as "autonomous decision-making units with diverse characteristics". Agents have their own goals and behaviors and are capable of adapting and modifying their behaviors. They are characterized by their attributes, behavioral rules, memory, decision-making sophistication (the amount of information an agent requires to make decisions), and resources/flows (Macal and North 2006b). An agent can be any type of independent component such as software, model, individual, organization, group, etc. (Bonabeau 2002). In applications of ABM to social processes, people or groups of people are considered to be agents, and agent relationships represent processes of social interaction (Gilbert and Troitzsch 1999). It should be noted that in this approach, it is assumed that people and their social interactions can be plausibly modeled at some reasonable level of abstraction for well-defined purposes (Macal and North, 2006b).

Environment: The environment includes pertinent elements of the simulated system that are not agents. The overall dynamics of the system and effects that influence agents are determined by the environment. In general, the environment provides agents with their perceptions, which are relative to the current structure of the system and to the arrangement of agents living in it (Bandini et al., 2009).

3.5.2 Classification of Agents' Behaviors and Interactions

Bandini et al. (2009) classified agents' behaviors into reactive and deliberative. Reactive agents have a defined position in the environment. Their actions are the consequences of their perception of stimuli (events in the environment that influence behavior). This perception comes either from other agents or from the environment. Therefore, reactive agents' behaviors are specified as a set of condition-action rules coupled with a selection strategy which helps to choose an action to be taken whenever different rules are activated. For deliberative, also called cognitive agents, the selection mechanism is more complex. Their behavior is based on agent knowledge about the environment and on memories of past experiences.

In addition to reactive and deliberative agents, a third class can also be defined called Hybrid, which is a combination of reactive and deliberative agents. In this class, agents can have a layered architecture. The structure of layers can be vertical or horizontal (Brooks 1986). There are no priorities associated to horizontal layers. In this structure, to analyze the agent's behavior, the results of the different layers must be combined. In vertical structure, there is a higher priority for reactive layers compared to deliberative ones and these layers are activated only when no reactive behavior is triggered.

The agent interaction models can be categorized into two models: direct and indirect interactions. In the former, which is the most widely adopted model, there is a direct information exchange between involved agents. In the indirect interaction models, an intermediate entity mediates agent interactions. This entity can even regulate the interactions (Bandini et al. 2009).

3.5.3 Proposed Agent-Based Model

The ABM proposed in this study is intended to provide a tool that helps to find effective management scenarios to encourage competing and conflicting parties to cooperate. It uses a new approach to consider parties' reactions to new decisions and to formulate suggested social and institutional enhancements. To develop an ABM for the situation in the Delta, the environment must be considered as the entire Delta system. This includes all areas hydraulically connected to the Delta. The agents must be assigned as all water users, operators, stakeholders, and parties of interest.

However, due to computational restrictions, the system was simplified and this study was accomplished on only a portion of the area. The environment is considered to be the San Joaquin watershed, which is one of the two main rivers discharging into to Delta. Three groups of agents were defined for this system: one decision-maker agent and two demand agents. The decision-maker agents are federal or state agencies and the demand agents are water diversions/farmers (demanding for water) and environmental sector (demanding for enough water flowing along the river with an acceptable quality). The agent type "diversions/farmers" is called "diversions" hereafter. The federal/state agents can be represented as deliberative agents, while the other two are reactive agents.

It should, however, be noted that in the actual scenario, the system is significantly more complex. Federal agencies as well as all other governing units can be considered decision-makers in addition to the state. Furthermore, different types of diversion agents can be defined based on the fact that some diversions might be concerned about the environment and cooperate; some might obtain more benefits by cooperation and have more willingness to cooperate; and some might not care about the environment and be persistent in noncooperation.

To deal with conflicts over water resources, an inter-institutional understanding of the whole system is required. In other words, the system must be contemplated as a whole, not only an individual part of the pattern. Therefore, it is important to specify the characteristics of each agent involved in the conflicting situation and the influence of these characteristics on the other agents. Figure 3.6 shows the characteristics of each agent. These characteristics include: attributes, behavioral rules, memory, decision-making sophistication, and resources/flows (Macal and North, 2006b). However, determining these characteristics is a complex task. It needs a comprehensive and accurate knowledge about each type of agents. It should also be taken into account that continuous hydrologic, social, and economic changes, shifting goals, and new principles and targets can all influence these characteristics. On the other hand, depending on the situation, the agents might be diplomatic and show characteristics other than what they really have.

To take into account the influence of agents' characteristics on the others, understanding the "system's perception" about water is important. However, system's perception without "mental models," which impact agents' behavior, has no meaning. Mental models are the assumptions, generalizations, or even pictures that influence our understanding about the world and how we take actions (Senge, 1990). In this respect, the world of perception has been added to the characteristics mentioned above. There are four worlds of perception: physical, emotional, knowing, and spiritual, which were defined by Wolf (2008) and discussed in Chapter 2. Physical and knowing perceptions have rational roots, and spiritual perception has emotional roots. Emotional perception, which is based on values, has a direct emotional root, but it can somehow be rooted by rational perception. Figure 3.7 shows the mental model developed in this study for the agents involved in the conflicting problem.

The action/behavior of each agent is based on its attitude, which is influenced by the environment as well as pressure from other agents. Figure 3.8 shows the overall influence of the environment and the agents on each other. As shown in this figure, the environment influences the attitude of all agents; because the environment determines water availabilities and limitations of the system. The agents also mutually influence the environment since their actions may directly impact it. Both diversions and environmental sector influence the attitude of the state by informing it about the concerns and demands, and justifying the importance of their goals. In addition, the state affects the attitude of the diversions by informing them about the new regulations, educational plans, assigned incentives, etc. The environmental sector's attitude is only influenced by the environment.

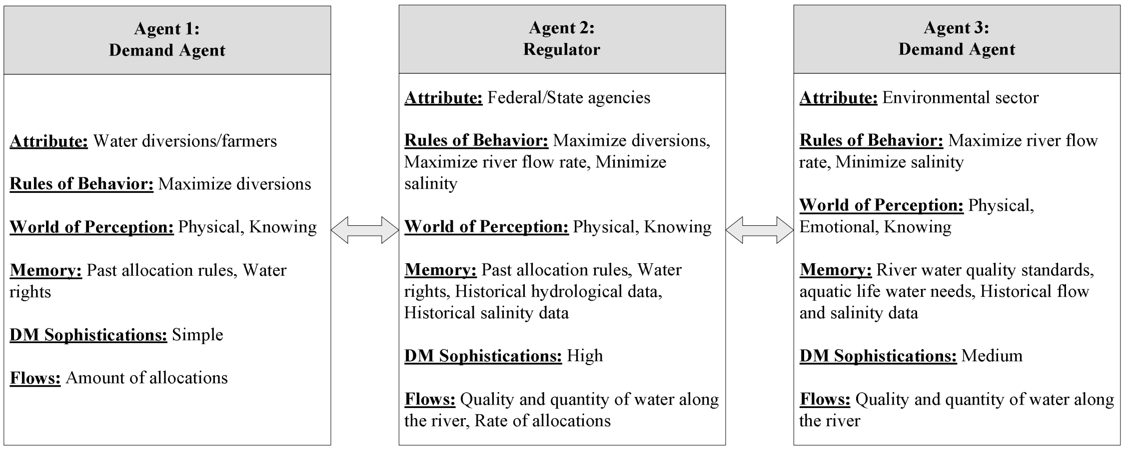

Figure 3.6 Agents in the study area and their characteristics

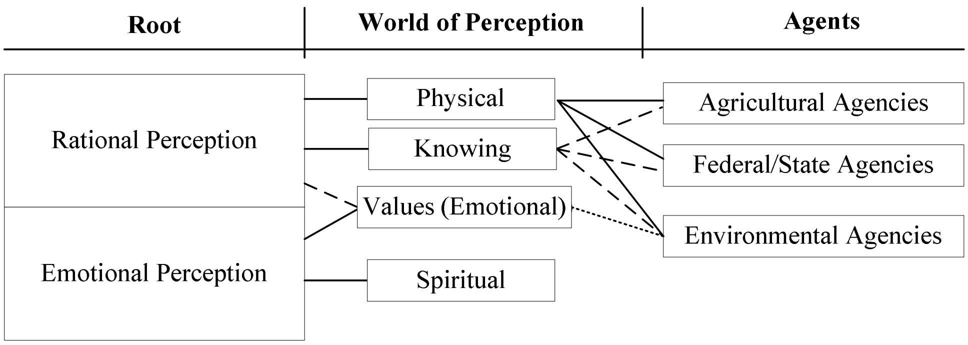

Figure 3.7 The mental model for the agents involved in the conflicting problem

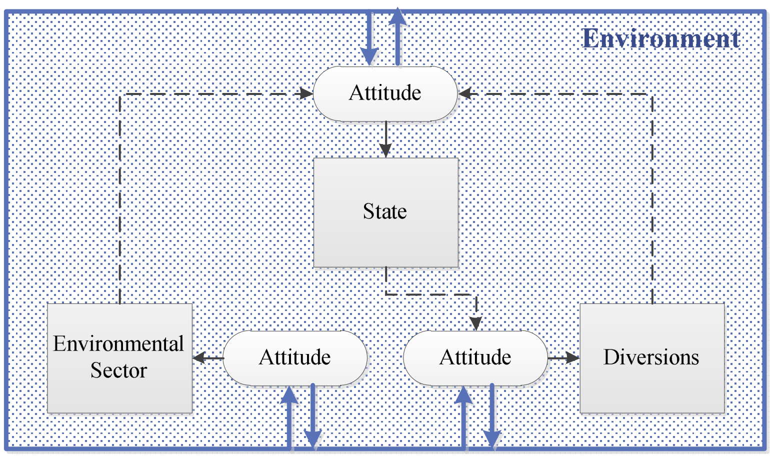

Figure 3.8 The influence of the environment and other agents on each agent

Figure 3.9 illustrates details of the agent-to-agent and environment-agent interactions. The State agent has a direct interaction with both diversions and environmental sector, but there is an indirect interaction between the diversions and the environmental sectors, having the state as the intermediate/mediator agent. As demonstrated in Figure 3.9, the environment determines the quality and quantity of water along the river as well as water available for allocations; while the interaction of all agents determines agricultural water demands for the environment. In indicating their water demands, diversions may have two types of behaviors: cooperative, and non-cooperative. In the case of cooperation, supplying their total demand will be compatible with the system's capability of supplying water and will not harm the environment. Therefore, the negative externalities between the diversions and environmental sector might be reduced to an unimportant level and the environmental sector might compromise minor violations.

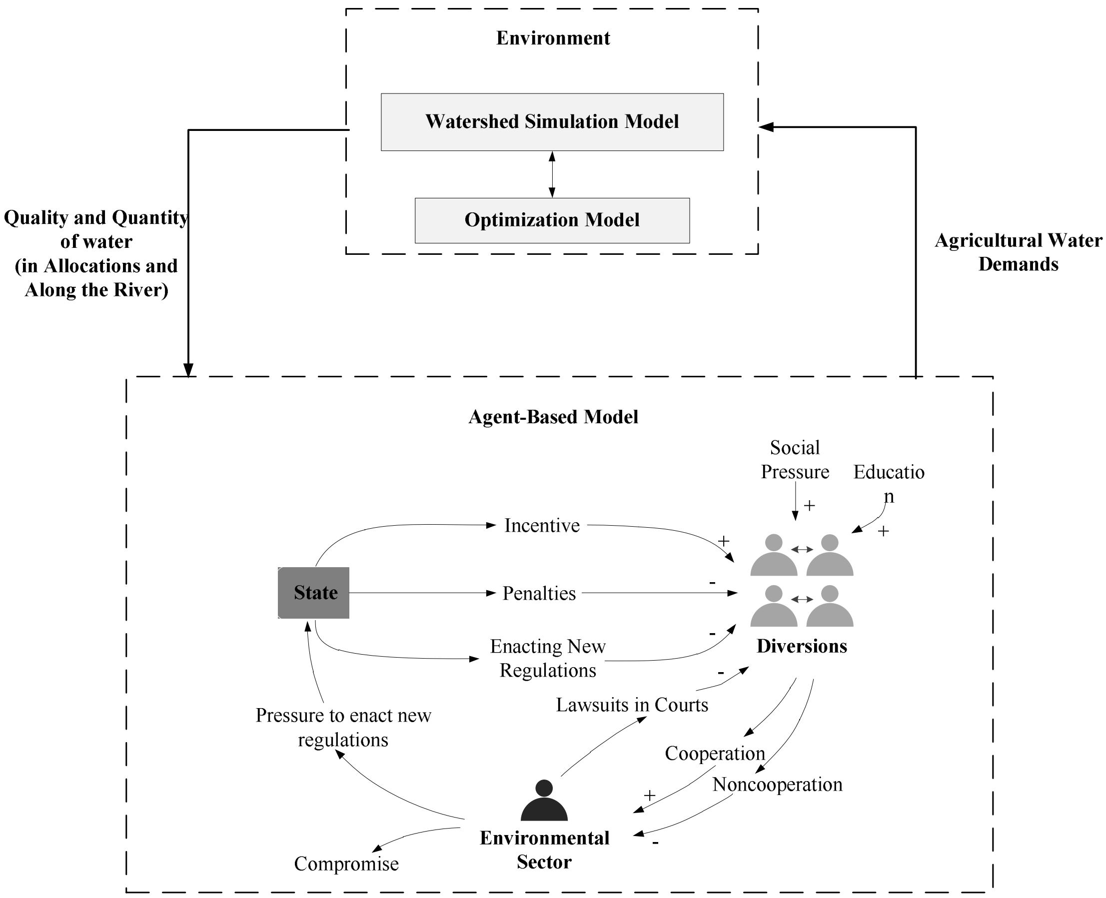

Figure 3.9 Agent-to-agent and environment-agent interactions

Diversions' non-cooperative behavior may result in three possible reactions from the environmental sector. If the impact of not cooperating in regard to the quantity and quality of the river water is minor or negligible, the environmental sector may compromise; otherwise, it may file a lawsuit, or put pressure on the state to create more limitations through enacting new regulations in order to protect the river's aquatic and environmental health. Meanwhile, the state can provide some incentives (as financial aids or loans) to encourage cooperative behavior. It can also consider some penalties for violators. Enacting new regulations can also result in more pressure on diversions to cooperate.

In addition to pressures from the environmental sector and the state's policies, social pressure and education are two other factors influencing the diversions' willingness to cooperate. Edwards et al. (2005) implies that in addition to an agent's personal interest, social pressure (influence of the behavior of its neighbors) has considerable effect on the decision of the agent to change its behavior. Figure 3.10 shows the impact of social pressure. Cooperation and noncooperation are, respectively, represented by "C" and "NC" in this figure. According to this figure, when the majority of the neighbors of an agent are of a certain type (cooperative in this figure), the agent is more likely to change its initial behavior to match its neighbors. In addition to the social pressure, increasing the knowledge of the parties in order to change their perception about the region's future can help encourage them to shift from their self-optimizing attitude. Education and social learning could change the stakeholders' perceptions about the fact that behaving like the status quo ultimately could end up with failure and may result in less benefit since the stakeholders should solve the problem on their own.

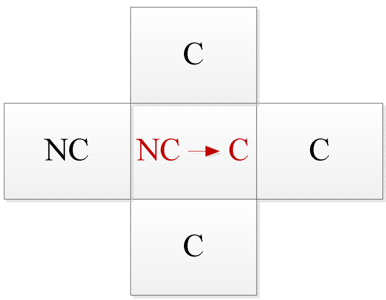

Figure 3.10 The influence of the social network on each agent

3.5.4 The ABM Formulation

In formulating the ABM, water allocations to diversions are determined by the environment (results from the optimization model using the watershed simulation model). These allocations may or may not satisfy diversions or environmental agents. In the case of dissatisfaction, these agents interact and influence each other's behavior. Then, the diversions specify their new water demands based on the interactions they had with each other and with other types of agents. This procedure is formulated as follows:

Total available water to be allocated to diversions is calculated by deducting the environmental minimum river water requirement from the total inflows (from precipitation, upstream inflow and tributary inflows) as shown in Equation 3.15. This value is then divided by the total area of agricultural lands in the study area and then multiplied by the area of each individual land *i* to determine the total water available for that diversion (Equation 3.16). If the water demand requested by agent *i* is more than the available water for this agent, the behavior of this agent is considered non-cooperative; otherwise, the agent is cooperating (Equation 3.17).

$$TAW_{y,m,d} = f\left(Q_{in,y,m,d}, Q_{min,y,m,d}\right) \qquad 3.15$$

$$AW_{i,y,m,d} = f\left(TAW_{y,m,d}, LA_i, CWD_i\right) \qquad 3.16$$

$$\begin{cases} If\ AW_{i,y,m,d} < D_{max,i,y,m,d} \quad => \quad i \rightarrow NC \\ If\ AW_{i,y,m,d} \geq D_{max,i,y,m,d} \quad => \quad i \rightarrow C \end{cases} \qquad 3.17$$

where,

$TAW_{y,m,d}$ is the total available water in day *d*, month *m*, year *y*;

$Q_{in,y,m,d}$ is the inflow to the river from the upstream and all tributaries;

$Q_{min,y,m,d}$ is the minimum river water flow rate required for environmental purposes;

$AW_{i,y,m}, d$ is the amount of available water for diversion *i*;

LA_i is the area of the agricultural land *i*;

CWD_i is the crop water demand being planted in the agricultural land *i*; and,

$D_{max,i,y,m}, d$ is the maximum water demand for water user *i*.

After designating the cooperative and non-cooperative agents, it is determined at what degree an agent is willing to change its behavior. The utilities of different agents, U_i, to change or keep their current behaviors are determined using Equations 3.18 through 3.21. These formulas have been adapted from Edwards et al.'s (2005) adaptation of Young's (1999) sociologic diffusion model for residential water domains.

$$U_i(C \rightarrow C) = a \times V_i(C) + F_m \tag{3.18}$$

$$U_i(C \rightarrow NC) = 1 - [b \times V_i(NC)] \tag{3.19}$$

$$U_i(NC \rightarrow C) = c \times V_i(C) + F_m \tag{3.20}$$

$$U_i(NC \rightarrow NC) = d \times V_i(C) + F_m \tag{3.21}$$

where, $U_i(C \rightarrow C)$ is the utility of agent *i* to cooperate if it has behavior *C* and is willing to keep its behavior, $U_i(C \rightarrow NC)$, is the utility of agent *i* to cooperate if it has behavior *C* and decides to change its behavior, $V_i(C)$ and $V_i(NC)$ are the proportions of neighbors of agent *i* of behavior *C* and *NC*, respectively. *a*, *b*, *c*, and *d* are parameters of the model. Edwards et al. (2005) considered $a = 0.7$ and $b = c = 0.3$. F_m is the modification factor and is a function of water availability, education, and pressures from the environmental sector and the State. In the above equations, the first term on the right-hand side represents the social pressure and the second term (in Equations 4 and 6) represents the pressures from the other agents and the environment as well as the effect of education.

If there is enough water available to allocate to the water users, $F_m = F_m^*$ and:

$$F_m^* = \begin{cases} 1 - [0.7 \times V_i(C)] & For \quad Eq. 3.18 \\ 1 - [0.3 \times V_i(C)] & For \quad Eq. 3.20 \end{cases} \qquad 3.22$$

Substituting F_m^* in Equations 4 and 6 results in $U_i = 1$ (or 100% utility). In other words, since the available water can supply the agent *i*'s demand, this agent is considered as a cooperative agent. Table 3.2 presents different values of modification factor due to various actions taken by the other agents. According to this Table, if the environmental sector files a lawsuit in a court, or if the State enacts new regulations, the diversions are obligated to cooperate. In this case, the modification is considered equal to F_m^* in order to achieve 100% utility for the corresponding agent to cooperate. In case the environmental sector compromises, there will not be any pressure on the agent to cooperate. The agent might only be influenced by its social network (the neighbors) in this case. Therefore, the value of modification factor is considered equal to zero.

Supposing that the state provides some incentives to encourage diversions to cooperate, the value of the modification factor is corresponding to the amount of incentives provided. In other words, a diversion's benefit might be reduced due to cooperation. The percentage of this reduced benefit that is compensated by the incentives is considered as the modification factor. Clearly, to encourage diversions to cooperate, the state does not need to compensate 100% of the lost benefit due to the fact that social pressure makes up a portion of it. The State can also consider some penalties for the violators. In this case, the modification factor will be a function of the negative impacts (or damages resulted from) of the agent's noncooperation (its extra water demand and/or the salinity of its return flow). The modification factor for education is determined based on the diversions' change of perception about the future. Therefore, it will be set as a function of the present value of potential future damages to the system.

Table 3.2 Modification factors for different state and environmental sector pressure

Category	Action	Modification Factor
Legal	Filling a Lawsuit in a Court	$F_m = F_m^*$
	Environmental Sector Compromises	$F_m = 0$
Management	Providing Incentives by the State	$F_m =$ Percent of the lost benefit
	Considering Penalties by the State	$F_m = f(D_i, x_3)$
	Education	$F_m = f(PV[future\ damages])$
Legislative	Enacting New Regulations	$F_m = F_m^*$

Now, the demand modification rate for agent *i*, D_i^m, is calculated as following:

$$\begin{cases} D_{i,y,m,d}^m = \left(D_{max,i,y,m,d} - AW_{i,y,m,d}\right) \times (1 - U_i); & \forall\ D_{max,i,y,m,d} > AW_{i,y,m,d} \\ D_{i,y,m,d}^m = 0; & \forall\ D_{max,i,y,m,d} \leq AW_{i,y,m,d} \end{cases} \tag{3.23}$$

and the agent *i*'s new maximum demand, ND_i, is determined as:

$$ND_{max,i,y,m,d} = AW_{i,y,m,d} + D_{i,y,m,d}^m \tag{3.24}$$

In case of a water shortage, if the agent cooperates, $U_i = 1$, the agent's demand modification rate will be zero; and therefore, its new demand will be equal to the available water. Otherwise, its demand modification rate will be greater than zero, and the agent claims for more water than what is available. However, this new demand might not be the same as the agent's initial water demand, since it has been influenced by the society, environment, and other agents. The new demand determined in Equation 3.24 is then introduced to the optimization model and substitutes its initial value in the corresponding constraint, which is the second constraint discussed in Section 3.1.

3.6 MEASURES TO PROVE THE HYPOTHESIS

To evaluate performance of the proposed ABM and effectiveness of the defined scenarios a measure is required. This measure may determine the level of water user's/stakeholder's satisfaction due to the allocations and decisions made. For this purpose, the utility functions of different water users/stakeholders are considered as a satisfaction measure. The general form of a utility function is shown in Figure 3.11. The vertical axis represents the utility in the scale of 0 to 100% and the horizontal axis depends on the type of stakeholder the utility function is being developed for. For diversions, the horizontal axis shows the range of allocations. For the environmental sector, two utility functions are developed. In one, the horizontal axis expresses the range of streamflow rate. For the other one, it represents the range of salinity concentration in the river water.

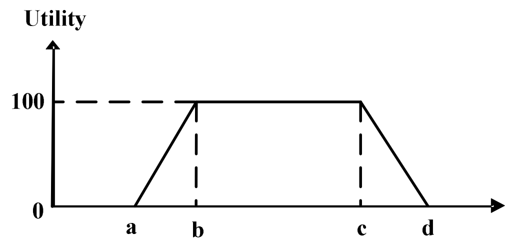

Figure 3.11 The general form of a utility function

Using these utility functions, each water user's/stakeholder's utility relative to its allocated water or the quality of water along the river is determined for all scenarios. These utilities are then compared with the corresponding ones in the status quo. Then, it is checked if implementation of management scenarios has resulted higher levels of satisfaction. If there is any increase in the water users/stakeholders satisfaction, it can be claimed that the conflicts have been reduced.

To compare the influence of the management scenarios with each other and with status quo, using the utility functions, statistical performance indices, such as reliability, resilience, and vulnerability introduced by Hashimoto et. al. (1982) will be used. These indices express different aspects of the model performance and show how often the system fails (reliability), how often the system recovers from failures (resilience) and how significant the severity of failures are (vulnerability) (Karamouz et al., 2006).

In this study, reliability (α) is assumed to be the probability of no failure within the planning horizon:

$$\alpha = prob[x_t \in S] \tag{3.25}$$

where, x_t is the status of the system at time step *t*, which in this study, it is considered as the flow rate or salt concentration in the San Joaquin River. *S* represents the set of all satisfactory conditions when there is enough water flowing in the river with an acceptable level of salt concentration. Reliability is the opposite of risk, which is the probability of system failure during the planning horizon. Resilience shows how quickly a system recovers from failure (such as violation from water quality standards) once it occurs. The resilience of a system in the planning horizon can be expressed as follows:

$$\beta = prob\{x_{t+1} \in S |\ x_t \in F\} \tag{3.26}$$

Where, *F* is the set of all failures. Vulnerability measures the magnitude of a failure if it occurs. The overall system vulnerability can be defined as (Hashimoto et al., 1982):

$$v = \sum_{i \in F} s_i p_i \tag{3.27}$$

where, p_i is the probability that x_i, corresponding to s_i, is the most unsatisfactory outcome that happens among a set of unsatisfactory states. The scenarios that result in higher reliability and resilience and lower vulnerability are designated as the most efficient scenarios for reducing conflicts.

3.7 SUMMARY

In this dissertation to this point, a conflict management model has been developed to reduce the partial conflicts among the water users/stakeholders, while their behaviors and interactions are simulated. This model has three models: optimization, watershed simulation, and behavioral simulation. The conflict management model solves a multi-criteria objective function that has three objectives: 1. maximizing the San Joaquin River flow rate at its outflow to the Delta; 2. minimizing the salinity load being transferred to the Delta area; and 3. maximizing the water allocations to diversions. Minimum environmental flow requirements and maximum crop water demands were considered as the constraints of the system. This multi-criteria objective function and all constraints were constructed on a daily basis during the entire time series. Therefore, the model simulates the timing of flow and allocations.

In the conflict management model, the behavioral simulation model, which was developed using agent-based modeling, simulates the behaviors and reactions of different water users/stakeholders in the system, called agents, to various management scenarios. It also simulates the agents' interaction with each other and with the environment. This model was linked to an optimization model which interacts with a watershed simulation model. The behavioral simulation model adjusted the maximum water demands of the agricultural water users/diversions. These water demands were then set as one of the constraints of the system in the optimization model.

The optimization model was developed using the surrogate worth trade off method. This model determines the amount of water allocations to diversions, while the watershed simulation model controls the validity of allocations in the actual conditions and determines the quality and quantity of water flowing in the river. This watershed simulation model was developed using ArcSWAT, which is a graphical user input interface for the SWAT model in ArcGIS-ArcView.

To evaluate the performance of the proposed model and effectiveness of different management scenarios, the utility functions of the water users/stakeholders were used as the measure of satisfaction level. Some performance indices, such as reliability, resilience, and vulnerability, were also defined to be used as measures for evaluating the results. If there is any increase in the satisfaction lever of water users/stakeholders, it can be claimed that the conflicts have been reduced.

Figure 3.12 represents the overall framework of the proposed model, illustrating the inputs and outputs of the model as well as the required auxiliary data. According to this figure, the boundary conditions, utility functions of water users/stakeholders, location of point sources, flow rate and salt concentration from point sources, crop water demands, and planting and harvesting times are introduced to the model as inputs. The model is also supported by some auxiliary data such as climate data, historical time series for flow and salinity, digital elevation maps, soil data, land cover, as well as flow and salinity objectives. The conflict management model tries a variety of management scenarios and determines the most effective one(s) in reducing conflicts. The outputs are then specified based on these most effective scenario(s). These outputs are the rate of water allocations to diversions, river water flow rate, and salinity concentration in the river water. Stakeholder satisfaction level and their adaptation to the new management scenarios are also the outputs of the proposed conflict management model.

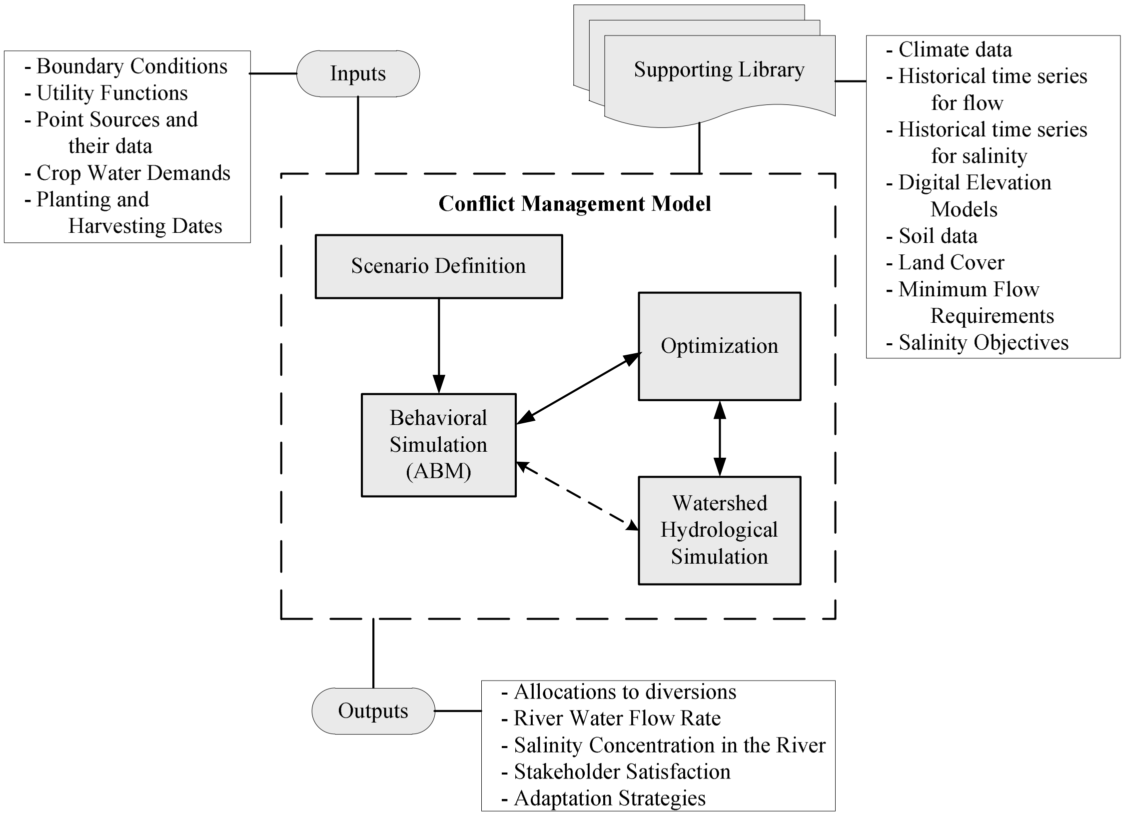

Figure 3.12 The overall framework of the proposed conflict management model and its inputs and outputs

CHAPTER 4

CASE STUDY

In the State of California, most of the lands are fertile and suitable for agricultural production. This fact has caused the state to become the top agricultural state in the country. This state is also the national leader in agricultural exports. In fact, agriculture is a multibillion dollar industry in California. The State's farm cash receipts totaled $36.1 billion in 2008 and ranked 1st among all 50 states in this year with approximately $13.6 billion agricultural exports. These exports help boost farm prices and income and support about 157,528 jobs both on and off the farm in food processing, storage, and transportation (USDA, 2009).

More than 350 crops as well as over half the country's nuts, fruits and vegetables are produced in California. The state's number one crop is cotton. Dairy products, including milk, cheese, butter and eggs, contribute greatly to the economy, with milk being the leading farm commodity (http://www.essortment.com/all/californiaagric_rwin.htm).

The majority of agricultural activities in California are performed in the Central Valley, which comprises Sacramento Valley (northern half) and San Joaquin Valley (southern half). The Delta area is shared between these two halves. There are six million acres of agricultural lands and 200 types of crops in the Central Valley, which are irrigated by the Bay-Delta water. The main sources for irrigation water supply to agricultural activities, especially in lower San Joaquin River watershed, is dependent on various sources including surface water diversions, groundwater pumping, and deliveries from the state and federal water projects (SWRCB, 2012 – Appendix X).

4.1 THE SAN JOAQUIN WATERSHED

The San Joaquin watershed has been considered as the case study of this dissertation. The San Joaquin River Hydrologic Region is the northern portion of the San Joaquin Valley, which is included in California’s Great Central Valley (Figure 4.1). Because of its significantly fertile soil, Central Valley is of great importance for agricultural activities.

Figure 4.1 The Central Valley Region

The Sierra Nevada and the coastal mountains of the Diablo Range are the east and west borders of the San Joaquin Valley, which contains portions of 13 counties. The land use includes about %31 public lands (such as forests, national parks, etc.), 20 % agricultural lands and 49% privately held lands (DWR, 2009). Figure 4.2 shows land use in the San Joaquin watershed. Being one of the longest rivers in

California, the San Joaquin River is almost 330 miles long. The river begins from the western slope of the Sierra Nevada and changes its direction to the northwest on the San Joaquin Valley floor toward the Delta where it confluences with the Sacramento River. The watershed approximately totals 15,550 square miles (SWRCB, 2012) which covers %9.6 of California State. This area on average receives 26.3 inches of rain annually (DWR, 2009). Figure 4.3 shows main inflows to and outflows from the San Joaquin Rivers and their magnitudes in 2005. The San Joaquin River's main tributaries, draining the Sierra Nevada, are: Merced, Tuolumne, Stanislaus, Calaveras, Mokelumne, and Cosumnes rivers.

More than two million people live in the San Joaquin River Hydrologic Region. It is projected that the population will grow to almost 4,900,000 by 2050 (DWR, 2009). Due to the significant population growth in some cities, which have been expanded into the surrounding agricultural lands, urban activities have increased over the last two decades. However, the dominant economic sector of the region is still agriculture. The San Joaquin Valley, which contains more than 2 million acres of irrigated cropland, is one of the most productive agricultural areas in the United States.

An important source of direct and indirect agricultural water supply in the San Joaquin Valley is the San Joaquin River downstream of Bear Creek (Kretzer and Grober, 1991). However, the San Joaquin Basin does not receive enough rainfall to supply all of its water demands. Surface water from the Sierra Nevada meets almost half of the local water needs. Imported water and groundwater are complimentary sources to meet the remainder water needs in the region. The imported water is brought into the San Joaquin watershed for irrigation purposes from the Sacramento River, to the northeast of the watershed, as well as the Delta region, to the west of the watershed, via the Central Valley Project (CVP) pumps at Tracy, located in the southwest of the Delta. Therefore, there is a circulation of water between the San Joaquin watershed and the Delta.

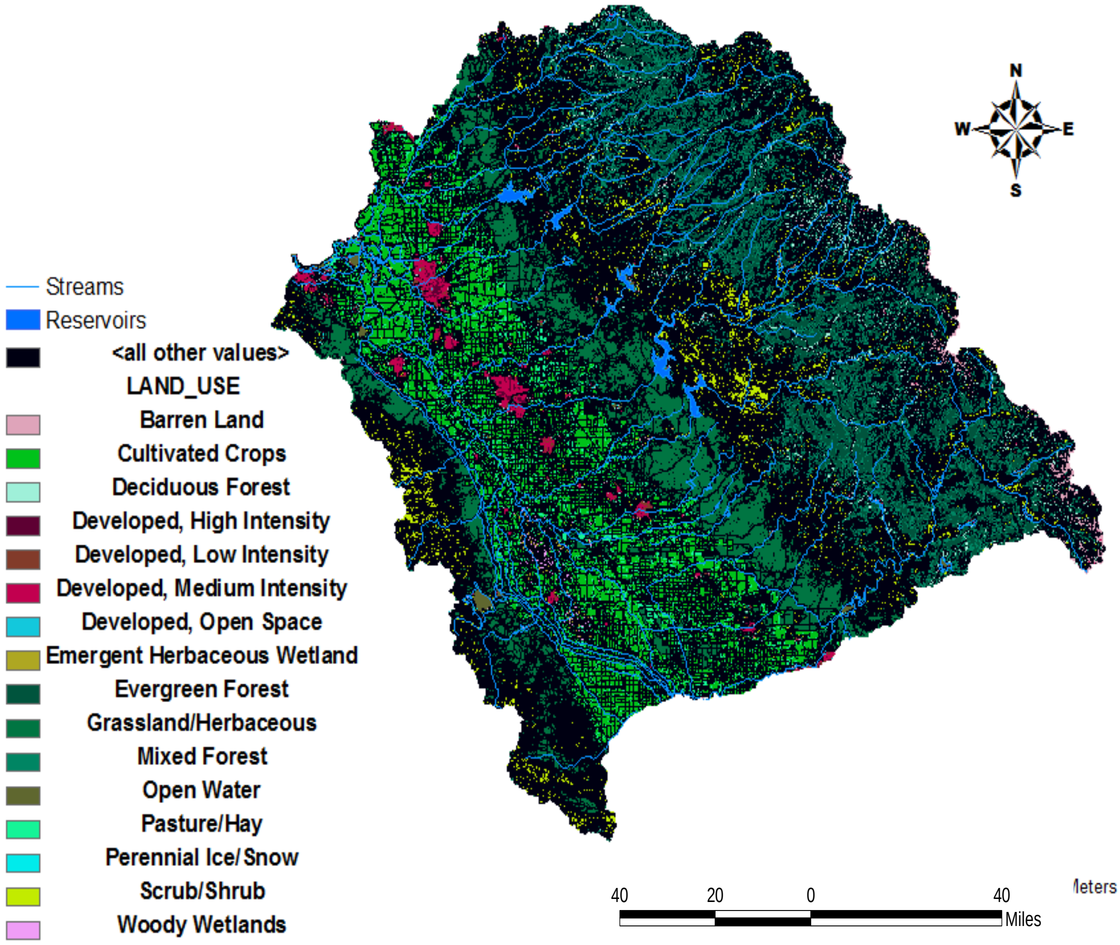

Figure 4.2 Land use in the San Joaquin watershed

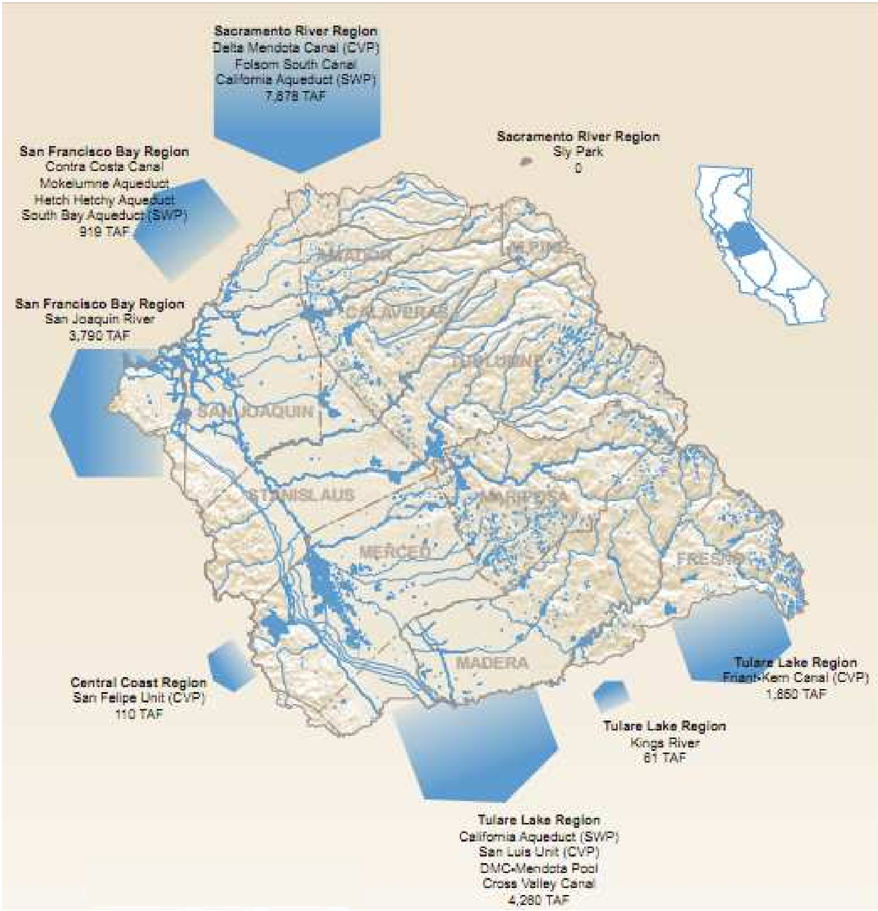

Figure 4.3 San Joaquin Hydrologic Region 2005 inflows and outflows (DWR, 2009)

Water is pumped from the river to agricultural lands for irrigation purposes and the drainage water is drained back to the river. The agricultural return flows, being discharged to the San Joaquin River, may have high levels of salinity. The imported water from the Delta Mendota Canal and Tracy (CVP) also has the corresponding salinity load from the Sacramento River and the Delta, respectively. On the other hand, the annual rainfall in the watershed is not enough to dilute salinity. Therefore, salinity has been continuously accumulating and increasing in the watershed for decades. Increasing salinity is one of the greatest long-term chronic water quality impairments to water resources in the Central Valley (Pitzer, 2009).

4.2 THE STUDY AREA

The San Joaquin River downstream of Bear Creek is the source of direct and indirect agricultural water supply in the San Joaquin Valley. Upstream the Bear Creek, the San Joaquin River is normally dry for a long stretch because of surface water and groundwater usage. Therefore, the study area of this dissertation has been considered as the San Joaquin River watershed, downstream of the Bear Creek. Data from the San Joaquin River gage and monitoring station at Stevenson, downstream of the Bear Creek, where the river resumes flowing again, have been used as one of the boundary inflows for the simulation model. The salinity of water in the San Joaquin River, downstream of the Old River, is mostly influenced by the estuary backwater (Herr and Chen, 2007). Therefore, due to the computational time limitations, the entire reach that will be simulated in this study is the San Joaquin River between the Stevenson Station, downstream of Bear Creek, and Vernalis Station, upstream of the Old River. Figure 4.4 depicts the study area. Vernalis is roughly the location where all non-floodplain flows from the San Joaquin River flow into the Delta. It is located 72 miles upstream of the confluence with the Sacramento River, and is upstream of tidal effects in the Delta. Figure 4.5 shows the San Joaquin River within the study area, its main tributary rivers, and the location of the Vernalis and Patterson stations (which will later be considered for calibrating the watershed simulation model).

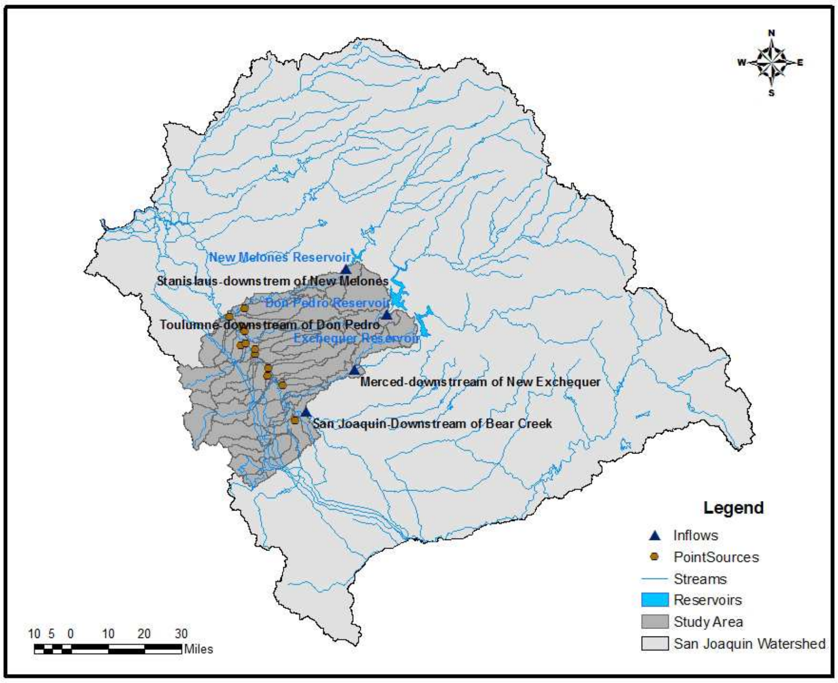

Figure 4.4 The San Joaquin Watershed with the study area highlighted within the watershed

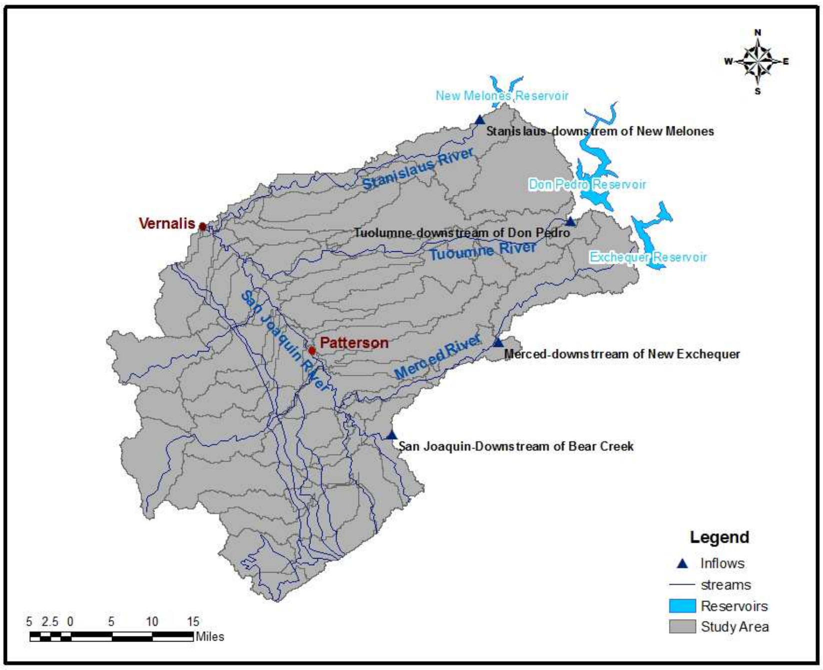

Figure 4.5 The San Joaquin River within the study area, its main tributary rivers, and the location of the Vernalis and Patterson stations

The main tributary rivers within the reach between Stevenson and Vernalis stations on the San Joaquin River are: Merced, Tuolumne, and Stanislaus Rivers (Figure 4.4). In order to save computational time, the quality and quantity of water released from the New Exchequer Reservoir (on the Merced River), New Don Pedro Reservoir (on the Tuolumne River), and New Melons Reservoir (on the Stanislaus River) have been considered as other upstream boundary conditions for the simulation model. Characteristics of the study area's main inflows are as follows (SWRCB, 2012):

1. Flow that enters the San Joaquin River upstream of the Merced River is a small portion of the entire flow to this river.
2. The Merced River flows into the San Joaquin River approximately 35 miles upstream of the Tuolumne River confluence. Total length of the Merced River is 135 miles and it drains a 1,270 square mile watershed. The distance between its confluence with the San Joaquin River and the New Exchequer Dam is approximately 63 miles.
3. The Tuolumne River flows into the San Joaquin River approximately eight miles upstream of the Stanislaus River confluence. The Tuolumne River drains an area of 1,870 square miles and is 155 miles long. The length of the reach between its confluence with the San Joaquin River and the New Don Pedro Dam is approximately 55 miles.
4. The Stanislaus River flows into the San Joaquin River approximately three miles upstream of Vernalis. The length of this river is 161 miles and it drains approximately 1,195 square miles of mountainous and valley terrain. The length of the reach between the New Melones Dam and the river's confluence with San Joaquin River is approximately 66 miles.

4.3 SOURCES OF SALINITY

Kratzer and Grober (1991) simulated a portion of the San Joaquin River from Bear Creek to Vernalis, downstream of the Stanislaus River (Figure 4.5). They indicated that at very low flows the factor that most affects salinity in the downstream, Vernalis, is the amount of upstream salt load (primarily from the sloughs). If flow in the Merced River is very low, higher flows in the San Joaquin River, just upstream of the Tuolumne, are correspondent to the worse water quality at Vernalis. Kratzer and Grober also virtually diverted the entire San Joaquin River upstream of the Tuolumne and found better water quality in Vernalis when the flow is primarily Tuolumne and Stanislaus River. From their research, it can be concluded that the salinity problems are mostly along the San Joaquin River, not the tributaries and the main causes of the salinity along the river are salt loads from the sloughs and from agricultural return flows.

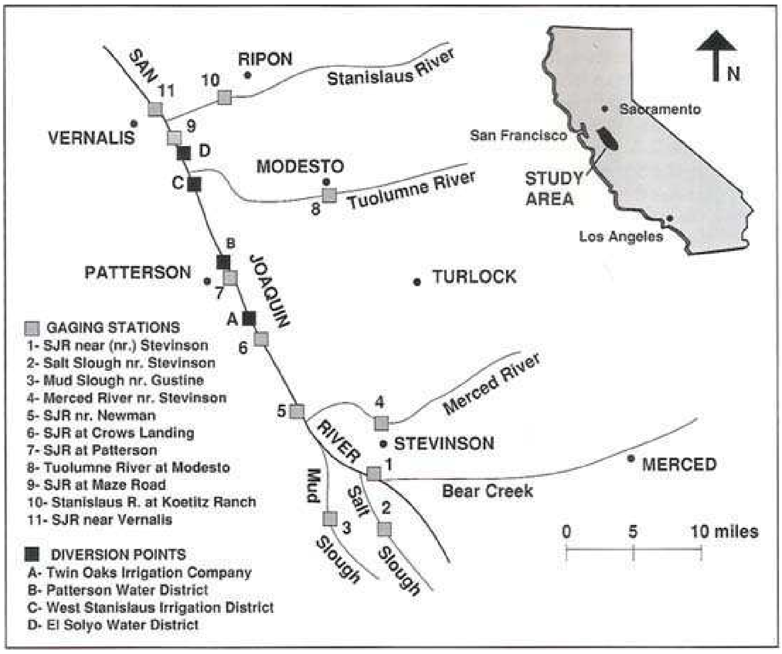

Figure 4.5 A portion of the San Joaquin River studied by Kretzer and Grober (1991)

In general, the main sources of salinity in the San Joaquin River are:

1. Agricultural drainage discharge as the primary source of dissolved salts in the river (Grober, 1996)
2. Groundwater accretions and seasonal wetland releases (Grober, 1996)
3. Salt dissolved in Delta Mendota Canal (CVP) water imports as the primary source in the lower San Joaquin River basin (Grober, 1996, and Water Facts, 2001)

4. Naturally occurring salts in soils (CALFED, 2007)
5. Salts from the estuary's back water in the lower San Joaquin River basin (up to the Old River)

The imported water is mostly transferred to the western parts of the valley, where naturally occurring salinity is present and drainage problems exist. More salinity is added to the drained water after irrigation due to various agricultural activities such as adding fertilizers, pesticides, soil amendments, and also evapotranspiration. This saline water is discharged into the Delta through the San Joaquin River and then after mixing with the Sacramento River water, which has its own salt loads, is again pumped up to the San Joaquin Valley (Water Facts, 2001). This circulation causes higher and higher salinity levels in the Valley.

4.4 SALINITY IMPACTS

A threat to food production and drinking water quality is growing due to the excess salinity in concentrations greater than the standard set to protect beneficial uses. The main negative impacts of excess salinity can be addressed as:

1. The higher the salinity in the San Joaquin River is, the greater the costs of water treatment for urban drinking water being supplied by it and wastewater treatment being discharged to it.
2. The salinity problem threatens the economics of the Central Valley and creates limitations on business and residential growth in the area.
3. Salinity decreases the productive life of the most fertile soils in the world.
4. High levels of salt limit water resource management options. The situation becomes significantly more sophisticated during droughts.

In addition, Howitt et al. (2009) reported that if salinity increases in the Central Valley at the current rate until 2030, the direct annual costs will approximately be $1 billion to $1.5 billion. The income impacts to the Central Valley will also be $1.2 billion to $2.2 billion. Furthermore, according to this report, “in terms of job losses the increase in salinity by 2030 could cost the Central Valley economy 27,000 to 53,000 jobs.”

4.5 SUMMARY

California has the most fertile lands in the United States. It is the first agricultural producer in the country and the national leader in agricultural exports. In this state, agriculture is a multibillion dollar business supporting more than 150,000 jobs. Central Valley is the heart of agricultural activities in California and includes Sacramento Valley and San Joaquin Valley. San Joaquin River Hydrological Region is the northern portion of San Joaquin Valley. A reach of this river, between Bear Creek and Old River, is of great importance as one of the main water supply sources for the majority of agricultural lands in this region. However, the return flows from these agricultural lands increase salinity rate in the river water, threatening aquatic life and environmental health in the river. Furthermore, increasing salinity with the current rate can impose significant costs to the state, highly impact the income, and cause job losses. Therefore, this reach of the San Joaquin River has been selected to be modeled in order to find some practical management scenarios to enhance the environmental conditions in the river while satisfying its water users.

CHAPTER 5

MODELS SETUP

This chapter explains how the watershed simulation model, the optimization model, and the behavioral simulation model have been set up. In this regard, data required to setup the watershed simulation model and perform the analyses, sources of data, as well as the steps to prepare the data to meet the simulation model's required format are discussed. Then, the setup process for each of the models is described. Development of a questionnaire to determine the surrogate values of trade-off functions is also explained. The chapter also explains minimum flow requirements in the study area and salinity objectives at Vernalis, as the location of outflow to the Delta area.

5.1 DATA ACQUISITION AND PREPARATION

Intensive geospatial data are required for the SWAT model in order to drive watershed dynamics. These data include: Digital Elevation Model (DEM), streams and water bodies, upstream boundary conditions and inflows, point sources, soil data, land cover, and climate data. In addition, to obtain accurate results, it is important to set up the model in a way that irrigation schedules match with the actual irrigation times. Therefore, planting and harvesting dates as well as crop water demands must be introduced to the model and to avoid allocating more water than available, minimum river flow requirements are defined as the constraints of the system. Furthermore, data for crop yields and prices are also prepared for performance analysis. The acquisition and preparation of these data is discussed in this section.

5.1.1 Input Data for the ArcSWAT Model

As explained in Chapter 3, Section 3.4, ArcSWAT is an interface of the Soil and Water Assessment Tool (SWAT) with ArcGIS. To set up a simulation model in ArcSWAT, multiple GIS layers and input data files should be provided to be introduced to the model. Before preparing any GIS layer, it is important to make sure that all GIS layers are in the same geographical coordinate system. The San Joaquin Watershed is located in Zone 10 of the North American Datum (NAD) 1983 in the Universal Transverse Mercator (UTM) system. The spatial reference of all GIS layers has been controlled to make sure they match with this zone and transformation has been fulfilled for the ones that are not compatible with the required coordinate system. The general input data for the ArcSWAT model include:

Digital Elevation Model (DEM): DEM is a digital model of a landscape's surface which is created from the elevation data. It is produced by the United States Geological Survey (USGS) through the National Mapping Program. DEMs are provided in raster file format and include an array of elevations sampled at a number of ground positions at regularly spaced intervals. ArcSWAT uses DEM data to delineate subwatersheds. To prepare the DEM data, first DEM files were downloaded from the Geo Community website and their geospatial reference was controlled. The entire San Joaquin Watershed is covered by 10 DEM files with 30-meter resolution. These raster layers were then combined into one layer to be imported to the ArcSWAT model.

The National Hydrography Dataset (NHD): The NHD is a digital vector dataset, which contains features such as lakes, ponds, streams, rivers, canals, dams and streams. There are two ways to introduce the stream networks to ArcSWAT: 1. The model delineates the stream network based on the drainage area threshold, using DEM data, and defines watershed boundaries; 2. Predefined watershed boundaries and streams can be imported to the model. Even if the first option is chosen, NHD data is required to double check and make sure that the model delineated the watershed correctly and designates all important streams. The NHD dataset is created by USGS and can be downloaded from the National Hydrography Dataset section of the USGS website. In this website, the area of interest is selected using a polygon and the resolution of the required file (medium, high, or local) as well as data format (Personal Geodatabase, File Geodatabase, or Shapefile) are specified. For this study, a shapefile with a high resolution has been selected. After downloading the file, the geospatial reference was controlled. Since the area of interest has been selected using a polygon, it is covering a larger area than the study area. Therefore, the file was first clipped to the extent of the study area and then imported to the ArcSWAT model.

Inflows: The model domain does not extend to the entire San Joaquin Watershed boundaries. Therefore, upstream boundary conditions must be introduced to the watershed simulation model. These boundary conditions include measured daily time series of flow and salinity. Four inlets are considered for the study area located at the San Joaquin River at Stevinson Station, downstream of Bear Creek, as well as in the base of the major dams on the Stanislaus River (New Melones Reservoir), Tuolumne River (Don Pedro Reservoir), and Merced River (New Exchequer Reservoir). Figure 5.1 demonstrates the locations of these inlets. The corresponding time series were downloaded from the USGS Real Time Water Data for California.

Point Sources: Point sources data have been derived from input data of the Watershed Analysis Risk Management Framework (WARMF) model. WARMF was developed as a decision support system for watershed management to facilitate TMDL analysis and watershed planning. According to the WARMF user's guide, there are 14 agricultural return inputs including four from canals of the Modesto Irrigation District (MID), six from the Turlock Irrigation District (TID), and four individual ones (Westley Wasteway, Moran Drain, Marshall Road Drain, and Spanish Land Grant Drain). There is also one municipal point source directly discharged to the river, the Modesto Water Quality Control Facility. Modesto WQCF has seasonal discharges to the river, which happens approximately from December through May. In addition, one of the natural seasonal flows, the Mud Slough, which has a significantly high salinity load, has been introduced to the model as a point source. Figure 5.1 shows the locations of these point sources.

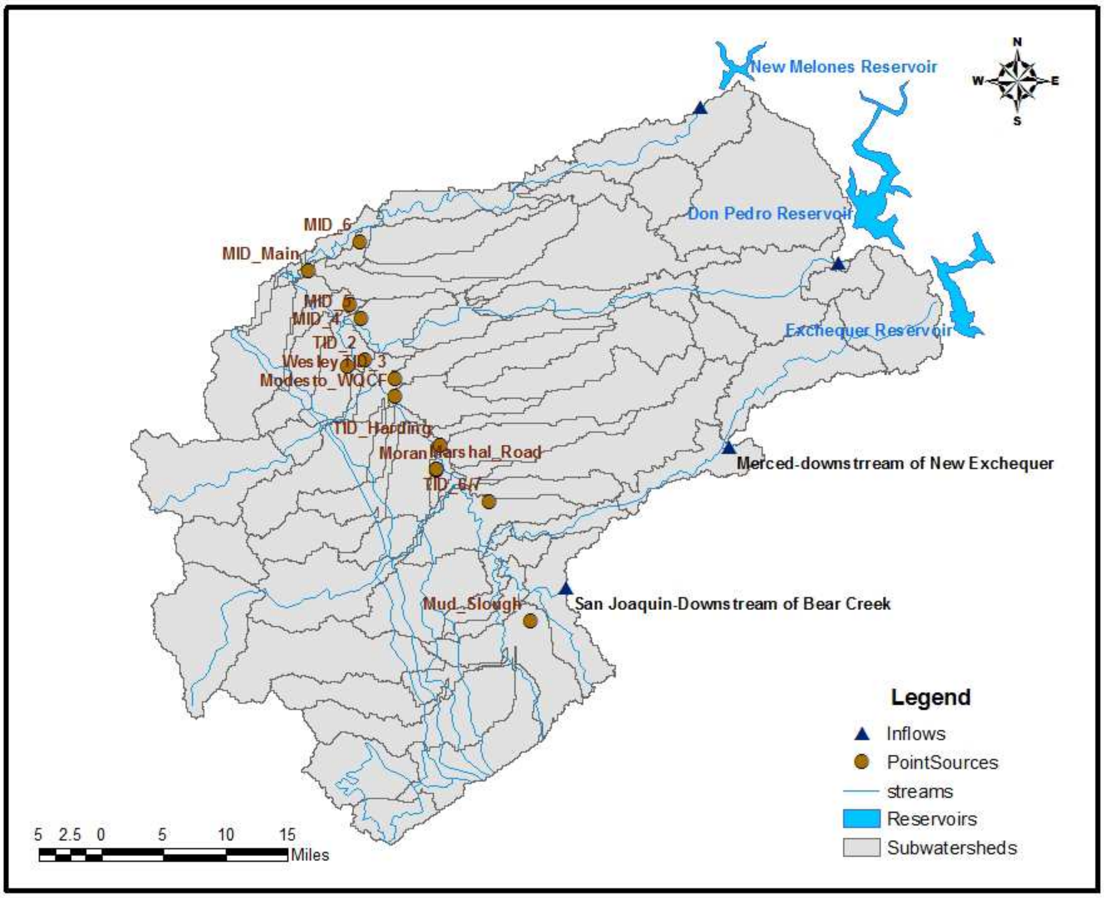

Figure 5.1 Locations of the inlets and point sources in the study area

Soil data: There are several different soil geographic data bases available such as State Soil Geographic database (STATSGO), Soil Survey Geographic database (SSURGO), National Soil Geographic database (NATSGO), etc. In each database, soils are grouped based on their infiltration characteristics. Among different forms of soil type data, STATSGO and SSURGO databases are the two key forms. STATSGO data is defined on a state-wide level and is available for the entire United States, whereas SSURGO is county-wide and has some spatial gaps. For this study, STATSGO soil data type has been used. The data was downloaded in shapefile format from the National Cartography and Geospatial Center (NCGC) of the Natural Resources Conservation Service (NRCS). After downloading the data the geospatial reference was controlled and the shapefile was clipped to the extent of the study area.

Land Cover: In ArcSWAT, the default land cover is based on National Land Cover Data (NLCD) for years 1992 and 2001. However, United States Department of Agriculture (USDA) produces National Agricultural Statistics Service (NASS) maps that have more detailed agricultural information, including the crop types in each field. Figure 5.2 shows the land cover of the study area based on NLCD database and Figure 5.3 demonstrates the land cover based on the NASS information. As illustrated in these figures, NASS data are more accurate for performing investigations on agricultural practices. Since the dominant land cover of the study area belongs to agricultural uses and the water demand of each agricultural field directly depends on the types of crops being produced in the fields, NASS data were selected to be used for this study. The data was downloaded from USDA-NASS Research and Development Division website. The downloaded map covers the entire state of California, so after controlling its geospatial reference, the shapefile was clipped to the extent of the study area.

Weather Data: To calculate runoff, evapotranspiration, etc., SWAT requires users to import measured weather data. The data includes daily precipitation in millimeter as well as daily maximum and minimum air temperatures in degree Celsius. Data from different weather stations within the study area must be imported to the model. Therefore, SWAT receives the weather data in the exact location of weather stations that have been introduced to it. Then, the model interpolates and/or extrapolates the weather data to cover the entire basin. Data from NRCS SNOwpack TELemetry (SNOTEL) stations were downloaded and used for the purposes of this study.

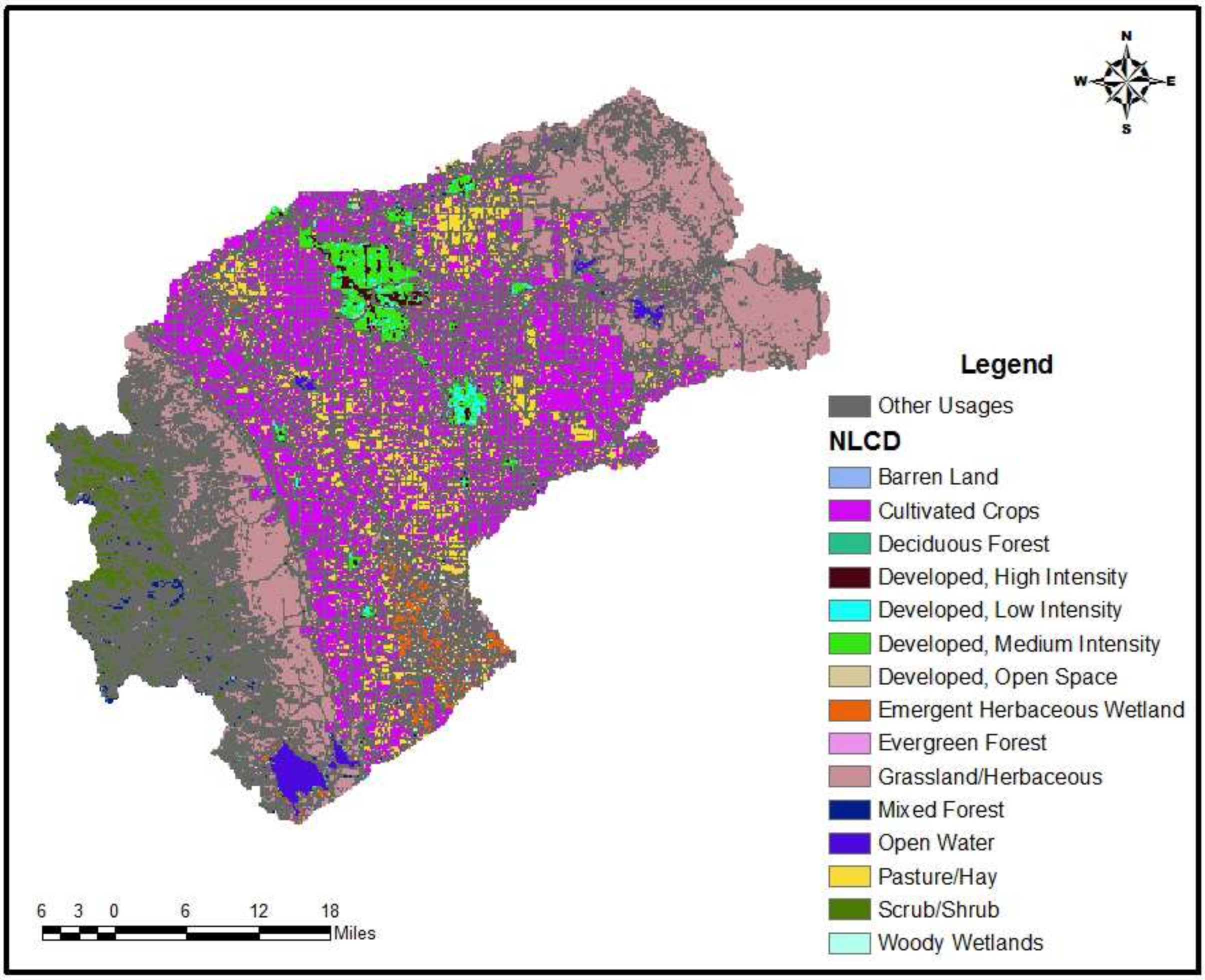

Figure 5.2 Land cover in the study area based on the NLCD data

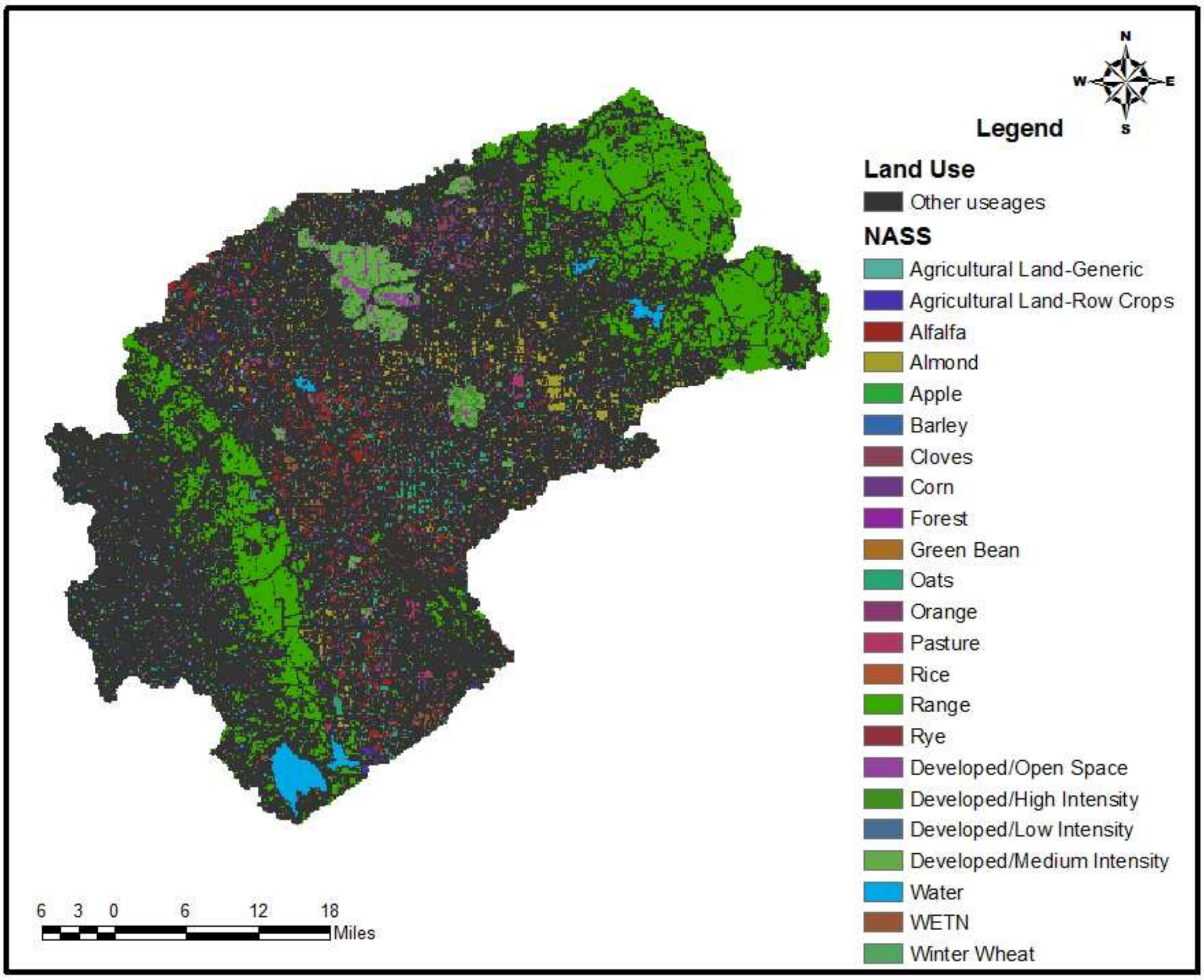

Figure 5.3 Land cover in the study area based on the NASS data

A summary of data sources and the corresponding websites that the data has been downloaded from has been presented in Table 5.1.

Table 5.1 Sources of data and corresponding website addresses

Data Type	Data Source	Website
Digital Elevation Model	USGS - The National Mapping Program	http://data.geocomm.com/dem/
National Hydrography Dataset	USGS - National Hydrography Dataset	http://viewer.nationalmap.gov/viewer/nhd.html?p=nhd
River water flow rates and salinity concentrations	USGS - Real Time Water Data for California	http://waterdata.usgs.gov/ca/nwis/current/?type=dailydischarge&group_key=huc_cd
Point Sources	WARMF input data	
Soil Data (STATSGO)	USDA – NRCS – NASS Soil Data Mart	http://soildatamart.nrcs.usda.gov/
Land Use Data (NASS)	USDA– NASS Research and Development Division	http://www.nass.usda.gov/research/Cropland/SARS1a.htm
Weather Data	USDA-NRCS SNOTEL data	http://www.wcc.nrcs.usda.gov/snow/

5.1.2 Crop Water Demands

To determine water demand of each agricultural field, the type of crop being planted in the field, its water demand, and the area of the field must be given. The type of crop being planted in each agricultural field can be obtained from the NASS data that have been imported to the SWAT model. The area of each field has also been determined by the model. Water demands for the dominant crops being produced in the study area have been specified and presented in Table 5.2.

5.1.3 Planting and Harvesting Dates

To obtain accurate simulation results, it is important to define planting and harvesting dates to the SWAT model, so the model irrigates agricultural fields only during that time period. USDA National Agricultural Statistics Service assembles usual planting and harvesting dates for major field crops across the United States based on the best and most recent information available. The dates do not account for exceptionally early or late practices forced by abnormal seasons caused by climatic or economic conditions. Table 5.3 presents usual planting and harvesting dates for major crops in California. The dates presented in this table are the average of most active dates between the beginning and ending dates, which are indicating when planting or harvesting is about 5 and 95 percent complete, respectively.

Table 5.2 Water demands (acre-feet per acre) for dominant crops in San Joaquin in 2005 (Howitt et al. 2008)

Crop	**Demand**	**Crop**	**Demand**
Agricultural Land-Generic	2.57	Oats	2.57
Agricultural Land-Row Crops	2.77	Onion	2.64
Alfalfa	4.62	Orange	3.26
Almond	3.4	Pasture	3.81
Apple	3.26	Peas	2.27
Barley	2.57	Rice	4.98
Cloves	1	Rye	2.57
Corn	2.77	Tomato	1.93
Green Beans	2.27	Winter Wheat	1.05

Table 5.3 Usual planting and harvesting dates for major crops in California

Crop	Planting		Harvesting	
	Month	Day	Month	Day
Agricultural Land-Generic	3	1	9	10
Agricultural Land-Row Crops	4	1	10	20
Alfalfa	9	15	2	28
Barley	3	1	9	10
Cloves	3	1	9	10
Corn	4	1	10	20
Grean Bean	5	15	9	20
Oats	3	1	9	10
Rice	5	1	10	10
Rye	3	1	9	10
Soybeans	5	15	9	20
Sugarbeets	9	1	6	20
Winter Wheat	10	20	6	15

Source: “Field Crops Usual Planting and Harvesting Dates, 2010, USDA, NASS

5.1.4 Minimum Flow Requirements

Minimum flow requirements are defined to the SWAT model as one of the system's constraints so only the excess water will be allocated to agricultural fields. Minimum flow requirements in San Joaquin River at Vernalis have been presented in Table 5.4. These values are subjected to the State Water Resources Control Board's (SWRCB) revised water right decision 1641. These guidelines have been provided based on Vernalis Adaptive Management Plan (VAMP) and San Joaquin River Agreement (SJRA).

Table 5.4 Minimum flow requirements for the main rivers in the study area (DWR, 2010)

River and Location	Flow	Agreement
Merced River, below Crocker-Huffman Diversion Dam	180-220 (cfs) (Nov – Mar)	Davis-Grunsky, Cowell Agreement, and FERC 2179
Merced River, Shaffer Bridge	25 – 100 (cfs)	FERC 2179
Tuolumne River, at Lagrange Bridge	94-301 (TAF/yr)	FERC 2299-024, 1995 (Settlement Agreement)
San Joaquin River at Vernalis		SWRCB D-1641, VAMP and SJRA

SJRA determines the target flow based on the "existing flow." Table 5.5 presents the SJRA target flows. Depending on the type of water year, these target flows may be modified. The water year type is determined, using the San Joaquin Valley "60-20-20" Water Year Hydrologic Classification. To modify target flows each water year type is given a numeric indicator. These indicators have been presented in Table 5.6. After specifying each year's indicator, the sum of the current year's indicator and the previous two years' indicators is calculated. If the sum is four or less, there is no need to provide flows above the existing flow; if it is seven or greater, the target flow will be one level higher (SWRCB, 2000); i.e., if the sum of the indicators is seven and the existing flow is 2500 cfs, the target flow will be 4450 cfs instead of 3200 cfs. Using the data presented in Tables 5.5 and 5.6, the target flows at Vernalis for years 2003 to 2006 are calculated. These target flows are presented in Table 5.7.

Table 5.5 The SJRA target flows (SWRCB, 2000)

Existing Flow (cfs)	Target Flow (cfs)
0 - 1,999	2,000
2,000 – 3,199	3,200
3,200 – 4,449	4,450
4,450 – 5,699	5,700
5,700 – 6,999	7,000
7,000 or greater	Existing Flow

Table 5.6 VAMP Hydrologic Classification (SWRCB, 2000)

Existing Flow (cfs)	Target Flow (cfs)
Wet	5
Above Normal	4
Below Normal	3
Dry	2
Critical	1

Table 5.7 Target flows at Vernalis for years 2003 through 2006

Year	Year Type[a]	Indicator	Score	Target Flow (cfs)
2000	AN	4	-	-
2001	D	2	-	-
2002	D	2	8	5700
2003	BN	3	7	5700
2004	D	2	7	4450
2005	W	5	10	Existing Flow
2006	W	5	12	Existing Flow

[a] Source: DWR, California Cooperative Snow Surveys, Chronological Reconstructed Sacramento and San Joaquin Valley, Water Year Hydrologic Classification Indices, http://cdec.water.ca.gov/ cgi-progs/iodir/WSIHIST

5.2 SETTING UP THE WATERSHED SIMULATION MODEL

To setup a watershed simulation model in SWAT, first the DEM data and stream networks are imported to the model. SWAT partitions the watershed into subunits as subbasins and assigns a reach segment in each subbasin. Subbasins have a geographic position in the watershed and are spatially connected to one another. SWAT performs a subbasin delineation using surface topography and determines the outlet of each subbasin, which is where the entire area within a subbasin flows to.

The land area in a subbasin may be divided into several hydrologic response units (HRUs), which are portions of a subbasin that hold unique land use, management, and soil attributes. Therefore, land use and soil data are imported into SWAT to create the HRUs. The main reason to create these HRUs is to simplify a run by combining all similar soil and land use areas into a single response unit. After creation of HRUs, all historical time series of weather data, as well as flow and quality of inlets and point sources are introduced to the model. The final step is to determine the starting and ending dates of simulation as well as the simulation's time step. Then, the model sets up all input files in its required format and creates a watershed master control file, which manages the input files and contains information related to modeling options, climate inputs, databases, and output specifications.

The simulation's starting and ending dates have been set to be 1/1/2000 and 12/31/2006, respectively. So, the model was warmed up from 1/1/2000 to 12/31/2001 and was calibrated using data from 1/1/2002 to 12/31/2004. The data of the last two years were used for validating the results. The calibration-validation process will be discussed in more detail in Chapter 6. After calibrating the model, analyses were performed for the time period between 1/1/2003 to 12/31/2006, which includes a blow normal year, a dry year, and two wet years (as presented in Tabel 5.7). The model divided the study area to 71 subbasins and created 614 HRUs, out of which 310 HRUs belong to agricultural practices. For the purposes of this study, these 310 HRUs were considered as agricultural fields. Therefore, the amount of water allocated to each HRU and the impact of each HRU's return flow on the flow and salt concentration of the San Joaquin River were considered for the optimization.

5.3 SETTING UP THE GENETIC ALGORITHM

As discussed in Chapter 3, the trade-offs between the objectives of the multi-criteria objective function of the problem defined in this study were created performing a genetic algorithm (GA) optimization. This GA model was developed using the genetic algorithm multiobjective (gamultiobj) function of the Global Optimization toolbox in MATLAB. To use the functions of this Toolbox, first a file was created containing all fitness functions and constraints of the system. The Global Optimization Toolbox minimized all optimization functions. Wherever an objective function was needed to be maximized, its negative value was minimized. After defining the fitness functions and constraints, the following settings were followed:

Determining initial population's lower and upper bands: Initial population specifies an initial population for the genetic algorithm. In MATLAB's genetic algorithm function, the initial population is generated randomly by default, unless the settings are changed. In this study, the individuals were considered as the amounts of water allocations to agricultural fields. The lower and upper bands were set equal to zero and the maximum water demand of each field, respectively.

Defining the population size: The population size specifies the number of individuals in each generation. Since the GA model, developed in this study, adjusts the water demand values of each field in SWAT input files, the population size must be corresponding to the number of agricultural fields, which is equal to 310 fields. However, to define the population size, it should be noted that a very large population size significantly increases the model's runtime and a very small population size may result in a local optimum. The population size must be at least the number of variables. To reduce the computational time, agricultural fields in the study area were categorized based on their water demand which is corresponding to the type of dominant crop being planted in each field. According to Table 5.2 there are 18 dominant crops in the study area. Among these, some crops have the same water demand including: agricultural land-generic, barley, oats, and rye (2.57 acre-feet per acre); agricultural land-row crops and corn (2.77 acre-feet per acre); apple and orange (3.26 acre-feet per acre); green beans and peas (2.27 acre-feet per acre). Therefore, agricultural fields were categorized into 12 categories. For this study, the population size was selected equal to 20.

Specifying the number of generations: Number of generations is one of the stopping criteria of the genetic algorithm function. It specifies the maximum number of iterations to be performed in case none of the other stopping criteria is not met. MATLAB’s default value for the number of generations is 100. This default value has been considered for this study.

Appointing the selection option: Selection option is set to specify how parents are chosen for the next generation. The default selection function of MATLAB, which is stochastic uniform, has been chosen for this study. Based on this function, each parent corresponds to a section of a line laid out by the stochastic uniform function. The length of this section is proportional to the corresponding parent’s scaled value. The algorithm randomly selects a fragment along the line and chooses a parent from that fragment. Then, it moves along the line in steps of equal size and chooses a parent from each fragment it lands on.

Designating reproduction options: Reproduction options include: elite count, crossover function, and mutation function. The default settings of MATLAB for these options have been considered for this study. Therefore, the elite count, which is the number of individuals being transferred to the next generation without any change, has been set equal to 2. The crossover function, which specifies how two individual parents are combined to form a crossover child, has been selected as *scattered function*. This function creates a random binary vector and selects the genes where the vector is a 1 from the first parent, and where the vector is a 0 from the second parent. These genes are then combined to form the crossover child. The mutation function, which specifies how random changes are made in the individuals to create mutation children, has been set as *Gaussian function*. This function adds a random number from a Gaussian distribution, with mean zero, to each entry of the parent vector.

After these setups, the GA optimization model was linked to the watershed simulation model. At the first step of optimization, the initial population was created. The values of the first individual in the initial population were written in the SWAT input files as agricultural fields maximum water demand. Then, the

SWAT model was run and the amount of water allocated to each agricultural field was calculated. These values were, then, read from SWAT output files and the value of all fitness functions were calculated based on these allocations. The above steps were repeated for all individuals in the generation. After calculating the value of fitness functions for all individuals, the next generation was produced and the above steps were again repeated until the final Pareto front was created. Figure 5.5 illustrates this process.

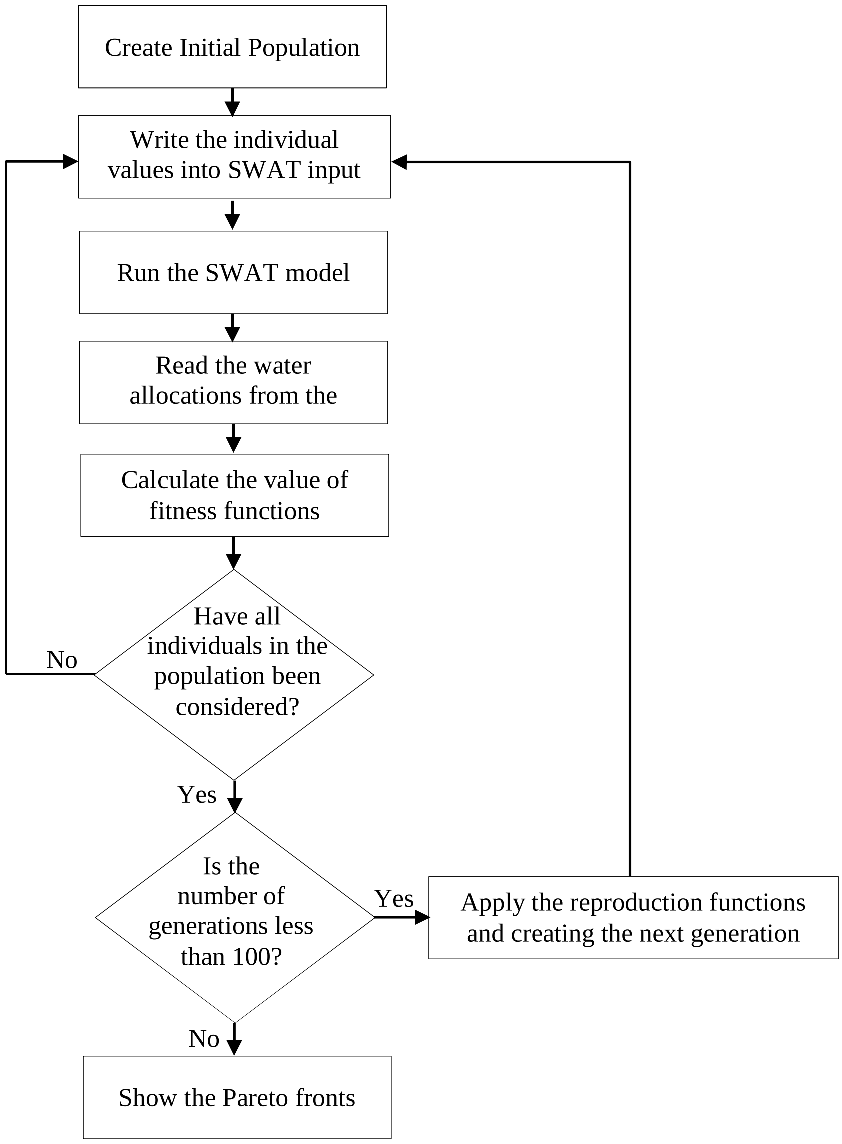

Figure 5.5 The optimization process

5.4 FINDING THE SURROGATE WORTH VALUES

To determine the surrogate worth values of the trade-off functions, a questionnaire was developed and sent out to different decision-makers and stakeholders in the study area. The agencies were selected from 1. San Joaquin River Group Authority (SJRGA), which consists of water users receiving water from the San Joaquin River and its tributaries; 2. The United States Department of Interior, including U.S. Bureau of Reclamation and U.S. Fish and Wildlife Service; 3. California Department of Water Resources; 4. The Environmental Community, such as the Natural Heritage Institute and the Bay Institute of San Francisco. Member agencies of the SJRGA in the study area include: Modesto Irrigation District, Turlock Irrigation District, Merced Irrigation District, and South San Joaquin Irrigation District.

In this questionnaire, the agencies were asked to determine the surrogate worth of the trade-off points on the Pareto front. In order to find a more actual insight about the problem, they were also asked some further questions to receive some feedbacks. The agricultural agencies were asked to determine their utility function and specify how willing they are to cooperate. The state agencies were inquired to indicate how willing they are to provide incentives and compensations to agricultural agencies in order to encourage them to cooperate. They were also asked to mention to what extent they would rather provide these incentives or compensations. The environmental agencies were requested to determine by how much they might compromise if minimum flow requirements or salinity objectives are violated.

5.5 Salinity Objectives in the San Joaquin River

Meeting southern Delta flow and salinity objectives are two of the main goals of this study. For this purpose, the effectiveness of different management scenarios in meeting flow and salinity objectives should be analyzed. The analysis was performed at Vernalis, as the outlet of the study area. Flow requirements at Vernalis were discussed in Section 5.1.4. In this section, salinity objectives at Vernalis are discussed. As mentioned before, electrical conductivity has been considered as the indicator of salinity. To protect agricultural beneficial uses of water in the southern Delta, the 1995 Bay-Delta Plan defines salinity objectives for the San Joaquin River at Vernalis. Based on these objectives, maximum 30-

day running average of mean daily electrical conductivity at Vernalis for all water year types should be as follows (CRWQCB Central Valley Region, 2009, Table III-5):

- 0.7 mmhos/cm from April 1 through August 31; and
- 1.0 mmhos/cm from September 1 through March 31

In addition, the municipal and domestic water use requires that electrical conductivity in the San Joaquin River shall not exceed the secondary maximum contaminant levels (MCLs) specified in Title 22 of the California Code of Regulations (RWQCB Central Valley Region, 2009, pp. III-3). The secondary MCL's for electrical conductivity has three levels as:

- Recommended level: 900 uS/cm
- Upper level: 1600 uS/cm
- Short-term level: 2200 uS/cm

5.6 SUMMARY

In this chapter, required setups to develop the watershed simulation model, the optimization model, and the behavioral simulation model were discussed. An intensive amount of data have been gathered and prepared to setup the watershed simulation model. These data included: digital elevation models, the national hydrography dataset, daily flow and salt concentration time series of inflows, point sources, soil data, land cover, weather data, crop water demand, and planting and harvesting dates. Sources of these data, as well as data preparation process to meet the model's required format were also explained. In addition, minimum flow requirements and salinity objectives in the San Joaquin River were defined in order to be considered as the constraints of the system. After setting up the watershed simulation model, steps to setup the genetic algorithm model were explained followed by the approach to determine surrogate worth of trade-off points on the Pareto front.

CHAPTER 6

RESULTS AND DISCUSSION

In this chapter, the results obtained from all models are presented and discussed. Since all analyses are performed on the outputs of the watershed simulation model, the performance of this model must be validated. Results from calibration and validation of the watershed simulation model are first explained. Then, the trade-off points obtained from the optimization model are expressed and responses from water users/decision-makers corresponding to these trade-off points are addressed. After that, the agent-based model is validated and its results are presented. The final sections of this chapter will evaluate the overall performance of the proposed conflict management model and discuss adaptation to the results obtained from this model.

6.1 SENSITIVITY ANALYSIS RESULTS

SWAT allows the users to adjust the model parameters in order to calibrate the model. These parameters are categorized into climate, hydrologic, sediment, nutrients, pesticide, bacteria, water quality, and channel processes parameters. In order to reduce calibration computation time, sensitivity of the San Joaquin River watershed simulation model to different parameters was analyzed and calibration was performed using only the parameters to which the model is sensitive. For this purpose, flow in the San Joaquin River at Vernalis and Patterson stations as well as the salt concentration at Vernalis station were considered as dependent variables. All SWAT model parameters were set as independent variables and used as calibration parameters. Then, 10 equal intervals were selected between the lower and upper bands of each parameter. The SWAT model was run for every interval of each parameter. The parameters that resulted in different outputs due to various intervals of the parameter were determined. Based on the results obtained from the sensitivity analysis, the San Joaquin watershed simulation model was sensitive to 18 parameters. These parameters as well as their sensitivity index and adjusted values are presented in Table 6.1.

6.2 CALIBRATION RESULTS

To calibrate the San Joaquin watershed simulation model, two USGS flow and water quality gauges on the San Joaquin River were considered. These stations are Vernalis, located downstream of the study area, and Patterson, located between the Merced and Tuolumne Rivers. Daily time series of flow and salinity (as EC concentration) from January 1, 2000 to December 31, 2006, were used. Two years were considered for the model warm up, three years for calibration, and two years for validating the calibrated results.

Figure 6.1 and 6.2 show the daily calibration and validation results for flow at Vernalis and Patterson, respectively. As demonstrated in Figure 6.1, the simulated flow at Vernalis has a sound fit with the observed data values. The model tends to underestimate flow at Patterson almost in the entire time series. However, as presented in Table 6.1 Values of different statistical criteria for evaluating the performance of the San Joaquin watershed simulation model high R^2 and NSE values and relatively low RE, PBIAS, and RMSE values for this station confirm that the model is reliably simulating flow in this station. Furthermore, according to Table 3.1, in Chapter 3, monthly NSE values between 0.75 and 1.0 imply “very good” performance of a model for streamflow and PBIAS values between 15% and 25% suggest that the performance of model is satisfactory. Therefore, it can be concluded that the simulation results for streamflow are accurate.

Table 6.1 Sensitive parameters of the San Joaquin watershed simulation model and their values and sensitivity indices

No.	SWAT Symbol	Definition of the Parameter	Units	Sensitivity Index	Adjusted Value	Lower Band	Upper Band
1	EPCO	Plant uptake compensation factor	-	-0.013	0.3509	0.01	1
2	SNOCOVMX	Minimum snow water content that corresponds to 100% snow cover	mm	0.003	489.1	0	650
3	ALPHA_BF	Baseflow alpha factor (days).	days	0.006	0.9267	0	1
4	GW_DELAY	Groundwater delay time	day	-0.004	26.36	0	60
5	GW_REVAP	Groundwater coefficient for water in shallow aquifer returning to root zone	-	-0.003	0.08152	0.02	0.2
6	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur	mm	-0.008	3702	0	5000
7	RCHRG_DP	Deep aquifer percolation fraction	-	-0.1	0.1381	0	0.25
8	REVEP_MN	Threshold depth of water in the shallow aquifer for percolation to the deep aquifer to occur	mm	0.001	337.5	0	500
9	ESCO	Soil evaporation compensation factor	-	0.117	0.9847	0.5	1
10	CANMX	Maximum canopy storage	mm		4.774	0	10
11	DEP_IMP	Depth to impervious layer in soil profile	mm	-0.002	2187	1500	2500
12	CN_F	Curve number factor	%	0.083	-0.09745	-0.1	0.1
13	CH_KII	Effective hydraulic conductivity in main channel alluvium	mm/hr	-0.029	318.5	-0.01	500
14	CH_NII	Manning's "n" value for the main channel	-	-0.001	0.0149	0.01	0.016
15	SOL_AWC	Available water capacity of the soil layer	%	-0.116	0.9726	-0.1	2
16	SOL_K	Saturated hydraulic conductivity	%	0.009	4.854	-0.5	5
17	CH_KI	Effective hydraulic conductivity in tributary channel alluvium	mm/hr	-0.002	263.7	0	300
18	CH_NI	Manning’s “n” value for the tributary channels	-	0.007	0.2742	0.008	0.3

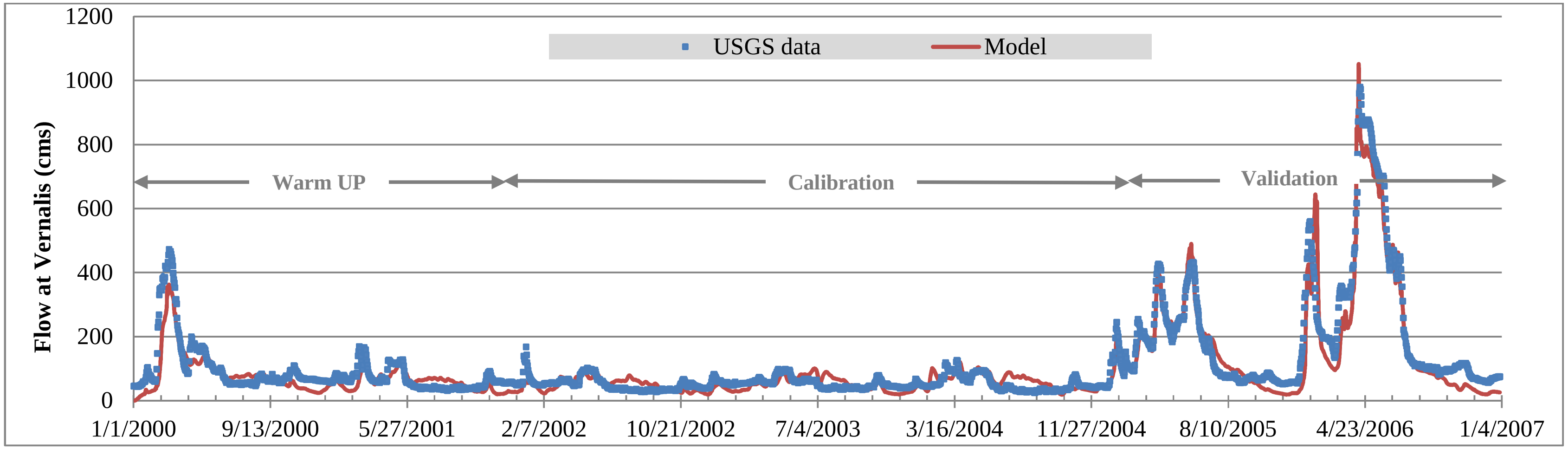

Figure 6.1 Comparison of daily flow data from model and USGS flow gauge at Vernalis

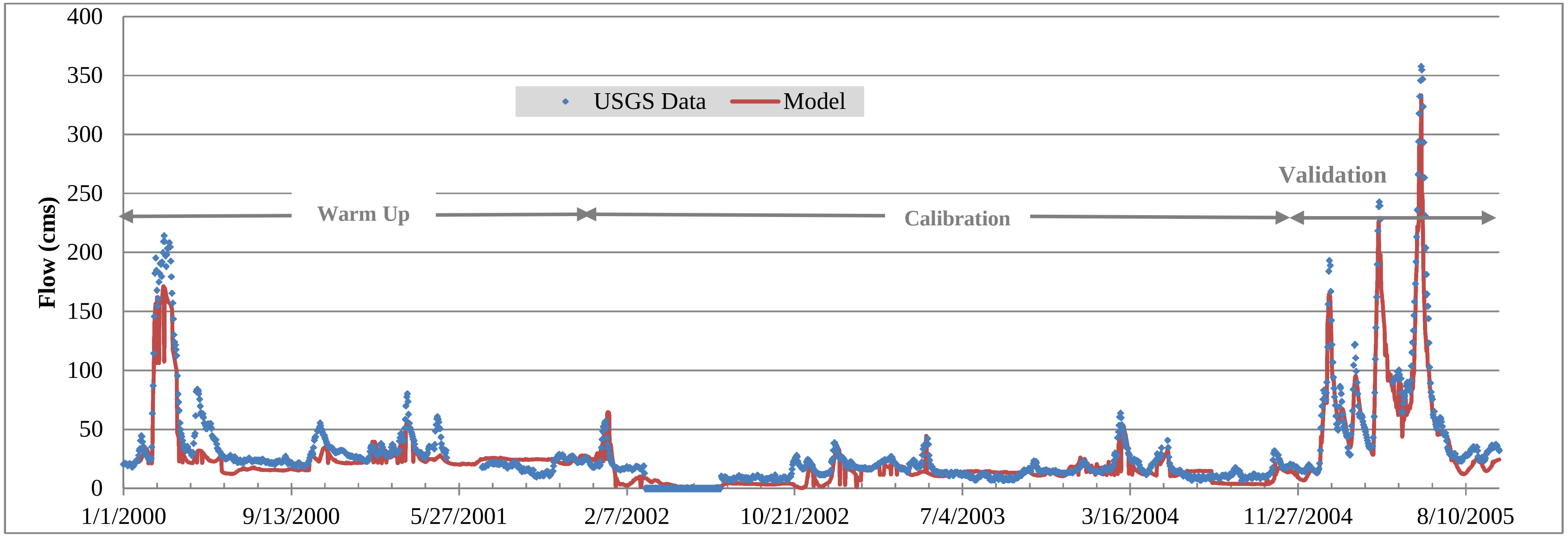

Figure 6.2 Comparison of daily flow data from model and USGS flow gauge at Peterson

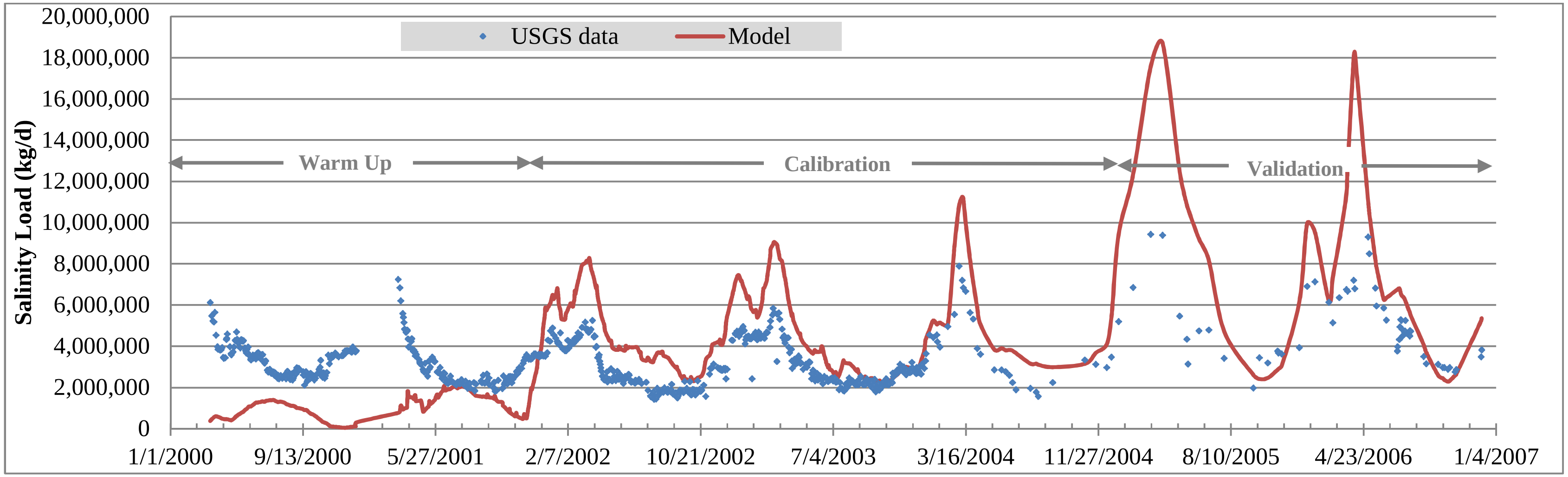

Figure 6.3 Comparison of daily salinity load data from model and USGS water quality gauge at Vernalis

Table 6.1 Values of different statistical criteria for evaluating the performance of the San Joaquin watershed simulation model

	RE(%)	PBIAS(%)	R^2	NSE	RMSE
Flow at Vernalis	8.44	9.42%	0.95	0.90	42.62(cms)
Flow at Patterson	15.9	- 12.3	0.91	0.88	147.9 (cms)
Salinity at Vernalis	- 44.3	47.9	0.84	-1.27	1.218* (tons/d)

* The average salinity load at Vernalis is approximately 2,250 tons/d based on the observed data

Comparing the observed and simulated values for salinity loads in Vernalis (as demonstrated in Figure 6.1 Comparison of daily flow data from model and USGS flow gauge at Vernalis**Error! Reference source not found.**), it can be deducted that the model tends to overestimate salinity loads, especially in late spring and early summer, when there is a peak for salinity loads. According to Table 6.2, simulated salinity loads result in high RE and PBIAS values. To justify these high values, Columns 4 and 5 of Table 3.1, which present the PBIAS values for sediment and nitrogen/phosphorous, respectively, are referred to. Even though the water quality variable of this study is salinity, which is not listed in Table 3.1, it can be concluded from this table that for water quality variables, higher PBIAS values are acceptable. The PBIAS value of up to 70% for some water quality variables such as nitrogen and phosphorous can still point to a satisfactory model performance. Furthermore, even though the model is overestimating salinity loads, it is following the trend of observed values, which results in a high R^2 value (84%). Therefore, since the trends are followed well, the salinity simulated values can be used for further investigations.

6.3 OPTIMIZATION RESULTS

As mentioned in Chapter 3, a multi-criteria objective function has been defined for the purposes of this study. This objective function maximizes the water and minimizes the salt load being transferred from the San Joaquin River to the San Francisco Bay-Delta region, while maximizing water diversions to agricultural fields in the San Joaquin watershed. This objective function was solved using the Surrogate Worth Trade-off method. In this method, the Pareto front between different objective functions should be first determined. Then, the points on the Pareto front are shared with water users/decision-makers to specify the best compromise solution. In this study, the Pareto front has been shaped using genetic algorithm (GA). To get feedbacks from different agencies and find the Pareto optimum (best compromise solution), some questionnaires were provided and sent out to these agencies. Sections 6.3.1 and 6.3.2 will discuss the results obtained from the GA and responses from water users/decision-makers, respectively.

6.3.1 Finding Theoretical Noninferior Solutions

Performing a multiobjective optimization using genetic algorithm, two Pareto fronts were formed. These include the Pareto front between 1. water diversions and outflow to the Delta area; and 2. water diversions and salinity load being transferred to the Delta area. These Pareto fronts, which represent the entire noninferior set of solutions, have been shown in Figure 6.4 and Figure 6.5. The vertical axes in these figures show the sum of diversions, in thousand acre-feet, from Jan. 1, 2003 to Dec. 31, 2006. The horizontal axes in Figure 6.4 and Figure 6.5, respectively, demonstrate the sum of outflow and the sum of salinity load being transferred to the Delta area from Jan. 1, 2003 to Dec. 31, 2006.

After forming the Pareto fronts, several points were chosen from them to be shared with the water users/decision-makers within the system. The water users/decision-makers were asked to specify values of surrogate worth function (SWF) corresponding to these points. To select these points, one strategy would be to choose both end points of the Pareto front as well as some points in between with fixed or random intervals. Clearly, the end points correspond to the extremes at each side and will never result in a compromise. In addition, knowing the fact that reducing diversions by a high rate will keep the agricultural sector away from cooperation, it is more reliable to select the points within a reasonable range of reduction in diversions. Therefore, the range between 6% to 65% reduction in diversions was considered and seven points in this range were selected. These points have been indicated by red circles around them in Figure 6.4Figure 6.5.

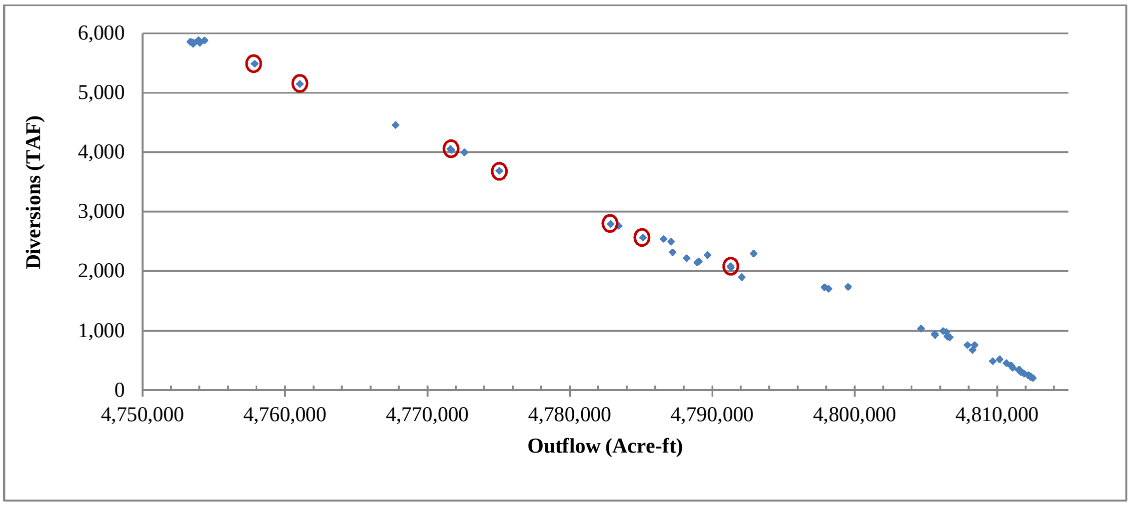

Figure 6.4 Trade-off points between diversions in the study area and outflow of the watershed

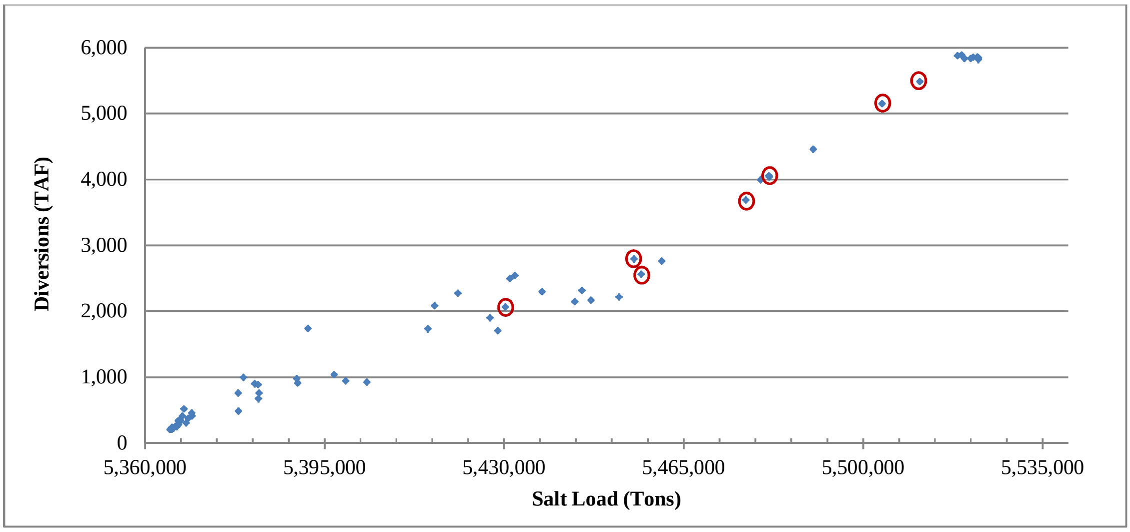

Figure 6.5 Trade-off points between diversions in the study area and salinity loads being transferred to the Delta

6.4 VALUES OF SURROGATE WORTH FUNCTIONS

To determine the values of SWF, three questionnaires were created and sent to 12 people in 11 different agencies in three categories: agricultural, environmental, and federal/state. Table 6.2 presents the list of these agencies and it shows whether or not each agency responded to the questionnaire. Appendices

A-1 through A-3 express these questionnaires. To prepare these questionnaires, the diversion, outflow, and salinity load values corresponding to the noninferior points highlighted in Figure 6.4 and Figure 6.5 were determined. Then, the ratio between these values and the status quo was calculated. For example in the status quo, the total water diversion from 2003 to 2006 is 5823.4 TAF. If it is reduced by 6%, the total diversion will be 5487.6 TAF, which results in 4% increase in outflow (4,757.9 over 4,753.4 TAF) and 2% reduction in salt load (5,511,024 over 5,522,477 tons).

In the questionnaires, the water users/decision-makers were asked to determine a surrogate worth between -5 and +5 for each ratio. Table 6.3 shows ratios corresponding to the selected noninferior points and the responses from water users/decision-makers. In this table, "*X*" is the percentage of agricultural water demand that is reduced from the current demands to meet the environmental purposes; "*Q*" is the percentage of increase in water transfer to the Delta area in “dry” and “below normal” water years corresponding to the reduced water diversions to agricultural fields (*X*); "*C*" is the percentage of decrease in the magnitude of violations from salinity objectives at Vernalis corresponding to the reduced water allocations to agricultural fields (*X*), and "*t*" is the percentage of decrease in the number of violations from salinity objectives at Vernalis due to the reduced water allocations to agricultural fields (*X*).

According to Table 6.3, for the agricultural agencies, the surrogate worth of 30% reduction in diversions is equal to zero; while the environmental agencies specified 65% reduction in diversions for the surrogate worth of zero. The federal/state agencies did not indicate any of the ratios as being equal to zero. As mentioned in Chapter 3, the best compromise solution is where the values of surrogate worth functions, determined by all decision-makers, are simultaneously equal to zero. In this study, this point does not exist. Therefore, the curves of the surrogate values were created (Figure 6.6) and the range between the points corresponding to zero values of the surrogate worth function on each curve was considered as the solution area.

Table 6.2 Agencies contacted to determine the values of SWF

Category	Agency	Response
Agricultural Agencies	Modesto Irrigation District	×
	Turlock Irrigation District	-
	Merced Irrigation District	-
Environmental Agencies	Natural Heritage Institute	-
	The Bay Institute (two people)	×
	Water and Power Law Group: Hydropower Reform Coalition	-
	Natural Resources Defense Council	-
State and Federal Agencies	California Department of Water Resources	×
	Department of Fish and Game	-
	San Joaquin River Group Authority	-
	US Fish & Wildlife Service - Pacific Southwest Region	-

Table 6.3 Ratios of the noninferior points and their corresponding surrogate worth

X	Q	C	t	Responses		
				Agricultural agents	**Environmental agents**	**federal/ State agents**
6%	4%	2%	6%	+2	-5	+5
12%	8%	6%	14%	+1	-3	+4
30%	22%	12%	38%	0	+3	-3
35%	23%	11%	27%	-5	+4	-4
50%	39%	18%	49%	-5	+5	-5
55%	42%	19%	51%	-5	+2	-5
65%	48%	19%	54%	-5	0	-5

The surrogate worth function of the environmental agencies has two points which are corresponding to zero, at 21% and 65% of reduction in diversions. Since, 65% will never result in a compromise, this point was disregarded. The range between 21% and 30%, where the values of SWF for the curves of environmental agencies and agricultural agencies are respectively zero, has been considered as the solution area. The value of SWF for the curve of federal/state agencies is zero where there is 22% reduction in diversions. The best compromise solution was selected as the arithmetic mean of these three values which is equal to 24.33%.

Figure 6.7Figure 6.8 show comparisons between the status quo and best compromise solution for flow and salt concentration at Vernalis, respectively. Reducing diversions by 24.33% will result in 17.12% increase in outflow to the Delta area in dry and below normal years, 10.5% decrease in magnitude of violations from salinity objectives at Vernalis and approximately 30% decrease in the number of days that the salt concentration in the San Joaquin River at Vernalis violates the standards.

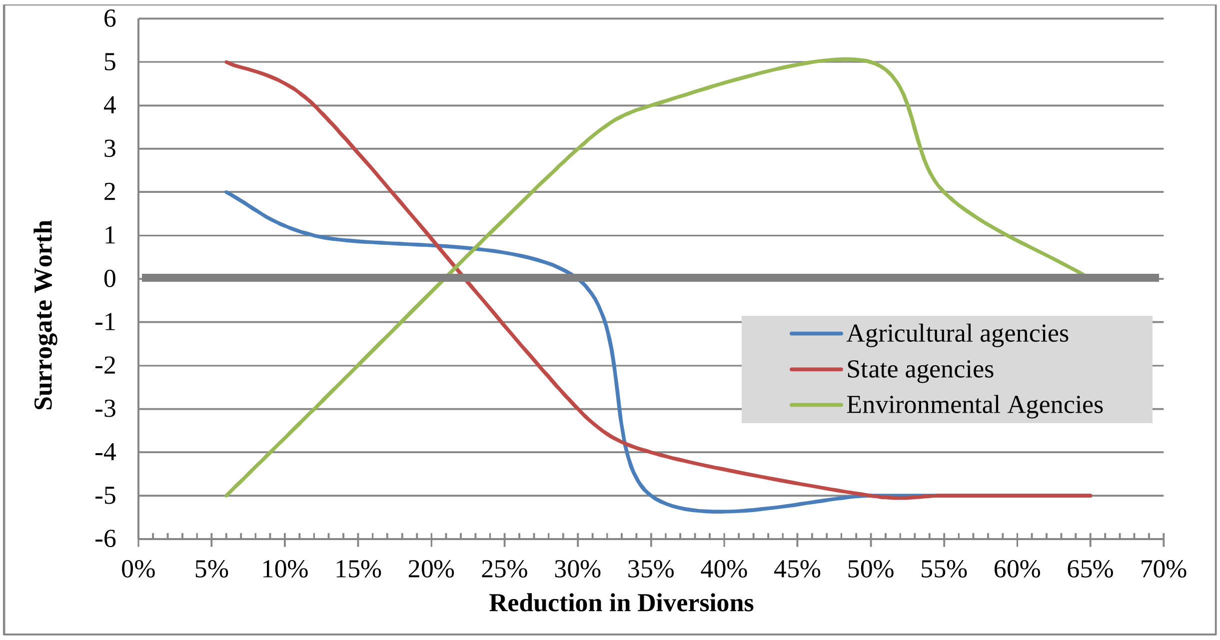

Figure 6.6 Values of surrogate worth functions corresponding to different ratios of reduction in diversions

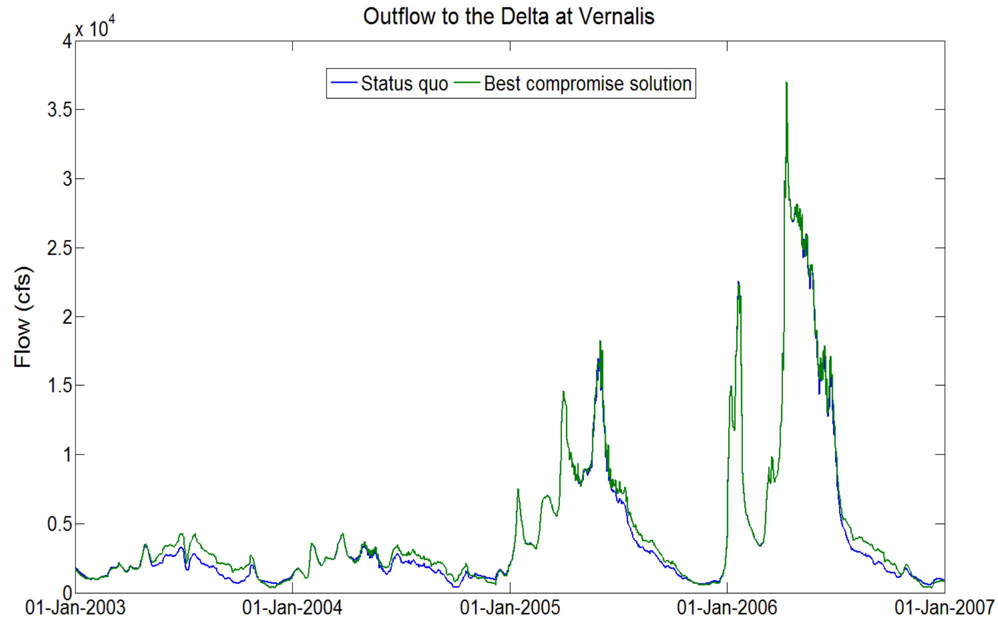

Figure 6.7 Comparison between the status quo and best compromise solution for flow at Vernalis

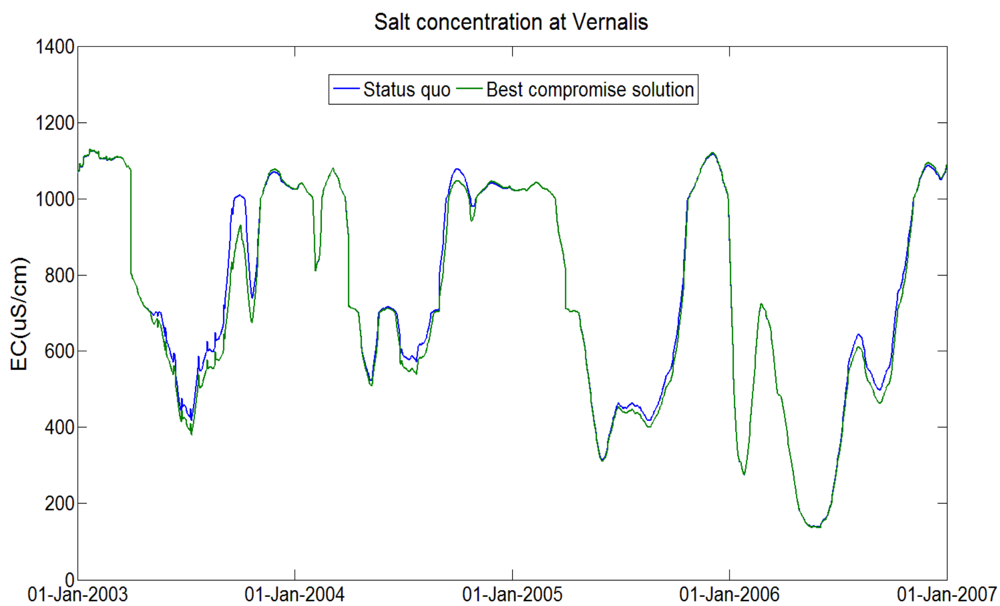

Figure 6.8 Comparison between the status quo and best compromise solution for salt concentration at Vernalis

6.5 RESULTS FROM THE BEHAVIORAL SIMULATION MODEL

As discussed in Chapter 3, Section 3.5.4, to calculate the utility of each agent (Equations 3.18 and 3.21), two terms have been considered. The first term represents the social pressure and quantifies the influence of each water user's surrounding neighbors on its utility to cooperate. The second term (only in Equations 3.18 and 3.20), reflects the impact of interactions between each agent with the other agents. Therefore, to be able to calculate the first term of the above mentioned equations, the first step is to determine the type of each agricultural field.

As shown in Equation 3.17, if the water demand requested by an agent is more than the available water, the behavior of this agent is considered non-cooperative; otherwise, the agent is cooperating. To determine the type of agricultural fields, the watershed simulation model was run on a daily basis and the available water to be supplied to each field for each day was determined. These values were then compared to the amount of each field's water demand during its irrigation period. If the field's water demand was less than its available water, the type of that field was considered cooperative for that specific day; otherwise, the field was considered non-cooperative for that day. Then, it was assumed that if each field is cooperating for 70% of days during its entire irrigation period, the overall behavior of that field is cooperative; otherwise its overall behavior is non-cooperative. It should be noted that the 70% is just an assumption and more detail study is needed to find a more accurate number. Figure 6.9 demonstrates the cooperative and non-cooperative fields in the study area.

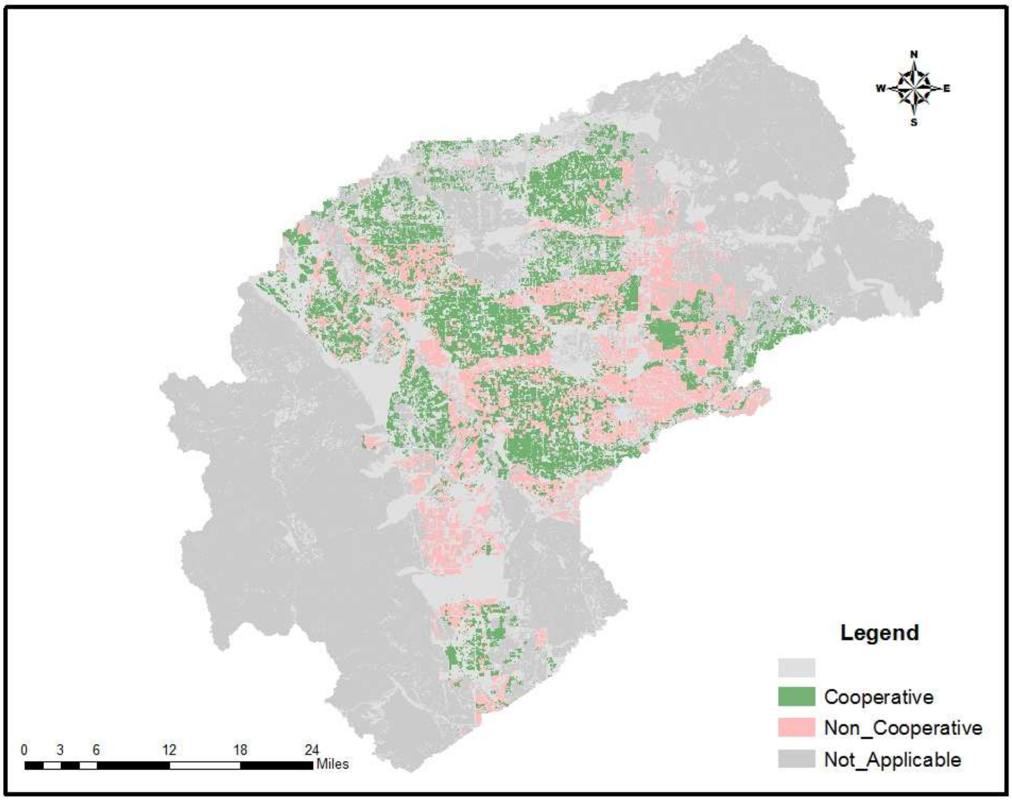

Figure 6.9 Spatial distribution of cooperative and non-cooperative types of agricultural fields

6.5.1 Validation of the Agent-Based Model

Before evaluating the impacts of different management scenarios using the behavioral simulation model, it is important to make sure its performance is reasonable. For this purpose, three hypothetical scenarios were considered:

1. New regulations are enacted so no more than the available water, in excess of environmental needs, can be allocated to the agricultural water users. This scenario will obligate diversions to cooperate. Therefore, the modification factor, F_m, for all agricultural fields will be equal to F_m^*, which results in a utility of 100% ($U_i = 1.0$) for them to cooperate.
2. The environmental sector compromises with all violations ($F_m = 0$). In this scenario, the agent might only be influenced by its neighbors and its utility to cooperate is only influenced by the behavior of its surrounding neighbors ($U_i \sim V_i$).

3. The state provides some incentives to encourage diversions to cooperate. The incentives are meant to compensate 50% the benefit lost due to the cooperation ($U_i \sim [V_i + F_m];\ \ F_m = 0.5$).

These three scenarios were introduced to the behavioral simulation model to evaluate the sensitivity of the model to different management scenarios. Figure 6.10Figure 6.11 show the sensitivity of the behavioral simulation model to different management scenarios for flow rates and salt concentration, respectively. As demonstrated in these figures, during the irrigation periods in each year, by increasing the water users' utility of cooperation, the outflow to the Delta increases and salt concentration at Vernalis decreases.

Sensitivity of the behavioral simulation model to social pressure has also been evaluated. Figure 6.12Figure 6.13 show the sensitivity of the behavioral simulation model to social pressures for flow rates and salt concentrations, respectively. To create these figures, a constant value of 0.5 has been considered for F_m and the influence of the behaviors of neighboring agricultural fields has been ignored. i.e. the first term in the right hand side of Equations 3.18 through 3.21 has been considered equal to 0. As demonstrated in Figure 6.9, the majority of agricultural fields are showing a cooperative behavior. These cooperative behaviors result in higher values for the proportions of neighbors of each agent, $V_i(C)$, in the first term in the right hand side of Equations 3.18 through 3.21, which results in higher values of the agent's utility to cooperate, U_i. Therefore, as shown in Figure 6.12Figure 6.13, considering the impacts of social pressure results in more outflows to the Delta and less salt concentration.

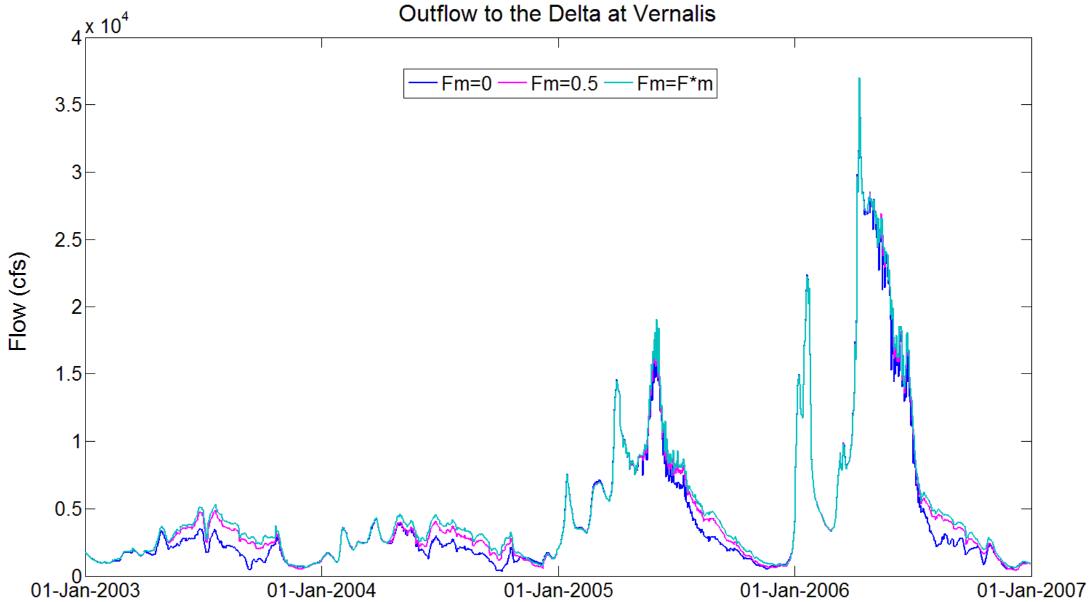

Figure 6.10 Sensitivity of the behavioral simulation model to different management scenarios for flow rates

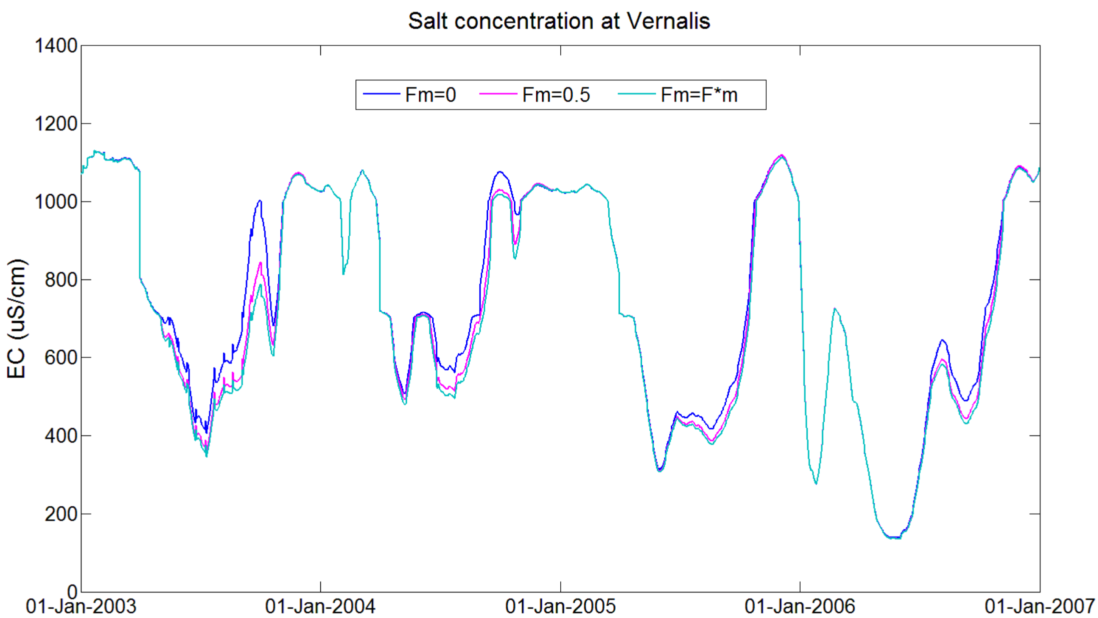

Figure 6.11 Sensitivity of the behavioral simulation model to different management scenarios for salt concentration

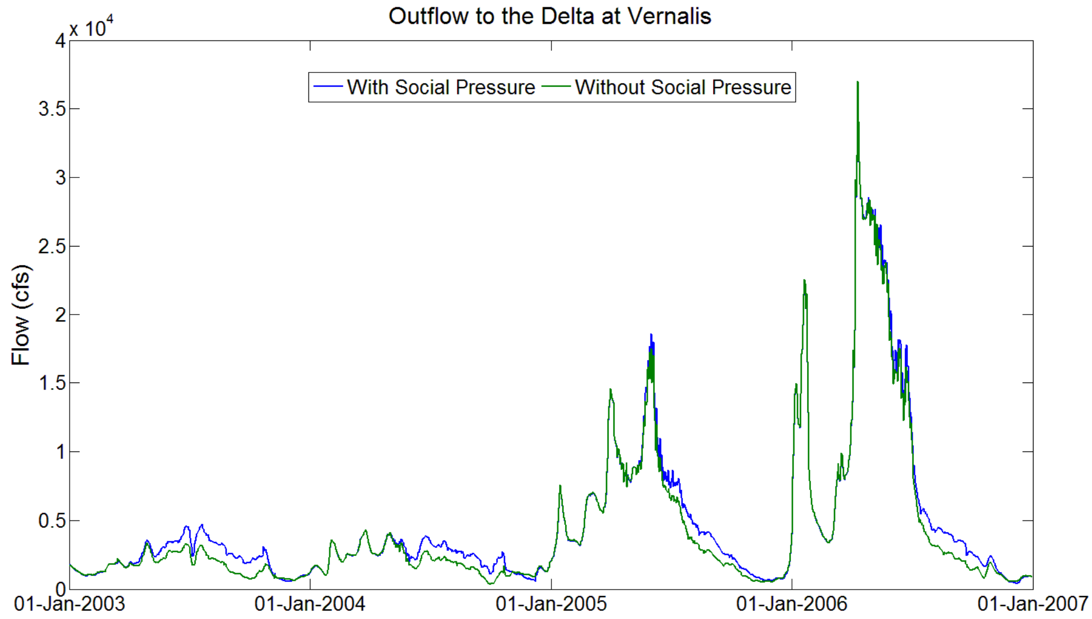

Figure 6.12 Sensitivity of the behavioral simulation model to social pressures for flow rates

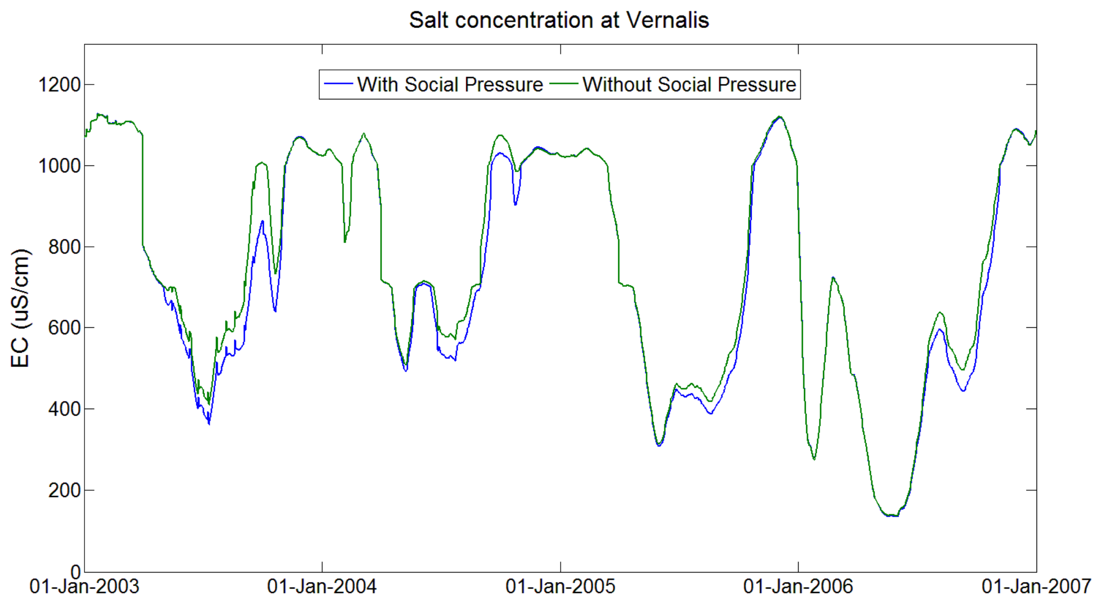

Figure 6.13 Sensitivity of the behavioral simulation model to social pressures for salt concentration

6.5.2 Evaluating Responses from different Agents

As mentioned earlier, some questionnaires were created and sent to different agencies to determine the surrogate worth of noninferior points. Another purpose of creating these questionnaires was to find a more actual perception of what different agencies think about managing diversions in the system. However, before the responses from these agencies are described, it should be declared that to encourage them to fill out the questionnaires, it was emphasized that the main purpose of the questionnaire is just to get opinions for this dissertation and it does not commit the agencies in any way. So, they were asked to response in a way that they think other agricultural, environmental, and federal/state agencies might accept. Therefore, the answers do not necessarily reflect the exact position of the agencies that responded to the questionnaire. A summary of responses to the questionnaires are discussed in the following:

1. The salinity impacts mentioned in Chapter 4 (Section 4.4) were explained in the questionnaires for agricultural and federal/state agencies and knowing these facts, they were asked by how much the agricultural water allocations must be reduced?

   The federal/state response to this question was 20% versus agricultural agencies who believe 15% reduction in water demand is enough.

2. The agencies were asked to assume that an incentive program is going to be planned for encouraging farmers to demand less water. The program would be planned to compensate the benefit they may lose regarding to the amount of water they gave up or the amount of investment required to implement modern irrigation technologies. In this case, they were asked by how much they would think farmers should give up with their current water demand (as a percentage of their current demand)? They were also asked how much compensation they would think is required (as a percentage of their potential benefit)?

   In this case, federal/state agencies believe that farmers should give up with 30% of their current water demand and 20% of their potential benefit (which is approximately equal to $60,000,000.00) should be compensated. However, agricultural agencies would be willing to give up with 20% of their current water demand, while 80% of their potential benefit is being compensated.

3. In case the salt concentrations in Vernalis violate salinity objectives indicated in Chapter 5, Section 5.5, environmental agencies might neglect these violations if they are not more than 10% of the salinity objectives. They might also compromise if salinity objectives are not violated for more than 30 days per year. Furthermore, violations in September may not raise environmental concerns.
4. The state agencies believe that the compensations should be based on the market value of the type of crop that otherwise would have been grown in a specific area, e.g. something similar to USDA insurance crop losses payments. To participate in the federal crop insurance program, producers will be compensated if they experience a loss in crop yields or if they experience a decline in revenue. USDA decides which crops in which regions are eligible for crop insurance and making these decisions depends on producers' interest in crop insurance and the level of risk associated with a particular crop in a specific region.
5. However, federal/state agencies believe that farmers will continue to grow their crops, even with the loss of surface water supply. They will pump groundwater in lieu until is not more economical or run out of groundwater. In areas, where there is no groundwater to pump, the losses will be significant. The overall impact will be less food supply security, unemployment increases, and higher food costs for the public.

As a summary of these responses, it can be concluded that there is a disagreement between agricultural and federal/state agencies over the amount of water that must be given up and the amount of compensations. The behavioral simulation model in the next section will be used to simulate the interactions between these agencies and evaluate the impacts of implementing different management policies on the flow rate and salt concentration at Vernalis as well as the amount of diversions.

6.5.3 Evaluating Management Scenarios Using the Agent-Based Model

As mentioned in the previous section, in case agricultural agencies give up with 20% of their water demand, they expect 80% compensation of the benefit that they may lose. This amount of compensation is corresponding to 16% of their total benefit. However, state agencies are willing to provide only 20% compensation if agricultural agencies give up with 30% of their water demand, which is corresponding to 6% of the agricultural agencies total benefit. In order to evaluate the effectiveness of providing compensations, the behavioral simulation model was first calibrated, so that providing 16% compensations will result in 20% reduction in diversions.

After calibrating the behavioral simulation model, providing 6% compensations was introduced to the model and the resulting reduction in diversions was determined. It was also evaluated to see if the theoretical best compromise solution, 24.33% reduction in diversions, is expected and how much compensation is required. Furthermore, the amount of required compensation in order to encourage agricultural agencies to give up 30% of their water demand was indicated.

Figure 6.14 andFigure 6.15 show the impacts of providing different levels of compensation on the amount of outflow to the Delta area and salt concentration at Vernalis. Figure 6.15 shows the 30-day moving average of mean daily electrical conductivity at Vernalis. In these figures, *Fm* represents the demand modification factor in Equations 3.18 and 3.20 and is corresponding to the amount of provided compensations. The resulting amounts of diversions as well as flow rate and 30-day moving average of mean daily electrical conductivity at Vernalis have been presented in Table 6.4. *X*, *Q*, *C*, and *t* in this table represent the same parameters as Table 6.3. *C** is the percentage of decrease in the magnitude of violations from salinity objectives at Vernalis, when the environmental sector relaxes the salinity objectives by 10% (as discussed in item #3 of Section 6.5.2), and *t** is the percentage of decrease in the number of violations from salinity objectives at Vernalis when the environmental sector relaxes the salinity objectives by 10%.

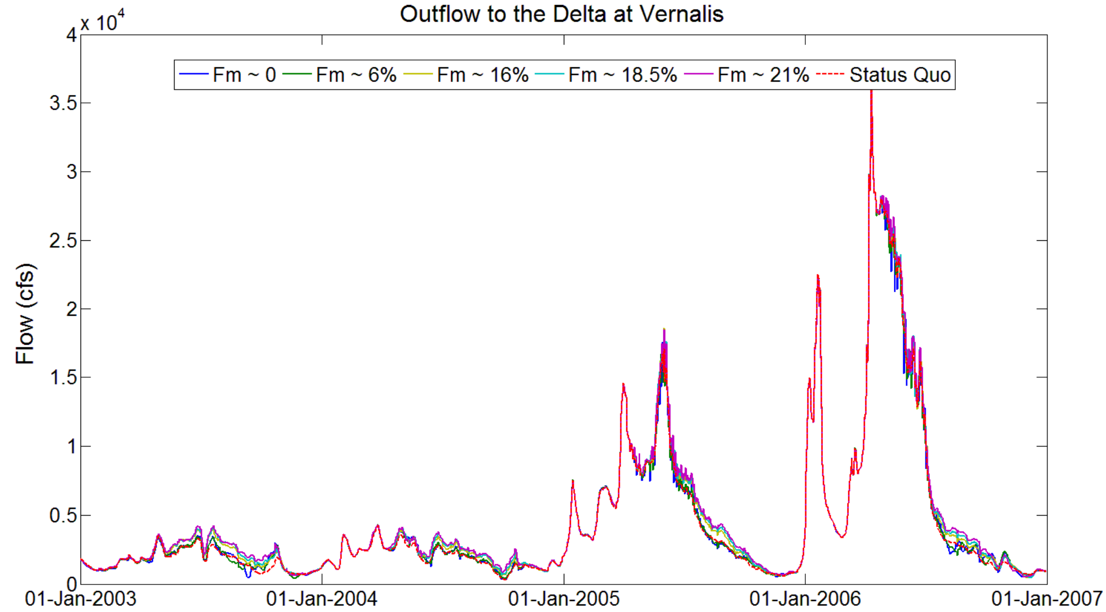

Figure 6.14 Outflow to the Delta area at Vernalis due to different levels of providing compensations

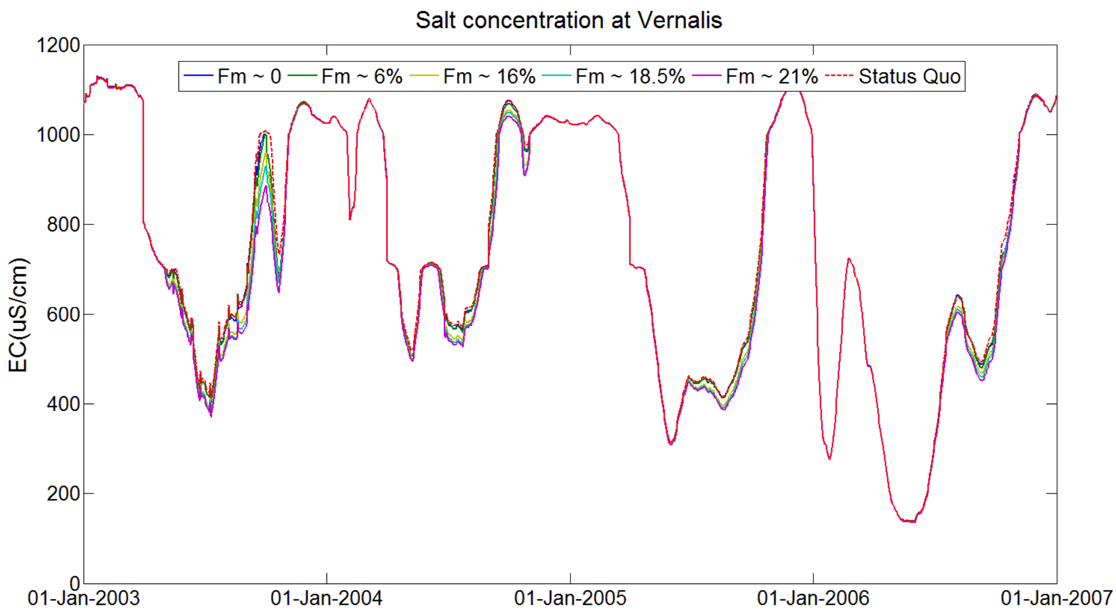

Figure 6.15 Salt concentration at Vernalis due to different levels of providing compensations

Table 6.4 Reduction in diversions due to different levels of compensations and their impact on flow rate and salt concentration at Vernalis

	X	Q	C	t	C*	t*
Only social pressure	4.5%	2%	0.9%	4%	1.1%	5%
6% compensation	6%	4%	2%	6%	2.5%	7.5%
16% compensation	20%	14.5%	9%	25%	11%	32.5%
18.5% compensation	25%	18%	11%	31%	13.5%	40%
21% compensation	31%	22%	12.5%	39%	15.5%	50%

According to Table 6.4, in case only 6% compensation is provided by the state agencies, and agricultural agencies would be willing to give up only 6% of their water demand. Providing 18.5% compensation will result in achieving the theoretical best compromise solution. In case the goal is to encourage agricultural agencies to give up 30% of their water demand, approximately 21% compensation should be provided. If no compensation is provided, due to the social pressure, it is likely that agricultural agencies give up 4.5% of their water demand, which results in 2% increase in flow rate and 0.9% decrease in salt concentration at Vernalis. However, providing 21% compensation may result in up to 22% increase in the outflow to the Delta area and 12.5% decrease in the magnitude of violation from salinity objectives. Furthermore, there would be up to 39% decrease in the number of times that violations from salinity objectives may occur. In case the environmental sector compromises and relaxes the salinity objectives by 10%, there would be up to 3% more decrease in the magnitude of violations from salinity objectives and 11% less number of violations.

It should, however, be noted that, if agricultural agencies are to be encouraged to cooperate only by providing compensation, state agencies will have to provide about 3.5 times more compensation than what they have considered, which is unlikely to happen. Therefore, other management strategies must be incorporated in order to achieve the goal of 24.33% or 30% of reduction in diversions. These management strategies include: education, enacting new regulations, and considering penalties by the state. As presented in Section 6.5.2, Item #1, by educating the agricultural agencies about the consequences of a non-cooperative behavior, it is likely that they give up with up to 15% of their water demand. By enacting new regulations, water diversions would become more limited, which may result in more conflicts.

Therefore, adaptation strategies must be developed in order to avoid possible consequences and sever conflicts. Penalties should be corresponding to the amount of difference between the potential compensations that could be provided by the state agencies and what is required (say 21% - 6% = 15%).

6.6 SATISFACTION AND PERFORMANCE ANALYSIS

To determine the satisfaction level of different water users/stakeholders, first, utility functions of different agencies must be determined so that the results due to different policies are compared with them. To form these utility functions, the agencies were asked in the questionnaires to determine the corresponding values for *a*, *b*, *c*, and *d* in Figure 3.10, which shows the general form of a utility function. It was mentioned to them that in this figure, *a* is the percentage of total agricultural water demands that is much less than their demands and will not satisfy them at all if being allocated to them; *b* is the minimum percentage of total agricultural water demands that completely meets their demands and satisfies them if being allocated to them; *c* is the maximum percentage of total agricultural water demands that completely satisfies them if being allocated to them (it can be less or more than %100); and *d* is the percentage of total agricultural water demands that is much more than their actual demands and if it is allocated to them it may damage their crops and make them unsatisfied (it should be more than %100). The values of *a*, *b*, *c*, and *d* obtained from the questionnaires have been presented in Table 6.5. Using these values, Figure 3.10 was modified for the agricultural and federal/state agencies (Figure 6.16).

Table 6.5 Values of *a*, *b*, *c*, and *d* for the agricultural and federal/state utility functions for diversions

	Agricultural	**Federal/State**
a	60%	50%
b	80%	70%
c	100%	90%
d	110%	101%

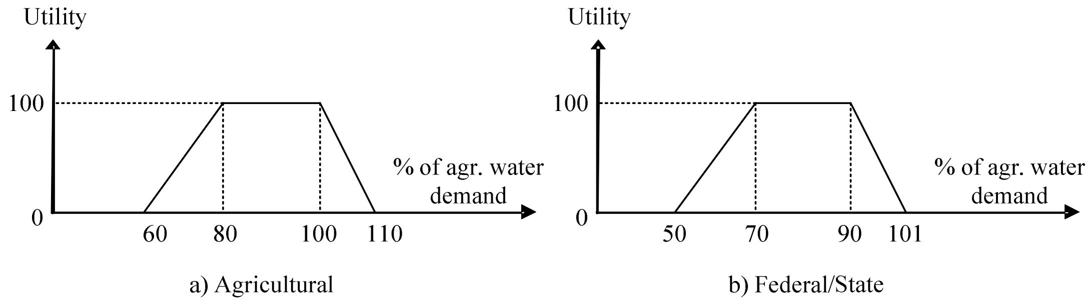

Figure 6.16 Utility functions of the agricultural and state/federal agencies

According to the utility functions shown in Figure 6.16, in case there is up to 20% reduction in diversions, agricultural agencies are 100% satisfied with the amount of their allocated water. Reducing diversions by 24.33% (the theoretical best compromise solution) will result in 78.3% satisfaction of the agricultural agencies. If diversions are reduced by 30%, the satisfaction of agricultural agencies will decline by 50%. The utility function of federal/state agencies shows that these agencies will be 100% satisfied in case of implementation of all different scenarios.

6.6.1 Performance Analysis

As discussed in Chapter 3, reliability is the probability of no failure within the planning horizon. Using this definition, the reliability indices for salinity objectives due to different scenarios have been calculated (Table 6.6). Environmental and municipal salinity objectives in this table have been discussed in Chapter 5, Section 5.5. As presented in this table, providing different levels of compensations may result in up to 31% reduction in diversions and can enhance the reliability of the system for environmental salinity objectives by up to 17%. This amount is also corresponding to 15% increase in the reliability of the system for environmental salinity objectives (if the objectives are relaxed by 10%), as well as 16% and 6% for municipal recommended level and upper level, respectively.

Table 6.6 Reliability indices for salinity objectives due to different scenarios

Salinity Objective	Status Quo	Percent of Compensation 0%	6%	16%	18.5%	21%
Reduction in diversions	**0%**	**4.5%**	**6%**	**20%**	**25%**	**31%**
Environmental salinity objectives	55%	57%	57%	66%	69%	72%
10% compromise in salinity objectives	61%	63%	64%	71%	73%	76%
Municipal recommended level	58%	60%	60%	68%	71%	74%
Municipal upper level	85%	86%	86%	89%	90%	91%

Resilience shows how quickly a system recovers from a failure. As shown in Figure 6.15, the variations of 30-day moving average of mean daily electrical conductivity at Vernalis follow the same pattern for all scenarios. Therefore, there is not a considerable difference in the resilience when different strategies are implemented. Vulnerability is the maximum severity of a failure in a set of unsatisfactory states. Table 6.7 presents the vulnerability of the system due to different scenarios. As presented in this table, providing up to 21% compensations, which results in almost 31% reduction in diversions, can reduce the vulnerability of the system by 455 uS/cm. This amount is corresponding to approximately 53% of the total vulnerability of the system in the status quo.

Table 6.7 Vulnerability of the system for salinity objectives due to different scenarios

	Status Quo	Percent of Compensation 0%	6%	16%	18.50%	21%
Vulnerability (uS/cm)	855	765	670	540	480	400

Even though there is not a considerable difference in the resilience of the system due to different scenarios, the significant increase in the reliability and decrease in vulnerability of the system justifies the implementation of these scenarios. However, choosing which scenario to be implemented depends on the availability of all financial, social, legislative, and technical resources.

6.7 ADAPTATION

Adaptation can be referred to as the set of practical steps that communities may take to protect themselves from the possible disruption and damage resulting from changing watershed conditions. It contains the development of strategies to take advantage of opportunities provided by changing conditions. In order to implement the new management strategies, which result in allocating less water for diversions in the San Joaquin River watershed, some adaptation strategies must be developed. The main intentions for developing these strategies would be reducing damage and avoiding possible drops in the satisfaction level of agricultural agencies.

Adaptation technologies can be classified to hard technologies and soft technologies. Hard technologies entail new constructions and soft technologies are referred to as managing behaviors (UNFCCC, 2006). Adaptation strategies that would be helpful to manage the conflicting situation and encourage agricultural agencies in the San Joaquin River watershed to cooperate will be discussed in the following:

6.7.1 Hard Technologies

As mentioned in Section 6.5.2, Item #5, in case of reducing water allocations from surface water resources to agricultural fields, farmers will continue to grow their crops by pumping groundwater in lieu until it is not more economical or run out of groundwater. In areas, where there is no groundwater to pump, the losses will be significant. Therefore, it is important to develop groundwater recharge plans and construct proper structures to harvest rainwater, in wet years, for this purpose.

Reducing water loss from water conveying systems by cutting leakage from pipes and repairing the linings of canals can increase water efficiency from the supply side. Furthermore, implementing modern irrigation techniques, such as installation of drip irrigation equipment, on the demand side can result in less water demand. Another hard technology to adapt with less water allocation strategies is changing land topography so water uptake would be improved and wind erosion would be reduced. For this purpose, large fields can be subdivided, grass waterways must have proper maintenance, and the land surface could be roughened (where required). However, implementation of each of these adaptation practices is highly restricted by financial limitations.

6.7.2 Soft Technologies

Soft technologies are mostly focused on management of behavior. Therefore, education, providing incentives, and adjustment in agricultural practices are involved in this category. As presented in Section 6.5, education and providing incentives can play a significant role in encouraging agricultural agencies to cooperate. However, the main target of these two strategies should be to provide farmers with the opportunity that even though they receive less water, they can still have almost the same amount of production. In other words, the soft adaptation technologies that help farmers to enhance current agricultural practices should be the target of providing incentives and education. Some of these soft technologies are:

- Educating farmers to change tilling practice to no till or strip till and split field to grow more water demanding crops in sections closest to water
- Providing subsidies to encourage farmers to produce different crops and shift to less water intensive and drought-tolerant crops. For this purpose, more research must be carried out to find on new varieties.
- Increasing irrigation efficiency by using brackish water (where possible), concentrating irrigation in periods of peak growth, and using drip irrigation
- Changing farming practices to conserve soil moisture and nutrients, and control soil erosion. This can be fulfilled by rotating crops and avoiding monocropping, as well as using lower planting densities
- Changing irrigation water pricing
- Enhancing crop insurance regulations

6.8 SUMMARY

The results from simulation and calibration of the San Joaquin River watershed as well as optimization of the system were presented in this chapter. Using these models and incorporating their results into the behavioral simulation model a variety of management scenarios were defined and their efficiency was assessed. The utility functions of the water users/stakeholders were formed and used as the measure of water users'/stakeholders' satisfaction levels. To evaluate the performance of the proposed conflict management model and effectiveness of different management scenarios, performance indices such as reliability, resilience, and vulnerability were used. The values of these indices were determined for different management scenarios and the status quo. These values were then compared with each other and with the status quo to determine how effective each scenario would be if being implemented. Finally, the adaptation technologies that are required in order to reduce diversions to the most effective level were explained.

CHAPTER 7

CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

7.1 CONCLUSIONS

Competition for use of water is increasing and leads to many conflicts among competing interests with complex goals in water management systems. To deal with the complex conflicting situations some major changes in management policies are required. Technical system models are essential to create performance and other decision information, but models to simulate views of the competing parties are also needed to help resolve or mitigate conflicts. These models can be used as helpful tools to designate effective strategies and water resources management policies that encourage parties to cooperate by accurately simulating the stakeholders' behavior and interactions. Agent-based models offer promise to fill this role and can be used to simulate complex systems with interactive components.

In the complex conflicting situations, such as the one in the San Joaquin River watershed, the dominant strategy of the competing and conflicting parties is to wait as long as possible to force others to cooperative, so that they can benefit from their non-cooperative strategies. However, since a collapse of the system can impose significant costs to both the governing units and water users/stakeholders, the sooner the parties cooperate, the less damage may occur. In this study, a new approach to agent-based modeling was introduced to simulate the behavior and interactions of the parties participating in a conflict scenario, which was modeled as a game. Water issues of California's San Joaquin River watershed were used as an example of a long-standing situation. The ABM simulated the behaviors of different agents and explained the interactions among the parties and how they could be encouraged to cooperate in the game to work toward a solution.

The proposed model can be used to manage conflicts in complex water resources systems as a powerful tool to set up rules based on the timing of flows, water demands, environmental concerns, and legislative resources. It provides a clear description of humans/organizations interactions and a better understanding of complex interactive systems by simplifying the complexity of views and interactions of competing parties. Using this proposed conflict management model, decision-makers will have more reliable support for their decision-making processes.

Although this model has specifically been parameterized for the San Joaquin watershed, California, it can also be adjusted to be used for other watersheds and more complex systems. More management scenarios can also be defined and easily introduced to this model to designate the most effective scenarios for encouraging different parties to cooperate in the game. Therefore, new management scenarios can be evaluated without requiring the user to develop and deal with complex formulas.

In the following, the main question and sub questions of this study are explained to confirm that this model enables decision-makers to define and examine management scenarios and understand the consequences of their decisions on different stakeholders and their behaviors.

Research Question 1: *Theories exist that although science and engineering are essential, conflicts like the ones in California are resolved ultimately by the legal and political processes and finance is always a big issue. Therefore, it is critical for scientists and engineers to identify and propose feasible solutions that are transparent and coherent, and which can lead to agreement among the competing parties. Therefore, it should be specified whether the conflicts in the San Joaquin River watershed can be reduced through some management enhancements?*

The results of this study showed that reduction of diversions by 20% would keep the satisfaction level of the agricultural agencies at 100%. However, to agree with this amount of reduction, the agricultural agencies demand for compensations corresponding to 16% of their total benefit. On the other hand, the state agencies believe that diversions must be reduced by 30% while only 6% of the total agricultural benefit is being compensated. The theoretical solution indicates that 24.33% is the optimum rate to reduce diversions. Therefore, the conflict management model was used to deal with the disagreements on the amount of reduction in diversions and the extent of compensations.

According to the results obtained from the conflict management model, to work toward a solution for this conflicting situation, some management strategies and institutional enhancements are required. The model helped to designate the effectiveness of different strategies and the extent of required enhancements. It was concluded that social pressure and education, as well as providing incentives are the most effective scenarios that result in consensus over more reduction in diversions, while keeping all stakeholders satisfied. However, to expand the influence of social pressure, education and increasing public awareness about the consequences of non-cooperation on the surrounding environment and security of agricultural related jobs in close future have a great importance. Furthermore, in providing incentives, a diplomatic approach is required so that the incentives are provided in form of subsidies to direct farmers toward more environmental friendly agricultural practices. For this purpose, adaptation strategies should be planned according to the available financial, social, legislative, and technical resources. More details will be discussed in the response to the research question #2.

Research Question 2: *In case the management enhancements can lead to a less conflicting situation, what social enhancements are more feasible and applicable? What are the most effective legislative improvements? In what degree different social and legislative enhancements must be incorporated?*

Here the most feasible, applicable, and effective strategies that could result in reducing conflicts over water resources management in the san Joaquin River watershed are addressed. These strategies can be categorized into social and legislative. In the social side, social pressure and education can considerably influence the behavior of farmers. Getting help from cooperative farmers to promote sustainability and encourage the others to cooperate is an effective approach. For this purpose, providing incentives and allocating subsidies, from the legislative side, to the cooperative farmers can help to promote cooperative behavior. In addition, the effect of education and informing farmers about the negative impacts of non-cooperation on the system as well as their own future job security can be considered as another effective social strategy.

From the legislative side, compensations can be planned in form of providing subsidies for less water intensive crops, adjusting current crop insurance regulations, providing loans to install modern irrigation techniques, etc. Other legislative strategies could be providing funds to research advance plant genetics, enhancing infrastructures, such as lining water conveyance canals, constructing proper structures to harvest rainwater in wet water years to recharge groundwater. Compensations can also be accommodated in monetary form for the most cooperative farmers to promote cooperative behavior.

Enacting new regulations to limit water diversions and assigning penalties for non-cooperative behaviors are other strategies. However, both of these strategies would exacerbate the conflicting situation and increase the dissatisfaction of agricultural agencies. Therefore, planning for adaptation practices is the main prerequisite to implement these types of strategies. The adaptation practices should be planned in a way that results in almost the same amount of benefit from agricultural production even though the water allocations have been decreased. Some examples of these practices are: changing tilling practice to no till or strip, shifting to less water intensive and drought-tolerant crops, increasing irrigation efficiency, changing farming practices to conserve soil moisture, changing irrigation water pricing, enhancing crop insurance regulations, etc.

7.1.1 Final Conclusion

It can, in general, be concluded that the most applicable and effective way to deal with the complex conflicting situation in the San Joaquin River watershed is to combine several different social and legislative strategies. Focusing on only one strategy not only will not result in resolving conflicts, but it may result in a never-ending effort to solve the problem. For example, if providing incentives would be considered as the exclusive solution, the amount of financial resources required for that is beyond the federal/state agencies budgets. Therefore, even though these agencies are spending money and partially compensating the agricultural benefit lost, farmers will never be encouraged enough to effectively cooperate. As another example, if it is decided to control the situation solely by enacting new regulations to limit water diversions, even though it completely satisfies the environmental agencies, it may result in significant dissatisfaction in the agricultural agencies.

7.2 SUGGESTIONS FOR FURTHER RESEARCH

Several key and under-served research areas pertinent to find ways to heal the environment and conflicting situation of the San Joaquin River watershed still exist. Some of these areas and potential avenues for future work to address these issues are discussed below:

Enhance the ABM for more accurate simulation of social systems and considering the impact of time

The behavioral simulation model proposed in this study simulates the impact of social pressure using the formulations developed in a previous study, by Edwards et al., which assumed homogeneous data for a kind of population. In my study, the agent-based model parameters (*a*, *b*, and *c* in Equations 3.18 through 3.20) were set equal to the ones introduced by Edwards et al. However, to obtain more accurate results, detail social research is required for the study area so that these model parameters are more reliable representatives of the actual conditions.

In addition, in the proposed behavioral simulation model, the cooperative or non-cooperative type of agents was designated on a daily basis. It was, then, assumed that if an agent shows a cooperative behavior for 70% of days during its entire irrigation period, the overall behavior of that agent is considered cooperative. However, more social research is required to determine whether or not the ratio of 70% accurately corresponds to the actual conditions.

Furthermore, the proposed ABM can be enhanced to consider the impact of time. In other words, after implementing the effective management scenarios, using the proposed ABM, some water users may change their behavior from non-cooperative to cooperative, or vice versa. In this case, the social network (Figure 6.9) will have a different impact on the utility of different agents to cooperate. Therefore, upgrading the proposed ABM to consider the impact of time will provide a more effective tool that can be used for predictions and future planning.

Developing Effective Adaptation Strategies

The majority of adaptation methods contain some forms of technology, including materials, equipment, and even a broad range of knowledge. Forms of adaptation technologies are generally quite familiar. However, more recent forms of technology that employ advanced materials science, advanced plant genetics, and new computer-aided techniques are not well acquainted. Moreover, in application of technology for adaptation, some methods can be fairly basic and some may engage much more complicated sorts of technology. Innovative research must be conducted to designate the most effective technologies, and the extent of their complication, that are applicable specifically for the San Joaquin River watershed. Besides designation of these effective technologies, from the management side of adaptation, it is helpful to consider water supply from both surface and groundwater resources. However, it is necessary to have a strict stewardship on exploitation of aquifers and assigning restrictions on groundwater withdrawal to avoid devastating this complementary resource. To plan the adaptation strategies, all available social, financial, legislative, and technical resources must be assessed.

Estimating the Impacts of Climate change on Managing Water Resources in the San Joaquin Watershed:

The traditional way of planning water supplies and distribution was to rely on historical data and experience. With the recent concerns and uncertainties due to climate change, however, the environment would be less predictable and a range of various possible climate scenarios should be considered. These scenarios must, then, be compared and ranked in terms of risks, costs, and benefits. In California, investigations show that water shortages will be the key resource through which climate change impacts will be felt. Therefore, the current conflicting situation in the San Joaquin River watershed is susceptible to be exacerbated in close future.

Detailed research is needed to estimate the impacts of climate change on water resources management in the area. For this purpose, the planning horizon must be determined and possible climate scenarios must be assessed. In addition, all technological changes and crop demand for the planning horizon as well as water availability, change in land use, change in perennial and annual crop yields, and change in crop prices must be taken into account.

Performing essential Economic Analysis

To determine the cost and benefit of different levels of reduction in diversions, economic analysis is required. It can also help to assess the economic feasibility of implementation of different management scenarios. In case it is intended to develop adaptation strategies, economic analysis would be needed to find the optimum set of adaptation strategies and optimize the location and timing of implementing various adaptation practices. Furthermore, this study showed that providing incentives and considering penalties are two effective management scenarios that could help to reduce conflicts in the study area. However, the extent of these incentives or penalties must be optimized using economic analysis.

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APPENDIX

SAMPLE OF QUESTIONNAIRES SENT TO DIFFERENT AGENCIES

APPENDIX A-1

QUESTIONNAIRE FOR THE FEDERAL/STATE AGENCIES

1. Affiliation

2. Your Name (optional)

3. Contact Information (optional)

4. The main objectives of this study are to increase the amount of water and reduce the salt load being transferred to the San Francisco Bay-Delta area from the San Joaquin watershed, while meeting agricultural water demands within the watershed. Clearly, the less water is diverted to agricultural fields the more water can be transferred to the Delta with the less salt load. For this purpose, different scenarios have been defined and the results are shown below.

"X" is the percentage of agricultural current water demand that is reduced to meet the environmental purposes

"Q" is the percentage of increase in water transfer to the Delta area corresponding to the reduced water allocations to agricultural fields (X) in "dry" and "below normal" water years

"C" is the percentage of decrease in magnitude of violations from salinity objectives at Vernalis corresponding to the reduced water allocations to agricultural fields (X)

"t" is the percentage of decrease in the number of violations from salinity objectives in the San Joaquin River violates the standards due to the reduced water allocations to agricultural fields (X)

Please rank the defined scenarios:

(-5) means the most undesirable

(0) means neutral/indifferent

(+5) means the most desirable

	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5
X = 6%; Q =4%; C = 2%; t = 6%;	○	○	○	○	○	○	○	○	○	○	○
X = 12%; Q = 8%; C = 6%; t = 14%;	○	○	○	○	○	○	○	○	○	○	○
X = 30%; Q = 22%; C = 11%; t = 27%;	○	○	○	○	○	○	○	○	○	○	○
X = 35%; Q = 23%; C = 12%; t = 38%;	○	○	○	○	○	○	○	○	○	○	○
X = 50%; Q = 39%; C = 18%; t = 49%;	○	○	○	○	○	○	○	○	○	○	○
X = 55%; Q = 42%; C = 19%; t = 51%;	○	○	○	○	○	○	○	○	○	○	○
X = 65%; Q = 48%; C = 19%; t = 54%;	○	○	○	○	○	○	○	○	○	○	○

Comments (Optional)

5. Imagine a, b, c, and d are different proportions of total agricultural water demands. These proportions are defined as following:

- "a" is the percentage of total agricultural water demands that is much less than their demands and will not satisfy them at all if being allocated to them.
- "b" is the MINIMUM percentage of total agricultural water demands that completely meets their demands and satisfies them if being allocated to them.

- "c" is the MAXIMUM percentage of total agricultural water demands that completely satisfies them if being allocated to them (it can be less or more than %100).
- "d" is the percentage of total agricultural water demands that is much more than their actual demands and if it is allocated to them it may damage their crops and make them unsatisfied (it should be more than %100).

Please specify these values (if a value is not applicable, leave the box blank).

"a" (%)

"b" (%)

"c" (%)

"d" (%)

6. Recent research shows that if salinity increases in the Central Valley at the current rate until 2030, the following consequences are expected:

    1. The direct annual costs will approximately be $1 billion to $1.5 billion.
    2. The income impacts to the Central Valley will also be $1.2 billion to $2.2 billion.
    3. The increase in salinity could cause 27,000 to 53,000 job losses by 2030.

Knowing these facts, by how much do you think agricultural water allocations must be reduced? (For example, if you write %15, it means that agricultural fields will receive %85 of their water demand)

Please specify this as a percentage of the current agricultural water demands (%)

7. Suppose that an incentive program is going to be planned to encourage farmers to demand less water. The program is planned to compensate the benefit they may lose regarding to the amount of water they gave up or the amount of investment required to implement modern irrigation technologies. In this case,

1. By how much water would you think farmers should give up with their current demand (as a percentage of their current demand)?

2. How much compensation would you think is required (as a percentage of their potential benefit and as a monetary value)?

Percentage of water (%)	
Percentage of benefit being compensated (%)	
Amount of compensation ($)	

8. What other types of compensations would you be willing to provide for the farmers to encourage them to compromise? (Optional)

9. Please add any comments, suggestions, concerns, etc. (Optional)

APPENDIX A-2

QUESTIONNAIRE FOR THE ENVIRONMENTAL AGENCIES

1. Affiliation

2. Your Name (optional)

3. Contact Information (optional)

4. The main objectives of this study are to increase the amount of water and reduce the salt load being transferred to the San Francisco Bay-Delta area from the San Joaquin watershed, while meeting agricultural water demands within the watershed. Clearly, the less water is diverted to agricultural fields the more water can be transferred to the Delta with the less salt load. For this purpose, different scenarios have been defined and the results are shown below.

> "X" is the percentage of agricultural current water demand that is reduced to meet the environmental purposes

"Q" is the percentage of increase in water transfer to the Delta area corresponding to the reduced water allocations to agricultural fields (X) in “dry” and “below normal” water years

"C" is the percentage of decrease in magnitude of violations from salinity objectives at Vernalis corresponding to the reduced water allocations to agricultural fields (X)

"t" is the percentage of decrease in the number of violations from salinity objectives in the San Joaquin River violates the standards due to the reduced water allocations to agricultural fields (X)

Please rank the defined scenarios:

(-5) means the most undesirable

(0) means neutral/indifferent

(+5) means the most desirable

	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5
X = 6%; Q =4%; C = 2%; t = 6%;											
X = 12%; Q = 8%; C = 6%; t = 14%;											
X = 30%; Q = 22%; C = 11%; t = 27%;											
X = 35%; Q = 23%; C = 12%; t = 38%;											
X = 50%; Q = 39%; C = 18%; t = 49%;											
X = 55%; Q = 42%; C = 19%; t = 51%;											
X = 65%; Q = 48%; C = 19%; t = 54%;											

Comments (Optional)

5. To protect agricultural beneficial uses of water in the southern Delta, the 1995 Bay-Delta Plan defines salinity objectives for the San Joaquin River at Vernalis. Based on these objectives, maximum 30-day running average of mean daily electrical conductivity at Vernalis for all water year types should be as follows (CRWQCB Central Valley Region, 2009, Table III-5):

- 700 micro mhos/cm from April 1 through August 31; and
- 1000 micro mhos/cm from September 1 through March 31

However, it could be likely that sometimes in especial conditions these levels are violated due to agricultural activities. In this case, by how much would you think the environmental sector might compromise. Please indicate it as a percentage of the thresholds mentioned above. (for example if up to 1050 micro mhos/cm could be acceptable in September, please write 5%).

Please also indicate, how many times per year the violations might be neglected (in days).

You can also indicate specific days, or months, or seasons that the violations can be neglected.

Percentage of violation that can be neglected (%)	
Number of days per year that the violations can be neglected	
Specific days, or months, or seasons that the violations can be neglected (optional)	

9. Please add any comments, suggestions, concerns, etc. (Optional)

APPENDIX A-3

QUESTIONNAIRE FOR THE AGRICULTURAL AGENCIES

1. Affiliation

2. Your Name (optional)

3. Contact Information (optional)

4. The main objectives of this study are to increase the amount of water and reduce the salt load being transferred to the San Francisco Bay-Delta area from the San Joaquin watershed, while meeting agricultural water demands within the watershed. Clearly, the less water is diverted to agricultural fields the more water can be transferred to the Delta with the less salt load. For this purpose, different scenarios have been defined and the results are shown below.

> "X" is the percentage of your current water demand that you would give up to meet the environmental purposes

"Q" is the percentage of increase in water transfer to the Delta area corresponding to your compromise level (X) in "dry" and "below normal" water years

"C" is the percentage of decrease in magnitude of violations from salinity objectives at Vernalis corresponding to the reduced water allocations to agricultural fields (X)

"t" is the percentage of decrease in the number of violations from salinity objectives in the San Joaquin River violates the standards due to the reduced water allocations to agricultural fields (X)

Please indicate how much you are willing to compromise with your water demands to help the environment (-5 means not at all willing; 0 means neutral/indifferent; +5 means very willing).

	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5
X = 6%; Q =4%; C = 2%; t = 6%;	○	○	○	○	○	○	○	○	○	○	○
X = 12%; Q = 8%; C = 6%; t = 14%;	○	○	○	○	○	○	○	○	○	○	○
X = 30%; Q = 22%; C = 11%; t = 27%;	○	○	○	○	○	○	○	○	○	○	○
X = 35%; Q = 23%; C = 12%; t = 38%;	○	○	○	○	○	○	○	○	○	○	○
X = 50%; Q = 39%; C = 18%; t = 49%;	○	○	○	○	○	○	○	○	○	○	○
X = 55%; Q = 42%; C = 19%; t = 51%;	○	○	○	○	○	○	○	○	○	○	○
X = 65%; Q = 48%; C = 19%; t = 54%;	○	○	○	○	○	○	○	○	○	○	○

Comments (Optional)

5. If you compromise a portion of your water demand,

a) What practices would you use to compensate your water loss?

b) What compensations would you expect the federal/state agencies provide for you to help you to make up for the loss of water?

6. Imagine a, b, c, and d are different proportions of your field's dominant crop water demands. These proportions are defined as following:

- "a" is the percentage of your water demand that is much less than your demand and will not satisfy you at all if being allocated to you.
- "b" is the MINIMUM percentage of your water demand that completely meets your demand and satisfies you if being allocated to you
- "c" is the MAXIMUM percentage of your water demand that completely satisfies you if being allocated to you (it can be less or more than %100)
- "d" is the percentage of your water demand that is much more than your actual demand and if it is allocated to you it may damage your crops and make you unsatisfied (it should be more than %100)

Please specify these values (if a value is not applicable, leave the box blank).

"a" (%)

"b" (%)

"c" (%)

"d" (%)

7. Recent research shows that if salinity increases in the Central Valley at the current rate until 2030, the following consequences are expected:

1. The direct annual costs will approximately be $1 billion to $1.5 billion.
2. The income impacts to the Central Valley will also be $1.2 billion to $2.2 billion.
3. The increase in salinity could cause 27,000 to 53,000 job losses by 2030.

Knowing these facts, how much are you willing to compromise with your water demand? (For example, if you write %15, it means that you will receive %85 of your water demand) please specify this as a percentage of your current water demand (%)

8. Suppose that an incentive program is going to be planned to encourage you to demand less water. The program is planned to compensate the benefit you may lose regarding to the amount of water you gave up or the amount of investment required to implement modern irrigation technologies. In this case,

1. How much water would you be willing to give up with (as a percentage of your current demand)?
2. How much compensation would you expect (as a percentage of your potential benefit and as a monetary value)?

Percentage of water (%)

Percentage of benefit being compensated (%)

Amount of compensation ($)

9. Please add any comments, suggestions, concerns, etc. (Optional)