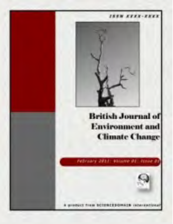


British Journal of Environment & Climate Change
3(3): 333-377, 2013

SCIENCEDOMAIN ***international***
www.sciencedomain.org

Integrated Water Resources Models to Support Analysis of Integrated Regional Water Management Programs in California

A. Taghavi[1*], R. Namvar[1], S. Najmus[1] and M. Cayar[1]

[1]RMC Water and Environment, 1451 River Park Drive, No. 142, Sacramento, CA, 95815, USA.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Research Article

Received 29th November 2012
Accepted 4th July 2013
Published 15th September 2013

ABSTRACT

Aims: Provide a review of key features and several applications of the family of Integrated Water Resources (IWR) models, as the key analytical tools used in evaluation of hydrologic conditions in support of the integrated regional water management (IRWM) programs in California.

Methodology: IWR models are a family of models consisting of the Integrated Groundwater and Surface water Model (IGSM), the Integrated Water Flow Model (IWFM), and the IWFM Demand Calculator (IDC). IGSM is an integrated model that simulates the complete hydrologic cycle for a basin. The California Department of Water Resources (CADWR) has upgraded and enhanced the IGSM code and developed an enhanced version, called IWFM. In addition, CADWR extracted the land surface processes module of IWFM as an independent unit, called IDC, which can be used as a stand-alone model for estimating agricultural water demand, groundwater pumping, and deep percolation. The IWR models have been applied to many basins throughout California to evaluate hydrologic conditions, including evaluation of land and water use, surface water and groundwater flow, stream-aquifer interaction, reservoir operation, land subsidence, and regional water quality conditions. An ArcGIS-based Graphical User Interface provides a robust modeling platform for the IWR models.

Results: The IWR models have had significant success in analysis of various types of water resources projects, such as integrated regional water management programs,

---

*Corresponding author: Email: ataghavi@rmcwater.com;

groundwater management and conjunctive use operations, groundwater recharge investigations, water transfer programs, water quality, water demand and supply analysis, seawater intrusion, and climate change vulnerability and adaptation analysis.
Conclusion: The IWR models are effective tools in analyzing the technical issues involved in integrated water management and planning in California. These IWR models are well suited for analysis of hydrologic conditions and alternative water management scenarios explored in various basin management and IRWM programs.

Keywords: Integrated water resource (IWR) models; integrated regional water management planning (IRWMP); integrated water resources planning (IWRP); integrated hydrologic modeling; integrated groundwater and surface water model (IGSM); Integrated Water Flow Model (IWFM); Climate Change Modeling; California Department of Water Resources (CADWR).

1. INTRODUCTION

During the last decade, integrated water resources management and planning has gained momentum among water resources practitioners as well as organizations and agencies responsible for water supply and land use planning in various parts of the world. A number of scholarly articles have been published on this integrated approach to water resources management. In addition, several conferences and symposia have dedicated sessions or full programs to explore integrated water resources planning. The 2010 International Association of Hydrological Sciences (IAHS) International symposium in China and the 2011 American Water Resources Association (AWRA) symposium in Utah are two key recent events, which provided forums to comprehensively explore this integrated approach.

1.1 Review of Literature

Increased attention to integrated water resources management and planning in the United States and other parts of the world has resulted in advancement of hydrological and water resources models by developing new features of the existing hydrologic models, integrating existing surface water and groundwater models into more powerful models, or development of new integrated hydrologic models. In reviewing the literature on integrated water resources or hydrologic models, one often times encounters application of various surface water and groundwater models that are linked externally, or coupled with some transition model/module. Another set of applications are those that simulate stream-aquifer interaction, and is many times claimed to be an integrated modeling application. In reality, a true integrated model, as described later in this article encompasses a large part of hydrologic cycle and their interaction. During our literature search, we encountered a number of models and/or model applications that have used the key word “integrated”. However, this section focuses on the review of literature on the models that are more established and are used more widely in the U.S.

The United States Geological Survey (USGS) has developed two sets of models to simulate the integrated water resources conditions, GSFLOW and MODFLOW FARM Package. MODFLOW has traditionally been used as a robust and reliable groundwater model with wide-spread applications throughout the world. MODFLOW package includes modules to simulate stream-aquifer interaction, which have been used in conjunction with the groundwater module quite often. In areas where there was a need to simulate the surface processes, such as land and water use, the users have used various models, often custom-made to simulate surface processes, such as agricultural water demand and/or deep percolation and recharge from irrigation applied water or rain. Both the GSFLOW and the MODFLOW Farm Package are now in use in several basins to simulate the fully integrated hydrologic and water resources conditions.

GSFLOW is a basin-scale model that was originally developed by coupling the U.S. Geological Survey (USGS) Precipitation Runoff Modeling System (PRMS) with the USGS three-dimensional Modular groundwater flow model (MODFLOW) [1-3]. GSFLOW was developed to simulate integrated groundwater and surface water in one or more watersheds by simultaneously simulating flow across the land surface, within subsurface saturated and unsaturated zones, and within streams and lakes. The latest version of GSFLOW is based on MODFLOW-2005 version 1.9.01 and PRMS version 3.0.5 [4]. The number of applications of GSFLOW to basins throughout the United States has been steadily growing. GSFLOW was used to evaluate the water management alternatives for the Chamokane Creek Basin, Stevens County, Washington [5]. Using several scenarios, they quantified the effects of potential increases in groundwater pumping on groundwater and surface-water resources in the basin. GSFLOW was also used to simulate all near-surface and groundwater hydrologic processes within three watersheds of the eastern Sierra Nevada [6]. The role of surface-water and groundwater interactions on projected summertime streamflows under climate change conditions was investigated. GSFLOW was used in a study to compare the model scale and structures for selecting hydrologic modeling approaches for climate change assessment [7]. GSFLOW, as a site-specific model, was compared to the large-scale Variable Infiltration Capacity (VIC) model and the basin-scale PRMS model. Their study showed that the three hydrologic models, using the same downscaled General Circulation Model (GCM) data, predicted different monthly, low flow, and peak flow changes due to climate change.

The Farm Package of MODFLOW was originally developed as part of a dissertation research and was later published by USGS as the Farm Process (FMP1) module for MODFLOW-2000 [8,9]. FMP1 allows the users to simulate conjunctive use of surface- and groundwater for irrigated agriculture for historical and future simulations, water-rights issues and operational decisions, non-drought and drought scenarios. More recently, the MODFLOW with Farm Package version 2, MF2005-FMP2 [10], was developed by integrating supply and demand components of irrigated agriculture with the MODFLOW model. A significant application of the FMP1 model has been development of the Central Valley Hydrologic Model (CVHM) [11]. USGS developed CVHM to simulate the complex hydrologic system of the Central Valley using the MODFLOW model combined with the Farm Package that accounts for supply-constrained and demand-driven conjunctive use of surface and groundwater in agricultural, urban, and natural settings. For the Central Valley, the Farm Package simulates unmetered pumping and surface-water deliveries over the model domain for 42 years. The Farm Package was recently used to simulate and analyze a conjunctive use aquifer storage and recovery (ASR) project in the Pajaro Valley, California [12].

The HydroGeoSphere (HGS) model was developed to simulate the entire terrestrial portion of the hydrologic cycle. The origin of the HydroGeoSphere is the code FRAC3DVS [13]. FRAC3DVS was designed to simulate variably saturated groundwater flow and advective-dispersive solute transport in porous and discretely fractures porous media. In 2002, a two dimensional (2-D) surface water flow and transport component were implemented in FRAC3DVS and the code was renamed HydroGeSphere [14]. HydroGeosphere has been applied to a number of basins, mostly in Canada and European basins. Other representative applications can be found in the literature [15-17].

The three integrated models which have been applied to the Central Valley of California have recently been reviewed from both theoretical as well as application perspectives [18]. This review was performed for the California Water and Environment Modeling Forum (CWEMF), and has been published in draft form on CWEMF Website. This review provides reasonably high level, yet concise set of information on the theoretical features of each code, with an eye on the application of each model to the Central Valley of California.

Danish Hydraulic Institute (DHI) has developed the MIKE SHE model for integrated modeling of groundwater, surface water, recharge and evapotranspiration [19]. The original MIKE SHE [20] model was developed and became operational in 1982, under the name Système Hydrologique Européen (SHE). The model was sponsored and developed by three European organizations: the Danish Hydraulic Institute (DHI), the British Institute of Hydrology, and the French consulting company SOGREAH. Later, the water movement module of MIKE SHE was linked with the channel simulation component of MIKE 11 for the development of an integrated surface water and ground water model [21-23]. MIKE SHE has been used in a number of basins in several parts of the world; with limited number of applications in the U.S., or in California [24-27].

The Stockholm Environmental Institute (SEI) has developed the Water Evaluation and Planning (WEAP) Model for simulation of integrated systems for large-scale planning studies [28]. WEAP was originally developed in 1988, with the aim to be a flexible, integrated, and transparent planning tool for evaluating the sustainability of current water demand and supply patterns and exploring alternative long-range scenarios. The model has undergone significant evolution from its early versions, and through many applications. WEAP can simulate water demand, supply, runoff, evapotranspiration, infiltration, crop irrigation requirements, instream flow requirements, ecosystem services, groundwater and surface storage, reservoir operations, and pollution generation, treatment, discharge and instream water quality, all under scenarios of varying policy, hydrology, climate, land use, technology and socio-economic factors. The first major application of WEAP was in the Aral Sea region in 1989 [29]. Since then, the model has been applied to several basins, including the application to the California's Sacramento River Basin to evaluate the impact of future climate scenarios on agricultural water management in the region, and to investigate whether water management adaptation could reduce potential impacts of climate change [30]. WEAP has been used for statewide modeling in California in support of assessment of statewide future water demand and supply scenarios, as part of the California Water Plan [31].

The California Department of Water Resources (CADWR), California State Water resources Control Board (SWRCB), and the U.S. Bureau of Reclamation (USBR) developed the Integrated Groundwater and Surface water Model (IGSM) [32], which was one of the first of its kinds to fully represent the integrated hydrologic processes. This model had a unique approach in integrating major components of the hydrologic cycle, including land surface processes, soil zone infiltration and vadoze zone flow simulation, estimation of agricultural water demand, rainfall-runoff simulation, estimation of deep percolation from rainfall and irrigation applied water, stream-aquifer interaction, simulation of operations of multi-purpose reservoir systems, subsurface flow processes, and mass transport and water quality simulation. Since its first application to the Central Valley, CA [33], this model has gone through significant evolution through its many applications to various basins throughout the

U.S., and mostly in California. The latest version of this model is released by WRIME, Inc. [34], and is described in more detail in other sections of this article. This latest version includes an ArcGIS based Graphical User Interface, which provides a state-of-the-art graphical modeling environment for the users [35]. The next generation of this model is developed by the CADWR and is published as Integrated Water Flow Model (IWFM) [36]. The IWFM has been applied to several basins in California, including a recent application to the California's Central Valley [37]. The Central Valley's application has recently been refined with detailed level of grid resolution and an ArcGIS Graphical User Interface [38].

The State of California has pioneered integrated water management planning at the regional level with involvement of stakeholders. One key component of these plans is to evaluate the water management conditions in light of changing climatic conditions. Various analytical tools have been used in supporting the regional water management plan development efforts. Specifically, a set of analytical tools and models that have successfully been used to analyze the integrated hydrologic conditions in various basins over the past two decades, have recently been used to provide analytical support to the development of Integrated Regional Water Management Plans (IRWMP). This paper presents the key features of this family of models, and examples of successful applications of these models.

The paper is organized as follows:

- An introduction, presenting the background on mission and scope of IRWMPs in California, and evolution and application of the Integrated Water Resources (IWR) models.
- A section on the key features of the family of IWR models, and their applicability to the analysis of IRWMPs when appropriate.
- Last section of the paper presents five applications of the IWR models in California, with appropriate reference to their application for analysis of climate change impacts, when applicable.
- A summary and conclusions section is provided at the end.

1.2 The California Experience

This section summarizes the integrated water management experience in California. The mission of the California Department of Water Resources (CADWR) is to manage the water resources of California, in cooperation with other agencies, to benefit the State's people and to protect, restore, and enhance the natural and human environment. CADWR has underscored the importance of IRWM in meeting these challenges [39]. To address these challenges, the State of California has made substantive effort to promote a bottom-up approach and a stakeholder-driven process in development of integrated water resources management plans. Such a plan is called an "Integrated Regional Water Management Plan" or IRWMP. The focus of IRWMP program is to develop "regional" partnerships with an open and transparent process of governance, which involves the local and regional

Components of the California IRWM Plans [39]

- Governance
- Regional Description
- Objectives
- Resource Management Strategies
- Integration
- Project Review Process
- Impact and Benefits
- Plan Performance and Monitoring
- Data Management
- Finance
- Technical Analysis
- Relationship to Local Water and Land Use Planning
- Stakeholder Involvement
- Coordination
- Climate Change

organizations and agencies in the lead role, supported by the state and federal agencies. As part of implementation of the IRWM program throughout the state, CADWR's objective is to ensure an adequate and reliable water supply for the citizens of California while improving public safety, environmental stewardship, and long-term economic stability. However, CADWR has direct responsibility for a limited portion of the state's water supplies, while local and regional water management agencies control a large portion of the state's water systems. As such, CADWR is working closely with regional and local agencies in a partnership effort to plan and implement the IRWM program.

The key water management challenges that California will face in coming years include, but are not limited to:

- Addressing the impacts of climate change on statewide and regional water needs and operations, including risk-based flood management
- Striking a balance among public safety, economic stability, and environmental stewardship
- Operating under a triple bottom-line framework of societal, environmental, and economic benefits and costs for long-term water sustainability in the State
- Accomplishing effective and continued engagement of key stakeholders and partner agencies
- Meeting evolving expectations of increased transparency and accountability as well as good governance

The IRWM planning process was initiated in 2002 by the California voters through a statewide proposition (Proposition 50, the Water Security, Clean Drinking Water, Coastal and Beach Protection Act) for funding regional planning and water supply infrastructure projects. In November 2004, the CADWR) and the State Water Resources Control Board (SWRCB) jointly released guidelines for the new IRWMP program. The program was funded by $500 million made available by Proposition 50. The intent of the initial IRWM Program was to promote a new model for water management by encouraging integrated regional strategies for management of water resources and to provide funding--through competitive grants—for projects that protect communities from drought, protect and improve water quality, and improve local water security by reducing dependence on water imported from the Sacramento-San Joaquin Bay-Delta and Colorado River. Funding for integrated planning and project implementation at the regional level was a major component of the program, providing incentive for regions to engage in this new form of planning. Plans developed through the program address a series of requirements – preparation of the IRWMP by three or more entities with water management authority; identification of regional water management objectives and priorities spanning multiple water management functional areas; integration of water management strategies to achieve regional objectives; and engagement of the public, including Disadvantaged Communities (DAC) and Environmental Justice (EJ) communities.

The IRWMPs developed through Proposition 50 represented the first generation of IRWM planning in California. Following Proposition 50, an additional $1 billion in funding was made available for IRWM planning and implementation through passage of the Safe Drinking Water, Water Quality and Supply, Flood Control, River and Coastal Protection Bond Act of 2006 (Proposition 84), providing further incentive for regions to strengthen their IRWM planning efforts. With this next wave of funding, CADWR implemented a series of changes in the funding guidelines designed to enhance the IRWMP program and refocus attention in the following areas: governance, geographic equity, assistance to disadvantaged communities, integrated flood management, and climate change planning.

Implementation and development of a typical IRWM program involves a series of steps, shown in Fig. 1:

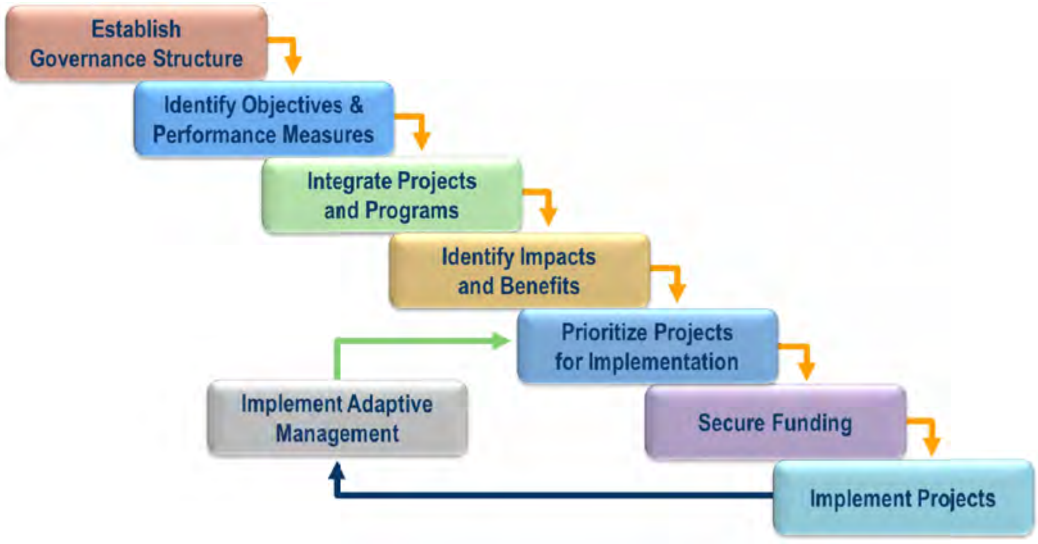


Fig. 1. Development and Implementation steps of a typical IRWM program

Today, with the grant and technical support of CADWR to the regional water management groups (RWMG), there are 48 RWMGs in California that cover 87 percent of the state's geographic area and 99 percent of the population (Fig. 2).

1.3 IRWM Strategic Plan

The IRWM program has created significant momentum and potential for long-term success in the management of water resources in California. In order to promote, advance, and continue the practice of IRWM in California, CADWR is working with the regional water management groups to develop a Strategic Plan for the future of IRWM. One of the key areas that the Strategic Plan will address is the future needs of data management and hydrologic modeling tools for successful implementation of integrated water management.

The specific needs for the Strategic Plan are listed below [40].

- Continue to build on the past successes of IRWM
- Further enable, empower, and support regional water management entities
- Continue to inspire, motivate, and facilitate the practice of IRWM
- Better align state and federal programs to support IRWM
- Prepare for changes in the nature and scale of water management challenges
- Identify, coordinate, and leverage integration opportunities across regions and across different aspects of water management

- Prepare for potential changes in state funding and develop a shared vision among the regional water management groups and between regional groups and the state, for funding priorities
- Inform and influence future water management policies and investments

Fig. 2. Forty eight RWMGs (IRWM regions) in California

The aim of the Strategic Plan is to describe a specific path from present conditions to the future vision, which will include goals and strategies. It will also define an approach for monitoring successes and adapting to changes and challenges during the implementation phase.

The desired future for IRWM is reflected in the IRWM Strategic Plan vision statement: “California embraces and practices IRWM as the best way to manage water and aligns related programs, policies, and regulations to advance IRWM.”

Integrated hydrologic models, other analytical tools, and database management systems are key elements supporting the implementation of the IRWM Strategic Plan because, adequate data and tools are essential for making sound water resources management decisions. The current state of fragmented data and analytical tools require a more robust, comprehensive, and integrated platform to be able to fully evaluate the many alternative and often competing water management objectives and tradeoffs in the state. The Strategic Plan should address and evaluate the availability and adequacy of existing data and decision support tools, as well as integrated models for IRWM.

1.4 Evolution of IRWM Analytical Tools

A successful IRWMP requires a host of analytical tools to support the planning process and evaluate alternative planning scenarios, including analysis of land and water use planning, hydrologic conditions, surface water operations, flood control and storm water management, urban water supply planning and operations, environmental planning and ecosystem and habitat restoration evaluation.

One of the major categories of analytical tools supporting the IRWMP process is integrated water resources models. An integrated plan requires a model that provides an integrated approach to the analysis of water resources in the region. Although there are a number of models that may provide similar simulation capabilities, some of which have been applied to similar projects; it is not the intent of this article to evaluate all options, and/or compare various models. Rather, the intent is to present background, methodology and applications on a widely used family of integrated water resources models in California, and their applications to support the IRWM programs.

Among the various hydrologic models that are used in California, a suite of models that may be categorized as a family of Integrated Water Resources (IWR) models has had significant success in supporting the regional groups in analyzing their water resources conditions in an integrated manner. This family of IWR models consists of a comprehensive approach for simulating integrated groundwater and surface water flow conditions, including the following components of the hydrologic cycle:

- Simulation of rainfall runoff for various land use conditions
- Calculation of agricultural water demand for various crop conditions and irrigation practices
- Simulation of groundwater and surface water supply to meet agricultural and urban demands
- Simulation of surface tile drainage and storm runoff
- Simulation of streamflow conditions, diversions from streams, return flow and runoff to streams, and stream-aquifer interaction
- Estimation of infiltration using a soil moisture accounting methodology, and calculation of recharge through unsaturated zone
- Simulation of quasi-3 dimensional groundwater flow
- Calculation of land subsidence
- Simulation of operations of multi-purpose reservoir systems
- Mass transport and water quality simulation

Fig. 3 shows a schematic of the components in an integrated water resources model.

The family of IWR models is based on the Integrated Groundwater and Surface water Model (IGSM) that was originally developed in 1976 at UCLA. Over time, the IGSM evolved as a very strong basin planning and simulation model applied widely throughout California and several other states [41-43]. By 2003, the IGSM became a widely used model, with significant improvements through various project applications involving code modifications for new features [34]. This model code is still being used throughout California for basin planning and support of IRWMPs, and is maintained and upgraded for the respective water agencies.

In 2002, CADWR embarked on a major overhaul of the IGSM code and built the Integrated Water Flow Model (IWFM), which is now the integrated hydrologic model used by CADWR for statewide and regional analyses. The IWFM has had substantial improvements in features, which makes it a suitable modeling platform for basin level water planning and management analysis [36]. Although the IGSM has traditionally been applied to many basins for water management program evaluations, and is still in use by many water agencies throughout the state, the upgraded and enhanced features of IWFM makes it a natural transition for the current IGSM applications. These new features provide an enhanced level of support for both state-wide and regional water management applications, including an ArcGIS-based Graphical User Interface (GUI). The IWFM provides a robust platform that is supported by the CADWR and the consulting community, builds upon over two decades of integrated water resources modeling successes brought about by the IGSM, and includes many of the features available in IGSM. As such, over the next few years, a migration of the IGSM applications to the IWFM platform, with new and enhanced features available in the IWFM platform, may occur. However, there are several major IGSM features and modules that are still not available in the IWFM platform. These include the simulation of operations of multi-purpose reservoir systems, simulation of particle tracking, and simulation of water quality and mass transport in an integrated groundwater and surface water system. We strongly recommend that CADWR considers conversion of these modules and features from IGSM into future versions of the IWFM.

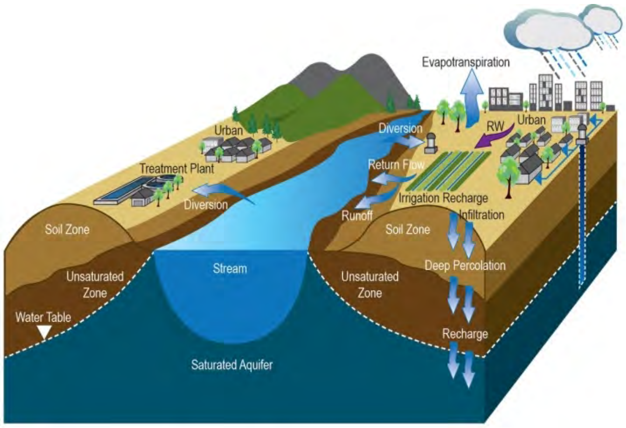


Fig. 3. Integrated water resources model components

For this paper, the features and components of the IWR family of models are presented as a collection of features available in both the IGSM and IWFM. The intent is not to compare and contrast the two modeling codes, rather, to focus on the commonalities between the two modeling codes and provide a general discussion of features and applications of both codes.

The IWR models have been applied in many hydrologic basins in California. Table 1 shows the basins where these models have been applied and Fig. 4 shows the application areas.

Table 1. Integrated water resources (IWR) model applications

Basin Name / Location	Model Area (Km^2)	Major Model Applications										
		Integrated Regional Water Management	GW Management and Conjunctive Use	Stream / Lake Impact Analysis	Ground-water Recharge and ASR	Statewide and Local Reservoir OperationIntegration	Water Transfer Programs	Flood Mitigation Analysis	Regional and Local Water Quality	Water Demand & Supply Analysis	Salinity Assessment and Seawater Intrusion	Climate Change Volnurebaility and Adaptation
Alameda County, CA [44]	310	✓	✓	✓	✓				✓	✓	✓	
Butte County, CA [45]	3,273	✓	✓	✓	✓		✓			✓		
Capay Valley, CA [46]	110		✓	✓	✓		✓			✓		
Central Valley, CA [32,65,37]	54,000	✓	✓	✓	✓	✓	✓	✓		✓		✓
Chino Basin, CA [41]	700	✓	✓	✓	✓				✓	✓	✓	
Friant-Kern Srvice Area, CA [47]	14,940	✓	✓	✓	✓	✓	✓			✓		
Imperial County, CA [48]	1,502	✓	✓	✓	✓		✓		✓	✓		
Kings Basin, CA [71]	4,216	✓	✓	✓	✓		✓			✓		✓
Lower Colusa Basin, CA [49]	1,186		✓	✓	✓					✓		
Niles Cone-South East Bay Plain, CA [50]	440		✓	✓	✓					✓		
Pajaro Valley, CA [42]	310	✓	✓	✓	✓		✓		✓		✓	
Pomona Valley, CA [43]	65	✓	✓	✓	✓							
Sacramento County and American River Basin, CA [68]	3,657	✓	✓	✓	✓		✓	✓	✓	✓		
Salinas Valley, CA [51]	1,683	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
San Joaquin County, CA [52]	5,037		✓	✓	✓		✓			✓		
Soquel Creek - Aptos, CA [53]	298		✓	✓	✓				✓	✓	✓	
Stony Creek Fan, CA [54]	2,745	✓	✓	✓	✓	✓				✓		
Yolo County, CA [80]	2,290	✓	✓	✓	✓		✓			✓		
Yuba County Basin, CA [55]	1,186		✓	✓	✓		✓			✓		

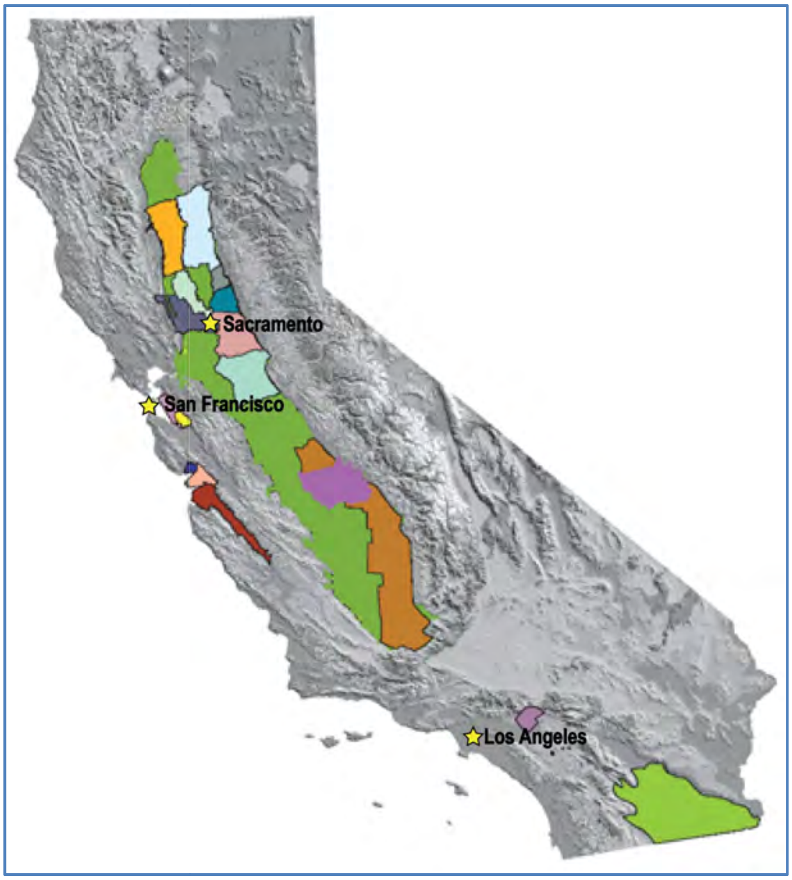


Fig. 4. Map of IWR model applications in California

1.5 Regional/Local Model Integration

The IWR models are designed and developed for planning and evaluation of water resources planning scenarios on a regional scale. There has been sometimes a need to perform localized analysis of water supplies and/or projects in a more detailed way than that provided by data and/or simulation capabilities of a regional model. In these cases, localized models based on the IWM code and platform or other platforms have been developed. A mere higher resolution spatial grid would not result in a better simulation for local scale modeling; the localized model should include spatial and temporal data at a much more detailed level than the regional model. In the past, the IWR model family has been linked to localized models based on MODFLOW, Dynflow, FEMFLOW 3D, IGSM, IWFM, and MicroFEM platforms [34]. An example of such regional/local model integration is provided in a case study for the Salinas Basin later in the article.

1.6 Integration with Reservoir Operation and Economic Models

The analysis of regional water supply and flood management often requires use of reservoir operations simulation models. The IWR model family includes an internal reservoir operation module that simulates the integrated operations of a series of local reservoirs with the operation of downstream surface water and groundwater facilities. However, at a more regional and state-wide level, the IWR models have been linked and integrated with California Water Resources Simulation Model (CALSim), a statewide operation model for California's Central Valley Project (CVP) and State Water Project (SWP). This integration has resulted in a more robust simulation of the CVP/SWP operations supporting statewide and regional planning.

In addition, there have been several applications of the IWR models in the Central Valley with linkage to agricultural production and economic models, such as Central Valley Production Model (CVPM) and Statewide Agricultural Production Model (SWAP).

Additionally, in recent years the Water Evaluation and Planning (WEAP) model has been used to support the California Water Plan [28]. The IWR models can also be linked with WEAP model for analysis of statewide and regional groundwater water conditions.

1.7 Integration with Global Climate Models

The IWR models are especially well suited for analysis of Global Climate Models (GCMs) at the regional level. Downscaled GCM simulations for various emission scenarios can be adapted to the IWR models. The downscaled GCM data adapted for IWR models affect several major IWR model data sets - temperature, precipitation, and evapotranspiration data, which affects the agricultural water demand calculation and the water use for land surface processes, including rainfall runoff; and infiltration and deep percolation estimations. The changes to precipitation resulting from climate change also affect the streamflows throughout the model domain, including inflows to the storage and regulatory reservoirs within or outside model boundaries, and consequently the operation of the surface water facilities. The process to utilize downscaled GCM data for IWMs has been implemented for the Salinas Valley and American River Basin applications.

Global climate changes may adversely affect historical operation of a watershed or basin in various ways. Some of the adaptation measures to offset the adverse effects may include, aggressive conjunctive use or operation of surface water and groundwater resources, re-operation of surface storage reservoirs, aggressive demand-side measures, and re-allocation of water supply sources to meet competing human and environmental demands). The IWR models are equipped with simulation capabilities to provide a robust analysis and evaluation of the effects of climate change on systems operations and water supply and demands in a basin.

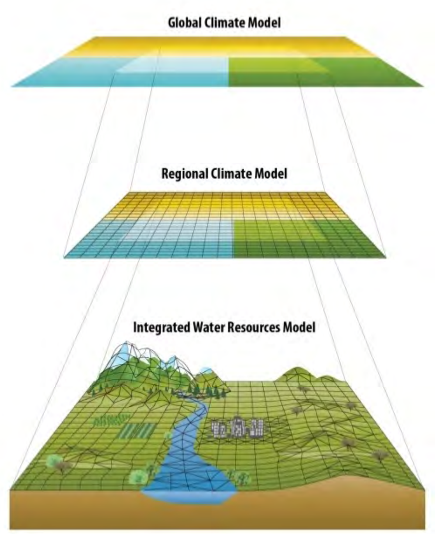


Fig. 5. Relationship between global climate models and IWR models

2. INTEGRATED WATER RESOURCES MODEL FEATURES

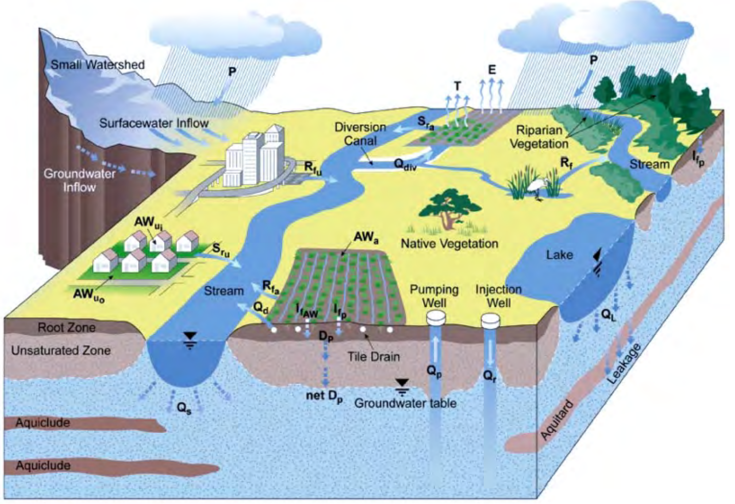


Fig. 6. Integrated hydrologic model components [36]

The IWR model code features presented here are a compendium of features within both the IGSM and IWFM models. For a more detailed discussion on the theoretical aspects of each feature, the reader is referred to the theoretical manual for IWFM [36], and to the IGSM manual [34].

Fig. 6 shows the detailed hydrologic system simulated by the IWR models. The detailed hydrologic system may be subdivided into three major components: stream system, soil and unsaturated zone, and groundwater system. The model simulates the movement of water from location to location in each of these components as well as the resulting interactions using mass balance or water budget accounting procedures. Fig. 7 schematically presents the interaction among the different hydrologic components. One important aspect of the IWR models is that they preserve the non-linear aspects of the surface and subsurface flow processes and the interactions among them while simulating these hydrologic components.

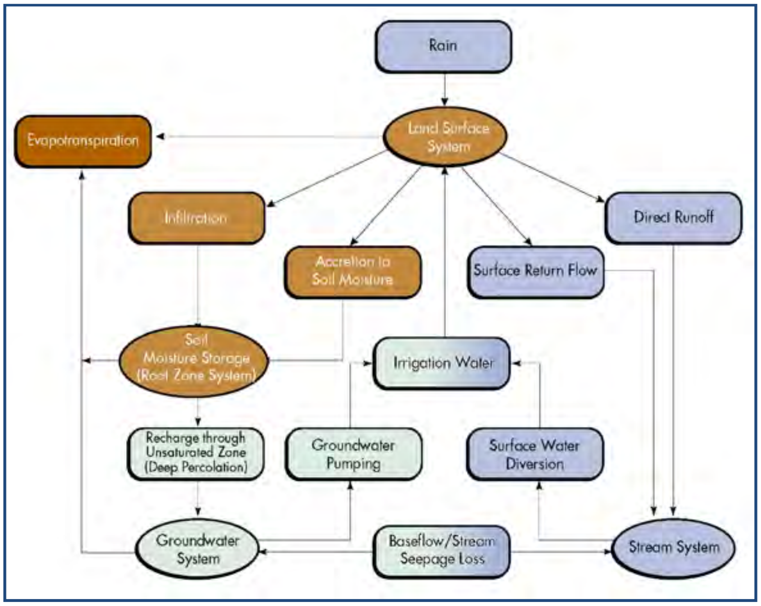


Fig. 7. Hydrologic components interaction

Another important aspect of IWR models is that they allow the user to divide the entire model area into smaller subregions or water management zones. This division can be based on hydrologic, geologic, or hydrogeologic properties (e.g. individual watersheds) or on the basis of water management practices and/or institutional boundaries (e.g. water districts). The division of the model into smaller subregions does not affect the mass distribution over the entire region; the subregions are used solely for the grouping and reporting of the simulation results. The input data required of IWR models can be independent of particular subregions, or appropriate data can be developed and input to the model on a subregional basis to make the best use of regional information generally available or information that can be easily estimated.

The key features of IWR model are described in the following sections.

2.1 Water Demand Estimation

Agricultural and urban water demands in IWR models can either be computed dynamically or specified by the user as input data.

The IWR models require the acreages of agricultural crops, urban and native vegetation lands in each subregion to compute agricultural crop water demand. In IWR models irrigation water demands throughout the simulation period are computed as a function of soil properties, crop characteristics and initial soil moisture content that is a result of previous precipitation and irrigation events. Therefore, computation of irrigation water demands in IWR models is connected to the routing of soil moisture in the root zone.

The monthly urban water use data are specified as input for each subregion. Outdoor water demand for urban areas is treated in the same way as agricultural water demand. Indoor water use can be obtained from the city and /or county records. In the absence of such records, estimates can be made using population records and unit per-capita water use data, which are available from public agencies.

A detailed explanation of how these demands are computed is provided in the user manual for IWFM Demand Calculator (IDC) [56,57]. IDC is the stand-alone soil moisture routing module that is extracted from the IWFM and is developed and maintained by CADWR. IDC, as a stand-alone agricultural demand calculator and analysis tool, can be used in conjunction with any other hydrologic and/or groundwater model, such as MODFLOW, MicroFEM, or other models. Two approaches to use IDC as a stand-alone model or in conjunction with MODFLOW were presented in 2011 [58].

2.2 Water Supply Analysis

An important objective of IWR models is to simulate the water supply to meet a specified agricultural, urban, municipal, or industrial demand. In developed watersheds, the stresses on surface and subsurface water resources are generally created by groundwater pumping and stream flow diversions to satisfy agricultural and urban water requirements. The model can specify stream diversion and pumping locations for the source of water supply to meet the urban and agricultural water demand. Imported water into the basin and/or exported water out of the basin and reuse of return flow can also be considered as a source of water. The application of all these water sources to meet these requirements also affects the surface and subsurface water system through recharge of the aquifer and surface runoff back into the streams.

2.3 Rainfall Runoff Simulation, Soil Moisture Accounting and Unsaturated Flow Simulation

The rainfall runoff/soil moisture accounting simulation component estimates direct runoff, infiltration, deep percolation, and evapotranspiration resulting from rainfall and irrigation applied water. The model computes rainfall runoff first, then effective precipitation, followed by deep percolation and evapotranspiration. Deep percolation is then adjusted for applied water and rain in excess of field capacity, and finally soil moisture is updated. Deep percolation leaving the soil zone travels through an unsaturated zone and eventually reaches the groundwater system. The relationship among rainfall runoff, soil moisture accounting and unsaturated flow components is shown in Fig. 8.

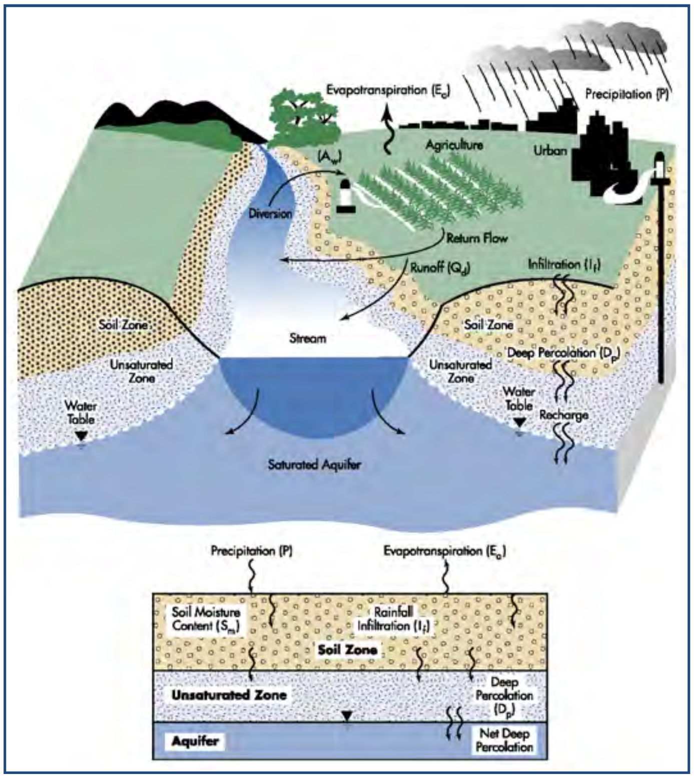


Fig. 8. Rainfall, runoff, soil moisture accounting and unsaturated zone simulation components

2.4 Groundwater Flow Simulation

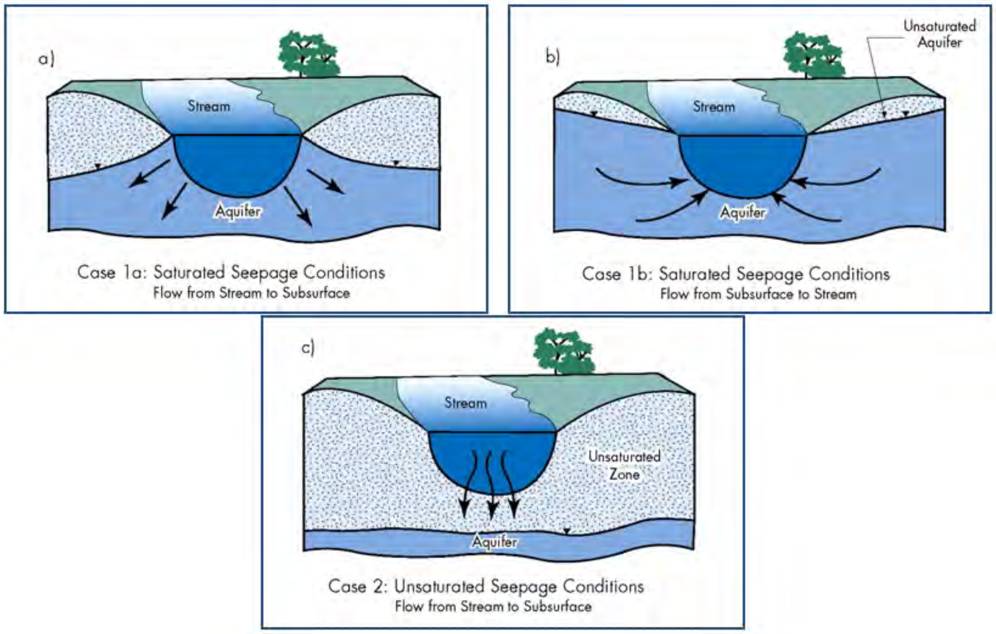
The IWR models simulate any combination of two-dimensional multi-layered confined, unconfined and partially confined (leaky) aquifer systems, and can transition among these aquifer types as groundwater levels fluctuate. Each layer may have a different spatial extent throughout the groundwater basin and may be separated by aquitards or aquicludes.

The three-dimensional nature of the flow is simulated in a quasi three-dimensional approach. The depth-integrated groundwater flow equation is solved for each aquifer layer in order to compute the two- dimensional groundwater head field. Vertical flow to and from each layer is computed through leakage terms that are treated as individual head dependent sources or sinks.

2.5 Stream Flow Simulation and Stream Aquifer Interaction

IWR models incorporate a stream simulation package that simulates the stream flows as a function of flow from the upstream tributaries and reaches, surface runoff, agricultural and urban return flow, diversions and bypasses, flow from upstream lakes and the exchange of water between the stream and the groundwater. The entire stream system is divided into a number of segments termed stream reaches. The stream reaches consist of a group of stream nodes coincident with the groundwater nodes. The outflows from upstream reaches are inflow to downstream reaches throughout the stream system. The IWR models solve the continuity equation at each stream node to simulate the stream flows.

IWR models provide a flexible and efficient simulation capability to represent the hydraulic interaction between the stream and aquifer systems. Stream-aquifer interaction formulation in the model simulates the seepage flow in the form of gain or loss at each of the stream nodes by solving the conservation equations for groundwater and streams simultaneously. Fig. 9 shows the schematic of various stream aquifer interaction scenarios for IWR models.



Case 1a: Saturated Seepage Conditions
Flow from Stream to Subsurface

Case 1b: Saturated Seepage Conditions
Flow from Subsurface to Stream

Case 2: Unsaturated Seepage Conditions
Flow from Stream to Subsurface

Fig. 9. Stream aquifer interaction options

2.6 Lake Simulation

The IWR models include algorithms to simulate lakes as well as lake-aquifer interaction. The lake storage changes and lake groundwater interactions are simulated in the model as a function of hydrologic phenomena such as rain, evaporation, and inflows to the lake (Fig. 10). The solution scheme for lake-aquifer hydraulic interaction uses a formulation similar to that of stream-aquifer interaction. Either a linear or non-linear solution scheme may be used.

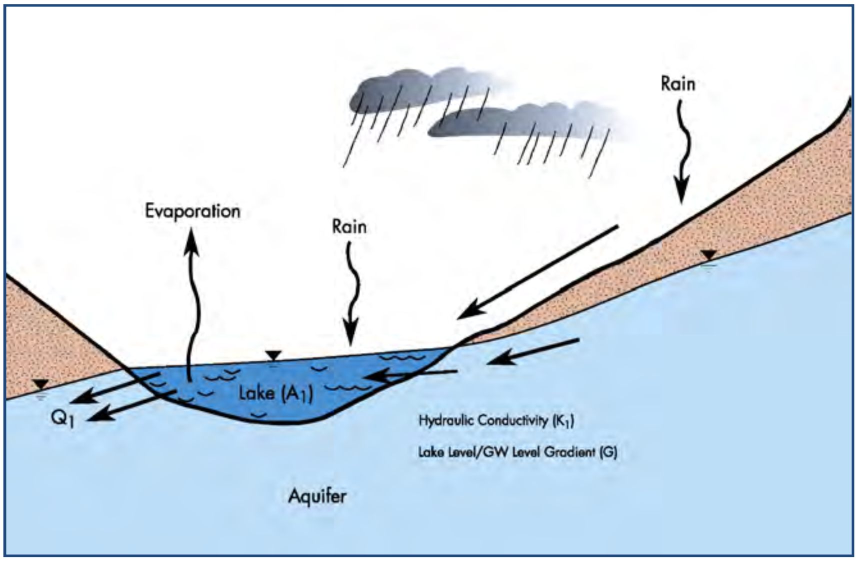


Fig. 10. Lake-aquifer interaction

2.7 Reservoir Operation

The reservoir operations simulation module contains algorithms, typically based on general basin-wide and/or reservoir-specific Operation Criteria and Plan (OCAP) for making release decisions based on user-defined input data. The IWR models includes the capability to simulate multi-purpose, multiple reservoir operations and diversions based on a designated priority system (Fig. 11).

The IWR model's river/reservoir operations module is based on a mass balance accounting procedure for tracking the flow of water through the model stream network. The procedure involves utilizing a specified priority system, physical data, and operational rules for each reservoir to compute reservoir releases to meet the following requirements:

- Downstream diversion requirements
- Downstream minimum in-stream flow requirements
- Transbasin diversions
- Reservoir on-site storage requirements, such as recreational demands
- Flood control requirements

The reservoir operation feature is currently only available in the IGSM code.

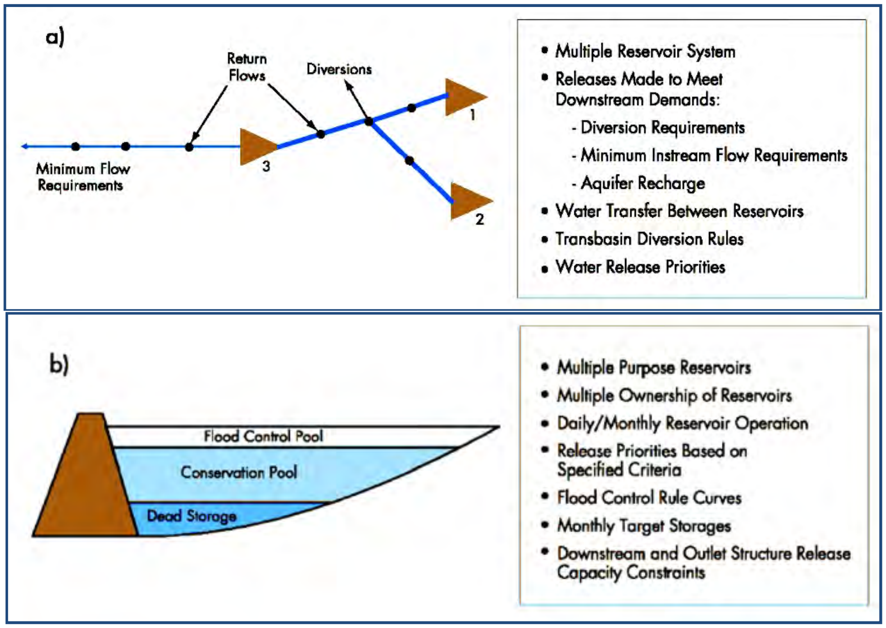


Fig. 11. River/reservoir operations simulations

2.8 Land Subsidence Simulation

IWR models account for changes in storage due to land subsidence. The change in soil structure, which causes subsidence, primarily occurs from pumping large amounts of groundwater in a given area. Modeling land subsidence is an important feature of IWR models because storage changes impact the available water supply.

IWR models calculate the groundwater head changes due to subsidence in relation to the vertical compaction of interbeds. Interbeds are lenses that have poor permeability within a relatively permeable aquifer. The following three items are used as criteria when defining an interbed [59]:

- The hydraulic conductivity of the interbed is significantly lower than the hydraulic conductivity of the aquifer material.
- The lateral extent of the interbed must be small enough so that it is not considered a confining bed that separates adjacent aquifers.
- The interbed thickness must be small in comparison to its lateral extent.

Land subsidence is a function of the change in the effective stress, elastic and inelastic specific storages of the interbed, and the initial interbed thickness, given that the geostatic and the hydrostatic pressures over the interbed are constant.

2.9 Water Quality and Particle Tracking Simulation

The water quality module of IWR models includes simulation of soil zone biochemical processes, transport and decay processes in the vadose zone, and transport and decay processes in the saturated zone. The soil zone biochemical process simulation for nitrogen includes mineralization, immobilization, adsorption, desorption, denitrification, and plant uptake. The transport processes in the saturated and vadose zones are simulated by solving the mathematical equations of transport that includes advection, dispersion, adsorption, desorption, and decay. The water quality simulation in the stream system is based on mass balance and first order linear decay rate.

The IWR models also have a particle tracking module to simulate the movement (pathways and travel times) of conservative particles in a flow system in an advective mode, i.e., without regards to diffusion, dispersion, and chemical reactions [60]. The particle tracking module was developed to compute two-dimensional flow paths using output from steady-state or transient (as small as daily simulations steps) groundwater flow simulations by any finite difference or finite element flow model. The particle tracking module uses a technique (in-element particle tracking) that traces particles on an element-by-element basis. Given a velocity field, a particle is traced one element by one element until either a boundary or an internal sink/source is encountered or the available time is completely consumed.

The particle tracking module allows forward or backward particle tracking analyses to be performed for transient as well as steady-state simulations. The module can also perform analysis such as delineating capture and recharge areas for conservative plumes. The tools in IWR models' Graphical User Interface (GUI) provide capabilities to visualize, analyze and animate data from particle tracking module within ArcGIS.

This feature is currently only available in the IGSM code (Fig. 12).

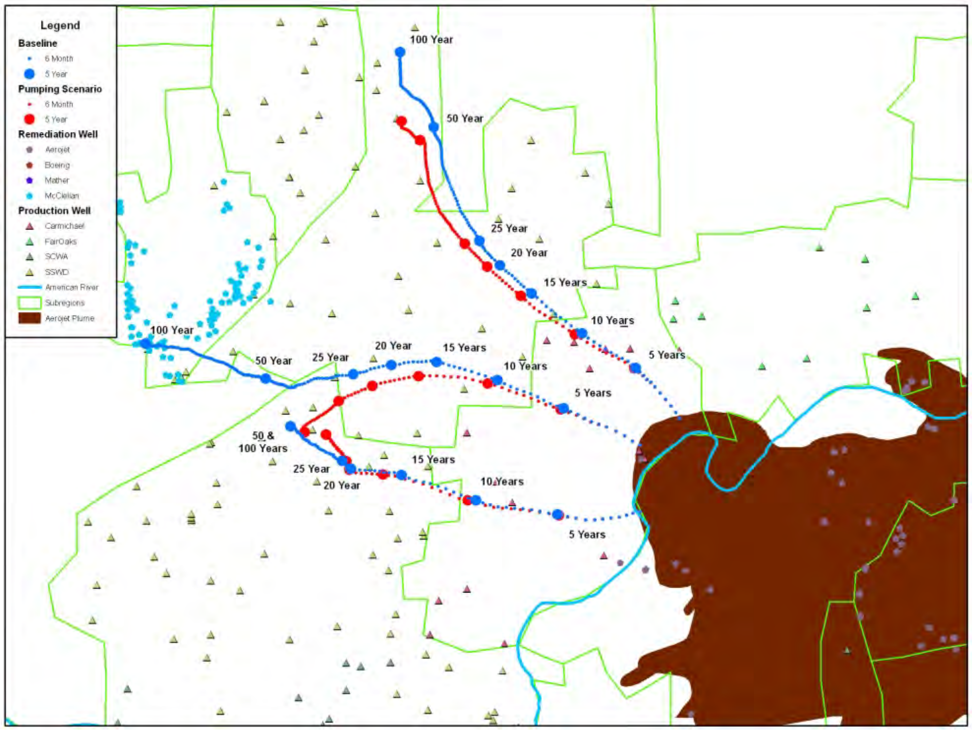


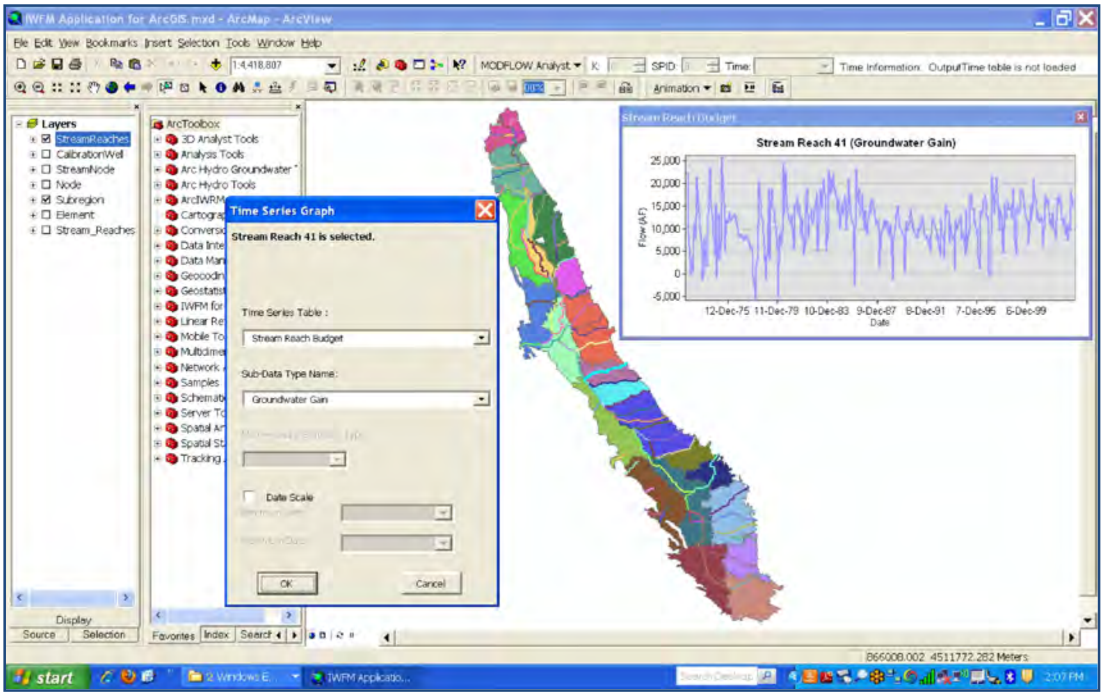
Fig. 12. Travel times and paths of particles

2.10 Graphical User Interface

IWR model ArcGIS GUI is a state-of-the art module that allows developing model input files from the existing model input datasets for a new model run, developing shapefiles for model grid generation, editing the input files and shapefiles for an existing model, running the model, storing the complete IWR model simulation results in an ArcGIS Geodatabase, mapping the model results, reporting the water budgets, and analyzing the stationary and temporally variable datasets and 3-D data in the same environment when completed. Custom made, user-friendly tools developed in an ArcGIS environment can serve a wide range of users [38].

Currently, the ArcGIS-based GUI has the following features:

- A geodatabase that stores model input and output data
- GIS tools to setup and perform model simulations
- Post-processing graphical tools to analyze model results:
-
    - Time series charts and hydrographs (Figs. 13-a and 13-b)
    - Statistical analysis of temporal and spatial data (Figure 13-c)
    - Contouring of spatial data such as groundwater levels (Figure 13-b)
    - Reporting Water Budgets (Fig. 13-b)
    - Animation of temporal and spatial data, such as changes in groundwater levels
    - Particle Tracking Analysis (Fig. 13-b)



Time Series Graph

Stream Reach 41 is selected.

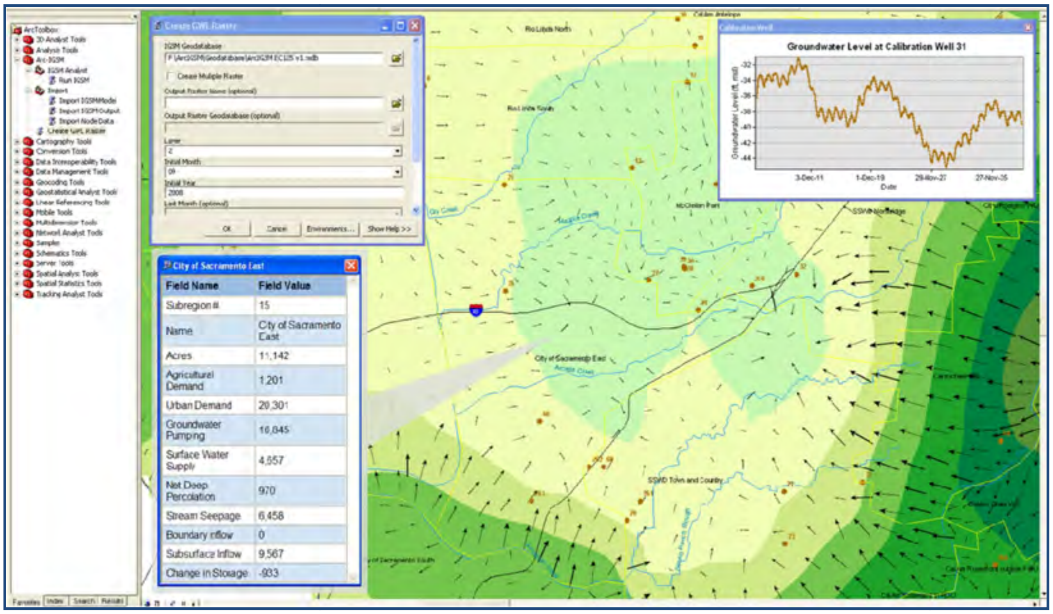
Time Series Table : Stream Reach Budget

Sub-Data Type Name: Groundwater Gain

☐ Date Scale

OK Cancel

Fig. 13-a. Graphical user interface – time series charts



IGSM Geodatabase: F:\ArcIGSM\Geodatabase\ArcIGSM EC125 v1.mdb

☐ Create Multiple Raster

Output Raster Name (optional):

Output Raster Geodatabase (optional):

Layer: 2

Initial Month: 09

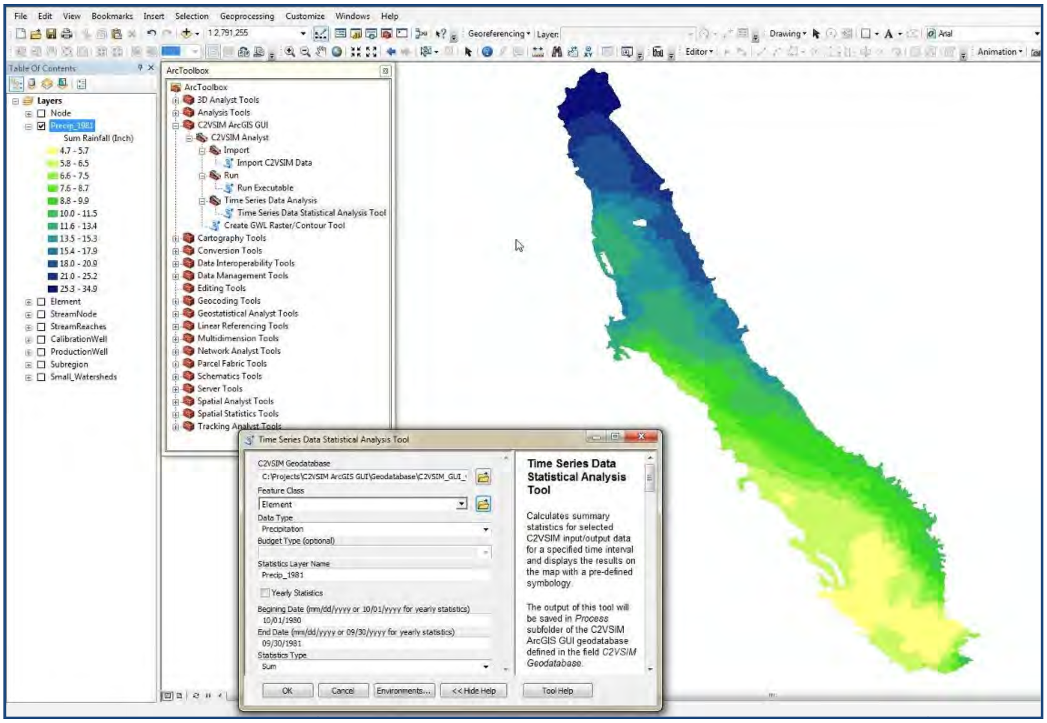
Initial Year: 2008

Last Month (optional):

City of Sacramento East

Field Name	Field Value
Subregion #	15
Name	City of Sacramento East
Acres	11,142
Agricultural Demand	1,201
Urban Demand	20,301
Groundwater Pumping	16,645
Surface Water Supply	4,657
Net Deep Percolation	970
Stream Seepage	6,458
Boundary Inflow	0
Subsurface Inflow	9,567
Change in Storage	-933

Fig. 13-b. Graphical user interface – hydrograph, reporting water budgets, groundwater level contours and groundwater flow vectors



C2VSIM Geodatabase: C:\Projects\C2VSIM ArcGIS GUI\Geodatabase\C2VSIM_GUI_

Feature Class: Element

Data Type: Precipitation

Budget Type (optional):

Statistics Layer Name: Precip_1981

☐ Yearly Statistics

Begining Date (mm/dd/yyyy or 10/01/yyyy for yearly statistics): 10/01/1980

End Date (mm/dd/yyyy or 09/30/yyyy for yearly statistics): 09/30/1981

Statistics Type: Sum

Time Series Data Statistical Analysis Tool

Calculates summary statistics for selected C2VSIM input/output data for a specified time interval and displays the results on the map with a pre-defined symbology.

The output of this tool will be saved in *Process* subfolder of the C2VSIM ArcGIS GUI geodatabase defined in the field *C2VSIM Geodatabase*.

Fig. 13-c. Graphical user interface – display of spatially distributed model data (In this case, total precipitation)

3. IWR MODEL APPLICATIONS

3.1 Central Valley of California

The Central Valley of California, with an area of 54,000 km^2, is the hub of the state's water supply system. An extensive network of dams and canals supplies surface water to users within the Central Valley and in the San Francisco Bay Area, Central Coast, and Southern California. Agricultural and urban users within the Central Valley consume an average of 16 billion cubic meters of surface water and over 9.9 billion cubic meters of groundwater per year. Approximately 2.5 billion cubic meters of water is exported annually to areas outside the Central Valley [61]. As availability of surface water supplies varies significantly from year to year, groundwater is used as a buffer when surface water supplies are reduced.

3.1.1 Hydrological characteristics of the Area

The two major rivers in the Central Valley are the Sacramento River and San Joaquin River. The Sacramento River flows from north to south and discharges into the Sacramento-San Joaquin River Delta (Delta). In contrast, the San Joaquin River flows from south to north before discharging into the Delta. Several other major tributaries in the Central Valley flow into these two main rivers, for example, the Feather River flows into the Sacramento River and the Kings River flows into the San Joaquin River.

The Sacramento River Basin occupies approximately 70,000 square kilometers and has an average annual runoff of 27 billion cubic meters [62]. The San Joaquin River Basin occupies approximately 35,000 square kilometers and has an average annual runoff of 4 billion cubic meters [63]. The long-term average annual rainfall ranges from 330 to 660 mm in the northern half and from 130 to 460 mm in the southern half of the Central Valley.

3.1.2 Associated IRWM areas

There are more than 15 IRWM areas and regional water management groups (RWMG) in the Central Valley (Fig. 2) that serve and represent the interests of numerous water providers and stakeholders [39]. The members of the IRWM areas consist mostly of irrigation and water districts, cities, and counties plus non-governmental organizations (NGOs) and other stakeholders. Three of the IRWM areas in the Sacramento, Kings, and Yolo basins and their associated water resources management issues are described in the following sections.

3.1.3 Hydrological model

The Central Valley integrated hydrologic model was originally developed in 1990 to simulate the Central Valley hydrologic system from 1921 to 1980 [33]. This model was developed as a tool to aid in water management planning and simulation of the response of the groundwater and surface water flow systems to surface water and groundwater stresses. The original model was developed based on the IGSM code, and was called "Central Valley Groundwater and Surface water Model (CVGSM)". In 2005, CADWR upgraded the model to the IWFM platform, updated the data, recalibrated the model, and renamed the model the "California Central Valley Simulation Model (C2VSim)". In 2012, CADWR updated and refined the model to simulate the hydrological conditions from 1921 to 2009 [61,37].

The latest version of C2VSim is on IWFM platform v. 3.7, and consists of a finite element grid with more than 30,000 nodes and 32,000 elements with the smallest element area of approximately 1,600 m^2 (Fig. 14). The model area, covering the entire Central Valley, is approximately 54,000 km^2 and is divided into 21 water management areas. The aquifer is simulated as a multi-layer system with a maximum thickness of 1,800 m [64,65].

The precipitation data is based on a 2-km^2 PRISM grid. Most streams in the Central Valley are gaged and are simulated as inflow to the model area. There are 210 ungaged watersheds, covering an area of 19,400 km^2, that are simulated as small-stream watersheds.

The Central Valley's surface water storage, conveyance, and delivery system is large and complex, and includes over 1,200 reservoirs and numerous canals, pumps, treatment plants and levees. The C2VSim uses 68 simulated rivers and canals, 105 stream reaches with 4,529 river nodes and 246 diversions to simulate the surface water delivery system of the Central Valley.

Using the root zone module of the model, the agricultural water demands are estimated based on crop type, land use and soil conditions, and rainfall. Because much of surface water supplies are monitored and reported, the agricultural groundwater pumping is estimated to be the balance between the estimated demand and surface water supplies.

Fig. 14. Central valley model area

3.1.4 Modeling results

The Central Valley model produces several budget tables that include monthly water balances for various model components such as land surface processes, river flow system, groundwater flow system, and small stream watersheds. The information from these tables can be summarized for any time period from one month up to the full model run. The summary includes water budgets for water management areas, hydrologic regions comprised of several water management areas, and entire model area. The subsurface flows between water management areas are also calculated to investigate the impact of stresses such as groundwater pumping on groundwater flow directions and magnitudes.

The C2VSim has been developed to meet the needs of current and future applications at Central Valley wide or regional levels. This model has been used for analysis of various water supply conditions and policies in the Central Valley and the impacts of these policies on the surface water and groundwater conditions, as well as the Delta inflows. Some of other potential model applications are:

- Evaluation of impacts of conjunctive use and water transfer programs on the interaction between the aquifer and river systems;
- Assessment of hydrologic impacts of climate change and emission scenarios
- Support of groundwater analysis in Calsim 3
- Evaluation of effects of reservoir re-operations on water supplies
- Analysis of water transfer program impacts on hydrologic systems
- Evaluation of economic impacts of water transfer programs in conjunction with the Statewide Agricultural Production Model (SWAP) and the Central Valley Production Model (CVPM)
- Support of California Water Plan’s Water Portfolio Analysis

3.1.5 Climate change implications

The C2VSim is an ideal analytical tool for evaluation of effects of climate change on the CVP and SWP systems. With detailed simulation capabilities, including the agricultural demand calculation, groundwater pumping estimation, surface water-groundwater interaction, and subsidence estimation, the C2VSim can provide a good assessment of the effects of climate change under various global emission scenarios on the water resources and ecosystem conditions in the Central Valley. The CADWR has initiated a program to perform this evaluation which will eventually require the use of C2VSim.

3.2 Sacramento County and American River Basin, CA

The Sacramento County and American River Basin is located in the southern Sacramento Valley in the Central Valley of California and is bounded on the north by the Feather River, on the west by the Sacramento River, on the south by the Mokelumne River, and on the east by the foothills of the Sierra Nevada. Sacramento, the capital city of California, is a large urban area and is located in the middle of this basin. The model area consists of the large urban area of Sacramento and suburbs in the center and large agricultural areas in the north and the south (Fig. 15).

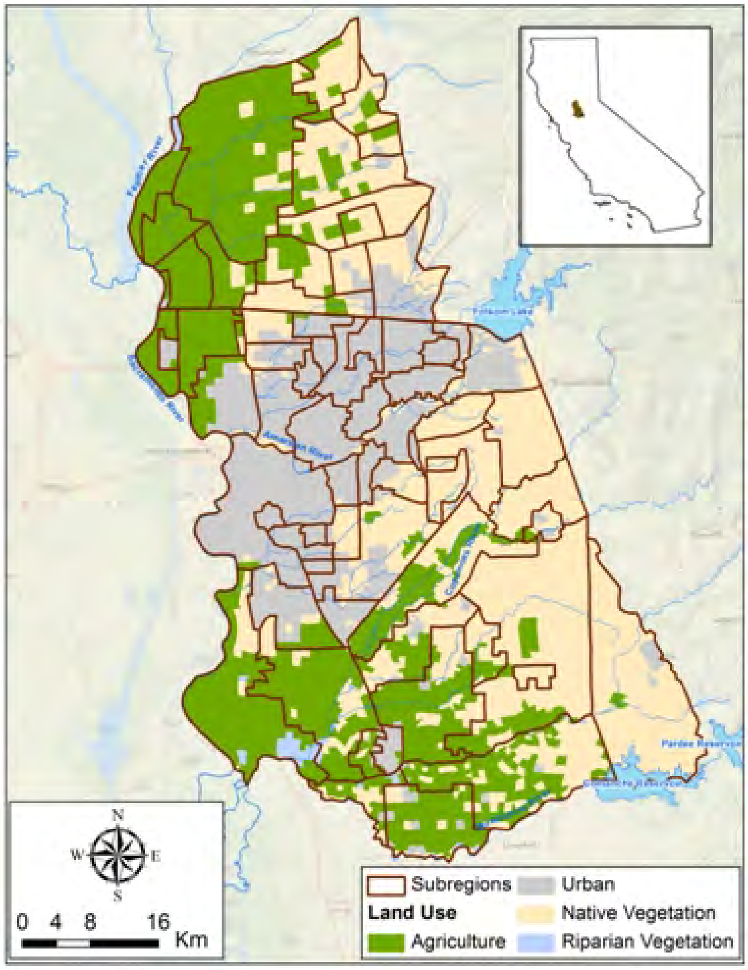


Fig. 15. Sacramento Integrated Water Resources Model (SacIWRM)

3.2.1 Hydrological characteristics of the area

The major rivers in the study area are the Sacramento River on the western boundary and the Feather River and Mokelumne River on the northern and southern boundaries of the study area, respectively. The American River runs through the urban areas from Folsom Lake on the east to the Sacramento River on the west. Cosumnes River, the only major river in the Central Valley of California with no dam and reservoir, runs from east to west in the southern parts of the study area. The long-term average annual rainfall is approximately 450 mm.

3.2.2 Associated IRWM area

The associated IRWM group is the Regional Water Authority (RWA) which is a joint power authority (JPA), formed in 2001, and serves and represents the interests of 22 water providers in the Sacramento, Placer, El Dorado and Yolo County region [66]. The RWA's primary goal is to ensure a high quality, reliable water supply to over 1 million people in the IRWMP area.

3.2.3 IRWM activities

RWA has implemented several regional projects such as the regional conjunctive use program, utilizing a $22 million grant from the CADWR, and a regional water efficiency program to help local purveyors implement best management practices on a regional basis. RWA developed a five-year strategic plan in 2009 to guide its activities toward achieving its goals of effective water resources management in the region. RWA has obtained more than $50 million of state and federal grant funds for its water supply, water quality, and environmental restoration projects.

3.2.4 Hydrological/water resources management issues

There are several water resources management issues and projects that are currently being evaluated, in part, by using the Sacramento model. Use of tertiary recycled water for outdoor urban and agricultural irrigation uses in the southern parts of the model area is being evaluated by the Sacramento Regional County Sanitation District (SRCSD).

The Cosumnes River is located in the south-central part of the study area and flows from the foothills on the east side to Sacramento River on the west side. Cosumnes streamflows are significantly impacted by the elevation of nearby groundwater levels and streambed losses to groundwater. The groundwater depression areas to the north and south of the Cosumnes River have resulted in reduced streamflows and impacted the fall salmon run. The Nature Conservation (TNC) has used the Sacramento model to evaluate the potential of importing additional surface water through re-operation of upstream state or federal system reservoirs to the Cosumnes River area and using the imported water in-lieu of groundwater by the agricultural and urban users [67].

There are several regional contamination sites in the model area including those at Aeroject/Boeing, McClellan, Mather, Kiefer Landfill, Army Depot, and the Railyard. The SacIWRM is an instrumental analytical tool for evaluation of rate and direction of movement of these contamination plumes as a result of the operation of water supply wells. In addition, the SacIWRM has supported the development of boundary condition for the localized groundwater models that are used to design and monitor the operations of the remediation projects.

3.2.5 Hydrological model

The Sacramento Integrated Water Resources Model (SacIWRM) was originally developed in early 1990's and has been maintained, upgraded, and applied to many projects, some of which have led to key policy decisions in the area. Currently, this model has an ArcGIS-based graphical interface and its model code, data, and graphical package are all open source, and available publically.

The Sacramento model is on the IGSM platform and simulates a multi-layered aquifer system up to a depth of 600 meters. It includes major water courses of the area including the Sacramento, American, Cosumnes, Bear, Feather, and Mokelumne Rivers (Fig. 14). It simulates land surface processes including six land use surveys, 14 types of agricultural crops, 21 rainfall stations, 45 stream flow diversions, and 776 groundwater pumping wells. The simulation period includes a 35-year hydrologic period with daily time steps.

SacIWRM is built upon ESRI's Geographic Information System (GIS) platform using a comprehensive geospatial database. The GIS is used to compile, collate, manage, analyze, store, and visualize large quantities of water resources data needed for the model, as well as to conduct simulation runs and view and analyze the model results.

A significant capability of the Sacramento model is simulation of particle tracking in a regional groundwater basin (Fig. 12). This capability of the model has been used in tracking direction and time for movement of particles in groundwater basins, which assists in assessing sources of pollution, travel times, and directions of movement of potential sources of pollution. The model has recently been used to evaluate movement of the plumes of the regional contamination sites of Aeroject/Boeing, McClellan, Mather, and Sacramento Railyard under various water management scenarios.

3.2.6 Modeling results

The SacIWRM has been used in more than 20 major applications, which have led to major water management plans and agreements in the area. Table 2 shows some of the major applications [68]. A notable application of the model has been to evaluate the yield of the American River Basin and its sub-basins. This evaluation was conducted in support of the historic Water Forum Agreement in the Sacramento Valley [69].

Table 2. SacIWRM major applications

Year	Project	Year	Project
1992	Evaluation of conjunctive use projects in the City & County of Sacramento	2009	Study of Cosumnes Basin hydrologic conditions and conjunctive use projects for the Nature Conservancy
1996	Development of basin yield estimates for the Water Forum Agreement	2009	Water Accounting Framework development for the Sacramento Groundwater Authority (SGA)
1996	Evaluation of regional and local scale projects for the American River Water Resources Investigation Study	2010	Groundwater Management Plan evaluation for the South Sacramento County Area
2002	Surface water discharge permit analysis for the Aerojet-Boeing Groundwater Extraction and Treatment (GET) project	2011	Regional Water Quality Risk Study for the SGA
2004	Analysis of hydrologic conditions to support the Zone 40 Water Supply Master Plan update	2012	Sacramento Regional County Sanitation District's South Sacramento County Recycled Water Feasibility Study
2007	Sacramento Area Flood Control Agency Flood Mitigation Analysis	2013	Analysis of climate change impacts on regional water supplies

Some of the other applications have been to evaluate the stream discharge permit analysis for the Aerojet–Boeing contamination site in 2002, impacts of the Freeport Regional Water Project (FRWP) in 2004, regional reservoir re-operation study in 2011, regional water quality risk assessment in 2011, regional groundwater banking evaluation [70], and regional recycled water delivery feasibility study in 2012. The model results have been used to illustrate the impacts of various water resources projects on changes in groundwater elevations, groundwater underflows between various areas of the model, streambed recharge, and streamflows. An example of a cross section showing the streambed elevation of Cosumnes River and the elevation of underlying groundwater in model layers 1 and 2 is shown in Fig. 16.

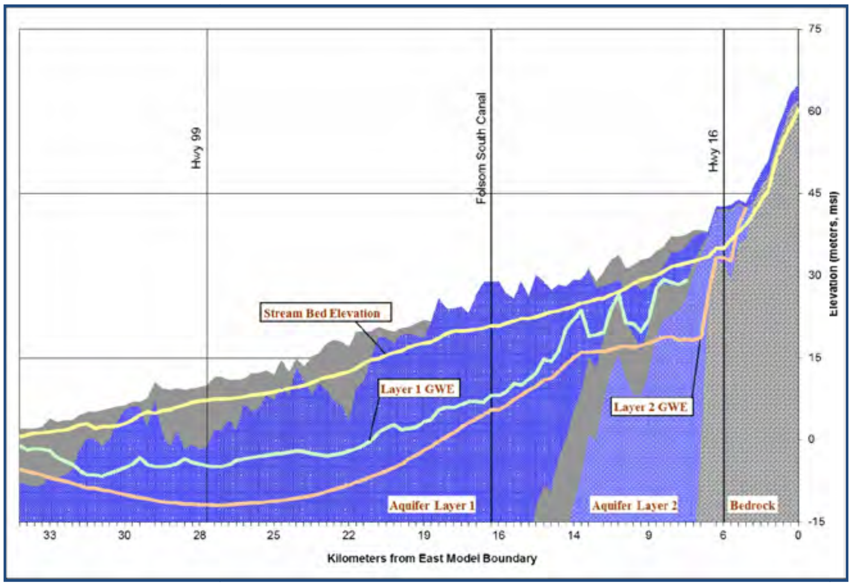


Fig. 16. Cross section of streambed and groundwater elevations of model layers one and two along the Cosumnes River

3.2.7 Climate change implications

The SacIWRM has been applied to more than two dozen water supply and demand scenarios and project applications. Many of these applications include scenarios that can easily be adapted to a change in the operation of the basin that can potentially be a result of a change in the climatic conditions. As such, the model has inherent design and capability, which lends itself to climate change analysis. The downscaled data from GCMs can be adapted to the model input data in the form of precipitation, stream flow, and evapotranspiration data. Data from the CALSim operations model for GCM scenarios which includes streamflows for American River below Folsom dam and surface water supplies from American and Sacramento Rivers can be used in the SacIWRM. The ungaged watershed module of the model can be used to estimate the stream flows for other ungaged tributaries, including the Cosumnes River. The model would then be capable of simulating the water demand and supply conditions and the potential changes to the operation of the basin resulting from climate change.

3.3 Kings Basin, CA

The Kings Basin is located in the central San Joaquin Valley in the Central Valley of California and is bounded by the San Joaquin River on the north and the Kings River on the south and west. The Kings Basin includes Fresno, Tulare, and Kings Counties. Agriculture is the principal industry in the region. In 2000, Fresno County was the top agricultural producer in the nation, with major crops including: grapes, cotton, almonds, tomatoes, fruit, and milk.

3.3.1 Hydrological characteristics of the area

The Kings River, with an average annual runoff of 2.2 billion m^3, is the main source of surface water for the Kings Basin. Limited quantities of surface water are delivered to the area from the San Joaquin River via the Friant-Kern Canal on the eastern boundary of the basin and from the Delta-Mendota Canal to the western areas of the basin. The long-term average annual rainfall in the basin is 205 mm [71].

3.3.2 Associated IRWM area

Several local agencies and organizations including water agencies, cities, counties, and environmental interests in the Kings Basin have been working over the past several years to collaborate and solve the water supply and quality problems of the basin. The local agencies have created the Upper Kings Basin Integrated Regional Water Management Authority (Kings Basin Water Authority), a JPA, to develop plans for a sustainable supply of the Kings River Basin’s finite surface and groundwater resources [72].

3.3.3 IRWM activities

The Kings Basin Water Authority was formed based on a shared vision to coordinate water management strategies and a planning process to deal with the groundwater overdraft conditions in the basin. The average groundwater levels have dropped by more than 10 m over the past 40 years and continue to decline. The depth to water at the groundwater depression area is more than 75 m. The overdraft problem in an expansive and interconnected groundwater basin cannot be effectively managed by local measures and actions taken individually by overlying users. In addition, a comprehensive exploration of water resources management alternatives requires an integrated look at the entire watershed and groundwater basin beyond the jurisdictional boundaries of any single local agency.

The Kings Basin Water Authority has received more than $35 million in state financial support for use toward planning and construction of projects that address groundwater, water conservation and efficiency, water quality, riparian habitat, flood corridors, and disadvantaged communities [72]. Other projects in development include water banking projects, storm water projects and surface water treatment projects.

3.3.4 Hydrological/water resources management issues

Key issues facing this primarily rural, agricultural region differ from those experienced by more urban regions. The primary challenges include the difficulty of engaging stakeholders over a large rural area and overcoming significant funding hurdles. However, the Kings Basin Water Authority has successfully planned for and constructed projects that address the most important local water resources management issues of groundwater depletion and supply reliability and quality.

3.3.5 Hydrological model

The Kings Basin hydrological model was developed in 2007 to serve as an analytical tool that can represent the groundwater and surface water flow systems and their interactions in the basin. The model was developed also to provide quantitative information on a comparative basis to support the analysis required for several projects planned by the Kings Basin Water Authority, City of Fresno, and other local agencies.

This model which is on the IGSM platform, has a simulation period of 1964-2004, which includes wet, dry, normal, and extreme conditions of the regional hydrology and uses a daily time step. The Kings model simulates a multi-layered aquifer system up to a depth of more than 365 m and includes the regionally imported E Clay layer.

The model area is approximately 4,200 km^2 and is represented by a grid that consists of 4,266 nodes and 4,689 elements (Fig. 17) and has an average element size of 0.9 km^2. The grid has a significantly higher resolution in the Fresno area for detailed analysis of projects of interest for the City of Fresno.

Water and land use in the model area is represented by 32 management areas. The management areas represent urban areas sphere of influence, individual water districts, irrigation districts, or other organized areas within the model. The City of Fresno management area is further divided into eight smaller areas representing the boundaries of pressure zones of water distribution system.

The complex system of surface hydrology in Kings Basin consisting of flows and stream-aquifer interaction of the Kings River, San Joaquin River, nine smaller river creeks and 22 major canals of the area are simulated by the Kings model by using 78 stream reaches and 790 stream nodes.

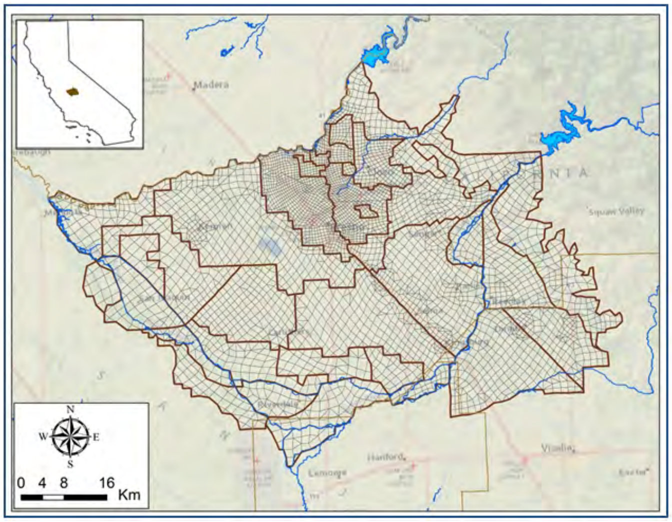


Fig. 17. Finite element grid for the kings basin model

3.3.6 Modeling results

The Kings model has been extensively used to simulate various water resources projects in the Kings Basin. The model applications include evaluation of the Kings Basin IRWMP's scenarios of future with and without project conditions and sizing capital projects. Another application is analysis of groundwater impacts of a proposed power plant, conducted in support of the permit application to the California Energy Commission.

The model grid is significantly refined in the Fresno area in the northern parts of the study area to allow simulation of projects of interest for the City of Fresno such as the development of the Metro Plan, a capital facilities plan for the city. The model was used to size projects, compare alternatives benefits and impacts, and support the preparation of required project level environmental documents.

3.3.7 Climate change implications

The Kings model includes specific features that provide simulation capabilities for evaluation of Kings River basin water supply and flood management under various scenarios of climate change. These include simulation of groundwater basin operation, agricultural water demand and supply conditions, Kings River diversion patterns and river flow conditions, a detailed stream-aquifer interaction, and in-stream flow requirements. The Kings model hydrologic data can be modified to reflect GCM data for selected emission scenarios, which would then help simulation of integrated hydrologic and water supply conditions in the basin.

3.4 Salinas Valley, CA

The Salinas Valley, a highly productive agricultural region, is located in Monterey County along the central California coast, approximately 180 km south of San Francisco and 515 km north of Los Angeles. The Salinas Valley borders the Monterey Bay and Pacific Ocean and the valley floor covers an area of 970 km^2. The region provides significant amounts of produce for the United Sates and exports agricultural products to several countries. Agricultural production generated $4.0 billion in 2010 [73].

3.4.1 Hydrological characteristics of the area

The main river in the area is the Salinas River with an annual discharge of nearly 350 million m^3 into the Monterey Bay. The Salinas River runs 275 km in the northwestern direction from its headwaters in the La Panza and Garcia Mountains in south to the Monterey Bay in the northwest end of the Salinas Valley. The Salinas River watershed has an area of 10,300 km^2 and it includes the major tributaries of the Nacimiento, San Antonio, and Arroyo Seco Rivers. Nacimiento and San Antonio Rivers, respectively, contribute nearly 250 million m^3 and 86 million m^3 annually to the Salinas River [74]. Two dams and their reservoirs on Nacimiento and San Antonio Rivers, built more than 50 years ago, control the contribution of these rivers to the Salinas River flows. The benefits of these reservoirs to the Salinas Valley include flood protection, conservation of winter flows for release during summer months, groundwater recharge, recreational opportunities, and power generation.

The Salinas Valley Groundwater Basin consists of five subareas: Upper Valley, Arroyo Seco, Forebay, Pressure and East Side. The Upper Valley, Arroyo Seco and Forebay subareas are unconfined and in direct hydraulic connection with the Salinas River.

Groundwater is the main source of water in the Salinas Valley for urban and agricultural uses. Groundwater is extracted from the unconfined aquifer in the central and southern parts of the Salinas Valley, while the groundwater extraction in the northern coastal areas occurs mostly from the confined 180-foot and the underlying, confined 400-foot aquifers. Groundwater extraction in 1999 included nearly 570 million m^3 of agricultural pumping and 50 million m^3 of urban pumping [74]. Groundwater extraction in excess of groundwater recharge has resulted in overdraft conditions and infiltration of seawater into both aquifers. As a result, several urban and agricultural wells have been abandoned.

3.4.2 Associated IRWM areas

There are two associated IRWM areas in the Salinas Valley: 1) the Greater Monterey County IRWM region and 2) the Monterey Peninsula, Carmel Bay, and South Monterey Bay IRWM region. The first region covers much of the Monterey County and all of the Salinas Valley model area [62] and the second region cover a smaller area consisting of the coastal areas by the City of Monterey and Carmel, in Monterey County [75]. The Greater Monterey County IRWM region covers all of the Salinas Valley; however, only the northwestern corner of the Salinas Valley is covered by the Monterey Peninsula, Carmel Bay, and South Monterey Bay IRWM region. The Monterey County Water Resources Agency (MCWRA) leads the efforts for development of the IRWM Plan for the Greater Monterey County IRWM region; while, the Monterey Peninsula Water Management District (MPWMD) leads the efforts of IRWM plan development. The IRWM efforts also involve several other agencies including the Marina Coast Water District (MCWD), Castroville Water District (CWD), Monterey Regional Water Pollution Control Agency (MRWPCA), City of Monterey, and Big Sur Land Trust.

3.4.3 Hydrological/water resources management issues

The water supply in the Salinas Valley is managed by several public and private agencies that are implementing projects to reduce groundwater pumping, restoring Salinas River flows and improving impacted habitat. The major water management issue for the Salinas Valley is seawater intrusion. The next important issues are nitrate contamination of groundwater supply and storm water runoff impacts within the Monterey Bay National Marine Sanctuary. Fifty percent of wells sampled in the Salinas Valley exceed the maximum contaminant level for drinking water of 45 mg/l (NO_3).

3.4.4 Hydrological model

The Salinas Valley Model was originally developed in 1993, revised in 1997 and later updated with additional data and recalibrated for the 1970-1994 hydrologic period (Montgomery Watson, 1994).

The Salinas Valley Model is on the IGSM platform and covers 1,680 km^2 and encompasses the entire groundwater basin underlying the Salinas Valley (Fig. 18). The model grid consists of 1,615 elements and 1,726 nodes. The average size of the model element is approximately 1 km^2. The grid orientation follows the general direction of groundwater flow and is consistent with the general surface water drainage pattern of the major stream systems within the model area. The model grid has been divided into six subregions for analysis of water budgets and hydrologic conditions for each subregion.

The model represents the groundwater system with one to three layers of aquifers and intervening aquicludes for different regions. The Pressure area in the north has three confined aquifers (180-foot, 400-foot, and 900-foot aquifers). The Forebay and East Side areas have a top unconfined aquifer underlain by two confined aquifers (400-foot and 900-foot aquifers).

Salinas River and its major tributaries as well as Nacimiento and San Antonio Reservoirs were incorporated in the model. The Salinas Valley Model simulates streamflows and gain and loss to the groundwater system through streambed infiltration. The releases from Nacimiento and San Antonio reservoirs are controlled by their operating rules, diversion priorities, and minimum flow requirements. The Salinas Valley model simulates the complex operating rules of these reservoirs.

The land use surveys as well as crop data of 1976, 1984, and 1991 were incorporated in the Salinas Valley model.

Fig. 18. Finite element grid for salinas valley model

3.4.5 Modeling results

The Salinas Valley model was used to estimate and quantify the hydrologic benefits of the Salinas Valley Water Project (SVWP) in reducing the reliance on groundwater. SVWP was developed to stop seawater intrusion, improve the balance between recharge and withdrawal, and provide sufficient water supply to meet urban and agricultural water needs. Other elements of the SVWP include enlarging the Lake Nacimiento Dam spillway to handle a maximum probable flood, reoperating the reservoir to prolong releases of water to the

Salinas River to maximize groundwater recharge, and installing a diversion structure on the Salinas River to divert water during dry periods for use in prevention of seawater intrusion. Additionally, the Salinas model has been used to simulate the use of recycled water for meeting the agricultural water demand in the area.

The Salinas model was used to model the alternatives evaluated in the SVWP 2001 EIR/EIS and the well relocation project for Marian Coast Water District (MCWD). Additionally, multiple model runs were completed to evaluate the benefit and/or impact of the water for fish passage on the groundwater basin [74].

A more recent application of the Salinas Valley model has been the simulation of the impact of a proposed desalination project on groundwater levels and seawater intrusion. As part of this project, nearly 1 m^3/sec saline groundwater would be extracted for use in a desalination plant. The modeling work included simulation of the saline groundwater extraction by two models - the Salinas Valley model and the North Marina groundwater flow and solute transport model (North Marina model). The Salinas Valley model is an established regional model for groundwater management in the Salinas Valley. The North Marina model is a refined local MODFLOW/MT3D with much finer cell size (61 m by 61 m) to improve resolution in the vicinity of the proposed project [76]. The two models were integrated by transferring aquifer parameters, recharge and discharge terms, boundary conditions and predictive scenarios from Salinas model to the North Marina model to ensure consistency between the two models.

3.4.6 Climate change implications

The Salinas Valley model was used to investigate the climate change impacts on water resources conditions in Salinas Valley and operation of the Nacimiento and San Antonio reservoirs [77]. The Geophysical Fluid Dynamic Lab Model (GFDL) and the A2 emissions scenario were selected for this study to be consistent with California's Climate Action Team. Downscaled data of GFDL model was used to develop estimates of future precipitation data for the Salinas Valley model. The simulation showed that the forecasted decreased precipitation due to climate change would adversely impact the surface water and groundwater resources of the basin. Reservoir storage would be stressed by emptying the two reservoirs earlier than under historical conditions. The changes in precipitation would also result in decreased surface water diversions due to insufficient streamflow as well as increased groundwater production. The rate of seawater intrusion would increase along the reduction of groundwater storage.

3.5 Yolo County, CA

Yolo County is located in the southern Sacramento Valley in Central Valley of California and is bounded on the north by the Colusa county line, on the south by the Putah Creek in Solano County, and on the east by the Sacramento River. Yolo County consists of mostly agricultural lands; the major urban areas are cities of Davis, Woodland, Winters, and West Sacramento. The market value of agricultural production in Yolo County was $549 million in 2011 [78]. The top five commodities in Yolo County are processing tomatoes, rice, wine grapes, alfalfa hay, and walnuts.

3.5.1 Hydrological characteristics of the area

Cache Creek, flowing from western parts of the study area towards the Sacramento River at the eastern boundary of the model, is a major source of surface water for the Yolo County. Significant stream/aquifer interaction exists along Cache Creek and historical data indicate that Cache Creek is a losing stream and significant percentages of high stream flows are recharged to groundwater. This provides important recharge, particularly after wet years and high stream flows, allowing for recovery of otherwise declining groundwater levels.

The annual rainfall in Yolo County is approximately 500 mm with more than 80% occurring during the non-growing season.

3.5.2 Associated IRWM areas

The associated IRWM group is the Westside IRWM Region composed of Cache Creek and Putah Creek watersheds. The watersheds of these two creeks include all of Yolo County and portions of Solano, Lake, Napa, and Colusa counties. The Westside IRWM Region consists of more than 70 service districts with various interests. The Westside Regional Water Management Group (RWMG) serves as a forum for integrating water management activities by developing collaborative solutions among different water agencies and stakeholders. The Westside RWMG has received a $1 million planning grant from CADWR to improve regional water planning efforts.

3.5.3 Hydrological/water resources management issues

The Westside RWMG is preparing its first IRWM Plan for the region. As part of the plan development, the RWMG has specified several challenges and opportunity focus areas ranging from water supply and water quality to recreation and education and awareness.

The water supply challenges include sustaining groundwater resources, ensuring reliable water supplies for beneficial uses during drought periods, and competing need for water supplies due to environmental regulations and climate change in the future [79].

3.5.4 Hydrological model

The Yolo model was developed in 2006 on an IGSM platform, as an analytical tool for evaluation of water resources projects in Yolo County [80]. It simulates groundwater flow, surface water flow, stream-aquifer interaction, and land and water use processes. The Yolo model covers nearly 2,300 km^2 of Yolo County in California (Fig. 19) and is bound to Sacramento River to the east, Colusa County to the north, and Solano County to the south. The model also extends into the Capay Valley. The model grid consists of 2,840 nodes and 3,068 elements grouped into 24 subregions representing the major urban areas, water purveyors, and hydrological areas. The Yolo model grid is further refined in subregions representing the cities of Woodland and Davis and the area along Cache Creek for improved model resolution for more detailed simulation of water resources projects.

Major rivers and creeks in Yolo County are represented by 424 stream nodes and 27 stream reaches. More than 50% of the stream reaches are used to represent the Cache Creek downstream of the Capay Dam. This additional refinement was developed for simulation of the Cache Creek Groundwater Recharge and Recovery Project (CCGRRP).

The Yolo model uses 30 years of hydrologic data from 1971 to 2000 and was calibrated with observed data from 105 groundwater wells and 10 stream flow gages.

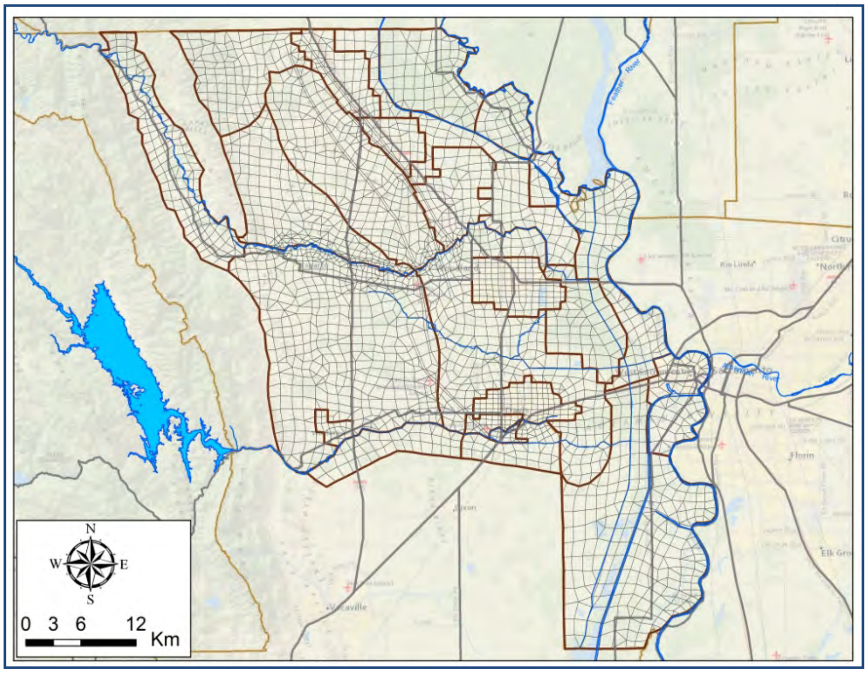


Fig. 19. Finite element grid for Yolo county model

The Yolo model was originally developed using the IGSM code and has been applied to a number of projects to support the local and regional planning programs, including evaluation of the impacts of the Woodland-Davis Water Supply project. The Yolo model has recently been converted to the IWFM code by CADWR for incorporation of the Yolo model in the collection of analytical tools of CADWR for evaluation of statewide and local water resources projects. The IWFM version is under review by local water management agencies before it is adopted as the official model to support the IRWMP. The conversion of the model from IGSM to IWFM is a relatively straight forward process as the format and content of most of the input data files are very similar and the two models share the same ArcGIS GUI.

3.5.5 Modeling results

The Yolo model was used for evaluation of the CCGRRP and its impact on groundwater storage in the vicinity of the Cache Creek. CCGRRP's main objective is to enhance the recharge capabilities of Cache Creek by increasing direct recharge and/or lowering groundwater levels that would result in increased available aquifer storage to receive higher volumes of recharged water. Enhanced direct recharge was evaluated by directing a portion of high winter streamflows to adjacent aggregate mining pits. Additionally, groundwater pumping in the vicinity of Cache Creek was increased in summer times. This would lower the groundwater levels and result in enhanced Cache Creek streambed recharge in winter times and during high streamflows. The simulations were used to quantify the increases in Cache Creek recharge rates and changes in aquifer storage.

The Yolo model was used for evaluation of delivery of surface water to the cities of Woodland and Davis, the two major urban areas in Yolo County. These cities rely on groundwater for meeting the municipal water demands. The City of Woodland uses shallow wells while the City of Davis uses deeper wells with better water quality. The recent regulations on wastewater discharge quality require the cities of Davis and Woodland to improve the quality of the treated wastewater before it is discharged. The solution pursued by Woodland and Davis is to replace the groundwater with high quality surface water from the Sacramento River. Changing the source water will result in acceptable wastewater quality. Replacement of groundwater with surface water from the Sacramento River was simulated to quantify the impact of the project on groundwater levels and changes in aquifer storage.

3.5.6 Climate change implications

The Yolo model includes specific features that provide simulation capabilities for evaluation of Yolo County water supply and flood management under various scenarios of climate change. Specifically, the detailed operation of the water supply conditions, including the operations of Cache Creek in conjunction with the groundwater basin, along with the detailed simulation of irrigation water supply system within the basin provides capabilities to simulate the effects of climate change scenarios on the surface water and groundwater resources in the area. This also includes evaluation of potential options for the operation of the basin that would result in long-term water resources sustainability in the area.

4. SUMMARY AND CONCLUSIONS

The State of California has pioneered in establishing the integrated water management plan at the regional level with greater transparency and involvement of stakeholders at various levels. One key component of the IRWM plans is to provide a technical evaluation of the water management conditions in light of changing climatic conditions. Various analytical tools are being used in support of the regional water management program. The IWR models have successfully been applied and used to analyze the integrated hydrologic conditions in many basins over the past two decades. This family of models includes the IGSM, IWFM, and IDC, all of which has recently been used to provide analytical support to the development of Integrated Regional Water Management Plans (IRWMP), and analysis of project impacts. The original code developed and applied successfully in many basins was the IGSM. The IGSM code features and simulation capabilities evolved to a robust level through many applications. The IGSM code evolved into IWFM through the work of CADWR. The IDC code was extracted out, by CADWR, as a stand-alone code for estimation of agricultural water demand and deep percolation. The IDC code can be used independently or in conjunction with any groundwater or hydrologic model for analysis of land use and surface water processes. There have been successful applications of integration of IDC with MODFLOW and other groundwater codes [81]. While the IGSM code is primarily supported by the private consulting firms, the IWFM code enjoys the technical support of the CADWR, and is evolving into the next generation integrated water model. Although some of the features of IWR models are only available in the IGSM code (reservoir operation and water quality simulation), CADWR may consider adding these features to the IWFM over time.

The main features of the IWR models are:

- Simulation of rainfall runoff for various land use conditions

- Calculation of agricultural water demand for various crop conditions and irrigation practices
- Simulation of groundwater and surface water supply to meet agricultural and urban demands
- Simulation of surface tile drainage and storm runoff
- Simulation of stream flow conditions, diversions from streams, return flow and runoff to streams, and stream-aquifer interaction
- Estimation of infiltration using a soil moisture accounting methodology, and calculation of recharge through unsaturated zone
- Simulation of quasi-3 dimensional groundwater flow
- Calculation of land subsidence
- Simulation of operations of multi-purpose reservoir systems
- Mass transport and water quality simulation

The IWR models have been applied to more than 20 basins and watershed throughout California. Five of the key applications have been highlighted in this paper, with reference to the type of projects analyzed using these models. These model applications are in Central Valley, North American River Basin and Sacramento County, Salinas Valley, Kings Basin, and Yolo County, California.

The IWR models are suitable tools for evaluation of statewide water resources to support the statewide program evaluations in California. The statewide applications can be linked to the reservoir operation models such as CALSim, as well as integration with other operational tools used to support the California Water Plan, such as the WEAP model.

The IWR models are superb analytical tools for evaluation of vulnerability and adaptation strategies under climate change scenarios. GCM information downscaled to regional scale, and combined with local and field level verified data can be used in IWR models to evaluate the impacts of climate change on the land and surface processes, as well as the groundwater system, and stream-aquifer interaction.

With significant simulation capabilities and features, ease of use, ArcGIS-based GUI, and diverse set of applications throughout California, the IWR models are excellent analytical tools for evaluation of projects and programs considered under the IRWMPs throughout California, and elsewhere.

ACKNOWLEDGEMENTS

This paper is dedicated to our long-term advisor and mentor, Professor Miguel A. Marino. Miguel has dedicated his professional life to the research, development, and application of groundwater and integrated hydrologic models, and other specialty areas such as reservoir operations and optimization of water resources systems. Many thanks to Miguel for his vision and dedication in integrating simulation models with optimization approaches and economic principles.

The authors and other professionals who have been involved in development, enhancement and application of integrated water resources models using IGSM are indebted to Dr. Young Yoon, who was the original author of the IGSM code. Young's legacy lives on.

The development and application of the IWR models could not have been possible without the direct involvement, supervision, interaction and review of the projects by the staff and management from the respective water agencies, such as CADWR, U.S. Bureau of Reclamation, U.S. Fish and Wildlife Service, Sacramento Groundwater Authority, Sacramento Central Groundwater Authority, Sacramento County Water Agency, the Water Forum, Kings River Conservation District, Monterey County Water Resources Agency, Yolo County Water Conservation and Flood Control District, and other agencies involved in many applications of the IWR model, the list of which is too long to be named in this paper. We express our sincere thanks to these agencies, their staff and management.

The models presented in this paper are the work of many engineers and scientists from various private consulting firms, and especially past and present staff from WRIME, Inc., and RMC Water and Environment, who have been involved in the development and application of much of the IWR models. Many of these staff are now working in public agencies or other private firms, and use these models for water resources planning and management for their respective projects and agencies. We appreciate and acknowledge their contributions and dedications.

Lastly, the authors express their appreciation to the reviewers for the constructive comments, which improved the quality of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Markstrom SL, Niswonger RG, Regan RG, Prudic DE, Barlow PM. GSFLOW-Coupled Ground-water and Surface-water FLOW model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005). U.S. Geological Survey Techniques and Methods. 2008;6-D1.
2. Leavesley GH, Lichty RW, Troutman BM, Saindon LG. Precipitation-runoff modeling system-User's manual. U.S. Geological Survey Water-Resources Investigation Report. 1983;83-4238.
3. Haarbaugh AW. MODFLOW-2005, the U.S. Geological Survey modular ground-water model – the Ground-Water Flow Process. U.S. Geological Survey Techniques and Methods. 2005;6-A16.
4. United States Geological Survey. Summary of GSFLOW. Coupled Ground water and Surface-water FLOW model based on the USGS Precipitation-Runoff Modeling System (PRMS) and Modular Ground Water Flow Model (MODFLOW-2005). Accessed 2013.
   Available: http://water.usgs.gov/nrp/gwsoftware/gsflow/gsflow.html (accessed 2013).
5. Ely DM, Kahle SC. Simulation of Groundwater and Surface-water Resources and Evaluation of Water-Management Alternatives for the Chamokane Creek Basin, Stevens County, Washington. U.S. Geological Survey Scientific Investigations Report. 2012;2012-5224.
6. Huntington JL, Niswonger RG. Role of surface-water and groundwater interaction on projected summertime streamflow in snow dominated regions: An integrated modeling approach. Water Resources Research. 2012;48:W11524

7. Surfleet CG, Tullos D, Chang H, Jung I. Selection of hydrologic modeling approaches for climate change assessment: A comparison of model scale and structures. Journal of Hydrology. 2012;464-465,233-248.
8. Schmid W. A Farm Package for MODFLOW-2000: Simulation of Irrigation Demand and Conjunctively Managed Surface-water and Ground-water Supply. A Dissertation submitted to the Faculty of the Department of Hydrology and Water Resources: The University of Arizona; 2004.
9. Schmid W, Hanson RT, Maddock T, Leake SA. User Guide for the Farm Process (FMP1) for the U.S. Geological Survey's Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, MODFLOW-2000. U.S. Geological Survey. Techniques and Methods. 2006;6-A17.
10. Schmid W, Hanson RT. The Farm Process Version 2 (FMP2) for MODFLOW-2005 – Modifications and Upgrades to FMP1. U.S. Geological Survey Techniques in Water Resources Investigation. 2009; Book 6, Chapter A32.
11. Faunt CC. Groundwater Availability of the Central Valley Aquifer, California. U.S. Geological Survey Professional Paper. 2009;1766.
12. Hanson RT, Schmid W, Faunt C, Lockwood B. Simulation and Analysis of Conjunctive Use with MODFLOW's Farm Process. Groundwater Journal; 2010.
13. Therrien R. Three-dimensional analysis of variably- saturated flow and solute transport in discretely-fractured porous media. Ph.D. thesis. University of Waterloo; Water- loo, Ont; 1992
14. Brunner PM, Simmons CT. HydroGeoSphere: A Fully Integrated, Physically Based Hydrological Model. Ground Water. 2012;50(2);170-176.
15. Li Q, Unger AJA, Sudicky EA, Kassenaar D, Wexler EJ, Shikaze S. Simulating the multi-seasonal response of a large-scale watershed with a 3D physically-based hydrologic model. Jour. Hydrol. 2008;357(3-4):20.
16. Pérez AJ, Abrahão R, Causapé J, Cirpka OA, Bürger CM. Simulating the transition of a semi-arid rainfed catchment towards irrigation agriculture. Journal of Hydrology. 2011;409(3–4, 9):663-681.
17. Sciuto G, Diekkrüger B. Influence of Soil Heterogeneity and Spatial Discretization on Catchment Water Balance Modeling. Vadose Zone J. 2010;9:955–969.
18. Harter T, Kourakos G, Morel-Seytoux H. Peer Review of Groundwater Models used in California's Central Valley. Prepared for the California Water and Environment Modeling Forum (CWEMF): Sacramento, CA; 2013.
19. Danish Hydraulic Institute (DHI). MIKE SHE model. Accessed 2013. Available: www.dhisoftware.com
20. Danish Hydraulic Institute (DHI). MIKE SHE Water Movement - User Guide and Technical Reference Manual, Edition 1.1. 1998
21. Danish Hydraulic Institute (DHI). MIKE 11 - User Guide and Technical Reference Manual.1998.
22. Yan J, Hopkin E, Sørensen HR, Kjelds JT. Integrated hydrological modeling in South Florida Water Management District. In: Proceedings of the 1998 International Water Resources Engineering conference.1998; Vol. One; Memphis, TN.
23. Yan J, Sørensen HR, Kjelds JT, Hopkin E. The development and applications of integrated surface water and ground water model in South Florida. In: Proceedings of 3rd DHI Software Conference, June 7-11. 1999; Helsingør, Denmark.
24. Begey MB, Gonella M, Teatini P, Refsgard A, Basberg L. MIKE-SHE application to the recovery project of a former industrial area in Ravenna, Italy, strongly polluted by toxic metals. In: Proceedings of 3rd DHI Software Conference. 1999; Helsingør, Denmark.

25. Sørensen HR, Jacobsen TV, Kjelds JT, Yan J, Hopkins E. Application of MIKE SHE and MIKE 11 for integrated hydrological modeling in South Florida. In: Proceedings of 3rd DHI Software Conference. 1999; Helsingør, Denmark.
26. Cargnelutti M., Quaranta N, Refsgaard A, Basberg L. Application of MIKE-SHE to the alluvial aquifer of River Adige's valley. In: Proceedings of 3rd DHI Software Conference. 1999; Helsingør, Denmark.
27. Stisen S, Jensen KH,Sandholt I, Grimes D. A remote sensing driven distributed hydrological model of the Senegal River basin. J. Hydrol.2008; 354(1-4): 131-148.
28. Stockholm Environment Institute (SEI). Water Evaluation and Planning Model (WEAP). Accessed 2013.
    Available: http://www.weap21.org/
29. Raskin EH, Zhu Z. Simulation of Water Supply and Demand in the Aral Sea Region. Water International J. 1992;17:55-67.
30. Joyce B, Vicuña S, Dale L, Dracup J, Hanemann M, Purkey D ,Yates D. Climate Change Impacts On Water For Agriculture In California: A case study in the Sacramento valley. White Paper: California Climate Change Center; 2006.
31. Rayej M, Juricich R, Groves D, Yates D. Scenarios of Future California Water Demand through 2050: Growth and Climate Change. World Environmental and Water Resources Congress. 2011;4423-4432.
32. JMM (James M. Montgomery). Documentation and User's Manual for Integrated Groundwater and Surface water Model. Sacramento, CA; 1990.
33. JMM (James M. Montgomery). Central Valley Ground and Surface water Model (CVGSM). Sacramento, CA; 1990.
34. WRIME. Integrated Groundwater and Surface Water Model (IGSM) User's Manual. WRIME: Sacramento, CA; 2003.
35. RMC-WRIME. Sacramento Area Integrated Water Resources Model (SacIWRM) - Model Development and Baseline Scenarios. Sacramento, CA; 2011.
36. California Department of Water Resources (CADWR), Integrated Water Flow Model IWFM v4.0 Theoretical Documentation. 2012. Accessed 2013.
    Available:http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/IWFMv4_0/v4_0_266/index_v4_0_266.cfm
37. Brush C, Dogrul EC. User Manual for the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), Version 3.02-CG. CADWR Technical Memorandum; 2013.
38. RMC-WRIME. Technical Memorandum: California Central Valley Groundwater-Surface Water Simulation Model (C2VSim) – Spatial Resolution & Development of ArcGIS-Based Modeling Environment. Sacramento, CA; 2012.
39. California Department of Water Resources (CADWR). Guidelines, Integrated Regional Water Management – Proposition 84 and 1E. Division of Integrated Regional Water Management; 2012.
40. California Department of Water Resources (CADWR). Strategic Plan for the Future of Integrated Regional Water Management in California – Development Approach. 2012. Accessed 2013.
    Available: www.water.ca.gov/irwm/stratplan/
41. Montgomery Watson, Camp Dresser & McKee, CH2M Hill. Chino Basin Water Resources Management Study; 1993.
42. Montgomery Watson. Pajaro Valley Groundwater-Surface water Model Update. 1993.
43. Montgomery Watson. Final Report on Groundwater Management Study for Pomona Valley Protective Association (PVPA); 1993.
44. JMM (James M. Montgomery). Alameda County Integrated Groundwater-Surface water Model; 1991.

45. CDM. Butte Basin Groundwater Model Update Phase II Interim Technical Memorandum; 2005.
46. WRIME. Hydrological Model of Capay Valley in Support of the CCCR Event Center Project TEIR. Technical Memorandum prepared for Analytical Environmental Services; 2010.
47. JMM (James M. Montgomery). Friant Service Area Groundwater Study; 1992.
48. Montgomery Watson. Imperial County Groundwater Study; 1996.
49. WRIME. Lower Colusa Basin IGSM Calibration Process; 2002.
50. WRIME. Niles Cone and South East Bay Plain Integrated Groundwater and Surface water Model (NEGIGSM); 2005.
51. Montgomery Watson. Salinas River Basin Water Resources Management Plan Task 1.09 Salinas Valley Groundwater Flow and Quality Model Report. Prepared for Monterey County Water Resources Agency; 1994.
52. CH2M Hill. Stanislaus Basin Integrated Groundwater and Surface Water Model Report. Prepared for U.S. Bureau of Reclamation; 1999.
53. Montgomery Watson, Ali Taghavi Associates, LSCE. Soquel-Aptos Integrated Groundwater and Surface Water Model (SQIGSM), Technical Memorandum 3: Model Input Data Development and Model Calibration; 1998.
54. WRIME. Stony Creek Fan Integrated Groundwater and Surface water Model (SCFIGSM) Model Development and Calibration and Baseline Analysis; 2003.
55. California Department of Water Resources (CADWR). Yuba County Groundwater Model Development, Calibration and Simulation Results. 1998.
56. California Department of Water Resources (CADWR). Integrated Water Flow Model: IDC v4.0 – Theoretical Documentation. Integrated Hydrologic Models Development Unit: Modeling Support Branch, Bay-Delta Office, CADWR, Sacramento, CA; 2012. Accessed 2013.
    Available: http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/
57. California Department of Water Resources (CADWR). IWFM Demand Calculator: IDC v4.0 – Theoretical Documentation and User's Manual. Integrated Hydrologic Models Development Unit: Modeling Support Branch, Bay-Delta Office, CADWR, Sacramento, CA; 2012. Accessed 2013.
    Available:http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/IDC/index_IDC.cfm>.
58. Namvar R, Cayar M; Traum J, Tijerina E, Najmus S, Taghavi A. IDC, Uniquely Positioned For Diverse Applications. Oral Presentation: CWEMF; 2011.
59. Leake SA, Prudic DE. Documentation of a computer program to simulate aquifer-system compaction using the modular finite-difference ground-water flow model. Department of the Interior, U.S. Geological Survey Open-File Report. 1988;88-482.
60. Cayar M, Najmus S, Taghavi A. A Particle Tracking Model, IGSM_PT, as a Post-Processor to Finite-Element Groundwater Flow Model, IGSM. Conference Paper and Oral Presentation In: World Environmental and Water Resources Congress; 2010.
61. California Department of Water Resources (CADWR). California Central Valley Groundwater-Surface Water Simulation Model, C2VSim. 2012. Accessed 2013.
    Available: www.water.ca.gov.
62. Domagalski JL, Brown LR. National Water-Quality Assessment Program – The Sacramento River. U.S. Geological Survey Fact Sheet. 1998;FS 94-029.
63. United States Geological Survey (USGS). Surface water monthly statistics for USGS 11303500 San Joaquin River near Vernalis, CA. Accessed 2013.
    Available: http://nwis.waterdata.usgs.gov
64. Taghavi A. California Central Valley Simulation Model (C2VSIM) Enhancement: Phase I – Spatial Refinement. Oral Presentation In: CWEMF; 2012.

65. Taghavi A, Namvar R, Cayar M, Tariq K, Charles B, Can D. C2VSIM (California Central Valley Groundwater-Surface Water Simulation Model. Poster In: CWEMF. 2012.
66. Regional Water Authority (RWA). Strategic Plan. 2009. Accessed 2013. Available: www.rwah2o.org.
67. The Nature Conservancy (TNC). The Premise of Reservoir Re-Operation: Implications for Integrated Water Management. 2011. Accessed 2013. Available: www.nature.org.
68. RMC. Sacramento County Integrated Water Resources Model (SacIWRM): A White Paper on the Model's Past, Present, and Future. 2012.
69. Water Forum. Final Environmental Impact Report. Sacramento Area Water Forum. 1999. Accessed 2013. Available: http://www.waterforum.org/EIRdocs.cfm.
70. Taghavi A, Cayar M, Swartz R, Traum J. Impact of Groundwater Banking and Extraction Program on Stream-Aquifer Interaction in North American Groundwater Subbasin. Poster In: CWEMF; 2012
71. WRIME. Kings Basin Integrated Groundwater and Surface Water Model (Kings IGSM) – Model Development and Calibration. In Coordination with: California Department of Water Resources; Sacramento, CA; 2007.
72. Kings River Conservation District (KRCD). Upper Kings Basin Integrated Regional Water Management Authority. 2012. Accessed 2013. Available: www.krcd.org/water/ukbirwma
73. Monterey County Agricultural Commissioner's Office. Monterey County 2010 Crop Report. 2010. Accessed 2013. Available: http://ag.co.monterey.ca.us/resources/category/crop-report.
74. Monterey County Water Resources Agency, Salinas Valley Integrated Regional Water Management Functionally Equivalent Plan, Summary Document, Update; 2006.
75. Monterey Peninsula Water Management District, Big Sur Land Trust, City of Monterey, Monterey County Water Resources Agency, Monterey Regional Water Pollution Control Agency. Monterey Peninsula, Carmel Bay, and South Monterey Bay Integrated Regional Water Management Plan; 2007.
76. Geoscience Support Services. North Marina Groundwater Model, Evaluation of Potential Projects; 2008.
77. Blanke J, Namvar R, Taghavi A. Impact of Precipitation Changes on Operation of Reservoirs and Sustainable Yield of Groundwater Basins. Poster In. Groundwater Resources Association of California Climate Change Conference; 2008.
78. Yolo County Agricultural Commissioner's Office. Yolo County 2011 Crop Report. Accessed 2013; 2011. Available: www.yolocounty.org.
79. Westside Sacramento Regional Water Management Group. Draft Section 5, Westside Sacramento Integrated Regional Water Management Plan: Prepared by Kennedy/Jenks Consultants; 2012.
80. WRIME. Yolo County Integrated Groundwater and Surface Water Model – Model Development and Calibration. Prepared for Yolo County Flood Control and Water Conservation District and Water Resources Association of Yolo County; 2006.

81. WRIME. Riverside-Arlington Groundwater Flow Model (RAGFM) – Model Development, Calibration, and Baseline Conditions. Sacramento, CA: Prepared for Riverside Public Utilities and Western Municipal Water District; 2012.

Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sciencedomain.org/review-history.php?iid=267&id=10&aid=2033