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Peer Review of the IWFM, MODFLOW and HGS Model Codes:

Potential for Water Management Applications in California's Central Valley and Other Irrigated Groundwater Basins

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The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the U.S. Bureau of Reclamation.

Contents

Abstract

Three groundwater modeling codes are reviewed that are highly relevant to developing groundwater models in California: HydroGeoSphere (HGS), Integrated Water Flow Model (IWFM), and MODFLOW. Each of these codes has potential strengths and weaknesses depending on the specific objectives for which the model is developed. The review summarizes the model codes' conceptual elements, their usability, and the potential for application to management of groundwater issues found in California or more generally to water management in irrigated agricultural groundwater basins.

The three codes are very good modeling codes. Each model code's individual usefulness as a (ground)water assessment and management tool, however, depends on the specific application, on available data, and on the expertise of the modeling team. MODFLOW with the "Farm process" and the IWFM model code are particularly well suited for studies of groundwater and water management alternatives in California's irrigated agricultural groundwater (sub)basins. To a large degree they were originally designed as regional assessment and planning tools. This is not to say that they cannot also be applied at much smaller scale for site investigations, especially when not all the capabilities of the model are required for a particular local study. Despite the fact that water operations are managed on a daily basis, both MODFLOW's Farm process and IWFM effectively operate on monthly time scales for water management. The model code Hydrogeosphere (HGS), was designed primarily as a research tool and is especially well suited for highly integrated hydrologic modeling involving detailed simulation of rainfall-runoff, infiltration, vadose zone flow, streamflow, and groundwater processes. But HGS is lacking the management simulation capabilities built into the MODFLOW Farm process and into IWFM. With care and effort, a management modeling tool may be added externally.

For transport of pollutants in groundwater, none of these three codes provide a full range of options. HGS provides the most comprehensive transport modeling capability by integrating transport across the surface water – vadose zone – groundwater continuum. HGS can account for sorption and degradation. It is also capable of simulating energy/heat transfers and variable density (e.g., saline water) flow. In the saturated and unsaturated zone, it can handle fracture flow, macropore flow, and porous media flow. MODFLOW is commonly coupled with MT3D to perform transport in groundwater (but not in the vadose zone or in surface water). Options exist for modeling heat transport, but not simultaneously with pollutant transport. MODFLOW with MT3D does not handle variable density flow. However, MODFLOW with the Farm process currently cannot be coupled with MT3D. IWFM does not offer a transport code, although a code developer could use IWFM results to run a separate transport modeling code. Hence, none of the three models provide transport simulation capacity coupled with water management simulations.

Nature is complex and its secrets are concealed in all but few details. Particularities of a (ground)water system are at best characterized in broad, but relevant strokes. Model code developers made the implicit and practical choice that it is better to obtain an approximate solution to a realistic situation than an exact one to a highly idealized situation. The latter approach is only used to verify model codes for a number of simple cases for which exact solutions are known. All three codes have been demonstrated to be accurate for such cases. All three codes also have been applied in a wide range of real world situations (including situations in California) and through calibration were able to match historical observations with reasonable accuracy. But while all solve the same groundwater equation, the conceptual and mathematical implementation of many of the necessary conceptual details drastically differ between the three codes. Even with the same data for a real concrete situation, each code will therefore give possibly significantly different results.

Generally, such lack of agreement stems from the fact that the scientific community does not offer a single best method for those processes that drive recharge to and discharge from groundwater flow systems, such as plant transpiration or the effects of plant stress under drought, or a farmer's decision—making process. For that reason, we recommend that planning studies that lead to large expenditure of funds require multiple codes to be used by separate modeling teams. If the relative difference in the results between two (or more) models is sufficiently small, one can proceed with confidence with the implementation of the plan. On the other hand, if the difference is not considered small enough, a more refined study is needed to determine what drives these differences. This in turn may lead to critically important data collection and monitoring programs. The associated additional study cost is likely justified in view of the alternate possibility of a much larger financial cost attached to an implemented plan that fails to meet its objectives due to model error.

Finally, in our experience, the use of these codes and the development of a groundwater model for a particular region and with specific objectives in mind are not simple tasks. Well qualified consultants, engineers, or scientists are necessary to apply these tools.

1 Executive Summary

The development of California's large and diversified economy has always relied on the availability and high quality of water resources. Groundwater is a significant and important element of California's hydrologic cycle, of its water resources system and of the water management infrastructure in the state. Groundwater is an important freshwater resource, but also subject to the many anthropogenic activities that affect groundwater quality and availability. Groundwater models of specific sites, groundwater basins, or regions rely on three key elements: field and literature data, a conceptual model, and a groundwater modeling code, also referred to as groundwater modeling program or groundwater modeling software. Groundwater modeling codes are a mathematical representation of physical, chemical, biological, and other hydrological, environmental, and sometime even legal, economic and policy concepts. The mathematical representation in these numerical (computer) codes allows the user to predict the dynamics of groundwater flow and/or transport and/or water quality dynamics throughout a groundwater site/basin/region based on key system drivers (e.g., pumping, recharge, pollution).

This review is specifically geared toward developing responses to the type of questions that typically arise around the use of model codes, when managers, decision makers and the general public are involved in water resource management issues in which groundwater models are employed to address concerns typically present in water resource planning and environmental assessment studies. Furthermore, this review focuses primarily on basin-scale or sub-basin-scale groundwater modeling under California conditions, which typically require simulation of agricultural water demands. Three groundwater modeling codes are reviewed that are highly relevant to developing groundwater models in California: HydroGeoSphere (HGS), Integrated Water Flow Model (IWFM), and MODFLOW.

The review summarizes the model codes' conceptual elements, the usability of each of these codes, and the application to various groundwater issues common to California. Each of these codes has strengths (and some potential weaknesses) and the decision to apply one or the other code for a specific groundwater model depends on the specific objectives for which the model is developed. It also depends upon the scope of the application, and the expertise and training of the groundwater modeler that builds the groundwater model, on the available field and literature data, and the conceptual model.

It was outside the scope of this review to implement a rigorous verification of each modeling code to ensure that the results obtained are sufficiently exact given the specific mathematical problem implemented. Existing reviews do not indicate significant shortcomings with any of the three modeling codes. However, while all three codes solve the same groundwater flow equation, and do so in a reasonably accurate way, they differ in the variety of associated modeling tools that help integrate the groundwater flow/transport/quality system into the broader hydrologic, economic, and policy frameworks that drive and control or depend on the groundwater flow/transport/quality system. In this review the aptitudes of the three codes are compared with respect to their capabilities to take into account groundwater recharge and pumping, conjunctive use management, land subsidence, etc. However, whatever code is applied, a case-by-case groundwater model sensitivity analysis and a rigorous assessment of groundwater model prediction inaccuracy due to uncertainty about model parameters and boundary conditions is a key component of each individual groundwater model development.

Groundwater models may be developed to support the assessment and decision-making process for a wide range of water management issues within these institutional, legal, and hydrologic-geographic frameworks. Some models may focus on a particular aspect, while others attempt to address a multitude of issues with the same (often integrated) hydrologic model. Frequently, groundwater models are developed to address water issues in the highly developed alluvial groundwater basins of southern, central, and coastal California. Southern California's adjudicated and predominantly urban groundwater basins monitor and report groundwater extraction providing a rich database on groundwater flows. However outside of these basins, the agricultural operations and their largely unmonitored use of and impact on water resources requires models capable of simulating both groundwater extraction and groundwater recharge based on expert knowledge about these agricultural systems. « An integrated hydrologic model to be applicable to California's agricultural groundwater basins (Central Valley, coastal basins) must be able to predict agricultural water demands, and to dynamically predict available water supplies in terms of surface water diversions and groundwater pumping to meet these demands » (DWR, 2012). Even less groundwater modeling work is done in California's undeveloped desert regions or on fractured rock aquifer systems in California's mountain ranges. Most groundwater models must therefore address a number of key processes in one form or another (modified from DWR, 2012, Appendix 2):

1. hydrogeologic characteristics of the aquifer and surface and subsurface flow interactions must be represented adequately,
2. land surface and root zone flow processes must be simulated in a reasonably accurate way,
3. spatial and temporal data/information availability must be appropriately reflected in the complexity of groundwater models,
4. economic and policy decisions that depend on the complex patterns of surface water and groundwater availability (in space and time) must be simulated to properly represent the dynamics of groundwater extraction, surface water diversions, irrigation management, wastewater discharges, and intentional recharge,
5. constraints on water management imposed by
    a. water rights,
    b. water quality and ecosystem regulations,
    c. water availability, and
    d. infrastructure (wells, canals, storage capacity in reservoirs and groundwater basins) must be represented properly, either by explicitly building these into model boundary conditions (internal or external) or by representing these as conceptual systems in the modeling code structure.
    e. future climate change and socioeconomic developments

The three model codes differ significantly in three areas: the computation of evapotranspiration, the flow and storage of water in the root zone, and the flow of water across the stream-aquifer interface. The conceptual and methodological differences between the three codes on these aspects may lead to significantly different predictions on water use and water fluxes. Neither approach is preferable or of higher accuracy. Differences are of conceptual nature and the choice depends on the user's objectives.

For solute transport, IWFM has no water quality simulation capability though its output could be used as input for a groundwater solute transport code. MODFLOW itself also does not address transport issues. However a separate code is available that tightly integrates with MODFLOW to also simulate transport and geochemical processes. In HGS, solute transport is part of the model code itself. Importantly, HGS – unlike the other two codes - follows the solute transport across multiple components of the hydrological cycle such as rivers, unsaturated zone, groundwater, and lakes. In addition HGS considers a variety of chemical and biological transformations. HGS also simulates the situation of non-isothermal and variable density situations.

For groundwater models that are used to make major, costly management decisions and involving large economic transactions (e.g., water transfers), the reviewers recommend that agencies (local, state or federal) consider the development of multiple groundwater models that are developed in parallel based on different model codes, perhaps by different modeling teams. Multiple groundwater models afford a better understanding of the magnitude and significance of errors associated with different conceptual methods associated with each code, particularly in the assessment of the evapotranspiration system, the root zone water system, the stream-groundwater interaction system and the determination of water levels in wells. It is difficult to assess the relative merit of a particular component when it is immersed within numerous other parts of a code. Groundwater models based on different codes are best compared on a case-by-case basis. This multi-model approach is currently lacking in the agency and in the model consulting culture. Additional costs are cited as a key constraint. However, for projects that incur large cost transactions, the development of multiple (instead of a single) groundwater models may dwarf the (otherwise unknown) potential errors associated with a single model. The use of multiple models is well accepted in other modeling communities, particularly in the climate change modeling community.

2 Introduction

2.1 The Process of Building a Groundwater Model

The development of California's economy is intrinsically tied to the abundance and high quality of the state's water resources. Groundwater is a significant and important element of California's hydrologic cycle, of its water resources system, and of the water management infrastructure in the state. Groundwater is an important resource for industrial and urban water uses, for drinking water supplies, and for irrigation water supplies. It is also intrinsically linked to ecosystem services in riparian and riverine areas. Groundwater is exposed to many anthropogenic activities that affect groundwater quality and availability.

The threat of long-term droughts and the uncertainty of climate change impacts on California's surface water resources continue to increase our interest in groundwater. Unlike surface water, groundwater resources are hidden from view, more difficult to quantify and rates of recharge and depletion are difficult to estimate with current monitoring. Groundwater availability and use, groundwater overdraft, groundwater quality degradation, land subsidence, and the connection between groundwater and surface water are all important aspects of water resources management in California.

Understanding groundwater movement, changes in groundwater storage, and the linkages between groundwater, groundwater uses, groundwater recharge, land-use, streams, and ecosystems is critical to sustainably managing California's water resources, which are the foundation to the state's economic health, the health of its people, and the viability and diversity of its ecosystems.

A wide range of groundwater modeling tools - conceptual, statistical, physical, or mathematical - have been used to organize data collected from groundwater systems. They have also been instrumental to advance our knowledge about groundwater. This includes the physical, chemical, and biological processes within groundwater systems, but also across the continuum of groundwater systems linked with or embedded within surface water systems, the hydrologic cycle, ecology, anthropogenic land-use systems, and economic and social systems.

In modern hydrogeological practice, the judicious use of conceptual models, computer models, and a large variety of other modeling tools is essential to all analyses, evaluations, and assessments about groundwater.

In this report, we review three prominent numerical (computer-based) physico-chemical groundwater model codes that have been applied to develop California-specific groundwater models for assessment of specific groundwater-related issues. The three model codes are:

- "MODFLOW" (Harbaugh, 2005) is currently the most popular numerical groundwater modeling code used in the United States and also widely used around the world. The acronym stands for the *mod*ular programming structure of this groundwater *flow* modeling code. Individual modules commonly are referred to as "packages". Packages can be assembled into a variety of codes, all of which together are here referred to as MODFLOW. Sometimes, it is helpful to talk about specific packages to identify a specific implementation of the MODFLOW code.

- "Integrated Water Flow Model (IWFM)" (DWR, 2012) is the State of California's own numerical groundwater modeling code, which has found applications in basin-wide groundwater modeling studies inside and outside of California.
- "Hydrogeosphere (HGS)" (Therrien et al., 2012) is an advanced hydrologic modeling code that includes the groundwater system as part of and fully integrated into a physico-chemical representation of the terrestrial hydrologic system.

Pioneering hydrogeologists in the late 19th century and early to mid-20th century were limited to representing groundwater in greatly simplified ways that would lend themselves for manual (analytical) solutions of the mathematical equations governing the physics of groundwater flow. In the late 20th century, numerical groundwater models have greatly expanded the application of physics and chemistry to highly complex natural groundwater systems.

While allowing groundwater modelers to represent many complexities of the natural system, all groundwater models are a simplification of nature. Numerical groundwater models are like a TV screen: The screen represents a complex image through a finite number of tiny pixels, each with just one color. Similarly, a groundwater model discretizes nature's complexity into a number of individual pixels (model cells or model elements), each of which represents an average property and state of groundwater for that cell or element. Importantly, groundwater models are designed to follow the physical principles of groundwater flow: the principle of mass conservation and Darcy's law. Darcy's law is an expression of the principle of energy conservation. On that basis, numerical models are entirely consistent with analytical mathematical models of groundwater physics, such as those used to analyze groundwater pumping tests.

Just as the TV image is only a simplification of reality, a numerical groundwater model is but a simplified representation of reality. For most questions about groundwater, a precise reproduction of reality is not only impossible, it is also not necessary to obtain relevant answers. The "art" of groundwater modeling is largely a task of simplifying the complexity of the real groundwater system given specific objectives. The simplification must capture essential and relevant processes and properties in sufficient spatial and temporal detail. Yet, the model cannot become overly complex and data intensive. That would make the model unwieldy in terms of either the required data input or the necessary computer runtime and memory.

Water resources agencies and private consultants have relied on numerical groundwater models to characterize groundwater resources, to estimate fluxes of water that recharge and are withdrawn from groundwater basins, to understand surface water – groundwater connectivity, to predict land subsidence, to assess groundwater contamination, to develop groundwater remediation systems, to evaluate the impact of construction projects that require any kind of groundwater extraction, to develop conjunctive use management plans, and for many other applications. Over the past three decades, some regions have seen the development of multiple groundwater models for a variety of purposes. This often leads to confusion among the public about both, the need for multiple groundwater models and the potentially conflicting results obtained from seemingly comparable groundwater models. Good communication about the purpose and nature of a model is therefore paramount.

Some of the confusion stems from the vague use of the term "model". Sometimes, this may refer to a computer program or software, sometimes the term refers to a particular project that utilizes computer software to simulate a specific site or aquifer. In this report we make a clear distinction between a "groundwater (modeling) code", which is a computer program that can be applied to many groundwater problems, and a "groundwater model", which is a specific application to a particular site, region, or groundwater basin for a specific purpose. For example, HGS, IWFM, and MODFLOW are modeling codes. Examples of groundwater models are CVHM (Faunt et al., 2009, an application of MODFLOW to the Central Valley) and C2VSIM (Brush, 2011, an application of IWFM to the Central Valley).

Groundwater models of any site or groundwater basin – as any other working model of natural systems – consist of three fundamental building blocks:

1. Data: Groundwater related data include water level measurements, measurements of groundwater hydraulic conductivity, transmissivity, porosity, storativity, etc., measurements that describe the geology of the subsurface to identify aquifer boundaries, measurements of spring flow, well discharge, and streamflow, climate measurements (precipitation, temperature, etc.), and many others. Data may be measured in the field, estimated in the laboratory, estimated by experience from similar aquifer systems, or they may be selected arbitrarily from a wide range of possible sources.
2. A conceptual groundwater model: The conceptual model describes the extent of the groundwater system of interest (horizontally and vertically), the physical processes that are considered relevant to properly represent what happens in the natural groundwater system, the chemical and biological processes that are considered relevant, the spatial and temporal scales at which these processes are represented, the aquifer properties and their spatial variability, the boundary conditions (both, internal to the modeling domain, e.g., wells, or along its boundary) that drive changes in groundwater flow and groundwater levels, and the initial conditions of the groundwater system. The conceptual model is a cartoonish representation of the real world, informed by the data available and the expert knowledge about groundwater processes and the hydrologic system.
3. The modeling code is the mathematical representation of the conceptual model. The groundwater modeling code solves a mathematical equation (or a set of mathematical equations). Aquifer properties are represented in the equation as parameters. The mathematical equation includes initial conditions describing the state of the groundwater at the beginning of the simulation time; and the mathematical equation includes boundary conditions – e.g., water levels and groundwater fluxes at internal or external boundaries to the aquifers system of interest. To solve the equation, the groundwater model area (or volume) is divided into thousands to hundreds of thousands or even millions of pixels (cells, elements). The code takes care of all the mathematical calculations necessary to obtain a numerical (computer generated) solution to the mathematical problem. The computer model reads input data prepared by the user based on the data (#1 above) and the conceptual model (#2 above). With the input data, the computer code is executed and then generates output data (simulation results).

Each individual groundwater model development requires the compilation of site-specific data, expert knowledge, and the development of a conceptual model (which in turn may drive the data development). With all that at hand, the next step is to process available information to create appropriate model input for the numerical code. With the proper input files, the code is executed. Then, simulation results are compiled, tabularized, and visualized, often using additional computer software. Post-processing software is not part of the groundwater model code, but essential to the proper processing and analysis of the results.

The groundwater model for a specific application is therefore built by the actions and the knowledge of many people, including field and laboratory technicians, academics, consultants, people familiar with water resources, geology, hydrology, climate, and land-use activities at a particular site or in a particular region (groundwater basin), groundwater model code developers, and ultimately the groundwater modeler, i.e., the expert that applies the data collection, the conceptual model, and the groundwater model code to generate the specific groundwater model itself.

Because a groundwater model is the product generated by a team of people that knit information together not based on a rigorous scientific protocol, but based on opinion, perception, and expert knowledge, the groundwater model results will vary from team to team, even if two teams were given the task to develop a groundwater model for the same site, region, or basin application (Zimmerman et al, 1998). Groundwater models are therefore difficult to compare and evaluate. For example the regional groundwater systems being simulated within these models are discretized according to the best judgment of the modeler and rarely match, making direct data comparisons difficult to perform. The data that drives these models is subjected to various assumptions as they are transformed from a raw measurement into a form that makes sense to a computer. Even if the groundwater model code can be assessed for its accuracy, groundwater models are difficult to evaluate when the data and knowledge processing details that lead to a specific model are not described in sufficient detail.

The numerical algorithms that comprise the groundwater simulation model can differ also, even though they are solving the same mathematical equation – some are more efficient while others provide a better match to the theory of groundwater flow and transport. The only certainty in groundwater modeling is that the same groundwater model code will provide the same simulation results again and again, if it is fed the exact same input again and again.

2.2 Model Code Review: Objectives

The primary objective of this review is to perform an independent perspective and assessment of the capabilities of three model codes: IWFM (Integrated Water Flow Model, developed and used by the California Dept. of Water Resources), MODFLOW (United States Geological Survey) and HGS (HydroGeoSphere, a proprietary model used by the U.S. Bureau of Reclamation). It should be emphasized that the models reviewed in this report were the models which existed and were documented as of May 2012. Many modifications to the codes may have taken place since then but have not been part of this review.

These models are capable of not only of modeling groundwater flow, but also unsaturated flow above the water table, and stream flow. Thus they are in fact integrated hydrologic modeling codes, (even though in this report, for brevity, they are generally referred to as groundwater codes). In other words, they include more than one or two major components of the hydrologic cycle with much attention to the interaction of these components. An example is water movement in soils and its relation to overland flow above and deep percolation to the water table aquifer below.

All three of these model codes solve the classic three-dimensional groundwater flow equation (Appendix 4) subject to initial and boundary conditions. Nevertheless the codes differ in the algorithms used to solve the equation, they differ in their representation of initial and boundary conditions, they differ in the degree to which they represent processes other than groundwater flow, such as solute transport in groundwater, groundwater quality, processes at the land surface that control groundwater recharge from precipitation or irrigation, land subsidence that may be the result of groundwater level changes, and interactions between groundwater and surface water. The three groundwater model codes also differ in the processing needed to prepare the model input, the documentation of the groundwater model code, the review and verification of the code, the ease or difficulty of learning how to apply the code to develop a groundwater model, and the information generated from each code's simulation.

All of these differences may be relevant to the development of a groundwater model for a specific application. Differences between model codes may affect the amount of development time necessary, the data and data processing necessary to support the groundwater model development, the amount of computer programming and handling expertise needed, and whether or not sufficient information is generated by the code for both, proper model development and successful information delivery to meet the application's purpose.

The review provides a basic evaluation of the capabilities of these three model codes for performing the various types of analyses for which groundwater models are typically employed with a focus on applications in California and, more specifically, in California's irrigated agricultural regions such as the Central Valley. The review will focus on each model's capabilities in the areas described above and a brief comparison and assessment of differences when simulating various hydrologic, biologic and water quality processes. The intention of the review is not to identify the best model but rather to facilitate a better understanding of the types of applications that each model is capable of performing. Even at that, this review can only begin to scratch the surface given the complexity of the model codes and the scientific issues behind them.

Our review is specifically geared toward water managers, decision makers and the general public involved in water resource management issues that require groundwater models. Groundwater models may address a wide range of concerns typically present in water resources planning and environmental assessment studies.

2.3 Anticipated Benefits

The expected primary benefits of this review include providing decision makers and other interested parties with an overview of the modeling process and an introductory comparison of groundwater models that are currently being used in California and in California's Central Valley. The goal is to answer some key questions about model capabilities that will promote a better understanding of the modeling process and the appropriate uses for these model codes and to help diminish conflicts over differences in modeling results.

2.4 Materials Reviewed

A number of documents were reviewed. A list of the principal reports reviewed is provided in the Reference section, with a separate list provided for each code. Reviewed materials include reports that were written by staff from DWR, the USGS and the developers of HGS, specifically to document the theory, algorithms and procedures used in the code as well as to serve as manuals for the actual use of the codes.

2.5 Outline

CWEMF suggested that the reviewers provide answers to a set of questions. These questions are listed in Appendix 1. This report addresses these points and a few additional points deemed important by the authors. Representatives of each model code development team were provided the same set of questions and had the opportunity to express their viewpoints. A one-day workshop was held in June 2012 (the workshop input from each of the model code development team was placed onto the CWEMF website: http://www.cwemf.org/workshops/PeerReviewWorkshop/GWPeerReviewWkshpNtc.pdf). Following the workshop, written comments were exchanged between authors and model developers for further clarification. These written statements have been freely quoted within this report. If necessary, agreement, reservations, or disagreement have been indicated. Written answers to this set of questions were provided by the model code development teams. These contain important and insightful information and are provided unabridged in Appendices 2 and 3.

Following the general distribution of the March 15, 2013 draft report, a workshop was held on April 29, 2013 for the purpose of presenting the report and to solicit comments. Comments were submitted. They are presented in Appendices exactly as submitted with specific responses included. Jon Traum has provided a rich set of comments which are useful complements to the report. They are included as Appendix 7 and for the reader interested in a full understanding of the codes its reading is recommended. The main part of the report has also been modified to address the comments as appropriate.

The remainder of this review is structured as follows:

- Conceptual Groundwater Code Elements – Overview
- Theoretical Considerations and Model Code Implementation
- Code Verification and Model Calibration, and Validation
- Code Usability
- Model Applications in Groundwater Studies
- Conclusions and Recommendations

3 Model Evaluation

3.1 Conceptual Elements in California Groundwater Modeling

California has a wide range of hydrologic, geologic, and climate environments to be considered in groundwater modeling. Predominantly, California has a semi-arid Mediterranean climate with precipitation focused in winter months and a very dry season from April/May to September/October. Southeastern California's deserts are dominated by arid climate with occasional winter storms and summer convection rains. Potable groundwater is most abundant in California's alluvial basins – the Central Valley, the coastal basins from the California-Oregon border to the California-Mexico border, the southern California inland basins, and the alluvial basins of the predominantly arid eastern and southeastern Basin and Range province. Land-use overlying these alluvial groundwater basins consists of primarily native vegetation in the desert east and southeast, residential, business, and industrial urban land-uses with some irrigated agriculture in coastal southern California and the Bay Area, and irrigated agriculture with scattered, but significant urban land-uses in the Imperial and Coachella Valleys of southern California, in the central coast basins, in the Central Valley, and in few smaller mountain valleys.

California's water management system is often a critical driver in groundwater dynamics and groundwater quality. The system is a mixed private and public enterprise with a multitude of local water management agencies (counties, water districts, irrigation districts, public and private water purveyors), and a few large water management agencies engaged in managing large-scale, statewide water infrastructures: the federal Bureau of Reclamation (operator of the Central Valley Project) and the Army Corps of Engineers (operator of several dams), the California Department of Water Resources (operator of the State Water Project), and the Metropolitan Water District of Southern California (operator of the Colorado River aqueduct and largest contractor of the State Water Project). Surface water supply, including that used for intentional groundwater storage, is governed by a mix of riparian water rights and prior appropriation water rights. Groundwater supply extraction, other than that from intentional groundwater storage, is regulated and monitored in several adjudicated southern California groundwater basins, but is otherwise not monitored though legally subject to the Correlative Rights doctrine (Harter, 2008). Model codes are often required to incorporate or even simulate elements of this management system and the legal constraints placed on water allocation, but also on water quality.

Groundwater quality is regulated through a variety of state and federal laws (Harter, 2008). Several federal acts (such as the Toxic Substances Control Act and the Resources Conservation and Recovery Act) are aimed at preventing groundwater contamination by regulating and controlling land-uses involving toxic chemicals, landfills and underground storage tanks, and pesticides. The California State Porter-Cologne Water Quality Control Act sets water quality objectives and regulatory guidelines for dischargers of wastewater (including discharges to groundwater). And the state-federal Superfund program implements the cleanup of locally contaminated groundwater.

Water plays a critical role in sustaining not only a healthy population and thriving economy in California, but also provides important ecosystem services throughout the state. The federal Endangered Species Act and the public trust doctrine, designed to protect ecosystems, therefore play a critical role in the management of joint management of ecosystems, water supplies, and water quality in California, including groundwater, a significant design element for some groundwater models.

Geographically, the water management landscape of California is predominantly shaped by the fact: (1) that most precipitation occurs in Northern California and in California's high elevation central and northern mountain ranges, while most water users are located in the low elevation basins and valleys of Southern and Central California, and (2) that the most precipitation occurs in winter months, while most of the need for water use is in the summer. Furthermore, California experiences extended periods of wet years with ample precipitation to meet water supply needs and drought periods of one to many years with very limited precipitation that does not meet established water supply needs. California's water infrastructure of dams in the foothills of most mountain ranges, its statewide network of canals from north to south, and the conjunctive use of groundwater basin storage and surface water is designed primarily to bridge this spatial and temporal gap between precipitation occurrence and water use needs.

Water quality management implies increasing regulatory control of urban and agricultural land-uses that potentially threaten water quality objectives. To the degree that water quality is linked to ecosystem services, to water flows, and to the connection between groundwater and surface water, integrated management of water use and water quality, and of groundwater and surface water is of increasing importance.

Groundwater models may be developed to support the assessment and decision-making process for a wide range of water management and contaminant site issues within these institutional, legal, and hydrologic-geographic frameworks. Some models may focus on a particular aspect, while others attempt to address a multitude of issues with a single (often integrated) hydrologic model. Frequently, groundwater models are developed to address groundwater contamination and water resources issues in the highly developed alluvial groundwater basins of southern, central, and coastal California. Much less groundwater modeling work is done in California's undeveloped desert regions or on fractured rock aquifer systems in California's mountain ranges. Most groundwater models must therefore address a number of key processes in one form or another:

1. hydrogeologic characteristics of the aquifer must be represented properly;
2. surface and subsurface flow interactions must be addressed adequately;
3. land surface and root zone flow processes must be simulated in a reasonably accurate way;
4. spatial and temporal data/information availability must be appropriately reflected in the complexity of groundwater models;
5. economic and policy decisions that depend on the complex patterns of surface water and groundwater availability (in space and time) must be simulated to properly represent the dynamics of groundwater extraction, surface water diversions, irrigation management, wastewater discharges, and intentional recharge;
6. Constraints on water management imposed by
    a. water rights,
    b. water quality and ecosystem regulations,
    c. water availability, and
    d. infrastructure (wells, canals, storage capacity in reservoirs and groundwater basins) must be represented properly, either by explicitly building these into model boundary

conditions (internal or external) or by representing these as conceptual systems in the modeling code structure

e. future climate change and socioeconomic developments

Southern California's adjudicated and predominantly urban groundwater basins monitor and report groundwater extraction providing a rich database on groundwater flows. However outside of these basins, the agricultural operations and their largely unmonitored use of and impact on water resources requires models capable of simulating both groundwater extraction and groundwater recharge from expert knowledge about these agricultural systems. An integrated hydrologic model to be applicable to California's agricultural groundwater basins (e.g., Central Valley, coastal basins) must be able to predict agricultural water demands, and it must be able to dynamically predict available water supplies in terms of surface water diversions and groundwater pumping to meet these demands given the various legal, natural, and infrastructure constraints. The three models address this wide range of requirements with remarkable success albeit in distinctly different fashion.

3.2 Theoretical Model Elements

Governing Physical Equations: Subsurface Flow Equations

The basic equation that controls the evolution of the potentiometric water level or "head" (for a definition, see Appendix 4) in a confined aquifer, or of water table elevation in the case of an unconfined aquifer, is that of mass conservation (Appendix 4). Mass conservation simply expresses the fact that if more water moves into a volume of the aquifer than leaves it, groundwater storage increases. As a result of storage increase, water levels or the potentiometric surface of groundwater ("head") rise. If less water is supplied into an aquifer than being released, there will be a corresponding loss in groundwater storage and head decreases. What governs the movement of water in the porous material of the aquifer is Darcy's law, which effectively describes an energy or momentum balance (see Appendix 4). External factors that withdraw or add water from an aquifer are the pumping from wells, seepage from reservoirs, rivers or canals, recharge from precipitation or irrigation, tile drainage, subsidence and evapotranspiration, among others. All three models use these concepts to account for changes in head, groundwater flow rates, and groundwater flow direction over time. The inclusion of Darcy's law within the expression of the principle of conservation of mass leads to the fundamental governing equation of water movement in the subsurface, be it in an aquifer or in soil. Those equations are described and documented in Appendix 4.

The governing flow equation is also valid for unsaturated flow in the vadose zone above the water table, but below the land surface, where pore space is only partially filled with water. This includes the soil and root zone, the latter typically consisting of the uppermost three to six feet of the vadose zone. The distribution of moisture in the soil is conditioned by the forces of gravity and "capillarity" (Appendix 4). The variables that contribute to an increase or decrease of moisture in the soil are infiltration from precipitation or irrigation, aquifer recharge by deep percolation, evaporation from the soil surface, and root water uptake driven by transpiration from plants.

HGS solves the variably saturated flow equation (also known as the "Richards' equation") continuously across both the unsaturated and saturated zone. In contrast, MODFLOW and IWFM solve the governing equation only for groundwater flow. In MODFLOW and IWFM, unsaturated flow above the water table is solved through separate mathematical models that simplify the equation of unsaturated flow, which is computationally expensive to solve. MODFLOW and IWFM represent the unsaturated zone using different, somewhat simplified mathematical concepts, while preserving mass balance. IWFM follows the time evolution of moisture in both the root zone and in the unsaturated zone below. In the package MODFLOW UZF, gravity-driven downward fluxes in the unsaturated zone are considered only, which yields more time-efficient simulations than the fully three-dimensional solution of Richards' equation. A MODFLOW package is available that couples MODFLOW with the unsaturated flow code HYDRUS-1D (http://www.pc-progress.com/en/Default.aspx?hydrus-1d). This package solves Richards' flow equation for vertical fluxes through the root zone and the unsaturated zone below the root zone. Lateral flow in the unsaturated zone is ignored with all but the MODFLOW VSF package. We note that many of these unsaturated zone flow packages do not operate with other MODFLOW packages/add-ons that users may be required to use (e.g., with the "Farm" package, FMP, for water systems management; or with the transport model MT3D, used for groundwater quality and transport modeling; see Appendix 7).

The approximate treatment of the amount of moisture flux in the unsaturated zone is often sufficient for groundwater simulations. Importantly, in many applications of MODFLOW and IWFM, the objective of including unsaturated zone models is (1) to estimate the amount of evaporation and transpiration actually taking place in the root zone, often aggregated over long time periods (e.g., week, month) and (2) to estimate the soil moisture deficiency that must be met by irrigation for healthy crop growth.

Governing Physical Equations: Surface Flow Equations

Flow of water overland or in channels is governed by the Navier-Stokes equation, which is generally simplified to the two-dimensional, depth averaged Saint Venant equations. Stream depth or flow rate are typically determined from Manning's equation (Appendix 4). Navier-Stokes equation, the Saint Venant equation, and Manning's equation, like the groundwater flow equation and Richards' equation, are also fundamentally based on the principles of mass and momentum (energy) conservation. In other words, these equations represent, in more or less simplified form, the basic physics of these flow processes. Contributing to an increase or decrease in channel (stream, river, canal) flow are precipitation, reservoir releases, canal diversions, groundwater return flow, seepage and evaporation.

HGS uses a general form of the Saint Venant equations to compute overland flow and flow within stream channels from user-specified precipitation and irrigation. This requires detailed knowledge of the topography. In contrast, MODFLOW with the Farm process relies on user-specified data for overland flow, while IWFM uses the frequently applied Soil Conservation Service curve number method to compute overland flow rates from user-specified precipitation. Neither MODFLOW nor IWFM compute overland flow equations[1]. Instead, overland flow is directly routed to user-specified stream nodes. Stream nodes connect stream segments of a stream and canal network. Stream nodes are used to represent the confluence of streams, canal diversion points or canal return flow points, and groundwater inflow or recharge.

[1] In the USGS software GSFLOW (Markstrom et al., 2008), the groundwater flow model MODFLOW has been coupled with the rainfall-runoff model code PRMS for watershed simulation.

For flow in streams, both MODFLOW (with the Streamflow Routing package) and IWFM either rely on user-specified input or else compute flow by simple mass balance at individual stream nodes (outflow from the stream node is equal to the sum of all inflows to the stream node minus the diversions at that node). From user-specified or computed flow rates in a stream segment between two nodes, the MODFLOW Streamflow Routing package uses Manning's equation to compute stream surface levels (stream depth) from stream flow rates. IWFM allows for a more general approach by applying a user-specified rating curve to compute stream surface levels given the stream flow rate in a stream segment. Either Manning's equation or other means would be applied by the user to develop the rating curve for use in IWFM. Stream surface levels in turn are a critical driver in computing the amount of local water exchange between groundwater and the stream.

Boundary Conditions (BCs)

All flow domains are bounded. Depending on the model to be developed, boundaries may be set to the edge the aquifer system itself. Laterally, aquifers are either bounded by geologic boundaries or arbitrary boundaries determined by the user. The bottom boundary of an aquifer of interest may be an impermeable or low permeable zone, a saline groundwater zone, or another aquifer system. The top boundary chosen for a model may be the recharge surface at the top of the aquifer, without the overlying stream, unsaturated zone, or root zone. In other simulations, groundwater is not the only flow system considered, but the aquifer, the unsaturated zone and/or streams are integrated into a single system. In that case, the upper boundary may be the land-vegetation surface.

Boundaries around flow systems or within flow systems can be no-flow boundaries (e.g., along certain types of geologic boundaries, or at the bottom of the aquifer), boundaries where the water table elevation of groundwater is known (e.g., underneath a lake, next to a spring, or next to streams and rivers connected to groundwater), boundaries where the flow rate is known (e.g., recharge across the top of the aquifer, or wells with known pumping rates). More specifically, boundary conditions fall into three categories: those that prescribe head (constant head or so-called Dirichlet boundary condition) and those that prescribe a flow rate across the boundary including zero-flow or no-flow (constant flux or Neumann boundary condition). The third type of boundary condition is a mixed form that prescribes flux across the boundary as a function of the difference in head (or water level) between some location with known head outside of the aquifer or surface water system and the unknown (computer calculated) head just inside the aquifer or surface water system (e.g., along certain stream-groundwater boundaries). Flux is computed by the model by multiplying a user-specified so-called conductance term with the head difference. This is the so-called general head boundary (GHB) condition, also known as the Cauchy boundary condition (Appendix 4).

The three models use these three types of boundary conditions to evaluate past and future response of the groundwater and/or surface water system to sudden or gradual changes in the conditions at one or many locations along the boundary of the flow system. Sometimes boundary conditions have names other than those used above, usually to indicate some additional capability in specifying a boundary condition. For example, in MODFLOW, the WELL package and the RECHARGE package both impose a constant flux (Neumann) boundary condition. In the WELL package, specified boundary flow rates (here due to wells) are defined by the user, in the RECHARGE package, specified boundary flow rates (here due to recharge) are computed from the depth of recharge provided by the user and the area of an individual model cell.

This provides added convenience to the user, but does not change the intrinsic nature of the boundary condition.

In MODFLOW and IWFM, the third (Cauchy) type boundary condition is extensively used as part of sub-models that are integrated into these codes to specifically simulate drains, rivers and streams, reservoirs and lakes. In HGS, the Dirichlet boundary conditions are imposed via the Cauchy condition by assigning an extremely large conductance value for the coefficient. In addition, specifically in the IWFM code, the small-stream watersheds process simulates overland and subsurface flow from ungaged watersheds adjacent to the model boundary to determine fluxes across the model boundary generated outside of the model itself.

Additional Modeling Systems to Simulate Boundary Conditions, Stresses, and Integration to Vadose Zone, Surface Water, Water Management, Land-use

The complexity of groundwater models can be divided into two categories: the internal complexity of the groundwater /aquifer system due to naturally varying geologic conditions that control groundwater flow; and, secondly, the complexity of the boundary conditions. The intrinsic aquifer complexity is represented in all three model codes by spatially varying aquifer properties (hydraulic conductivity, transmissivity, storage coefficient, porosity), at least to the degree that they are known and considered relevant to the modeling analysis. The limit to representing aquifer variability is determined by the grid or cell size of the groundwater model. The model cannot explicitly account for effects of aquifer variability at a scale smaller than the model's grid cell. It may do so implicitly by adjusting parameters, if these can properly capture the effects of heterogeneity. Given that aquifer complexity is expressed in all three model codes through spatially variable aquifer properties, this type of aquifer complexity can be equally represented by all three modeling codes. Differences between the codes are strictly due to their different internal numerical representation of elements, element nodes, grid cells, and grid nodes, which results in slightly different results, but – based on each code's reported verification - would be expected to provide effectively identical answers if executed properly for the same aquifer heterogeneity pattern under identical boundary conditions.

The second area of complexity (boundary conditions) is dealt with very differently between the three models and constitutes the main source of distinction between the three models:

- MODFLOW was initially developed as a groundwater flow model. Additional, modular components that represent certain types of "boundaries" or even "boundary systems" to the aquifer system, including unsaturated zone flow to the water table, stream recharge to the water table, groundwater pumping, evapotranspiration from the water table, etc., are added to the model code via so-called packages, which can be thought of as sub-models within the model code. This includes packages that take care of surface water – groundwater interaction (e.g., STREAM and LAKE package), vegetation – root zone – groundwater interaction (e.g., ET, RECHARGE, and UZF package), and modeling water management decisions (Farm package), as needed by the user. As noted earlier, not all packages are compatible with each other, thus constraining some of the choices (see Appendix 7)
- IWFM was developed from the start as an integrated model, but with an emphasis on integration of hydrologic components to specifically suit the groundwater modeling needs (not the surface

water modeling needs). Hence, the stream flow routines in IWFM are not as refined as they would be for a flood prediction system. They are designed primarily to satisfy the groundwater modeling needs. But IWFM always included water management systems as part of its modeling domain. Neither IWFM nor MODFLOW are mathematically as integrated as HGS: at the core, IWFM and MODFLOW solve the groundwater flow equation. Mathematical models that represent sub-systems along the boundaries of the aquifer (streams, root zone, plant-water interaction etc.) are coupled to the groundwater flow equation but sometimes solved separately. An iterative process at each time step ensures the integration.

- HGS is a truly integrated hydrologic model in that it does not draw a boundary around the aquifer, but around the broader groundwater – unsaturated zone – surface water – vegetation system as a whole. Hence boundary conditions are defined around the integrated components of these systems rather than having individual models "talk" to each other via their respective boundary conditions in an iterative process. Because HGS mathematically integrates multiple hydrologic systems, it does not need to provide for a wide range of sub-modules to specifically deal with boundary conditions around, e.g., the groundwater system, representing certain hydrologic conditions. On the other hand HGS does not include any economic or water management modeling capacity. It is a purely physical model.

The fully integrated hydrologic representation in HGS has computational advantages, especially for modeling coupled groundwater-surface water systems. But for many California applications, the distinction between the coupling of multiple systems via an iterative process (MODFLOW, IWFM) and the fully integrated, implicit multiple-system approach (HGS) will effectively make no difference to most users. Properly implemented, all three codes provide adequate answers to many groundwater and groundwater – surface water modeling projects.

Two salient components on the boundary of California hydrogeologic systems are the evapotranspiration from natural vegetation and crops, and human management decisions affecting availability of irrigation water. These systems are discussed next as they have a significant impact on the model design process.

Evapotranspiration.

Evapotranspiration (ET) is the combined flux of water from the land surface or from open water surfaces into the atmosphere (evaporation), and from within plants through their leaf stomata into the atmosphere (transpiration). Plant transpiration is supplied by root water uptake within and across the depth of the root zone. Evapotranspiration is a function of vegetation cover, vegetation type, vegetation age, vegetation health, soil moisture, solar radiation, wind speed, air humidity, air temperature, cloud cover, etc.

The evapotranspiration process has three separate important drivers: the effect of climate on ET, crop-specific effects on ET, and the effect of root zone moisture on ET.

ET – first driver (climate): To characterize the variability of evapotranspiration due to climatic variations over time or between regions, a so-called reference evapotranspiration (ET_o) is computed. The reference evapotranspiration represents the evapotranspiration from an internationally agreed upon reference crop. Typically, the reference crop is a grass cover without any shortage of water or nutrients in the root zone. Another typical reference evapotranspiration sometimes used is the amount of water that would be evaporating from a shallow pan of water (pan evapotranspiration). Reference ET, ET_o, is either computed from climate data using empirical equations or it is obtained in the field from weighing lysimeter measurements that track the total weight of the root zone, its moisture content, and its overlying plant cover, or other instruments that detect moisture and heat fluxes at the plant-atmosphere interface. In MODFLOW and IWFM, reference ET, ET_o, is a user-supplied time series. In HGS, reference ET is computed internally on the basis of net solar radiation, temperature, degree of humidity, wind speed, etc. using the approach by Kristensen and Jensen (1985). In all model codes, if large regions are modeled, or the elevation difference between various model locations is significant, the reference ET time series may vary spatially.

ET – second driver (crops): The second driver of ET, the specific characteristics of the barren land surface or the evapotranspiration from specific crops is obtained by measuring crop-specific ET, under known conditions of (non-) stress to plant growth, and relating it to reference ET to obtain the so-called crop-coefficient (the ratio of crop-specific potential ET, ET_p, to reference ET, ET_o). A computer model can then calculate ET_p occurring in a specific, unstressed or typically stressed crop as the product of reference ET_o and the so-called crop coefficient, k_c. IWFM and MODFLOW use the crop coefficient, which are supplied as input data: crop-specific or land use specific crop coefficients are multiplied with the user-supplied reference ET to compute ET_p (for HGS, see below).

ET – third driver (soil moisture): Often, the actual ET, ET_{actual}, is less than the potential ET due to a lack of available soil moisture in the root zone (relative to the conditions for which the crop coefficient was derived in field work) or due to very wet conditions that cause a lack of proper aeration within the root zone (a condition called anoxia). When the amount of soil moisture available during a time period of interest is either not sufficient to meet the ET_p of a location-specific crop, or too high to allow for proper aeration, the actual ET, ET_{actual}, is less than the potential ET, ET_p. For agricultural crops as well as natural vegetation, a reduced ET_{actual} during the early vegetative periods can have subsequent effects on ET_{actual} at later periods due to crop damage, even if sufficient soil moisture were later available to meet ET_p. Lack of soil moisture occurs when moisture storage is depleted and not replenished by precipitation, irrigation, or groundwater directly wicked into the root zone (or available within the root zone).

IWFM only accounts for wilting condition. MODFLOW with the Farm process has the option to also account for anoxia conditions through user-defined or internally parameterized functions that are hard-coded into the Farm process. The parametrized functions were developed by simulating a range of idealized unsaturated zone conditions with the unsaturated zone flow model HYDRUS (Schmid et al., 2006).

HGS distinguishes between different crops or land cover on the basis of the so-called leaf area index (LAI). LAI describes the fraction of the land surface covered by vegetative materials. In HGS, crops are not distinguished on the basis of specific crop indices. The computation of actual transpiration, T_{act}, (in the HGS manual: T_p, Therrien et al., 2012) accounts for reference ET (*ET driver* 1), leaf area index (*ET driver 2*), and for wilting conditions or anoxia through user-specified, soil moisture dependent functions (*ET driver 3*, see eq. 2.62 in Therrien et al., 2012). Like IWFM or MODFLOW, HGS does not account for the effects of prior crop stress on plant growth (the LAI is user-supplied and not simulation dependent).

After computing actual transpiration, HGS then calculates the evaporation from within the soil or from the surface of the soil by one of two possible approaches: Option 1 is that evaporation is the difference between the reference ET, ET_o (misleadingly labeled E_p on p. 32 of the HGS manual, Therrien et al., 2012), and the sum of actual transpiration, T_{act} and canopy evaporation (through interception). Option 2 is to compute evaporation as function of the computed reference ET, ET_o, the canopy evaporation, and the leaf area. In HGS, evaporation occurs across a user-specified thickness of the soil immediately below the land surface. Evaporation is distributed evenly or linearly with depth. Transpiration is distributed throughout the root zone using a user-defined root distribution function.

> "In IWFM ET [evapotranspiration] is input specified, whether monthly or weekly, or daily. Crop ETc [actual crop evapotranspiration under optimal growing conditions] or adjusted crop ET (ETcadj; if the user can quantify the effects of crop diseases, salt build-up, etc on ETc) is input by the user. Thus, the responsibility for the reliability of that input data is placed on the user. In the past for example we at DWR have relied on several sources including DWR Bulletin 113, FAO, Cal Poly's ITRC for computed values, and DWR's CIMIS network (which uses the Penman-Monteith equation). We've also computed ETo's [reference evapotranspiration] using the Hargreaves-Samani temperature-based equation (especially going back in time) and appropriate crop coefficients, or satellite processed estimates including SEBAL and MODIS. If dealing with future climate scenarios DWR has relied on GCM downscaled data. Essentially, IWFM assumes that the user-specified ET rates represent the current, historical or future (depending on the simulation mode) climatic, soil and crop management conditions with sufficient water." (DWR, 2012, Appendix 2)
>
> "MODFLOW makes ETo [reference evapotranspiration] estimates from Hargreaves-Semani approximation and Presley-Taylor approximation of the Penman-Monteith equation. MODFLOW also calculates actual ET from remotely sensed data using LANDSAT, MODIS with methods such as SEBAL and METRIC as well as developing canopy from NDVI estimates and crop coefficients from METRIC/MODIS estimates of ETo. We have published and used GCM estimates (Hanson et al., 2012)." (USGS, 2012, Appendix 3).

To use HGS in California, where the evaporative demand of crops is typically known through the crop coefficient and reference ET data measured and published by the Department of Water Resources, requires an assessment of the appropriate climate data and LAI that the user would input into the HGS model to obtain the same potential ET as with the crop coefficient concept. This may not always lead to identical results. The equations used to compute reference ET for MODFLOW and IWFM typically differ from that used by HGS, which is based on Kristensen and Jensen, 1985. For this review, we did not evaluate the approach in Kristensen and Jensen, 1985.

In all model codes, determining actual ET, ET_{actual}, requires additional modeling capabilities to track soil moisture, either through a root zone soil moisture model (IWFM) or through an unsaturated zone model (MODFLOW UZF, MODFLOW VSF, MODFLOW Hydrus 1D) or by having an integrated, variably saturated subsurface flow model that can handle saturated and unsaturated conditions simultaneously (HGS).

The ability to account for anoxia in HGS and MODFLOW when computing actual crop ET, ET_{actual}, would in theory, everything else being treated the same, allow ET_{actual} to be lower than in IWFM, which ignores the effects of anoxia. In California applications, this may lead to significantly different results between these model codes, if this aspect is not carefully developed in specific models.

There are other differences between the three models that affect ET_{actual}: namely, the three models each differ in the modeling of soil moisture storage, and, in the case of MODFLOW and IWFM, they differ in the conceptualization of water management decisions that are being modeled to simulate the farmer's irrigation behavior in response to potential future plant stress. These differences are difficult to quantify by simple comparison and without extensive modeling exercises, as they have complex interactions, which may ultimately lead to significantly different estimates of ET_{actual} and the water source and amount used to meet ET_{actual} (surface water, irrigation water from a well, or direct groundwater uptake by the crop).

Root zone thickness and water holding capacity are key variables controlling the moisture content that is available (or not) for meeting the evapotranspiration demands of the overlying vegetation cover. These variables also control the degree of aeration in the root zone. In IWFM, root zone thickness is input as a constant value over various time intervals. It varies with subregion, soil type and crop. In MODFOW and HGS, the root zone thickness can be specified by the user to vary with time.

Many of the differences related to evapotranspiration are listed in Table 2 below. Some important differences are pointed out here: In IWFM, the root zone contributes water to the water table in form of recharge, but the water table cannot contribute toward meeting evaporative or ET demands, even if the "capillary fringe" (Appendix 4) of the water table is within the root zone. This conceptual simplification likely has its root in the California-centric design of IWFM. In California's irrigated agricultural regions, the water table is generally managed to stay below the root zone, if only by installing tile drains below the root zone. Even if the water table is shallow and its capillary fringe reaches into the root zone, IWFM assumes that irrigation water managers keep the moisture zone sufficiently wet to impose effectively a downward moisture flux gradient, rather than an upward flux.

MODFLOW utilizes the Farm package with the UZF package to compute evapotranspiration and irrigation water demands. It does not calculate a soil moisture profile in the root zone. The root zone is assumed to be of constant moisture content (water that infiltrates in one time step cannot be stored for use by the plants in a later time step). HSG, in contrast, fully accounts for the spatio-temporal variability in soil moisture storage, as it computes root zone fluxes as part of its integrated subsurface flow equation.

HGS and MODFLOW with the Farm package, determine ET_{actual} based on the position of the water table, the potential contribution of the water table to plant ET_{actual}, the amount of surface water available for irrigation, and the amount of groundwater available for irrigation. No field experiments exist to the authors' knowledge that either confirm or discourage the application of the anoxia concept to California irrigated agriculture conditions.

Because anoxia may significantly reduce ET_{actual} when the water table is near or within the root zone, ET rates and, hence, irrigation demands, computed with HGS and with MODFLOW with the Farm package are highly sensitive to the simulated water table elevation. Alternatively, MODFLOW can be used without the Farm package. Then, pumping and recharge rates, and their variations in space and time, are computed by the modeler *a priori* and used as input to the groundwater model.

In MODFLOW with the Farm process, the time-step length must be on the order of one month or longer to avoid errors due to the assumption of constant moisture content. This imposes a significant operational constraint on the model. Furthermore, in MODFLOW with the Farm process (FMP1) a determination of soil moisture is not necessary to estimate the transpiration by plants. Instead, the contribution of groundwater to transpiration is evaluated based on the position of the water table (say below or above the extinction depth). In the original MODFLOW procedure an "extinction depth" is empirically provided. In MODFLOW with FMP1, the extinction depth is calculated and the size of the active root zone is also calculated depending on the location of the water table. The procedure is based largely on runs made with the unsaturated flow model Hydrus. They are limited however to 3 soil types.

In HGS, root zone moisture dynamics are simulated fully consistent with a three-dimensional Richards' equation (see above) and ET_{actual} is computed based on the leaf area index (LAI, Kristensen and Jensen, 1975). HGS also accounts for interception of precipitation by plant surfaces or urban structures that is subsequently evaporated (not available for infiltration or runoff). Interception is a function of user-defined coefficients and the leaf-area index (LAI).

Finally, none of the models automatically account for salinity induced stress and ET reduction. That would require simulation of salt transport and knowledge of plant-specific salinity stress responses. With all three models, in plant systems that are not in direct contact with groundwater, salt stress may be computed *a priori* using other available root zone flow and transport modeling tools that account for plant stress due to salinity and also for computation of resulting pumping needs and recharge (e.g., ENVIRO-GRO, Pang and Letey, 1998).

Modeling Decision Management

Many human decisions inadvertently or by design affect the behavior of the hydrologic system – surface water flow and reservoir storage, unsaturated zone flows, and groundwater storage. Intentional water management decisions include operational decisions on releases from surface water reservoirs, irrigation water diversions from rivers and canals, irrigation distribution among and within farms, construction and pumping from wells, etc. These decisions are made on a day-by-day basis. When expressed as model variables they are given a names such as "stresses", "excitations" or "forcing functions. The hydrologic system responds to these stresses or excitations by changing the heads in the aquifer, discharges in rivers, transpiration from crops, etc. These outcomes, in modeling jargon, are referred to as system responses or system states. System states respond to stresses on a minute-by-minute, hourly, or daily basis. Other man-made decisions are made on a seasonal basis such as which crop to plant and which acreage to plant with a given crop. Yet other decisions refer to the infrastructure, e.g. when and where to place new wells, which may be once-in-a-lifetime changes. To be useful for the evaluation of diverse management strategies, a model must be able to address the impact of these daily or seasonal stresses and of infrastructure changes. IWFM and MODFLOW have extensive capabilities to "model" these anthropogenic decision-making processes. HGS does not include simulation of water management decision processes – these must be simulated by the groundwater modeler using other, external modeling tools prior to or coupled with the HGS-based model. Table 2 provides a more detailed comparison of some of these modeling concepts in MODFLOW with the Farm process and in IWFM.

Spatial and Temporal Discretization – Options and Limitations

The basis for the construction of the three models is the knowledge of the physical laws that govern the storage and flow of water in aquifers, streams, canals, lakes, reservoirs, wells, soils, and even atmosphere, etc. Ideally, the model would describe what happens in the system at every location in space in the system and at every moment of time according to these laws. However, as mentioned in the analogy with a TV screen earlier, numerical computer models impose a discretization of the time and space continuum. Only average conditions are assumed to exist within a time-step and within a cell or element (much like a single color is represented in a screen pixel). Proper discretization in time and space is a critical part of the conceptual model to ensure that the approximation of the space-time continuum by discrete grid cells and time-steps is adequate for the purposes of the model design.

Thus, the differences between the three models lie in the approximate application of these laws for practical purposes. For example, the finite difference discretization technique (FDD), used in MODFLOW, calculates average values of a state variable, such as water table elevation in an unconfined aquifer, over a certain area. The finite element discretization technique (FED), used in IWFM calculates values of that same variable for specific points. With either approach, one does not get to know the value of the variable everywhere. To estimate it everywhere one has to use approximate techniques of interpolation which no longer represent the physical laws. Having started with a physically based model one would end up with a somewhat conceptual one. Whether either one of these two approximations (FDD or FED) works better will always be circumstantial and strongly depend on the information one wants from the model. HGS has the ability to use either the FDD or the FED technique. In the case of IWFM the model can be converted to the FDD method by simply using rectangular elements. In this case the algebraic system of equations to be solved is identical. In theory the FED method as presented in textbooks is said to calculate values at a point. However when expressing mass conservation one must invoke a volume as it has no meaning at a point. Thus, while using the so-called “mass lumping” method, the calculation of a value for a specific “node” location is actually the mean value of the state variable, say the groundwater head, over the zone of influence of that node. Thus in this regard the FED offers little advantage over FDD. It does retain some advantage in terms of the ease of location of the nodes at prescribed locations. This may be especially useful for the proper representation of a stream network and the estimation of the flow exchange between the stream and the aquifer.

The theory of the FDD or FED proves that the numerical approximations lead to the exact solution when the time steps and the space increments are very small. In practice, the salient question is, how small or large can grid size and time-steps be chosen. The fewer grid cells or elements and the fewer time steps, the faster the model code will compute a solution given fixed computer resources. Choosing proper discretization is somewhat of an art, but largely depends on the information available and the questions that need to be addressed by the model.

For groundwater modeling purposes, long-term annual and inter-annual trends and seasonal changes in water levels are common points of interest. Groundwater transport models to characterize existing contaminant plumes require significantly finer discretization than most groundwater resources (flow) simulations, but also operate on typically very large time scales. The minute-to-minute variations in the infiltration process during a rainfall event are typically not of interest. Integrating the overall contribution to groundwater recharge from multiple infiltration events over the course of a day, week, month may suffice without compromising the groundwater flow solution.

In IWFM there are two modes of simulation time steps: i) time tracking simulation and ii) non-time tracking simulation. In the first case the allowable time steps are listed in a table in the user manual and vary from 1 minute to 1 year. In the second case the time steps can be any non-zero number. The available time steps in MODFLOW and HGS are specified by the user and may vary from seconds to years. In HGS, the unsaturated zone problem is solved using 3D Richards' equation and including transpiration and evaporation as a sink term. This requires generally very fine grids for accurate solutions and short time steps. For simulations of large groundwater basins, such resolution is largely impractical. At large space and time discretization, the HGS solution may not be more (or less) accurate than the MODFLOW or IWFM solutions, which are based on simplified processes.

Numerical Solution Schemes

IWMF simulates steady or transient, confined or unconfined groundwater flow. While some of the documented verification problems are 1D and 2D (Ercan, 2006), it is principally designed to be used as a three-dimensional groundwater model with two-dimensional and one-dimensional surface water features. IWMF solves the groundwater flow equation with the Galerkin finite element method for the horizontal discretization and with the finite difference method for the vertical discretization. IWMF allows linear triangular or quadrilateral elements. Higher order elements, sometimes used in the finite element method, are not available. In case of triangular elements, the finite element integration is based on analytical formulas, while 2- point Gauss quadrature is used for integration of quadrilaterals.

MODFLOW is able to simulate steady and unsteady cases, both confined and unconfined using the finite difference method. MODFLOW is capable of simulating 1D, 2D and 3D problems. MODFLOW solves the groundwater flow equation using the finite difference technique. Finite difference discretization results in square or rectangular grid cells that have a uniform width and height for each row and column of the grid.

Similarly HGS is able to simulate steady and transient state groundwater flow, in confined and unconfined cases. HGS utilizes the control volume finite element method. HGS uses linear elements only (e.g., hexahedral and prism, higher order elements are not available).

MODFLOW offers three solvers i) Strongly Implicit Procedure, ii) Preconditioned Conjugate Gradient method, and iii) a direct solver. Other solvers are available from third parties as additional packages. HGS can be used with one of three iterative preconditioned solvers ORTHOMIN, GMRES and BiCGSTAB. IWFM provides two solution schemes: SOR and GMRES.

It should be also noted that none of the models describe any ability to run problems on parallel computer systems, but to the degree that the original modeling code can be compiled with the appropriate software, these modeling codes are not limited to being performed on single processor machines.

All models provide recommendation for the choice of solver techniques and parameter settings to use. Model documents provide comparison of efficiency between solver techniques provided, such as Table 1 below for MODFLOW. Some comparison in the efficiency of these or similar algorithms exist in the numerical mathematics literature, however it would be difficult to assess, whether anyone algorithm among IWFM, MODFLOW and HGS is a much more efficient solver than others. Typically, the choice of solver is made by the computer modeler based on experience. All models provide at least two solvers, which provide some flexibility to the users. And all models report global mass balance dynamically during the simulation process.

Table 1. Comparison of D4 (direct solver) and PCG solvers (Harbaugh, 1995)

Simulation Type	Layers, rows, columns	Number of D4 solutions, eliminations of [A]	Total of PCG iterations	D4 execution time (sec)	PCG execution time (sec)
A – Steady state, linear	2, 20, 30	2, 1	23	2.3	3.1
B- Steady state, non-linear	2, 20, 30	4, 4	38	8.2	5.5
C – Transient, linear, constant time step	2, 20, 30	20, 1	108	6.9	15.2
D – Transient, non-linear	2, 20, 30	30, 30	199	61.0	30.4
E – Steady state, linear	4, 40, 60	2, 1	44	226.5	49.2

Groundwater Transport, Variable Density Flow, Non-Isothermal Flow, and Water Quality Modeling

MODFLOW and IWMF are both designed strictly for solving groundwater flow. They cannot simulate groundwater solute transport or contamination migration. However, MODFLOW can be coupled with the solute transport and water quality code MT3DMS and related codes (e.g., MT3D, RT3D). Customized data management codes would need to be developed to utilize IWFM in conjunction with an existing transport modeling code. In contrast, HGS offers the broadest simulation platform with solute and heat transport being an integral part of the model itself. Also, HGS follows solute transport across multiple components of the hydrological cycle such as rivers and groundwater. This is not possible with MODFLOW and MT3D. In addition HGS considers a variety of chemical and biological transformations (e.g., biodegradation of gasoline products by soil and aquifer bacteria). HGS is also capable of simulating non-isothermal flow and variable density flow.

3.3 Verification, Calibration, and Validation Procedures

Overview

Verification, calibration, and validation of a groundwater model refer to three distinctly different work tasks that are all aimed at increasing the confidence in the relevance and accuracy of modeling results.

Verification of a groundwater model code such as HGS, IWFM, or MODFLOW is the process of comparing simulation results for groundwater flow problems with known mathematical solutions for the exact identical problem (a problem posed by the above governing equation with a specific set of initial and boundary conditions). A known mathematical solution may be obtained either by solving the partial differential equation problem using analytical mathematical solutions or using another, already verified numerical groundwater model. Verifications are usually performed by the code developers as part of the software publication process and documentation of code verification is provided as part of the user documentation. Verification can also occur through independent peer review processes. Verification is model code specific but not specific to a particular groundwater model application. Verification sets up a general assessment of a model's accuracy under a wide range of modeling conditions, relative to known solutions, albeit of often highly idealized/simplified, generic groundwater scenarios. We did not perform model code verifications as part of this review.

In contrast, calibration and validation are specific to a particular groundwater model developed for a specific project area and for specific purposes. Calibration of a groundwater model refers to the manual or automatic adjustment of groundwater parameters (hydraulic conductivity, transmissivity, storage coefficient, etc) or of initial and boundary conditions to minimize the discrepancy between model simulation results and measured data (e.g., water level data, spring flow data, data on groundwater discharge to tile drains or streams). Model calibration is part of the development of a groundwater model for a specific application. It is usually performed by simulating a historic period of groundwater conditions for which simulated results can be compared against available data.

Validation of a groundwater model refers to the testing of a calibrated groundwater model against a new set of historic groundwater conditions for which measurement data of water levels or groundwater flow (to springs, tile drains, streams) is also available, but that have not been used for the calibration process. The model validation process may occur as part of the groundwater model development project, by splitting a historic data set into two sets – one set of which being used for calibration and the other set (usually the later one) for validation. On the other hand, in a "post-audit", a completed groundwater model is validated against newly measured data that had not been available during the original groundwater modeling development project. A post-audit is also a form of groundwater model validation.

Code Verification and Reviews

Typically codes are verified on problems for which analytical solutions are available. Since such analytical solutions are rare and involve relatively simple geometries and boundary conditions the information deduced from such tests is quite limited. Such tests do confirm that the equations and their discretization have been formulated correctly.

MODFLOW, in its core groundwater flow formulation, and many of its packages include some code verification as part of the official manual, but it has also been verified by third parties on many instances. Part of MODFLOW's popularity stems from its time-tested reputation in court proceedings, where it has withstood the scrutiny of many expert scientists. However, the same level of extensive verification does not apply to the Farm package, which is relatively recent and is not commonly applied with MODFLOW. IWMF was verified on 11 simple tests ("Verification problems for IWFM". DWR, Bay Delta Office, July 2006.).

Similarly HGS shows that its numerical solution of Richards' equation matches well with experimental result. But in order to do so «adaptive time-stepping used an initial time-step size of 0.01 minutes and a maximum time-step size of 1 minute.» (Therrien et al, 2012). Again the verification proves that the discretization of the governing differential equation was done properly and its numerical solution technique worked. It proves that the numerical solution will converge to the correct one as the time step and the space increment become infinitesimally small. However the verification casts no light on how well the numerical solution would approach the exact one had the time step been of the order of a day (1,440 minutes) or longer, as is often the case in groundwater models.

Reviews have been written of MODFLOW and some of its packages including a more recent review of MODFLOW-2000 (http://igwmc.mines.edu/software/igwmcsoft/MODFLOWreview.htm), a review of the local grid refinement method employed by MODFLOW (Mehl et al., 2008), a review of simulating multi-aquifer wells with MODFLOW (Neville and Tonkin, 2004) and reviews of MODFLOW-associated software (GMS, MT3D, and RT3D, see http://igwmc.mines.edu/software/review_software.html).

A concise and very accessible review of HGS was recently provided by Brunner and Simmons (2012), which confirms the scientific value of HGS. No external reviews are currently available for IWFM.

Model Calibration

Calibration is a standard procedure to refine estimates of parameters that cannot be measured directly or for which direct measurements are relatively uncertain. To be done properly, the modeling expert needs to select the proper type and number of parameters given the specific availability of data in a project. In the hypothetical case of a model with a huge number of parameters – more than the total number of observations in space and time - one could obtain a perfect fit, at least using statistical methods. However the model thus fitted would be extremely unreliable especially if the future boundary conditions deviated appreciably from the historical stresses to which the model was fitted against available observations.

The three model codes can all be calibrated using standard groundwater model calibration software. In the case of MODFLOW, the USGS has designed a specific set of tools for the calibration of MODFLOW. But all three modeling codes are commonly calibrated using third-party calibration software such as PEST (Doherty, 2012). There are no intrinsic, design-based disadvantages among the three modeling codes with respect to calibration. The key point in linking the three models with external calibration tools is the ease of use (see below) and the effort required to write additional computer programs which write/read the input/output files and eventually link the model with the calibration tool. However, due to the implicit complexity of HGS, calibrations with HGS may need significantly more CPU time and resources than comparable groundwater models that are based on IWFM and MODFLOW. This is only a qualitative statement and may not apply to specific models.

Model Validation

According to Konikow (USGS), for hydrologic models in general, and for ground-water models in particular, it may be a fallacious assumption that they can be validated. Together with Bredehoeft (1993, page 178) they make the point that calibration, better called "history matching" (when using time series for the process of adjustment of the parameters of a model) is just that, and «to claim more for that process, using words like validate and verify, is to delude ourselves, mislead the public, and make us look foolish to our scientific colleagues». No history matching, however apparently good it may seem, can by its nature contain fully reliable information about the long-term behavior.

«One way to assess the predictive accuracy of groundwater models is by comparing the actual response of a groundwater system with that predicted by the model, and performing such a comparison a **sufficiently long time after the prediction was made** so that the state of the system at the time of evaluation will not be dominated by its "memory " of conditions during the calibration period……This type of assessment of model reliability has been called a "post-audit" (Konikow, 1986)» (Konikow, 1995, page 61). No such post-audit assessment is available from the three models.

Among the three models MODFLOW is the one with the largest number of references in peer reviewed publications followed by HGS, while the number of publications where IWFM was used is rather limited. For example in the journal article library "ScienceDirect" (http://www.info.sciencedirect.com) the term "MODFLOW" returns 1,280 publications, the term "HydroGeoSphere " 74. For the IWFM case neither the acronym nor the full name is representative of the publication. Naturally the fact that the model is cited (and probably used) does not per se indicate that the model is correct but rather that it has been accepted generally by the groundwater model users. In fact, in some (albeit rare) publications some aspect of the model may actually be criticized (e.g. Mehl and Hill, 2010). In others some component may be verified (e.g. Liu and Luo, 2012). By the same token, the lack of publications on IWFM should not be interpreted as an indication that it is less suited for modeling tasks than the other two modeling codes.

3.4 Usability

Existing Code Documentation

All three codes come with extensive sets of documentation and examples. The documentation is geared to the professional user and groundwater modeler. It will be of only limited accessibility to a general audience (and was not intended for such). For all three models, manuals separate the theoretical basis and structure of the model and the instructions manual for actual use of the model. One exception is the MODFLOW-2005 report, which integrates these two aspects. This makes it difficult, for example, to evaluate the determination of the actual transpiration and evaporation in MODFLOW FMP1 on pages 11 to 16. Even reading references suggested in the report did not help. Clarity was missing there as well. In other words the reading of these documents is for the professional specialist in hydrology and computer science and not the general public. Similarly, HGS has very limited documentation, for example, of its approach to computing evapotranspiration, other than by identifying a generic equation and conceptual model with a reference to details outlined in a 1975 publications (Kristensen and Jensen, 1975). For all three model codes, the handling of crop and water management related simulation tools has complexities that are not completely documented in the manuals, generally requiring interaction between modeler and code developer (or user forums).

Input Management

For HGS, from a positive side, Brunner and Simmons (2011) had this to say: « The preprocessor writes all relevant information to clearly structured ASCII files, and the user can rapidly check all aspects of the problem. Another positive feature is the highly flexible way to assign properties and boundary conditions. Because of the intuitive nature of the input instructions, the lack of a GUI is, in our opinion, not a negative point at all because it allows the user to take full control of the input. Therefore, a very high level of transparency is achieved throughout the modeling process. It also forces new users to understand how the code is structured and works. The text file structure also allows implementing of model parameter changes rapidly, and also makes the coupling to parameter estimation codes such as PEST (Doherty 2010) straightforward.» and «Another positive point is that the software can be installed without any problems whatsoever. Also, the stability of Windows is not affected through use of HGS. We have not observed a single-forced termination of the executables, even during very long execution times (e.g., several days). HGS requires significant computational power, which can slow down single core machines considerably.»

> « IWFM has a very user-friendly format for input and output data. Input files are plain text files, and include comments and a brief explanation of each variable that the model requires. The users are allowed to insert their own comments into the input files. For instance, the users can document the data development process directly in the input files turning these files into a "living" document of the IWFM application. Time series input data have date and time stamps and organized neatly in a table format, allowing easy reading and QA-QC.» (DWR, 2012, Appendix 2).
>
> « Input and output data are well structured and accessible in GIS and ASCII formats for many features of MODFLOW. We have developed free tools that allow the construction of these data sets with particular emphasis on complex temporal data sets that are difficult to construct with commercial GUI's. Most of the input instructions are also accessible through a publicly available web site supported by USGS. » (USGS, 2012, Appendix 3).

None of the three model codes includes a graphical user interface. Therefore the communication between the users and the models is achieved through a series of ASCII input files where the users specify their options. Each model has its own standardized format, which is in the form ASCII flag - Value. All the programs provide detailed information and explanation regarding the structure of input files, the format and the available options. For MODFLOW, a number of commercial third-party software packages exist that provide a graphical user interface for ease of data management (http://groundwater.ucdavis.edu/Materials/Groundwater_Modeling__Web-Links/). More recently, MODFLOW developers have provided their own graphical user interface (Winston, 2009).

Sample input files are available for all three models. MODFLOW contains examples in the documentation of the model code, while websites with downloadable examples are available for HGS and IWFM. HGS has created a small user community that can assist with questions. The input format varies. MODFLOW and IWFM have multiples input files, organized by modules. HGS has a single input file, which provides some ease in sharing and editing. It also is convenient to create problem-specific templates. Due to the research-based nature of HGS, HGS provides some newer options that are not documented (see review by Brunner and Simmons 2012).

For IWFM, the Department of Water Resources has released the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), for which the developers of IWFM have created example files of all the available IWFM packages. These can be used as templates for other studies. DWR occasionally also provides workshops for users of IWFM.

Output Management

All three model codes provide output data either in ASCII or binary format, but not in any graphical format. Therefore the direct presentation of output data is not an option (and not intended to be an option). Users rely on their own means of translating the output data to graphs, animations, tables, etc. A list of relevant software links can be found at the UC Davis groundwater website (http://groundwater.ucdavis.edu/Materials/Groundwater_Modeling__Web-Links/).

HGS offers the ability to export the data into the GMS® and Tecplot® software, both available commercially. On the cautious side a recent review for HGS found: « Although we do not consider the "outsourcing" of visualization and postprocessing as a limitation, the user has to keep in mind that these third-party products are quite expensive, and that some time is required to get familiar with TECPLOT or GMS. Beginners would also benefit from a short tutorial on how to import and manipulate HGS-output data in such programs. Also, we miss the option to write zoned water budgets. While an option is provided to extract water fluxes through slices, this option does not work for the extraction of surface-subsurface exchange fluxes or for subareas of transpiration/evaporation rates. While these fluxes can be extracted via TECPLOT, a direct option would be required to use the output data in parameter estimation processes. Another small but in some cases immensely helpful option would be to allow the postprocessor HSPLOT to write HGS-output files directly to TECPLOT or GMS format, without taking the detour of converting the binaries to often extremely large ASCII files.» (Brunner and Simmons, 2011).

IWFM provides a series of Support Tools for visualization and water budget calculations. These support tools link IWFM with commercial software such as ESRI ARCMap®, TECPLOT®, and others for visualization and mesh generation, and to Microsoft Excel® for budget calculation. «Output data also have date and time stamps and organized neatly in a table format that allows easy reading as well as easy copy-paste into other software such as Microsoft Excel. Utility programs that transfer output data into Excel with a click of a button are also developed and available for users for free. Time series data can be input from and output to USACE's HEC-DSS database as well.» (DWR, 2012, Appendix 2).

The easiest way to post-process the outputs in case of MODFLOW is through the use of the commercial pre/post processor software available via commercial GUIs or the USGS GUI software wrapped around MODFLOW. Each GUI has its own capability and shortcomings in transferring data in and out of the GUI to third-party software such as ESRI ARCMap®, TECPLOT®, or Microsoft Excel®.

Options for Customization

MODFLOW and IWFM are both open (freely available) source codes written in Fortran programming language. It is therefore possible for a modeler to modify the code. In HGS, however, the code is not available and all proposed modifications have to be communicated with the developers of the code. Note also that HGS is only available commercially, except for some academic applications.

3.5 Code Applications

Application to Specific Groundwater Applications: Overview

The following specific situations have been selected by CWEMF as relevant example applications for which water managers, policy and decision makers, and consultants may consider the development of a groundwater model. The discussion here is meant as a brief, qualitative review of potential considerations when selecting specific model codes for these applications. It is outside the scope of this document to provide a detailed technical comparison of these model codes or rank them in any fashion with respect to their applicability to any of these applications. Ultimately, the choice of code is not only a function of the application, but also a function of available data, of the choice of conceptual model – especially about processes controlling boundary conditions and water management, and the expertise of and toolbox available to the groundwater modeler. Any of the three codes can be "tweaked" to be applied to the applications listed below with the proper use of the code and with the aid of additional modeling tools available to groundwater modelers.

Application A – Aquifer Safe Yield

Safe yield and aquifer sustainability are somewhat vague terms often referring to the potential maximum allowable groundwater extraction rate that will not cause undesirable harm to an aquifer system, to the (human and natural) environment supported by the aquifer system, or to the environment supporting the aquifer system. Naturally, groundwater systems are in a dynamic balance with their surroundings. The sum of the inflows into an aquifer system minus the sum of the outflows from the aquifer system determines the rate of change in groundwater storage within the aquifer system – much like a bank account. None of the freshwater aquifer systems in California are closed off from the environment (at the land surface). Hence, any extraction of water from a well, however small, takes away from the flow of groundwater somewhere else: less discharge to a stream, less uptake by groundwater dependent plants (e.g., in wetlands, riparian corridors), less groundwater in storage, less evaporation from dry lakes, and so on. By the same token, any additional recharge will result in additional outflow to a stream, to other wells, and/or into groundwater storage. Groundwater models are ideally suited to determine how a change in stress to an existing groundwater system affects groundwater flows to existing well users, to streams and other groundwater dependent ecosystems, to neighboring groundwater basins, and to flow into and out of groundwater storage.

Aquifer safe yield is driven by mass balance. Because groundwater model codes are intrinsically built upon the concept of mass balance, all three model codes can be used to quantify the limits where resource development will not lead to undesirable environmental effects. All three models are expected to effectively yield identical results for a model system of identical properties and exposed to the same stresses. The distinction between the codes lies in their representation of the systems at the boundary of the aquifer system: the surface water system, the ecosystem, the agricultural system, the water management system, the well pumping management system. Some of the distinctions in the representation of these boundary systems are discussed above, some in the following scenarios. An example of how difficult it is to compare the models directly, due to their difference in representing these boundary systems, can be found in Schmid et al. (2011).

Application B – Conjunctive Use Modeling

Conjunctive use is the simultaneous management of surface water and groundwater resources, most often to take advantage of groundwater storage to balance short-term or intermediate term variability in surface water supplies due to seasonal or inter-annual climate variations. This includes, for example, managed recharge of surface water during relatively wet years for extraction during drought years (groundwater banking).

All three modeling codes can be applied toward simulating groundwater flow and groundwater storage changes resulting from various conjunctive use management practices. As mentioned earlier, IWFM and MODFLOW have added capabilities for the simulation of water management systems that, in some cases, may simplify the construction of an appropriate conjunctive use management model. For HGS, and in some cases for IWFM and MODFLOW, simulating such management systems requires the development or use of additional simulation models that must be coupled to the modeling code. Such external coupling may impose some restrictions on the use of the model and/or introduce significant sources of error that only rigorous testing on a case-by-case basis would reveal.

Application C – Groundwater – Surface Water Interaction

The three model codes are all considered integrated hydrologic models. All three codes allow for the simultaneous modeling of surface water features and groundwater, although surface water is simulated quite differently between the three codes (see above). All three models also couple the surface water systems with the groundwater system. Thus, they can be used to construct

Textbox 1: Stream-Groundwater Interaction. When the Dupuit-Forchheimer (D-F) approximation is used for the water table aquifer, no head gradient is assumed in the vertical direction. Flow is then treated as two-dimensional (2D) in the horizontal plane. This provides greater simplicity for the computations, a great relief, especially when dealing with large (regional) systems. However, when a river (or canal) reach penetrates an aquifer with which it is in hydraulic connection, the direction of the exchange flow at the bottom of the reach can be significantly vertical over a sizable fraction of the perimeter. For illustration see Figure 1. In the vicinity of the river (or canal) reach, the D-F approximation does not hold. In order to treat the problem accurately, one would need to use a three-dimensional (3D) model with small cells under and in the vicinity of the reach. Even in the symmetrical case with this refined grid of 480 cells the calculated numerical value for the one-sided conductance is 0.368 whereas the analytical one is 0.389, or an error still of 5 %.

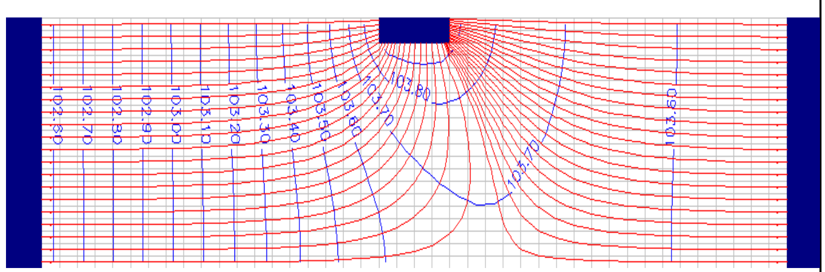

Figure 1: Seepage from a rectangular channel with different heads at the left and right boundaries. Flow path and potential lines. (after Miracapillo and Morel-Seytoux, 2012)

To account for the additional resistance due to the necessity for flow to turn from a vertical to a horizontal direction the models introduce artificially the added resistance of a clogging layer, which may not exist in reality. The approach can be useful through calibration of the clogged layer characteristics. However the calibrated conductance cannot be used with a different grid system than the one for which they were calibrated.

groundwater models that account for the interactions between surface and groundwater, be it entire hillslope watersheds, large, relatively flat, agricultural and/or urban watersheds, or the interaction of specific rivers, canals, and lakes with groundwater.

In all three models, the approach used to describe the flow exchange between a stream and an aquifer is only approximate, albeit distinctly different between each code. All three codes effectively assume that there is a clogging layer within the river bed. With all three codes, this assumption can be remedied using a highly detailed, three-dimensional (3D) approach for the case where the river and the aquifer are in hydraulic connection.

There are many situations, where such a clogging layer is not present. In MODFLOW, the clogging layer is referred to as "river bed". In HGS, the clogging layer is referred to as a "thin boundary layer": "In HydroGeoSphere, the fluid exchange between the surface and subsurface domains is calculated using a first-order leakage relation based on the assumption that the two domains are separated by a thin boundary layer" (Park et al, 2009). This assumption is an artifact to substitute for a more correct, but computationally expensive analysis of the phenomenon (see Textbox 1).

If groundwater levels fall below the bottom of the river bed, unsaturated conditions may develop between the river and groundwater. In HGS and MODFLOW, capabilities exist to model the unsaturated flow between the river bottom and the water table surface. In IWFM, recharge from streams is allocated directly as recharge to groundwater, without delay. For many applications, this is an adequate simplification.

Application D – Land Subsidence

IWFM and MODFLOW calculate the vertical displacement of the land surface due to permanent compaction of low permeable clay layers (subsidence) and its impact on water flow within the aquifers. The two model codes use a similar approach based on the Terzaghi (1925) theory. Both, IWFM and MODFLOW track the movement of the so-called pre-consolidation head, the lowest water level experienced by an aquifer system, which controls the onset of subsidence. Recently, a similar option has been added to HGS (Calderhead et al., 2011). None of the three model codes simulate horizontal (as opposed to vertical) displacement due to sediment compaction.

For subsidence modeling, we have found that MODFLOW provides the best documented, most versatile, and most often applied model code. MODFLOW includes the ability to simulate clay interbeds with time-delayed subsidence, a phenomenon often observed in thicker clay beds, in addition to simulating instantaneous, non-delayed compaction (usually in thinner clay beds). IWFM and HGS only simulate non-delay, instantaneous compaction of interbeds. In IWFM, subsidence of thick claybeds may be simulated by dividing the clay layer into several thin model layers. This approach would be less computationally efficient than MODFLOW's delayed bed feature in the subsidence package (MODFLOW SUB).

Application E – Integration of Land-use Driven Urban and Agricultural Water Management

Urban and agricultural water management is a critical aspect of groundwater use in California. Over 80% of California's groundwater is pumped for agricultural irrigation with the remainder being pumped for urban uses. For many California groundwater basins, urban and agricultural extraction is the largest or – especially in south-central and southern California – the only groundwater output. Other significant groundwater outputs from groundwater basins include lateral flows into neighboring groundwater basins and discharge to streams. The extraction of groundwater for urban and agricultural uses occurs based on the water demand needs of urban water suppliers and agricultural water users.

Some water users rely exclusively on groundwater to meet their water demands. Some water users rely entirely on surface water to meet their water needs; and some water users rely on a mix of surface water and groundwater and will manage the two water resources according to individual needs and preferences. Urban water users (usually public water supply companies or agencies) must meet significant water treatment requirements that are distinctly different between surface water and groundwater supplies. Hence, the management of mixed surface water and groundwater use by municipal water suppliers is a highly structured planning and decision-making process. Availability of surface water versus groundwater is but one major element in the decision making process.

In contrast, agricultural water users that depend on a mix of surface water and groundwater resources will often meet their water demands first from available surface water and only once surface water resources are exhausted, at any given time, groundwater will be used to meet the water demand. Surface water may be available at full allocation for part of an irrigation season, or surface water may be available to meet partial water demands during the entire irrigation season. In some areas, only groundwater is available.

In California, surface water use is highly regulated through the state's water rights process and through laws regulating environmental minimum flows. Irrigation and water districts supply surface water to agricultural or urban water users and measure and report these deliveries. Riparian water uses are limited by water rights allocations. In contrast, groundwater extraction is generally not reported, even if an individual user will meter it, except in some urban areas and in adjudicated groundwater basins of southern California. Hence, for purposes of groundwater modeling - even when modeling of historic conditions - a significant and often the largest component of groundwater boundary flows is unknown and must be estimated either prior to building the groundwater model using techniques that are external to the groundwater modeling software, or via techniques that are built into the modeling process.

In many basin scale applications of groundwater models, future water uses, whether surface water or groundwater, are unknown and need to be estimated based on future availability of surface water and groundwater at the point of water extraction. Local water availability is influenced by climate, water use decisions of upstream or upgradient water users, water rights limitations, administrative water delivery decisions, etc. Local surface water use has potentially significant influence on surface water and groundwater availability elsewhere and, similarly, local groundwater pumping has significant influence on both, surface water availability and groundwater levels elsewhere. From a modeling or prediction perspective, this poses a vexing chicken-and-egg situation, where water use decisions are interdependent through the mutual effects on groundwater and surface water flows and storage.

For basin or sub-basin groundwater modeling purposes in California's highly managed water landscape, it is therefore often desirable to simultaneously model both, the water management decision-making process and the groundwater and surface water flow and storage processes, as they move forward in time.

The water management process, urban or agricultural, can be simulated at many different levels of complexity, requiring process elements to be expressed in form of rules, mathematical equations, decision parameters, etc representing individual water management agents/agencies or groups of water users at various degrees of detail. The water management process model may be external to the groundwater model software and be coupled explicitly, with information exchanged at each time step, or the water management model maybe implicitly coupled with the groundwater (and surface water) model within a single software platform.

HGS is a purely hydrologic model with no internal representation of water management processes. In applications with HGS, water management processes, including the simulation of groundwater extraction rates, must be performed external to HGS. The external model must then be coupled explicitly to HGS with information between HGS and the external water management model being exchanged at user-defined time-points. Generally, this will require the development of a specific computer code that allows HGS to communicate with the external water management model, however simple or complicated that external model may be.

IWFM and MODFLOW include water management modules that are highly relevant to California's water landscape. In MODFLOW, the water management model is represented through the "Farm Process" (Farm) package. The name of the module is somewhat misleading, as the module can be used to simulate both, agricultural and urban water management decisions at a wide range of spatial discretization. A so-called "farm" is a water demand accounting region for which specific water deliveries are designated. Both, IWFM and MODFLOW, aggregate water demand on a cell or element (ultimately integrated within the zone of influence of a nodal point) basis from the specific land use (crop type, urban area) composition within the cell/element, soil and climatic conditions within the cell/element, and crop management practices (e.g., irrigation efficiency, return flow) associated with each crop within a cell/element. The models decide where the water comes from (precipitation, surface water delivery, groundwater pumping) and how much water comes from each of these water sources. The models also have the capability to check on water availability and curtail actual deliveries in a user-specified order, if water demands are not met by available water (see Application K – Policy).

A detailed review of the water management models in IWFM and MODFLOW is beyond the scope of this report. The reader is referred to the user's manuals for details and especially to two very relevant publications that provide detailed comparisons between the two model codes for water management purposes (Dogrul et al., 2011; Schmid et al., 2011). Figure 2 below illustrates the complexity of the water management module that integrates the multitude of management decisions with the various hydrologic compartments. The following table, following mostly Dogrul et al. (2011), briefly summarizes and compares the principal water management simulation concepts implemented in IWFM and MODFLOW. HGS is a hydrologic model that does not incorporate management strategies. To use HGS for management one needs to construct a separate code that communicates with HGS to get the hydrologic information needed for the management. For this reason HGS is not included in Table 2 below.

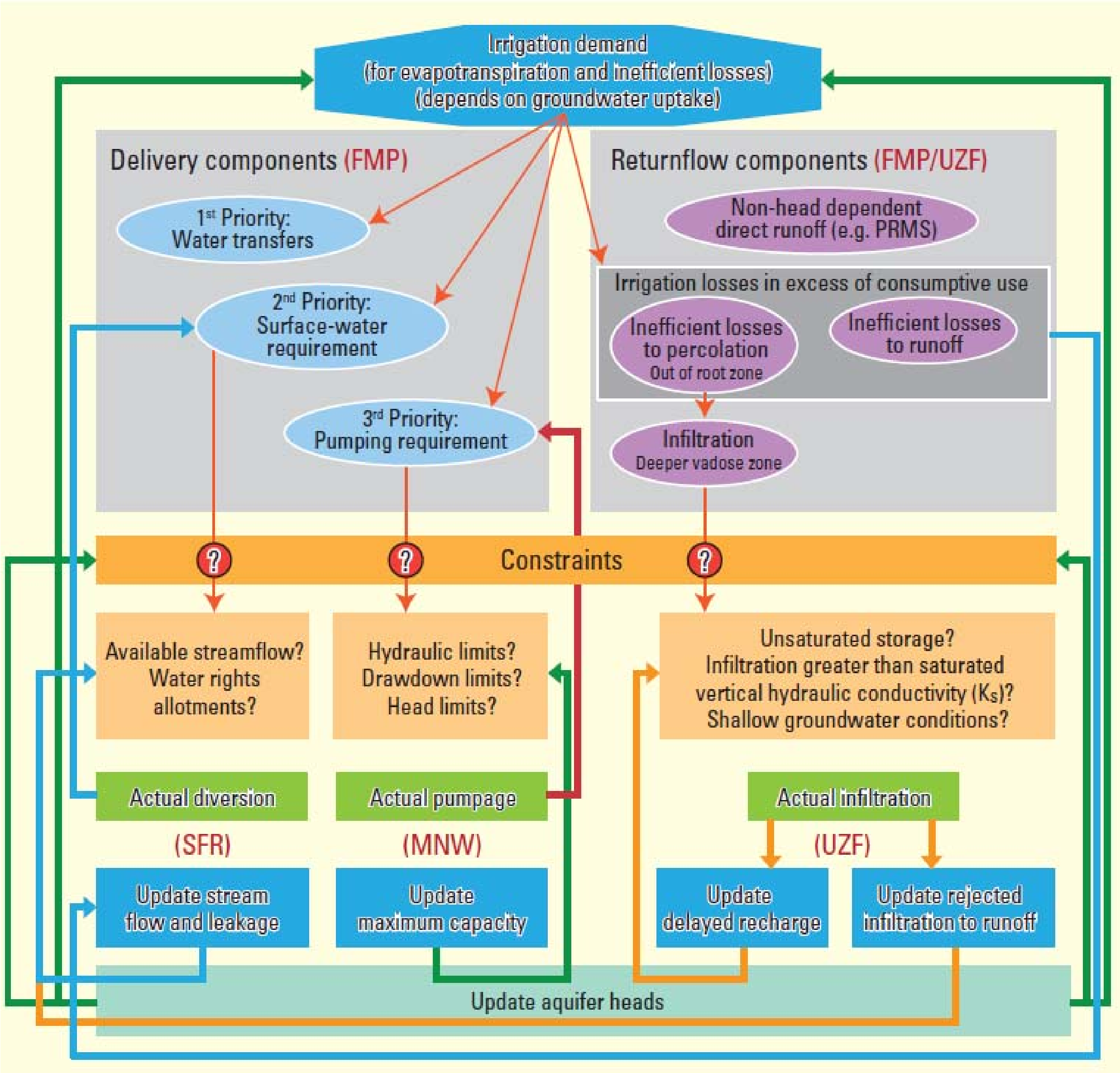

Figure 2: Interdependencies within the MODFLOW Farm process (Version 2) and related constraints on the supply and demand components (Schmid et al., 2009). FMP: farm management package (handling water demands), UZF: unsaturated flow zone package (handling unsaturated zone flow processes), SFR: stream flow routing package (handling streamflow processes), MNW: multi-node well package (handling groundwater pumping processes).

Table 2. Comparison of the handling of water movement and management at the farm level by IWFM and MODFLOW based on Dogrul et al., 2011. Equations or page numbers refer to Dogrul et al., 2011, unless mentioned otherwise. Symbols for rates are ET for EvapoTranspiration, DP for deep percolation, R for surface runoff, I for irrigation supply. Abbreviations: ag for agricultural, gw for groundwater.

Issue	**IWFM**	**MODFLOW WITH FARM PROCESS, MF-FMP**
mesh type	finite element	finite difference
tracks changes in root zone water content	yes (For details, see Section 3 in "IWFM Demand Calculator IDC v4.0 Theoretical Documentation and User's Manual, DWR 2012" and Section 2.8 in "Integrated Water Flow Model IWFM v4.0 Theoretical Documentation, DWR 2012"	no
key limitation of not tracking soil moisture storage		● requires long time-steps (1 month or longer); (Ruud et al., 2004. "....currently limited to time-steps of several days or longer...." (p.23) ● when only precipitation occurs and no irrigation, the effects of drought conditions will be different ● in irrigation, when there is a lot of root zone storage change (deep roots, high water holding capacity) over several months ● pre-irrigation for later crop water demand not possible, when over > 1 month ● (see p. 53 on the above points)
tracks changes in deep (i.e. below root zone) vadose zone water storage	yes	somewhat when using kinematic wave (MODFLOW UZF, Niswonger et al., 2006)
vadose zone flow below root zone	down only	down or up
root zone to vadose zone flux	mass balance driven (using Darcy's law and controlled by field capacity,	direct loss calculation or kinematic wave (UZF) or Richards' equation (VSF, HYDRUS package for

Issue	IWFM	MODFLOW WITH FARM PROCESS, MF-FMP
	time-step)	MODFLOW)
groundwater uptake to ET (EvapoTranspiration)	no	yes
multi-aquifer groundwater pumping to meet agricultural demand	multi-aquifer pumping using the Kozeny equation (Driscoll, 1986; Dogrul, 2012, p. 4-8)	MODFLOW MNW package with various wellbore intakes.
streamflow	yes, similar to SFR1 package	yes, SFR1 package
streamflow	rating table (user-specified)	Manning equation or other options
stream-groundwater interaction, general (Dogrul, 2012,p.2-29ff.)	According to Darcy's law the discharge across the streambed is directly proportional to hydraulic conductivity, cross-section wetted perimeter, length of river reach (segment), and the difference in head between the aquifer below the streambed and the stream stage. The flow is inversely proportional to streambed thickness. (Appendix 4 for more details)	same as IWFM
stream-groundwater interaction when disconnected	direct recharge	direct recharge or delayed recharge through use of MODFLOW UFZ to simulate unsaturated flow
stream-groundwater interaction, when water table is below the streambed	equation used by IWFM produces lower seepage rate when stream stage is small (on the same order or smaller than the thickness of the streambed below). The results are the same as for MODFLOW only, if stream stage is much higher than streambed thickness. (Appendix 4 for more details)	equation assumes that streambed is always saturated. In reality, streambed may require rewetting, which affects streamflow, if it is small. Hence, this is different if the stream is disconnected and if the stream depth is much less than streambed thickness. Difference may be minimal after calibration, but could affect forward simulations (Appendix 4 for more details)
reservoir simulation	yes	yes
lake simulation	yes	yes
routing of water through surface water network of canals, stream, lakes, reservoirs	yes	yes

Issue	IWFM	MODFLOW WITH FARM PROCESS, MF-FMP
surface water management storage accounting	the control volume includes the root zone and the water stored above the land surface	the control volume is strictly the water above the land surface
surface water management accounting resolution	subregion (can be the same as a cell, p. 19) - spatial resolution for computing: ● infiltration ● precipitation runoff ● agricultural-return flow ● deep percolation evapotranspiration	"farm" (can be the same as a cell, but is not intended to work that way) - spatial resolution for: ● precipitation ● non-, semi-, fully-routed surface water deliveries ● gw pumping deliveries ● evaporation and transpiration from gw ● external deliveries ● natural flows ● water budgets in the model output for: ○ irrigation, precipitation, groundwater derived E and T ○ runoff ○ deep percolation ○ *Note: The above flows are not available at the resolution at which they are computed. The flows actually vary from cell to cell.*
soil types	user-specified: four categories defined by retention parameter, field capacity, total porosity; assigned by FE cell and aggregated by zone of influence of the nodal point.	four categories (with coefficients that are each defined by preset HYDRUS simulations; these also account for wilting and anoxia), or user-defined (Schmid et al, 2006, Schmid, 2004). Also assigns capillary fringe to each category. Soil type is assigned by considering largest fraction soil type within FD cell.
spatial resolution of soil type	mesh cell	mesh cell
assignment of soil type	area-weighted average of soil properties from SSURGO where available, otherwise from STATSGO.	one soil type per grid cell, user - defined

Issue	IWFM	MODFLOW WITH FARM PROCESS, MF-FMP
	Example: page 62 of the C2VSim v3.02-CG User Manual (available at http://baydeltaoffice.water.ca.gov/modeling/hydrology/C2VSim/index_C2VSIM.cfm). In Version 4 of IWFM, higher resolution is achieved (by landuse type within a cell.	
farm/subregion land-use types, p.19	urban, ag (many user-specified crops), natural, riparian, aggregated, by area-weighted averaging, to the subregion (see Table 1, p.20); many per subregion.	land-use type (called "crop-type ID"), assigned to cell (see Table 1, p.20); one per cell. In CVHM, the properties are a spatially weighted average of all the land-uses in the cell. "Crops" can be virtual (e.g., zero-transpiration for recharge basins)
land surface flow resolution	four fluxes for each subregion (one per land-use)	by farm (not by cell)
root zone flow resolution	four fluxes for each subregion (one per land-use)	no root zone storage; fluxes are computed cell by cell, since land-use is by cell; but the output budget only provides an aggregrated flux for each farm.
root zone flow to groundwater resolution	specific to cell as a function of the specific land-use assigned to a cell.	by cell, since land-use is by cell; but information in the water budget output only provides an aggregrated flux for each farm.
summary of crop physical and management properties	see Table 1, page 20	see Table 1, page 20
effects of wilting on water uptake by crops	yes: water uptake decreases linearly from optimal water uptake once water content falls below a fraction of the field capacity, usually 50% (DWR,2011,p 2-49)	yes, via parametrization provided by Farm process or user-defined
effects of anoxia on water uptake by crops	no	yes, via parametrization provided by Farm process or user-defined
groundwater contribution to ET	no	yes. An example is the Central Valley model, CVHM (Faunt, 2009), where about 10% of ET is met by direct groundwater uptake (Faunt, 2009, Figure A23, p.53)

Issue	IWFM	MODFLOW WITH FARM PROCESS, MF-FMP
non-linearity in soil root zone flow modeling	yes: nonlinear on irrigation fluxes: ET and deep percolation from the root zone to the deep vadose zone below depend on end-of-time-step water content; uses Newton-Raphson approach to solve non-linearity.	yes: nonlinear between root zone fluxes and groundwater heads.
stress-response function for plant water uptake	no	yes (anoxia, wilting point)
root zone water budget	the increase in water content in the root zone is equal to the precipitation, the irrigation and the groundwater influx rate minus the actual crop ET, the surface runoff and the deep percolation outflux rate. (Appendix 4 for more details)	no changes in root zone water storage are considered and the root zone cannot provide water for plant uptake that has been delivered to the root zone during previous time steps.
computational solution of soil water equation	Newton-Raphson for nonlinear conservation equation (ET and DP depend on water content at end of time step); independent from gw-streamflow coupled solution, but solved once for each iteration of the gw-streamflow solution to compute irrigation need for given pumping and diversion. P.23	not applicable
spatial and temporal resolution of soil water budget	subregion with crops aggregated (for solving above equation); time-step (explicit solution, since not coupled to groundwater)	cell, iteration (implicit solution for time-step to allow for coupling with groundwater)
precipitation	by cell but then aggregated to subregion by land-use category	by cell
ET	combined flux; area-weighted average ET_c-pot of all crops for "ag" (p.24). Urban, native, and riparian is separate.	six fluxes: E and T from precipitation, irrigation, gw; potential ET user-specified or from ETref times crop coefficient (user specified) (p. 28); ET is FIRST met by gw, SECOND by precipitation, THIRD by irrigation. On the other hand, UZF FIRST uses moisture content, SECOND uses groundwater. Separate computation of E and T allows for evaluation of irrigation

Issue	IWFM	MODFLOW WITH FARM PROCESS, MF-FMP
		types (currently sparse data available to take advantage of this) (p.51)
potential crop evapotranspiration (unstressed crop) ET_c-pot	user-specified time series for each crop	user-specified or internally computed as product of ET_reference and crop coefficient K_c. user specified (non-transient) fraction K_t separates ET_c-pot into transpiration and evaporation
actual crop evapotranspiration (stressed crop) ET_c-act	Actual ET is potential crop ET if water content is greater than or equal half of field capacity; otherwise linearly proportional to ratio of water content over half field capacity. (Appendix 4 for more details)	from HYDRUS2-D simulations that also account for wilting, anoxia => typically about 72% of IWFM (see (p. 54)
crop stress	yes, once water content falls below half of field capacity (Allen et al., 1998, use a user-specified moisture content; in IWFM it is set to half of field capacity)	yes, if ET_c-act is derived for “unstressed” conditions, then wilting and anoxia can be optionally considered to compute T_c-act and T_c-act-max
crop stress memory for life of crop	no	no
runoff from precipitation	curve number method; runoff losses occur, **before** computation of ET	no
runoff from irrigation	The first estimate of the surface runoff from irrigation supply is a fraction of the irrigation supply. However a fraction of it is recuperated for reuse and thus the final estimate of the surface runoff non reused is the difference between the two (p. 33). (Appendix 4 for more details)	no
interflow	no	two user-specified fractions are input; two runoff losses (to immediate crops) are calculated as product of these fractions respectively to the difference of P minus ET and I minus ET (p. 34); in other words fractions apply to what’s left over from precipitation and irrigation **after**

Issue	IWFM	MODFLOW WITH FARM PROCESS, MF-FMP
		computation of EvapoTranspiration (hence, name "interflow" ?). Once added these two runoffs are routed to a user-specified stream or to the nearest stream. Soil moisture assumed constant. (Appendix 4 for more details)
runoff as a result of supply rate in excess of saturated hydraulic conductivity	yes	optional, via UZF
runoff from waterlogging	no	optional, via UZF
return flow	implicit to same cell, as fraction of runoff. Or to downgradient cell as applied water (IDCv4, p.17)	explicit to user-specified point of diversion, as fraction of runoff.
agricultural reuse	yes (same cell or downgradient cell, user-defined fraction)	no, returns to water supply; from there, maybe reused.
urban water irrigation	user-specified	user-specified or dynamically computed (as the unmet water demand)
agricultural water irrigation	user-specified or dynamically computed. Unmet water demand dynamically computed such that soil moisture target is met, IDCv4, p. 26) => field capacity or user-specified fraction of field-capacity to simulate deficit irrigation	user-specified or dynamically computed (as the unmet water demand)
unmet demand that is the basis for irrigation water application computation (that is, if not user-specified)	irrigation demand is calculated as the difference between the remaining (but depleted soil moisture storage) and the current precipitation, and as a function of runoff, deep percolation and crop ET. This is computed in each time-step and then corrected (i.e. increased) using runoff fractions in lieu of irrigation efficiency to compensate for losses on the way to the farm through the distribution system. The MAD (maximum	crop irrigation requirement is the sum of the transpiration and evaporation irrigation requirement. These are calculated as deficits between the potential values and those contributed by precipitation and groundwater extraction. Eqs. (12), (13), (19). (21), (23), and (26) (in Dogrul et al, 2011) appear circular: how does runoff or DP loss get accounted for?

Issue	IWFM	MODFLOW WITH FARM PROCESS, MF-FMP
	allowable depletion) is crop specific, but an area-weighted average of MAD is used by subregion (not by cell, see pages 35-36) In contrast to version 3 (which supports the current version of C2VSIM), in version 4 of IWFM the computation is for each land-use in each cell: $\theta^{t+1}Z^{t+1} = \theta^{t}Z^{t} + \Delta t\left(P^{t+1} - R_p^{t+1} + A_w^{t+1} - R_f^{t+1} + G^{t+1}Z^{t+1} - D_r^{t+1} - D^{t+1} - ET^{t+1}\right) + \Delta\theta_a^{t+1}$ (1) (IDCv4.0 Manual, p.10)	Equation (27) may be the answer: a "farm efficiency" is defined relative to the ET from irrigation water (after precip and groundwater contributions to ET); fraction is related to IWFM fraction through (28); this is computed separately for each cell (not by farm or subregion!)
deep percolation below from bottom of root zone to water table	based on soil moisture content in the root zone using Darcy's law to calculate the flux. That calculation can be done by using either Campbell's method (eq.29) or Van Genuchten equation (IDCv4 manual, p.19). In the latter case an iteration procedure is needed as part of solving the mass balance for the root zone. Schmid et al, 2011 (TIR2), p.13: "deep percolation is a function of soil moisture contributing to the crop-irrigation requirement" (Appendix 4 for more details)	based on infiltration to below root zone, which is input to UZF1 (kinematic wave plus ET losses plus groundwater uptake) or instantaneously recharged. Schmid et al, 2011 (TIR2), p.13: "deep percolation is the total inefficiency losses less surface water runoff, estimated **after** the calculation of crop irrigation requirements"
drainage of rice, ponds during ponding period	yes (IDCv4, p.18)	no
ET of applied water	yes, by subregion and land-use (4 per subregion, in Version 4 of IWFM: 4 per cell)	yes, by farm, input by crop
ET of precipitation ("effective precipitation")	yes, by subregion and land-use (4 per subregion, in Version 4 of IWFM: 4 per cell)	yes, by farm, input by crop
ET of other sources	yes, by subregion and land-use and soil (4 per subregion, in Version 4 of IWFM: 4 per cell)	yes, by farm, input by crop; "design" irrigation demand of a "virtual zero-transpiration crop" (p. 42)
maximum ET	potential crop ET, ET_c-pot	reduced potential crop ET or "actual"

Issue	IWFM	MODFLOW WITH FARM PROCESS, MF-FMP
		crop ET, ET_c-act due to wilting and anoxia (p.54 and FMP1 documentation: on average about 72% of ET_c-pot, which leads to irrigation water in MF-FMP to be 62% of that in IWFM)
water demands	irrigation for ag, irrigation for urban, municipal, industrial	same
urban water demand	user-specified time-series (to allow for standardized per-capita evaluation of the demand)	subtracted from non-routed external deliveries PRIOR to meeting ag water demand
municipal and industrial needs	as fraction of urban water demand, user-specified time-series	
ag vs. urban demands	demands met separately within subregion	
sequence of sources to meet demands	1. precipitation and soil moisture 2. imported supplies, stream diversions 3. groundwater pumping	1. precipitation and groundwater uptake 2. non-routed deliveries in the user-specified ranking sequence; routed deliveries and routed deliveries from modeled streams; routed deliveries are limited by available streamflow.
pumping	well pumping or element pumping	MNW package (with well-bore flow); maximum pumping rate constrained
aquifer storage and recovery (ASR)	no	yes, through well or well field prioritization
non-recoverable losses	user-specified, by individual water supply	
supply and demand imbalance	optional (can either enforce or not enforce a balance)	
optimization of land-use management	no	Optional: To optimize the economic return from surface water and groundwater irrigated acreage under water availability constraints that force land fallowing: economic values are associated with each crop and account for crop specific cost of irrigation water

Issue	IWFM	MODFLOW WITH FARM PROCESS, MF-FMP
inefficiency losses (Schmid et al., 2011, TIR2)	inefficiency losses from precipitation and irrigation to surface runoff are computed first, then subtracted from total precipitation and irrigation before crop irrigation requirements are estimated (see abstract)	first computes crop irrigation and total farm delivery requirements, then subtracts inefficiency losses from runoff and deep percolation
CPU time for test case (Schmid et al., 2011, TIR2)	58 minutes (see abstract); Comment: root zone model highly constricted and possibly affecting CPU time?	4 minutes

Important Differences between IWFM and MODFLOW - and some notes on HGS. With respect to simulating water management decisions, there are some differences that may lead to potentially very different outcomes in groundwater model results. This discussion does not provide an exhaustive analysis, but points to a few important differences. Neither model's approach is right or wrong. But users may have a preference for one management representation over the other, depending on the particular application and the ability to couple their IWFM or MODFLOW model to (customized) external models dealing with water management.

Spatial resolution of land-use: IWFM is designed as a basin groundwater model, but can also be applied to other groundwater flow modeling applications. Due to the lack of a transport code, it is generally not applied to contamination site models that span a few tens of acres to a few hundreds of acres. Its strength is application to problems that call for simultaneous simulation of both, groundwater and surface water flows and water supply management decisions. IWFM can also be applied to small watersheds and groundwater basins / sub-basins. MODFLOW has been applied at many scales, from highly refined local site models of less than an acre to a few tens of acres, to very large basin scale models encompassing tens of thousands of square miles. MODFLOW's Farm package, the MODFLOW module used to simulate water demands and water management, is designed primarily for larger (sub-basin or basin) scale applications and currently lacks the ability for transport modeling (streamline tracking being the exception).

In IWFM and MODFLOW, water demands are defined by land-use. Land-uses are categorized into urban, agricultural, riparian, and natural vegetation. Agricultural land-uses are further categorized into many different, specific crop groups, each with its specific crop ET, which is defined in IWFM and MODFLOW via the reference ET and a crop-specific "crop-coefficient". Crops are also characterized by their root zone depth dynamics and by their specific irrigation demands. Both models consider the land-use mix across individual cells (MODFLOW) or elements (IWFM). Users may define water supply options by "farm" (MODFLOW), where a farm is a collection of individual MODFLOW cells, or by "subregions" (IWFM), where a subregion is a collection of individual IWFM elements. Farms or subregions can be as small as an individual cell or element. In HGS, such distinctions are made by mapping the leaf area index (LAI) across the modeling domain, but HGS does not simulate water supplies other than those defined by the user prior to the simulation (lack of water demand simulation).

Temporal resolution of land-use dynamics: Both, IWFM and MODFLOW allow for a flexible temporal design. Two levels of time-stepping are distinguished in both codes: the time-stepping associated with the numerical solution algorithm (flow time-stepping). This time-stepping defines the temporal resolution (sequence) at which fluxes, water levels, hydraulic pressure, and stream stages are computed. In IWFM, this time-stepping is referred to as the "simulation time-stepping". In MODFLOW, this is simply referred to as the "time step". While water flows and water level changes may occur rapidly (over the course of seconds, e.g., in the unsaturated zone during an infiltration event, minutes to hours, e.g., in streams during a storm event, or minutes to days, e.g., in groundwater upon commencement of pumping), requiring the simulation to be performed in many, short time steps, the driving land-use dynamics that control water management decisions and the external (boundary) stresses to the system occur over longer time period (days, weeks, or months). These changes in external stresses on the flow system are therefore often defined at time-steps exceeding the length of a flow time-step. Multiple flow time-steps typically form a single "stress period" with a constant pumping rate, ET rate, etc during that period. In MODFLOW, land-use related time-stepping is referred to as a "stress period", while IWFM refers to these as "time series data". In HGS, data are also supplied as time series data.

Due to its lack of soil moisture storage tracking, MODFLOW's Farm package is best applied at time stepping scales of at least one month. Then, land-use water demands in the Farm process are best handled by defining monthly averages/totals. IWFM provides the user with a preset list of commonly used time-stepping choices, ranging from 1 minute to 1 year. In HGS, the time-stepping is user-defined and unrestricted, but convergence issues will likely constrain the maximum time-stepping chosen.

Water source priority ranking to meet water demands: The user of IWFM or MODFLOW may choose between prescribing a time-series of pumping rates at specific wells or model cells, or elect to have the software compute groundwater pumping as a function of unmet water demands. The latter is often used to determine groundwater pumping for agricultural crops, driven by the crop ET and a crop's user-specified irrigation demands (relative to crop water demand). IWFM and MODFLOW will go through a different sequence of priorities to determine, whether or not groundwater pumping is needed, and if so, how much groundwater pumping is needed to meet water demands, in any given time-steps. No such capability exists within HGS.

IWFM will first allocate any precipitation to meeting water demands, next it will allocate user-specified surface water irrigation supplies (which may be constrained by streamflows, water rights, environmental flow requirements), and finally it will allocate available soil moisture storage toward meeting crop water demands. If these sources of water are not sufficient, the difference between the water that these sources provide (in a given time-step), and the water demand will determine the amount of groundwater pumping.

MODFLOW with the Farm process will first determine direct root uptake from the groundwater table, if the groundwater table is within the capillary fringe below the root zone, and allocate direct groundwater uptake toward meeting ET driven water demands. Water demands not met by direct groundwater uptake next met by available precipitation. Remaining water demands are met by user-specified surface water supplies (including those that may be restricted by streamflow, water rights, environmental flow requirements). If these water sources do not meet the crop water demand, the difference between water available from these sources and the water demand becomes the computed groundwater pumping.

"Although some agricultural diversions are measured historically, pumping, a major stressor for the Central Valley aquifer system is for the most part (unlike urban pumping) not measured or regulated." (DWR,2012, Appendix 2). MODFLOW Farm process and in IWFM therefore estimate the pumping from wells on the basis of the optimal amount of water needed to supplement the surface supply. The differences between the two models in prioritizing water sources, especially direct groundwater uptake may lead to large water budget differences in a groundwater model. Also, it must be recognized that the water management simulations greatly simplify actual farmer behavior. When calibrating parameters using historical records, these simplified decision-making approaches may lead to inaccurate values for the parameters. Such potential errors can be evaluated through rigorous sensitivity analyses.

***Important differences in the hydrologic conceptualization that affect water management decisions*:**

Runoff: In IWFM, runoff losses are a function of precipitation and irrigation and are subtracted from the amount of water infiltrating into the soil and available for ET. A user-defined fraction of the runoff is allocated for re-use, the remainder is routed to a user-specified stream. In contrast, MODFLOW computes runoff as a fraction of the residual precipitation and residual irrigation water that is left over after accounting for the precipitation and irrigation amount, respectively, that goes toward meeting ET demands. Runoff is routed to user-specified streams, from where it can be reused. In HGS, runoff will follow topographic slopes. Streams form naturally as part of the simulation. However, HGS has no provision for simulating irrigation systems.

Root zone moisture storage and unsaturated zone fluxes: IWFM accounts for root zone water storage changes dynamically, using a combination of a tipping bucket model and a one-dimensional form of the unsaturated flow equation (see above) to determine the rate of downward percolation out of the root zone. Downward percolation is a function of soil moisture content (soil moisture storage) in the root zone "bucket", constrained by the assumption that drainage from the root zone is gravity-driven only (no moisture-gradient driven drainage). The tipping bucket model accounts for all the inflows to and outflows from the root zone (irrigation, precipitation, runoff, ET, deep percolation, etc.) and tracks the resulting changes in soil moisture content in the root zone, which in turn drives the amount of deep percolation (non-linear coupling). At the end of a time step, after water content has been depleted by evapotranspiration and deep percolation, IWFM assumes that any remaining amount of water in excess of "field capacity" (Appendix 4) will leave the root zone as surface return flow. The unsaturated zone below the root zone can be divided into a user-specified set of layers, which act as a series of further tipping buckets, receiving inflow from above and percolating water downward into the next "bucket". The downward percolation from each bucket is computed in the same manner as that from the root zone.

MODFLOW makes an *a priori* assumption that there are no changes in root zone soil moisture content over the user-defined time-step. All inflows into the root zone (precipitation, irrigation) over a time-step equal the total outflows (interflow-runoff, ET adjusted for direct uptake from the groundwater table, deep percolation) over that time-step. Soil moisture cannot be accumulated in the root zone for later use by plants (except with the user-defined time-step period). Unsaturated zone fluxes between the root zone and the water table are computed based on a one-dimensional form of the unsaturated flow equation. In contrast to IWFM, which assumes gravity flow only, the MODFLOW solution to the unsaturated flow equation allows for suction-gradients to vary to simulate situations of capillary water rise into the root zone from the water table (upward flow), when the water table is sufficiently shallow.

HGS has the physically most correct representation of the unsaturated zone, which is simulated as part of the variably saturated subsurface system. HGS makes no physical distinction between groundwater and unsaturated flow – the model code automatically deals with these concepts in a physically consistent manner. However, this physically consistent approach is computationally quite demanding and may limit the spatial discretization or the temporal discretization of the hydrologic system or both. Computer run-times are likely by far longer with HGS than with MODFLOW or IWFM due to the better, consistent handling of the unsaturated zone.

Direct groundwater uptake to ET: IWFM does not account for crop water uptake directly from the water table, even if the water table is within or above the root zone. MODFLOW satisfies ET from direct groundwater uptake if the water table's capillary fringe or the water table itself is within or above the root zone. Among the three codes, HGS handles direct groundwater uptake in the physically most consistent manner, since the subsurface is simulated as an integrated system.

Anoxia and wilting point effects on crop ET: IWFM does not account for reduced crop ET due to root zone water saturation that may lead to anoxia (lack of oxygen). However, crop ET is reduced due to wilting if the root zone moisture is very low. MODFLOW and HGS account for reduction in crop ET due to anoxia from root zone saturation. Root zone saturation is assumed to occur regularly, if only temporarily, during irrigation events and also when the water table rises into the root zone. Due to the assumption that irrigation leads to temporary anoxia, actual crop ET is always lower in HGS and MODFLOW than in IWFM for the same user-specified crop ET demand. Like IWFM, HGS and MODFLOW also accounts for reduced ET from wilting due to lack of water supply to the root zone. However, the algorithms differ between the three models due to their difference in representing the root zone moisture content.

Stream-to-groundwater flows: For situations where the water table in groundwater is below the bottom of the streambed, HGS, IWFM, and MODFLOW use somewhat different algorithms to compute stream recharge to groundwater (see above, Application C), which affects water availability in streams and groundwater level elevations. These differences in turn affect water allocations simulated by these models.

Application F – Water Quality and Transport in Groundwater and Surface Water

Section 3.2 already outlines the water quality and contaminant transport capacities of HGS. IWFM and MODFLOW are not designed for water quality and contaminant transport simulations. However, MODFLOW is frequently coupled with either MODPATH to simulate advective transport and to delineate source areas and impact areas, or with the code MT3D to simulate steady state or transient, 3-dimensional groundwater transport. Both, MODPATH and MT3D are specifically designed to work with MODFLOW. All graphical user interface software for MODFLOW that are available (e.g., Visual MODFLOW, Groundwater Vistas, GMS, and USGS ModelMuse) integrate MODFLOW, MODPATH, and MT3D in ways that make the use of these codes seamless. For practical purposes, MODFLOW (with MODPATH or MT3D) can therefore also simulate transport processes to evaluate changes in groundwater quality. For purposes of further discussion, we here consider HGS and MT3D (the latter used in conjunction with MODFLOW). Note that the MODFLOW Farm process can currently only be used with the particle tracking code MODPATH, but not with a transport model.

Both, HGS and MT3D solve the advection-dispersion equation with options to also solve for linear, instantaneous sorption processes. MT3D (but currently not HGS) further allows the use of a non-linear Freundlich type sorption isotherm or a Langmuir (saturation-limited) sorption isotherm. MT3D is also capable of simulating first order rate-limited sorption processes and first order exchange of solutes in a dual-domain (mobile-immobile) transport process (Zheng and Wang, 1999). Solute transformation (e.g., biodegradation or radioactive decay) is simulated as a first order decay process. HGS and some advanced versions of MT3D are capable of tracking these transformations across either simple (single parent / single daughter product) or more complex (multiple parent compounds or multiple daughter compounds) reaction chains. RT3D (http://bioprocess.pnnl.gov/rt3d.htm, accessed 1/4/2013) is a public (free) version of MT3D that allows for extensive chemical multi-species reaction simulations within the standard MODFLOW GUIs and has the flexibility to add user-defined, complex reaction systems in the dissolved and sorbed phase. This includes precipitation-dissolution reactions at the water-solid interface in saturated systems, which cannot be simulated with HGS.

HGS (but not MT3D) has the ability to simulate heat (energy) transport, as discussed above, and adjust temperature-dependent solute transport parameters as temperature changes over time.

A major limitation of MT3D (and its variants) relative to HGS is the focus on simulating transport processes in groundwater (saturated zone). As an integrated hydrologic model, HGS is capable of simultaneously tracking solute and contaminant transport across the surface water domain, the unsaturated zone domain, and the groundwater domain. Similarly, HGS is capable of tracking heat across these integrated systems. In California, integrated transport is of interest for nutrient and salt transport across watersheds and underlying aquifers, while integrated heat transport across the subsurface-surface interface is of interest in evaluating possible stresses on stream ecosystems resulting, e.g., from reduced groundwater inflows to streams due to pumping.

Both, HGS and MT3D, are capable of simulating specified concentration (Dirichlet) and specified solute flux (Neuman) boundary conditions.

Both, HGS and MT3D solve the transport equation numerically using the same model grid used for their respective solution of the flow equations. MT3D includes several options for the numerical solution of the advection part, including Eulerian-Lagrangian algorithms and a Total Variation Diminishing (TVD) method, both of which minimize numerical errors (numerical dispersion and numerical oscillations in concentration profiles), while applying an implicit finite difference method to solve the dispersion part of the equation Zheng, 2005). HGS has the option for using either a Galerkin finite element method or a control volume finite element method. A critical limitation in the application of these transport codes is that the dispersivity parameter, which has units of length and which controls the dispersion behavior of solutes in the subsurface and in streams, must be at least on the same order as the largest grid cell or grid element of the modeling domain (so-called Peclet criterion). On the other hand, the transport time stepping (inversely related to the CPU time of the transport model) is controlled by the grid size – smaller grid size requires shorter time-stepping and more CPU time and computer memory (so-called Courant criterion). With these codes, transport modeling is therefore limited to simulations of sites that are on the order of several tens to several thousands of acres in size. Application of these codes to large groundwater basins (100s to 100,000s of square miles) is impossible due to the discretization necessarily being much coarser (larger) than the dispersivity length governing the transport of solutes and contaminants in surface or subsurface systems (Kourakos et al., 2012).

Application G – Tile Drainage

Tile drainage is an important hydrologic element in many agricultural or even in non-agricultural regions. Tile drains represent lateral flow paths in the uppermost, shallow aquifer that divert recharge and shallow groundwater away from the water table, via pipes or ditches, toward streams. HGS, IWFM, and MODFLOW all have the capacity to simulate tile drains, but do so in somewhat different fashion, similar to how stream-groundwater interactions are simulated differently.

In HGS, tile drains are modeled as linear, one-dimensional surface flow features, where surface flows are coupled to subsurface flows in a manner similar to streams. While computationally more demanding than in the IWFM and MODFLOW approach, the approach appeals through its physical consistency.

In IWFM and MODFLOW, tile drains are simulated using a Cauchy-type, head-dependent flux boundary conditions when the water table is higher than the user-specified elevation of the tile drain. The flux into the tile drain increases linearly as the water table in the aquifer rises above the tile drain. The proportionality factor ("drain conductance") is a user-supplied variable that is related to the design of the tile drain, the model grid, potential low-conductance zones around the tile drain, and other factors. In IWFM and MODFLOW with the Farm process, tile drain flow is routed to user-specified stream network locations.

Application H - Evapotranspiration

See Sections 3.2 – Evapotranspiration and this Section, Application E.

Application I – Estimation of Groundwater Pumping

IWFM and MODFLOW have built-in functionality to estimate groundwater pumping, while HGS does not allow for such estimation without adding some external code linked to HGS. See discussion in Application E (this Section)

Application J – Groundwater Management Optimization

HGS, IWFM, and MODFLOW can all be used to optimize groundwater management options. HGS and MODFLOW with MT3D can be used to optimize groundwater remediation at contaminated sites. However, the optimization and the control of groundwater management options must be implemented through an external, user-supplied program. In principle, the application of these three groundwater flow codes to optimization of groundwater management would consist of setting up the groundwater(-surface water-unsaturated zone) flow model with either of these codes. A separate code would be used to simulate the optimization problem, which may control the location and extraction depth of wells, the pumping rate, and the time of pumping, or the location, rate, and timing of other groundwater management elements, such as recharge basins, etc. For each configuration chosen by the optimization program, the flow model would be run with HGS/IWFM/MODFLOW. For remediation optimization, the transport model would be run when using HGS or MODFLOW with MT3D. The external program would need to be able to rewrite the input files for and read the output files from HGS/IWFM/MODFLOW to automatically interact with these codes. Sometimes it may be necessary and convenient to create customary code that links the optimization model with the flow (and transport) model.

"IWFM itself does not include optimization methods implicitly. However, it has been designed so that the groundwater component can be linked to dedicated optimization tools. This was a deliberate numerical engine design decision to allow IWFM to tap into the power of other software products designed specifically for such purposes." (DWR, 2012, Appendix 2).

"MODFLOW FMP can be linked with GWM to perform formal optimization of state variables (Q's) subject to constraints such as salt loads, streamflow requirements, hydraulic gradients, etc. MODFLOW FMP can not only address constraining or optimizing urban pumpage but also agricultural pumpage separately with the additional feature of groundwater allotments for each "farm" and surface-water allotments for the entire model that are built in limits on the allocations of water to individual farms or the entire model. MODFLOW FMP also has built in optimization options for operational drought scenarios for acreage optimization, water-stacking, or conservation pool. Finally, MODFLOW FMP also has the ability to simulate deficit irrigation where demand is reduced to limited supply…this is critical for climate change and adaptation scenario modeling." (USGS, 2012, Appendix 3)

Application K – Incorporating Regulatory and Policy Aspects

MODFLOW with the Farm process and IWFM enforce water rights and maximum pumping limitations as well as environmental flow constraints on surface water demands. The two codes can also be used to evaluate the impact of external water transfers to or from the region of interest or within the region of interest. The implementation occurs through user-defined numeric limits/constraints that have the same spatial and temporal resolution as the numerical grid (spatial resolution) and stress period (temporal resolution). This cannot be done with HGS, except by creating external, additional code.

In IWFM, the adjustment of surface water deliveries and pumping to meet water demands is an explicit iterative process solved by following a simplified rule set of adjustments to diversions at each iteration that are a function of user-specified rules and diversion rankings (DWR, 2012a). Importantly, IWFM only considers equal appropriation allotments.

Similarly, MODFLOW with the Farm process applies an iterative process to obtain flow solutions that meet user-specified constraints and policies. MODFLOW has the option of considering equal appropriation allotments (every water user suffers equally from water shortage), somewhat similar to IWFM, or prior appropriation allotments following a prior appropriation water rights scheme. MODFLOW further provides the option to priority rank water supply wells, which allows, for example, the simulation of an aquifer storage and recovery (ASR) program (Figure 2 below). MODFLOW also has the option to simulate five drought response policies during periods when neither surface water nor groundwater are sufficient to meet agricultural water demands: Simple shortage without policy, acreage-optimization (using a linear optimization algorithm and economic crop value functions) with or without a water conservation pool, and deficit irrigation with or without water-stacking for priority crops (Schmid et al., 2006, 2009).

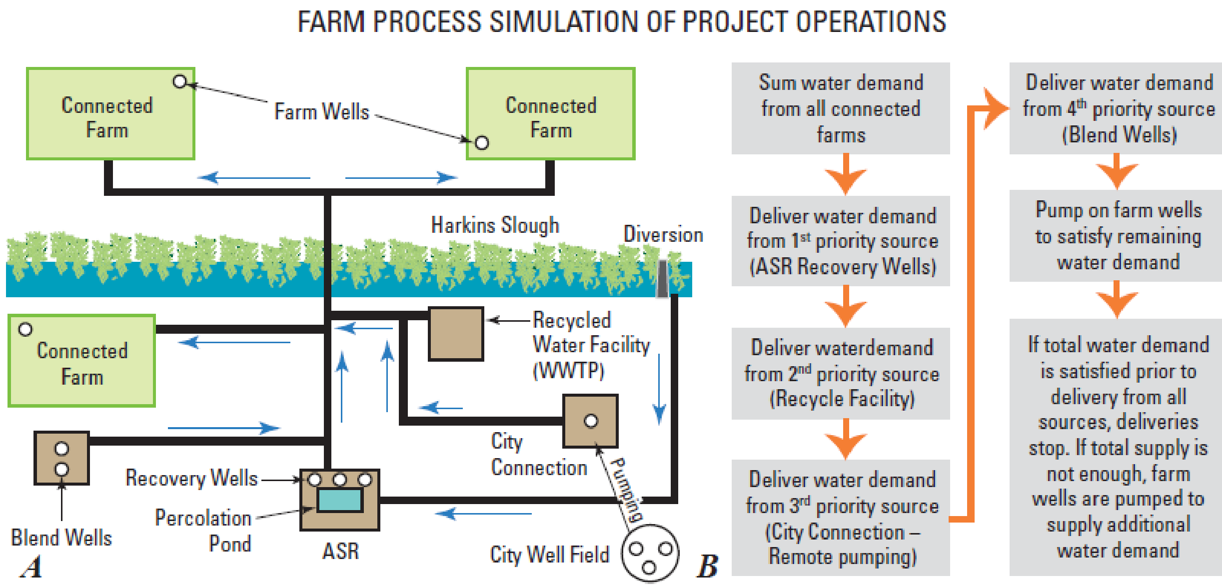

Figure 2: (A) Structure of local deliveries and flow chart showing (B) the order of operation of the simulation scheme for deliveries from an Aquifer-Storage-and-Recovery System (ASR) to regions serviced by the Coastal Distribution System, Pajaro Valley, California (Hanson et al., 2008b; Schmid et al., 2012).

It is difficult to assess the functionality of these regulatory/policy aspects of the model as they do not represent physical laws with precise solutions. The algorithms used are attempts at representing a complex set of human decisions, water rights, and environmental flow requirements through simplified conceptual approaches that can be expressed by simple, linear mathematical constraints. Application of these modeling schemes can be found in the literature generated by the use of these models (e.g., Hanson et al., 2008). IWFM and MODFLOW are sufficiently dissimilar in their conceptual representation of these constraints, but also in the conceptual basis for presenting some parts of the hydrologic system that they will likely yield potentially very different results for the same study area. This cannot be construed as one model being better or worse than the other, but represents the uncertainty arising from the difficulty of finding adequate mathematical descriptions (algorithms) of social processes (water management decision making).

4 Conclusions and Recommendations

Extent of Physical Correctness

The three model codes evaluated here provide a wide range of advanced tools to simulate groundwater flow and transport as part of an integrated hydrologic system and associated water management features.

With respect to the physical representation, there are (at least) two major concerns of importance to the water manager. One concern is about the methods to determine irrigation requirements. Irrigation is driven by crop ET, but when it comes to evapotranspiration the three model codes, HGS, IWFM, and MODFLOW are quite different. This is the result of multiple conceptual approaches being offered by the science community on computing plant transpiration, associated soil surface evaporation, and the reaction of plants to stresses (drought, flooding, etc.). IWFM and MODFLOW use essentially the same data for potential (or reference) evapotranspiration. However their method to calculate crop response to water stress is quite different and offer different user choices. MODFLOW with the Farm process accounts for anoxia (lack of oxygen due to soil saturation), which causes the model to reduce crop ET under typical California conditions (unless the modeler makes parameter adjustments). Neither IWFM nor HGS account for anoxia. In addition, the computation of water flow in the root zone, and between the root zone and groundwater is mathematically very different between the three model codes. IWFM is largely based on mass balance based storage routing approach and does not account for root water uptake from groundwater. MODFLOW with the Farm process performs a mass balance based on the assumption that root zone moisture storage never changes, but uses a simplified 1D flow equation for calculating recharge below the root zone. If the capillary fringe of the water table is within the root zone, ET is met first by plant uptake from groundwater. HGS is capable of a fully physical solution, but the mathematical representation may not be valid at large scales (a fundamental problem in modern soil physics).

The recommendation for IWFM is to develop a strategy in order to estimate a contribution of groundwater to transpiration. The recommendation for MODFLOW is to develop a methodology to dynamically adjust moisture content in the root zone and provide California based data to guide the parameterization of the effects of anoxia on agricultural crop ET. For HGS, guidelines are needed on how to properly discretize large basins when using a 3D Richards equation to compute unsaturated zone fluxes.

The second concern is with the treatment of the stream-aquifer flow exchange when the stream and the aquifer are in hydraulic connection. A low conductance term is artificially inserted between the stream and the aquifer, effectively representing a low hydraulic conductivity layer in the riverbed. Riverbed hydraulic conductivity is rarely measured, the low conductance term is also a function of the groundwater model grid discretization, and in many situations, there may not be a low permeable riverbed, but a highly permeable sand or gravel bed. Through a calibration process using good data ultimately one may obtain a good estimate of the flow exchange but this is not guaranteed. Finer discretization may alleviate the numerical inaccuracy, but only at the cost of much higher CPU time.

This issue cannot be overcome easily, as the scientific literature lacks widely accepted formulas for evaluating the stream-aquifer flow exchange with reasonable accuracy at the watershed scale, while staying true to the underlying physics that also drive water chemistry and temperature. Appropriate calibration and sensitivity analysis are the common remedy to address such shortcomings.

Finally the three models, when used at a large regional scale, calculate groundwater heads as average values over large horizontal areas, typically of the order of one mile by one mile. These values are used, for example, to determine if a cell (or zone of influence of an element node) will go dry or whether plants may use groundwater (instead of precipitation or irrigation) for ET. When a well pumps it is assumed that its withdrawal rate is taken uniformly over the entire cell area. In reality the flow pattern is not uniform due to the small size of the well bore. A huge cone of depression sets around the well and the drawdown in the well is much larger than the average drawdown in the large cell. Actually the cell never goes dry; the well does. Such assumption leads to a highly optimistic estimate of the availability of groundwater for extraction. In addition the use of that average drawdown to calculate the pumping cost when trying to decide on a cost effective choice between use of groundwater versus use of surface water will underestimate significantly the pumping cost. It is recommended that the model developers design an approach (somewhat approximate naturally) to relate the drawdown in the well (or wells) to the average drawdown in the cell where the well (or wells) is (are) located. Analytical solutions are also available to approximate the difference between model cell drawdown and well drawdown.

Adequacy of Spatial and Temporal Discretization

There is a point of decreasing return to reduce the spatial scale as the data are no longer available with the smaller size of grid cells. Much depends on the size of the region to be studied and the availability of data. Of course much also depends on the numerical power available to the user.

The model codes are typically applied to develop models as part of planning studies but not for water operations. Water operations are conducted on a daily basis. For water management purposes, a planning model is only as good as it can be implemented on a daily basis. A practical goal is therefore to create these models with a time step of one day. In this case river flows will need to be routed. The challenge is to develop a routing model that is simple enough and yet sufficiently accurate.

Models, while only a conceptual approximation of reality, typically produce satisfactory match of modeled heads and fluxes with measured heads and fluxes, when calibration is used with an extensive set of parameters that cannot be measured readily and are averaged over large areas. The three models are fundamentally based on a continuous mass balance, which is critical. However, the large number of parameters that need to be estimated by calibration may not provide unique solutions unless a sufficient number of field data are available to constrain the model solution space.

Available Documentation of Verification of Approximations in Physical Processes.

A sufficient number of verification exercises have been implemented with the three codes to conclude that the codes conform to the theory and the algorithmic approximations derived from the theory, at least with respect to the principles of groundwater flow, but also with respect to some of the ancillary model systems. However, for these ancillary systems (e.g., the evapotranspiration system) a verification does not prove that the underlying conceptual model itself is correct. Most of the verifications were done at the initiative of the code developers and to some extent are not comprehensive and also do not necessarily verify more salient points. It would be useful if some tests were performed that are designed by an independent party (e.g., university, state agency) and run either by the model developers (if they have the time to do it) or run by other practitioners familiar with the codes. More verifications could prevent adversarial presentations, say in courts, tarnishing the credibility of a particular model for a given application by showing that under some circumstances, not previously tested, the model can be significantly in error.

Efficiency and Accuracy of Numerical Techniques

It is clear that the "solvers" are quite efficient for the three codes. There have been internal comparisons of efficiency of different solvers developed within a model (e.g. Table 1). There have not been comparisons of solvers developed and/or used between different models. Solvers are primarily developed outside of the groundwater modeling community. They are a critical component of many numerical techniques. Groundwater modeling codes take advantage of these existing, very efficient solvers. Much of the testing has been done within applied mathematics.

Parameter Estimation and Calibration Techniques

Numerical models involve many unknown parameters. A common practice, known as calibration, is to estimate them by choosing values for these parameters and attempting to match as best as possible the results of runs to available observations say of heads and discharges. It is done by trial and error or more systematic procedures using optimization codes. Statistically it is well known that increasing the number of parameters to be calibrated leads generally to a better match. Yet, the reliability of the model for future prediction diminishes (Graybill, 1961).

Generally the three codes use computer programs designed for that purpose such as PEST (the model-independent Parameter Estimation and Uncertainty Analysis software) and others. Some indication of the adequacy of the fitting, using some statistical measure such as the standard error of estimate, is generally obtained. There is no universally accepted threshold to scientifically delineate a bad fit from a good fit; it remains highly subjective.

Water Management Capabilities of Models

IWFM and MODFLOW with the Farm process have capabilities to provide answers to management questions. By changing inputs or selecting a particular option in the code, the user can compare a variety of management options. MODFLOW has some optimization capabilities but mostly for agricultural goals. Neither model seems to have much capability in terms of environmental concerns such as meeting flow requirements in the streams. Realistically to implement such requirements there would be a necessity to route the flow on a daily basis. For the correct implementation of water rights, again a daily time step would be necessary. Both models are planning tools; they are not operational tools. HGS is primarily an integrated hydrologic model for detailed watershed analysis. As with other codes it can be used for management but it was primarily intended for hydrologic evaluations not for management. This is part of the reason why it is mostly used in academic circles for research purposes. Just the same it can be used for management. Indeed this can be an advantage because the potential user can (and must) design its own management code and is not limited by the management choices already imbedded in MODFLOW and IWFM. For consulting jobs, this approach is generally not feasible (i.e., too expensive).

Documented Applications of Models

Of special interest would have been applications of the models by users other than the developers, with reports of users' evaluation of the tools would have been instructive. Unfortunately these were not readily available to this review. Many of the documents provided to us, in particular journal articles, are authored by the developers and by academicians that perform research under contract by the model developers. They essentially provide verification for components of the models but they are not applications in the real world even though they may use real data. Understandably, it is not the vocation of DWR or USGS to track applications or experiences of other parties. Their mission is to serve their agency. They provide the computer codes to others and do help them to learn how to use their models. Unfortunately, few reports are produced by the "customer". Instead, much of the information is shared at conferences.

Reliability of Results of Application of Models for Management Studies

The models provide answers given the data provided as inputs and the calibrated values of the parameters. The models per se do not provide a measure of the accuracy of the results. It is up to the user to test the sensibility of the results to changes in inputs or values of the calibrated parameters.

General availability of computer code and technical support

«IWFM web site includes a sample problem and IWFM developers are available for user support. IWFM developers generally meet with potential users, give them an overview presentation of IWFM features and help them jump start their applications. DWR organizes users group meetings to keep the water community informed about IWFM developments and to stay informed about IWFM applications and modeling needs of the water community.» (DWR, 2012, Appendix 2).

«MODFLOW is constantly being improved, expanded, and corrected if necessary. New versions are released frequently and come in a wide variety of versions to special considerations (http://water.usgs.gov/software/lists/groundwater/). MODFLOW and all of its source code is free, open source, and completely available to anyone. In addition, we collaborate and welcome collaboration with other groups that want to add or improve features within MODFLOW …An important requirement for adding new features to MODFLOW is that they are being applied to a real complex problem in conjunction with development (ex. FMP1). …. We do provide support, but substantial support or modifications need to be part of funded projects since the USGS relies on external funding for much of its operational costs.» (USGS, 2012, Appendix 3).

HGS is a proprietary model that can be licensed to organizations under different terms and fees depending on the organization type that wishes to use HGS. Not all the information about the code is accessible however, even to those who have secured a license. «Until recently, the code was free for academic research, while commercial users paid a license fee between 3000 and 6000 US dollars depending on the number of CPU cores the code will use in a parallel computational platform. The code can be downloaded by contacting the developers through the website: http://hydrogeosphere.org/.» (Brunner and Simmons, 2011)

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6 Appendices

6.1 Appendix 1: CWEMF Set of Typical Questions Regarding Groundwater Models From Water Managers

Peer Review Questions

Theoretical Considerations

Q1. What are the theoretical considerations (in brief) for groundwater modeling particularly in areas relevant to California and the Central Valley?

Q2. Describe the capabilities of each model in terms of 1-, 2-, or 3-dimensional modeling, and steady versus unsteady state confined and unconfined groundwater flow?

Q3. What – if any – are the model-specific limitations on time steps?; Can hourly, daily, monthly, annual, variable time steps be simulated?

Q4. Discuss any model specific pros and cons and inherent uncertainties in terms of model approaches related to underlying theory or solution technique(s)? Are there differing numerical solution options available to the modeler? Is there a class or classes of applications that are appropriate or inappropriate as related to the governing equations and/or numerical solution technique(s)?

Q5. Does each model simulate groundwater flow and transport and, if so, are the governing equations coupled or is an iterative solution technique used?

Q6. Are there known performance issues documented with respect to particular model scales, types of problems or applications?

Q7. What are the types of boundary conditions that can be simulated? What types of monitoring data is required for the various boundary conditions? Are there unique or model specific treatments of boundary conditions in the numerical solution procedure?

Q8. Have there been any peer review(s) or publications available on any of the three models? If so, please document these references.

Groundwater Studies

Q9. How well have the models been tested? i.e., has there been formal validation studies performed on each model? Are the validation studies documented or included in or with the model documentation?

Q10. What is the quality of model documentation for each of the three models? Are model assumptions clearly defined and documented? Does each model's documentation effectively discuss how model assumptions can impact possible modeling objectives? Does each model's documentation clearly and effectively describe the uses, conditions, and types of applications that the model can be used for?

Q11. What are the pros and cons of each model in terms of accessibility of input and output data, the use of standardized data formats, and the availability of sample problems and user support?

Q12. What are the capabilities for the modeler to customize or modify each model? Include a brief indication whether each model is open-source or proprietary.

Model Implementation, Calibration/Validation, and Applications

Q13. Assess and discuss each groundwater model's ability to simulate the following applications. As part of the discussion, please include past applications of the models to the California Central Valley as well as any other applications known prior to or brought about during this peer review related to California Central Valley water resources management. Wherever possible, relate the discussion to the aspects or features of each model; or indicate whether none of the three models are appropriate for a given application. Also, include in the discussion, any assumptions or necessary context with respect to monitoring data requirements. For prior applications and, if available, summarize the public's acceptance of model results.

a. Aquifer Safe Yield: Can the models be used to quantify the limits where resource development will not lead to undesirable environmental effects? Describe the types of groundwater stresses that can be simulated (e.g., groundwater pumping or groundwater recharge projects)?

b. Describe briefly how each model could be used in a conjunctive use modeling assessment?

c. Surface Water and Groundwater Interaction: What are each of the models' approaches to surface water and groundwater interaction?; is the model fully integrated or would the groundwater model need to be combined with another surface water model?

d. Land Subsidence: With respect to each model, can aquifer dewatering or subsidence be simulated and if so how is it treated in the model?

e. Land-use: What are each model's functionality in incorporating and simulating differing land-use types and characteristics?

f. Surface and Ground Water Quality: Specifically, which physical, chemical, and biological parameters and constituents can be simulated by each model, if at all? If the groundwater model does not allow water quality simulation, what options are available to the user? For example, are there companion models that can be used? With respect to each model, can salt (mass) flux be simulated in aqueous and/or solid phases? How well do the models' account for chemical and/or biological transformations and partitioning between soil, water, and air? How well do the models account for surface sources of contamination (e.g., landfills, industrial waste sites, septic tank fields)?

g. Tile Drainage: Can the models simulate different types of agricultural irrigation practices like tile drains, for example?

h. Evapotranspiration: How are evaporative and transpiration losses treated in the model; i.e., are evaporative and transpiration losses lumped or are the components treated separately?

i. Groundwater Optimization: Can each model determine the minimum number and optimum location of extraction wells for groundwater production or groundwater contamination remediation?

j. Regulatory and Policy Aspects: If regulatory and policy aspects were a part of the model application, how well can each model address those aspects?

Q14. Are there any specific pros and cons with integration of monitoring data for model performance testing? i.e., model calibration and verification?

Q15. Have post-simulation analyses been performed on applications of the three models to data for California or the Central Valley? If so, how well have the three models met their calibration targets?

Q16. How well does each model use the "range of error" in the model calibration in drawing conclusion about the model results?

Q17. Does each model output include a water budget? If so, is the model output clear and meaningful?

Q18. Can the results from each model be readily represented to non-technical audiences either directly through its native interface or using associated software? Could this model be used to facilitate discussion in public forums?

Conclusions and Recommendations

Q19. What are your recommendations for model uses or model improvements for each of the three models for the California Central Valley?

Q20. What do you consider to be this model’s strongest/weakest capabilities?

6.2 Appendix 2: DWR Responses to Questions

NOTE: This was an exchange of communications between DWR staff and Morel-Seytoux over an extended period of time. **This is not part of the reviewers' report.** However it might be of interest to the reader and eventual user of IWFM to know the points of views of the model developers. These views may not have been incorporated in the main report either because they were not considered relevant, they had already been expressed in a different way, or because the reviewers did not agree with them, or simply for lack of space.

Note: Questions are presented in black italics

Question and Comments by Morel-Seytoux are shown in blue

Answers by DWR are provided in black

Theoretical Considerations

Q1. What are the theoretical considerations (in brief) for groundwater modeling particularly in areas relevant to California and the Central Valley?

What particular physical, geographical, environmental and economic aspects do you feel need to be well represented in a model to be applicable to the Central Valley of California. Is your model specially suited to meet these requirements, which ones?

A1. The Central Valley of California presents challenges for applying an integrated hydrologic model as do many other similar basins, including:

1. hydrogeologic characteristics of the aquifer must be represented properly
2. surface and subsurface flow interactions must be addressed adequately
3. land surface and root zone flow processes must be simulated in a reasonably accurate way
4. spatial and temporal data availability

An additional and significant challenge is inherent in the Central Valley: the agricultural operations and their impact on the water resources. Agricultural water use amounts to about 85% of California's total water use, impacting the quantity and quality of surface and subsurface water resources. Although some agricultural diversions are measured historically, pumping, a major stressor for the Central Valley aquifer system is for the most part (unlike urban pumping) not measured or regulated. For an integrated hydrologic model to be applicable to the Central Valley, it should be able to predict the agricultural water demands, and compute dynamically the water supplies in terms of diversions and pumping to meet these demands. In other words, the model should not only address the physical routing of the water through the surface and subsurface flow system (which requires the knowledge of the stressors such as pumping and diversions) but should also address the dependency between water demand and water supply (which allows the prediction of the stressors that are used in routing the water) especially for planning purposes. Addressing the linkage and balancing between water demand and water supply in a dynamic manner also allows addressing questions regarding environmental and economical issues which are also important in California.

IWFM is designed to compute dynamically water supplies to meet the water demand as well as to route the water through the complex surface and subsurface flow system of California's Central Valley. Because of its capability to compute agricultural water demand as a function of climatic parameters, soil properties, crop characteristics and farm management parameters, and because it allows an automated "adjustment" of water supplies to meet this water demand, IWFM is suitable to address major water-resources related issues in the Central Valley including the effects of climate change and conjunctive use.

Q2. Describe the capabilities of each model in terms of 1-, 2-, or 3-dimensional modeling, and steady versus unsteady state confined and unconfined groundwater flow?

It is pretty clear that IWFM has these capabilities. With respect to 3 dimension it is not strictly 3-D but rather what one calls quasi 3-D. Is there something in your model that makes the treatment of these matters particularly numerically effective and accurate?

A2. In IWFM stream, lake, and the groundwater equations are fully coupled, and they are all solved simultaneously. The groundwater equation is discretized spatially using the finite-element method and all equations are linearized using the Newton-Raphson method. The resulting coefficient matrix is non-symmetric due to the treatment of stream flow equation, sparse, and has large scale variability. Sparsity and scale variability of the coefficient matrix are not unique to IWFM; all fully-coupled integrated hydrologic models, where conservation equations for processes with different spatio-temporal scales are simultaneously solved, possess these characteristics. In IWFM a unique algorithm, Preconditioned Generalized Minimum Residual method, developed by the Department of Computer Science of the University of California at Davis for DWR is used to solve the system of equations iteratively in an effective manner. This method has been shown to produce up to eight times runtime speedup compared to the widely used Successive Over-Relaxation (SOR) method.

Q3. What – if any – are the model-specific limitations on time steps? Can hourly, daily, monthly, annual, variable time steps be simulated?

It is pretty clear that IWFM can, in theory, simulate a system at any of these time steps. However are there limitations from a **theoretical** point of view to use a daily time step or weekly time step? Are there **practical** limitations to use a daily time step if the entire Central Valley is being studied with a numerical grid of the order of one square mile?

A3. Technically speaking, yes, one can use hourly, daily, monthly or annual time steps with IWFM, except the variable time step. The time step chosen is used for all simulated flow processes.

However, from a theoretical point of view there are two limitations to using any particular time step:

1. IWFM uses a no-storage approach in simulating the stream flows; i.e. storage in streams is not simulated or routing is instantaneous. This approach works well when the time step is large enough so that in a single time step period an inflow at an upstream boundary leaves the stream system at the downstream boundary. If the time step is too short, then the no-storage approach in stream routing may impose errors in the results. For the Central Valley, a time step less than a week may start introducing lag-time errors in the stream flow simulations.

2. IWFM uses the SCS Curve Number method for the simulation of rainfall runoff. Although this method was developed for individual rainfall events with durations measured in terms of hours or maybe days, DWR has been using it with larger time steps by calibrating the curve numbers. This approach works

reasonably well but every time the time step is modified the curve numbers may have to be recalibrated.

The main practical limitation to using a daily time step for a Central Valley model with grid size of one-square mile would be the availability of daily data. Historical diversions for the Central Valley have been compiled at a monthly time step. Measured diversions are continued to be reported at monthly intervals. Using a daily time step requires disaggregating monthly diversion data to daily intervals. Previous efforts at DWR on this issue have shown that this is not a simple task.

Q4. Discuss any model specific pros and cons and inherent uncertainties in terms of model approaches related to underlying theory or solution technique(s)? Are there differing numerical solution options available to the modeler? Is there a class or classes of applications that are appropriate or inappropriate as related to the governing equations and/or numerical solution technique(s)?

This discussion is particularly relevant when the equations are nonlinear. If different solution options are available to solve the system of equations are there clear criteria when one technique should be used versus another? Is it simply a matter of numerical efficiency or also of accuracy of the solution?

A4. IWFM offers two options to solve the system of equations: SOR and Preconditioned GMRES (PGMRES) approaches. Our tests have shown that although SOR is a very robust methodology it can be very slow. PGMRES is a much faster solver although not as robust as the SOR method. As far as the accuracy goes, they produce similar results.

As a purely groundwater model (stream, land surface and root zone components are all turned off) IWFM can be used at any scale with any time step. However, as a full-blown integrated hydrologic model IWFM was designed mainly for large-scale applications where the use of a large time step (weekly or monthly) is more appropriate.

Q5. Does IWFM simulate groundwater flow and transport and, if so, are the governing equations coupled or is an iterative solution technique used?

My reading of IWFM documents indicates that the model is not designed for groundwater transport of dissolved substances.

A5. Correct, IWFM does not simulate transport.

Q6. Are there known performance issues documented with respect to model scales, types of problems or applications?

You have already indicated that some methodologies used in IWQFM limits its applicability to time steps shorter than a couple of weeks.

A6. The fact that IWFM does not track the change in the stream storage limits the choice of time-step length for a given application. The time-step should be large enough such that flow entering the streams at the upstream end can travel through the modeled streams and leave the model domain in the duration of a single time step in order for this approach to be valid. Due to this limitation as well as the limitations in the input data, IWFM is generally run with monthly time steps. As far as the spatial scale is concerned, IWFM is designed for basin-scale applications that include multiple farms where lumped values for soil properties, farm water and crop management parameters can be used for each model cell. It is not designed for applications at farm or sub-farm scales where the spatial changes in the water movement as affected by the micro-scale soil properties are needed.

Q7. What are the types of boundary conditions that can be simulated? What types of monitoring data is required for the various boundary conditions? Are there unique or model specific treatments of boundary conditions in the numerical solution procedure?

IWFM can model the standard types of boundary conditions and treats them in a very standard way, i.e. coupling them within the system of equations to be used. However specially in the case of the stream-aquifer boundary condition the coefficient and the head difference appearing in the general head (also called Cauchy) type boundary condition are not necessarily correct.

A7. It is correct that the treatment of the boundary conditions in IWFM is in standard form. However, we have modified the expression that represents the stream-aquifer interaction when groundwater and stream are hydraulically disconnected. The standard expression for stream-aquifer interaction in this particular case is

$$Q_{sg} = K_{st} w L_s \left(\frac{d+s}{d} \right) = K_{st} w L_s \left(1 + \frac{s}{d} \right) \qquad (1)$$

where Q_{sg} = stream-aquifer interaction (L^3/T), K_{st} = hydraulic conductivity of stream bed material (L/T), w = width of the stream channel (L), L_s = length of the stream segment (L), d = thickness of the stream bed material (L), and s = depth of stream flow (L). Equation (1) assumes that the stream bed is saturated at all times. Particularly for seasonal streams going from a dry period to a wet period, the stream flow can be a trickle. In this case, the stream depth compared to the thickness of the stream bed can be small, such that s/d can be much less than 1. In this case, a seepage rate will be computed that can be larger the stream flow itself. IWFM developers' experience is that the resulting seepage terms from this approach can show unreasonably high oscillations and the solution process can become unstable (when the stream seepage is larger than the stream flow itself, the situation is very similar to the drying and wetting of aquifer layers). To avoid such issues, IWFM approximates the above equation as

$$Q_{sg} \cong K_{st} w L_s \left(\frac{s}{d} \right) \qquad (2)$$

Although this is not an accurate representation of the Darcy equation, it does produce lower seepage rates when the stream stage is small. It should be noted that the offset between (1) and (2) is small in relation to Q_{sg} when s/d is sufficiently larger than 1 and that Q_{sg} is computed using the standard Darcy equation if the stream and aquifer are hydraulically connected.

Q8. Have there been any peer review(s) or publications available on any of the three models? If so, please document these references.

Please provide the most important one. If you have already provided a number of files please indicate which one is particularly relevant.

A8. There are several peer-reviewed publications on some of the methods used in IWFM as well as an application paper:

- Flow computation and mass balance in Galerkin finite-element groundwater models (Dogrul and Kadir, J. Hydraulic Engineering, 2006)
- Drought resilience of the California Central Valley surface-ground-water-conveyance system (Miller et. al, JAWRA, 2009)
- Error control of iterative linear solvers for integrated groundwater models (Dixon et. al, Ground Water, 2011)

These publications were made available to the peer review committee as part of the IWFM peer review materials. The independent peer review of IWFM and MODFLOW-FP as documented in TIR-1 and TIR-2 were also provided.

The first and third publications are on specific components of IWFM (a post-processor and the matrix solver, respectively). The second publication is probably the most relevant for this peer review process as it shows how C2VSim (IWFM's application to California Central Valley) can be used to answer questions about water resources in California under different climate scenarios.

Groundwater Studies

Q9. How well have the models been tested? i.e., has there been formal validation studies performed on each model? Are the validation studies documented or included in or with the model documentation?

A **wrong** model with **wrong** parameters calibrated on **good** data and showing a good fit can give the impression that the model is adequate and "validated". Have there been studies done that partition the historical data in a "calibration" set and another "validation" set? The purpose being to test if the model has a good **predictive** capability particularly when studying different management strategies.

Also were the extreme data included in the calibration set or left in the validation set? Or also did the calibration set include the rather normal data while the validation set did on the contrary contain the more extreme historical data?

Please provide just one example of calibration that meets this standard. If documented please make file available.

A9. We have tested IWFM using 11 test cases. A report titled "Verification problems for IWFM" by Ercan (2006) has been prepared and is available on the IWFM web site. This report was also made available to the peer review committee as part of the IWFM peer review materials. This report compares IWFM groundwater head simulations to analytical solutions when such solutions are available. In some of the test cases, the effects of grid and time step size on the simulated heads are also studied.

Additionally, DWR staff has been calibrating the California Central Valley Groundwater-Surface water Simulation Model (C2VSim). In this process, the calibration period was chosen to be 1972 through 2009, while the validation period was 1922 through 2009 overlapping the calibration period. Both periods included extreme cases (droughts and floods). The documentation of this effort is nearly complete and will be made available to the public soon.

Q10. What is the quality of model documentation for IWFM ? Are model assumptions clearly defined and documented? Does the model's documentation effectively discuss how model assumptions can impact possible modeling objectives? Does each model's documentation clearly and effectively describe the uses, conditions, and types of applications that the model can be used for?

The documentation regarding assumptions used and how the assumptions can impact possible modeling objectives is quite good. However the documentation in the Theoretical Documentation does not stress the types of applications that the model can be used for. Did I miss something there? On which pages? Or is it more clearly stated in the User's manual?

A10. All IWFM documentation along with a sample problem application is available on IWFM's web site. These documents were also made available to the peer review committee for their review.

No, current IWFM documentation does not state the applications that the model can be used for. This information should and will be included in the future updates of the model

Q11. What are the pros and cons of the model in terms of accessibility of input and output data, the use of standardized data formats, and the availability of sample problems and user support?

A11. IWFM has a very user-friendly format for input and output data. Input files are plain text files, and include comments and a brief explanation of each variable that the model requires. The users are allowed to insert their own comments into the input files. For instance, the users can document the data development process directly in the input files turning these files into a "living" document of the IWFM application. Time series input data have date and time stamps and organized neatly in a table format, allowing easy reading and QA-QC. Output data also have date and time stamps and organized neatly in a table format that allows easy reading as well as easy copy-paste into other software such as Microsoft Excel. Utility programs that transfer output data into Excel with a click of a button are also developed and available for users for free. Time series data can be input from and output to USACE's HEC-DSS database as well.

IWFM has extensive output for each simulated hydrologic component rendering the need for the users to intercept the source code redundant. I have a question about intercept.

"Intercepting code flow is commonly used in programming today to mean adding code (WRITE statements) to print out variables that are not part of the standard output." (Tariq Kadir, email communication).

IWFM web site includes a sample problem and IWFM developers are available for user support. IWFM developers generally meet with potential users, give them an overview presentation of IWFM features and help them jump start their applications. DWR organizes users group meetings to keep the water community informed about IWFM developments and to stay informed about IWFM applications and modeling needs of the water community.

Q12. What are the capabilities for the modeler to customize or modify the model? Include a brief indication whether each model is open-source or proprietary.

IWFM is not proprietary but that does not make it open-source. It is not clear if the model's complete source code is available to the general public.

It is not clear in this question who the "modeler" is? DWR staff or a general user not affiliated with DWR? DWR has indicated earlier in the questions that it would provide limited support to users and probably would not customize a model to suit the particular needs of a user, at least not for free.

A12. IWFM is open-source as the source code is available for download from the IWFM web site without any restrictions. We use Intel Visual Fortran compiler along with Microsoft Visual Studio to compile

IWFM executables. To aid interested users to compile the executables we also supply Microsoft Visual Studio project files (similar to a makefile that specifies the dependencies between source code files to aid the compiler) on the IWFM web site. With Microsoft Visual Studio and Intel Visual Fortran compiler available, a user can download the IWFM source code and compile it to produce the IWFM executables from scratch within 10 minutes.

The programmer (assuming this is what is meant by "modeler" in the question) for IWFM is Emin Can Dogrul, part of DWR staff.

DWR so far has made an effort to accommodate individual users' specific needs and have customized the IWFM model accordingly (e.g. for WESTSIM application to the western San Joaquin Valley and, recently, for a company in South Korea). However, due to the available resources and its defined mission, it is not possible for DWR to officially promise the customization of the model for every special need. However, DWR promises support on the officially released versions of IWFM as a modeling engine to make sure that there are no unintended programming bugs.

Model Implementation, Calibration/Validation, and Applications
Q13. Assess and discuss IWFM model's ability to simulate the following applications. As part of the discussion, please include past applications of the models to the California Central Valley as well as any other applications known prior to or brought about during this peer review related to California Central Valley water resources management. Wherever possible, relate the discussion to the aspects or features of each model; or indicate whether none of the three models are appropriate for a given application. Also, include in the discussion, any assumptions or necessary context with respect to monitoring data requirements. For prior applications and, if available, summarize the public's acceptance of model results.

a. *Aquifer Safe Yield: Can IWFM be used to quantify the limits where resource development will not lead to undesirable environmental effects? Describe the types of groundwater stresses that can be simulated (e.g., groundwater pumping or groundwater recharge projects)?*

   The answer is yes to both questions. Both groundwater pumping or recharge can be simulated.

A13.a. Inference of safe yield can be quite subjective, and cannot necessarily be inferred from all applications (e.g., a one year application does not provide enough information about long-term withdrawals without affecting reference ground water elevations or storages). There is sufficient output (water budgets) in IWFM to allow the user to post process results to determine long-term impacts and sustainability of pumping and recharge on storage and elevations. In IWFM the groundwater module is linked to stream module so the effects of these projects on stream flows can also be studied.

b. *Describe briefly how IWFM could be used in a conjunctive use modeling assessment?*

   Answer is Yes. IWFM is a simulation model. It does not have optimization capabilities. However it can be run repeatedly to simulate various strategies to manage surface and groundwater conjunctively.

A13.b. IWFM is very suitable for performing conjunctive use studies. Through its land surface and root zone component, IWFM allows dynamic computation of crop water demand (urban demands are user specified) which is a function of crop type, soil parameters, climatic conditions and irrigation management practices. This demand can then be met through stream diversions or pumping or both. IWFM allows multiple diversions and pumps to be used to meet a certain water demand. The user can specify (through input-driven data) IWFM to adjust automatically some or all of these water sources in order to meet the demand (i.e, balancing supply and demand). Diversions and pumping are limited by the available stream flows and aquifer storage in IWFM, so it is possible that the demand may not be met. If both diversions and pumping are requested to be adjusted to meet the demand, diversions are adjusted first. If the diversions are not adequate to meet the demand then pumping is adjusted to meet the unmet demand. IWFM does not consider water rights or seniority levels during the supply adjustment process. It is assumed that all diversions have equal rights. However, IWFM can be linked to operations research type models such as CalSim to address water rights and seniority levels during supply adjustment more accurately. A future enhancement for IWFM being considered is to prioritize diversions during limited supply conditions. A more detailed discussion of this topic can be found in Chapter 4 of IWFM v3.02.

An example application for this feature of IWFM is the use of the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim) to analyze scenarios for the Sacramento Valley Water Management Program (SVWMP). In this project, the aim was to investigate substituting Sacramento River surface diversions with pumping up to 180 TAF/year at 280 well locations during water years that were characterized as non-wet years according to the Sacramento River Index, and allowing for recovery during wetter years. The question to be answered was "What percentage of the 180 TAF/year that was not diverted from the Sacramento River actually reached the Sacramento-San Joaquin Delta?". By using the dynamic demand computation and automated supply adjustment features of IWFM, it was possible to assess the conjunctive use project using historical data from 1972 through 2003. A technical memorandum was prepared summarizing the results and shared through several presentations and posters (e.g. AGU conferences). These materials are available on the IWFM web page.

c. *Surface Water and Groundwater Interaction: What is IWFM's approach to surface water and groundwater interaction?; is the model fully integrated or would the groundwater model need to be combined with another surface water model?*

The model is fully integrated. However the approach used to describe the flow exchange between a stream and an aquifer when in hydraulic connection is not correct. It can be adequate through calibration. However the calibrated parameters cannot be used with a different grid system than the one for which they were calibrated.

A13.c. IWFM is a fully integrated hydrological model. It includes stream flow, lake, and land surface components to represent surface flow dynamics. Stream flow and lake components are fully integrated with the groundwater component; i.e. groundwater, stream and lake conservation equations are solved simultaneously. Stream-groundwater and lake-groundwater interaction terms are expressed similar to a general head boundary condition (the conductance of the stream/lake bed multiplied by the head difference between stream/lake and the groundwater; more details can be found in sections 2.5.2 and 2.6.1 of the IWFM v3.02 Theoretical Documentation). The land surface component addresses the rainfall runoff and agricultural return flow dynamics. Land surface component is linked to the groundwater component through the root zone component and the optional unsaturated zone component. The infiltrated rainfall and irrigation water is routed through the root zone component as a one-dimensional vertical flow. The vertical outflow at the bottom of the root zone is then routed through the optional unsaturated zone component vertically, again with a one-dimensional approach. The root zone and the groundwater components have a one-way interaction; i.e. only the flow from the root zone into the groundwater is considered.

The land surface and root zone components also have an implicit link to the groundwater component through pumping. Pumped groundwater is used as applied water which is routed vertically through the root zone and the optional unsaturated zone to compute the recharge to the groundwater. IWFM uses the Newton-Raphson approach to linearize and iteratively solve the coupled stream, lake and groundwater conservation non-linear equations. Because of their implicit linkage to the groundwater component, land surface, root zone and the unsaturated zone components are also included in the Newton-Raphson iteration. This approach leads to global mass balance in cases where user-specified pumping is reduced due to drying of groundwater cells or in IWFM applications where pumping is dynamically computed to meet crop water demands.

Two example applications that depend on the ability of IWFM to simulate surface water and groundwater interactions are the use of C2VSim for the Sacramento Valley Water Management Program as described in the previous reply, and the Walla Walla Basin IWFM Model application (simulated area located at the Oregon-Washington border). The former application studied the effects of groundwater pumping on the Sacramento River flows, and the latter application studied the effects of lining the channels on naturally occurring springs in the Walla Walla Basin (a report of this project is available).

It is true that the values of parameters for the simulation of the stream-aquifer interaction are obtained through a calibration process, and most likely they won't be useful for a different grid system. However, it can be argued that modifying the grid system, although a common approach when testing models for hypothetical cases where the exact solution to the mathematical problem is known, is rather an impractical and infeasible approach for real-world integrated hydrologic models. Most parameter values used in IWFM, particularly those for the land surface and root zone processes, depend heavily on the grid system and the values of some of these parameters are obtained directly through calibration (although some rule-of-thumb values do exist). Modification of the grid system generally means performing the input data analysis from scratch (e.g. land use acreages, many root zone soil properties, precipitation and evapotranspiration rates, etc. at each grid cell) and re-calibrating the model which require a substantial amount of man-power and additional computer run-times. Therefore, although theoretically attractive, modifying the grid system after the calibration of an integrated hydrologic model leads to a level of effort that is similar to developing a brand new model from scratch, and often is not performed.

d. *Land Subsidence: With respect to each model, can aquifer dewatering or subsidence be simulated and if so how is it treated in the model?*

It is treated in this model.

A13.d. Yes. A detailed description of the methods and assumptions used in IWFM can be found in Sections 2.3 and 3.1.5 of IWFM v3.02 Theoretical Documentation.

e. Land-use: What is IWFM functionality in incorporating and simulating differing land-use types and characteristics?

IWFM can simulate differing land-use types.

A13.e. IWFM simulates 4 land-use types: agricultural (with user defined crop types), urban, native vegetation and riparian vegetation. A detailed explanation of the simulation methods used in land surface and root zone components can be found in sections 2.7 and 2.8 of IWFM v3.02 Theoretical

Documentation. Computation of land-use specific demands is explained in Chapter 4 of the same document. Below is a brief description of how IWFM characterizes each land-use type.

Agricultural lands are divided based on user-defined individual crop acreages in the modeled basin. The number of agricultural crops is variable and defined by the user. Crop acreage, potential ET, irrigation efficiencies, minimum soil moisture requirements are the time series input data for each agricultural crop. Rooting depths for each crop are also required but they are time independent. Combined with soil properties (field capacity, total porosity, hydraulic conductivity, SCS soil hydrologic group and curve number) and precipitation, IWFM computes crop water demands and routes precipitation and applied water through agricultural lands and agricultural root zone.

Urban lands are divided into indoor and outdoor urban areas. Total urban acreage, potential ET, urban water demand and indoor-outdoor applied water split are the required time series data. Rooting depth for the urban outdoor vegetation is also required. The routing of the precipitation and applied water at urban outdoors is similar to the routing methods for agricultural lands. Any precipitation less evapotranspiration and applied water for the urban indoors is assumed to become 100% runoff and return flow, respectively.

Native and riparian vegetations are simulated in a similar way. Acreages and potential ET are time series input data, and rooting depths are specified as time independent data. Only precipitation is routed through native and riparian vegetation lands and through their corresponding root zones.

Agricultural and urban lands are implicitly linked to stream and groundwater components through stream diversions and pumping, respectively, to meet water demands. All land-use types are linked to stream and groundwater components because rainfall runoff and return flow of applied water (available only for agricultural and urban lands) flow into

streams while the infiltrated precipitation and applied water are routed vertically through the root zone to compute the groundwater recharge.

f. *Surface and Ground Water Quality: Specifically, which physical, chemical, and biological parameters and constituents can be simulated byIWFM , if at all? If the groundwater model does not allow water quality simulation, what options are available to the user? For example, are there companion models that can be used? With respect to each model, can salt (mass) flux be simulated in aqueous and/or solid phases? How well do the models' account for chemical and/or biological transformations and partitioning between soil, water, and air? How well do the models account for surface sources of contamination (e.g., landfills, industrial waste sites, septic tank fields)?*

IWFM has no capability to simulate water quality.

A13.f. While IWFM is a generic input-driven model, it was developed principally to meet the needs of DWR's Bay-Delta Office to complement evaluating impacts of SWP-CVP project operations for planning purposes. Currently, IWFM does not include a water quality component. However, the simulated groundwater heads from IWFM can be post-processed to calculate the velocity vector field which can be used as input for a water quality model.

g. *Tile Drainage: Can the models simulate different types of agricultural irrigation practices like tile drains, for example?*

Yes it can.

A13.g. Yes, IWFM can simulate tile drainage as well as other aspects of agricultural irrigation practices such effects of irrigation efficiencies due to different irrigation methods as well as re-use of return flows on land surface and root zone flow dynamics. Simulation of tile drainage is explained in section 2.2 of IWFM v3.02 Theoretical Documentation while irrigation efficiency and re-use are explained in sections 4.2.1 and 4.2.2 of the same document.

h. Evapotranspiration: How are evaporative and transpiration losses treated in the model; i.e., are evaporative and transpiration losses lumped or are the components treated separately?

In IWFM the evaporation and transpiration losses are treated together.

A13.h. Evapotranspiration is simulated as a lumped term of evaporative and transpirative losses. Potential ET is time-series input data specified for each land-use type. Actual ET is simulated as a function of the soil moisture in the root zone. When soil moisture is above half of soil field capacity, actual ET is the same as potential ET. Otherwise, actual ET decreases linearly with respect to the moisture.

Regarding the source of data for evapotranspiration:

In IWFM ET is input specified, whether monthly or weekly, or daily. Crop ETc or adjusted crop ET (ETcadj; if the user can quantify the effects of crop diseases, salt build-up, etc on ETc) is input by the user. Thus the reliability of that input data is on the user. In the past for example we at DWR have relied on several sources including DWR Bulletin 113, FAO, Cal Poly's ITRC for computed values, and DWR's CIMIS network (which uses the Penman-Monteith equation). We've also computed ETo's using the Hargreaves-Samani temperature=based equation (especially going back in time) and appropriate crop coefficients, or satellite processed estimates including SEBAL and MODIS. If we are talking about future climate scenarios we rely on GCM downscaled data. Essentially, IWFM assumes that the user-specified ET rates represent the current, historical or future (depending on the simulation mode) climatic, soil and crop management conditions with sufficient water.

i. Groundwater Optimization: Can each model determine the minimum number and optimum location of extraction wells for groundwater production or groundwater contamination remediation?

IWFM does not deal with water quality. IWFM does not include an optimization component. However the determination of "good" if not optimal extraction rates at wells existing locations can be done by repetitive simulation.

A13.i. IWFM itself does not include optimization methods implicitly. However, it has been designed so that the groundwater component can be linked to dedicated optimization tools. This was a deliberate numerical engine design decision to allow IWFM to tap into the power of other software products designed specifically for such purposes.

j. Regulatory and Policy Aspects: If regulatory and policy aspects were a part of the model application, how well can IWFM address those aspects?

IWFM emphasizes meeting water needs and especially irrigation needs.

A13.j. IWFM simulates a large part of the hydrologic cycle and the effects of anthropogenic activities (urbanization and agricultural activities) on the flow components of this cycle. IWFM also generates detailed water budget outputs for each simulated component. Effects of any regulatory and policy changes (assuming that these changes can be represented through the input data of IWFM) on the flow dynamics and interactions between different components will appear in these water budget outputs allowing the modeler to study the consequences of these changes. Alternatively, IWFM can be linked to systems type models such as the reservoir simulation model CalSim to study these issues in more detail.

Q14. Are there any specific pros and cons with integration of monitoring data for model performance testing? i.e., model calibration and verification?

A14. S. S. Papadopulos and Associates, Inc. have developed utilities specifically for IWFM to aid in linking it to the Parameter ESTimation (PEST) tool. PEST is a powerful, model independent calibration and uncertainty analysis tool which was used in calibrating the C2VSim model. These tools are available for download from PEST's web site.

Q15. Have post-simulation analyses been performed on applications of the three models to data for California or the Central Valley? If so, how well have the three models met their calibration targets?

No such analysis has been performed with IWFM.

A15. A draft document on C2VSim development, calibration, and historical simulation was released for internal DWR review June 1, 2012 and will be available to the public in the near future. Internal and informal comparisons between C2VSIM and the USGS' CVHM have been made.

Q16. How well does IWFM use the "range of error" in the model calibration in drawing conclusion about the model results?

A16. This is a subjective question for the end user to interpret error metrics and IWFM does not interpret these metrics. For example, IWFM has been used quite successfully with PEST. PEST has several metrics and documentation is available on the web. The upcoming C2VSIM document (mentioned in Q15) will describe DWR's metrics for this particular application.

Q17. Does IWFM's output include a water budget? If so, is the model output clear and meaningful?

A17. IWFM produces numerous and clearly intuitive and well-defined water budget outputs for each hydrologic component simulated. The output data is in an easy-to-read tabular format with date and time stamps attached for easy comparison to measured data when available. IWFM v3.02 User's Manual include detailed definitions of each column in each water budget output.

Q18. Can the results from IWFM be readily represented to non-technical audiences either directly through its native interface or using associated software? Could this model be used to facilitate discussion in public forums?

A18. The native format of the IWFM output is in plain text and in a tabular format that is easy to read and understand. DWR has also developed tools to quickly transfer this data from text files into Excel for more detailed analysis, charting, etc. IWFM can also print out results in an HEC-DSS database format. DSS files can be opened using the free HEC-DSSVue software which can be used for charting and it comes packed with many time-series data analysis tools. IWFM can also print out groundwater and subsidence simulation results in a TecPlot-ready file format. TecPlot is a proprietary software that can generate 2-D and 3-D animations which are very powerful in conveying information that originally relies on thousands of data points. All these 4 possible output formats make IWFM results available and understandable for audience with different backgrounds and interests.

Conclusions and Recommendations

Q19. What are your recommendations for model uses or model improvements for each of the three models for the California Central Valley?

A19. I am not sure if this is a question for us or for the peer review committee! Correct.

Q20. What do you consider to be this model's strongest/weakest capabilities?

It is its simplicity because it only deals with the important aspects of an integrated hydrologic model relevant to applications in the Central Valley of California. User is not confused with many options which are not of value to simulate what happens in the Central Valley.

A20. IWFM's very user-friendly input and output data file structure should also be added as one of its strengths. The input files are intuitive and well organized. Given the sheer volume of input data for the Central Valley application (or any large scale integrated hydrologic model), such a file structure makes it easy to modify and QA/QC the input data for different scenarios with little room for error. The well organized output budget tables also allow fast analysis of simulation results for different scenarios.

6.3 Appendix 3: USGS Reponses to Questions

NOTE: This was an exchange of communications between USGS staff and Morel-Seytoux over an extended period of time. **This is not part of the reviewers' report.** However it might be of interest to the reader and eventual user of MODFLOW (and associated packages) to know the points of views of the model developers. These views may not have been incorporated in the main report either because they were not considered relevant, or they had already been expressed in a different way, or because the reviewers did not agree with them, or simply for lack of space.

Note: Questions are presented in black italics

Question and Comments by Morel-Seytoux are shown in blue

Answers by USGS are provided in black

Theoretical Considerations

Q1. What are the theoretical considerations (in brief) for groundwater modeling particularly in areas relevant to California and the Central Valley?
What particular physical, geographical, environmental and economic aspects do you feel need to be well represented in a model to be applicable to the Central Valley of California. Is your model specially suited to meet these requirements, which ones?

A1. Yes MF-FMP is especially well suited because we can simulate the important detail of the supply and demand components that will need to be addressed for conjunctive use analysis. This includes the ability to include all the pathways of water use and movement including direct uptake from groundwater, wellbore flow across the Corcoran, partial dry-land farming, spatial and temporally variable land use, aquifer-storage-and-recovery systems, and connectivity to land subsidence with a vertically deformable mesh. CVHM using MF-FMP is the model of choice for CVSALTS that will be used with WARMF and connected to MODPATH and MODPATH-OBS to quantify the movement of salt and nutrients. Finally, the complete connectivity of flows in MF-FMP allows CVHM to more properly simulate the potential changes from a surface-water to a groundwater dominated water-supply system that is driven by climate change (Hanson et al., 2012). MF-FMP possesses all of the features that that are necessary to assess the secondary effects or rate controlling components of the conjunctive use of water quality and quantity needed to assess the Central Valley and other major agricultural areas

Q2. Describe the capabilities of each model in terms of 1-, 2-, or 3-dimensional modeling, and steady versus unsteady state confined and unconfined groundwater flow?

It is pretty clear that MODFLOW has these capabilities. Is there something in your model that makes the treatment of these matters particularly numerically effective and accurate?

A2. The ability to simulate wellbore flow properly is unique to MF-FMP. The ability to simulate unsaturated infiltration as wetting and drying waves with FMP connected to UZF. MF-FMP's ability to connect to Lakes, Rivers, and Canal systems is also unique. Finally, the ability to simulate the vertical conductance in a wider variety of ways from harmonic to geometric means and to simulate dislocated layers that are adjacent along faults (flow barriers, HFB) allows some unique ways of simulating vertical and horizontal flow that may be needed in regional alluvial aquifer systems and are not available in the other codes.

Q3. What – if any – are the model-specific limitations on time steps? Can hourly, daily, monthly, annual, variable time steps be simulated?

It is pretty clear that MODFLOW can, in theory, simulate a system at any of these time steps. However are there limitations from a **theoretical** point of view to use a daily time step or weekly time step? Are there **practical** limitations to use a daily time step if the entire Central Valley is being studied with a numerical grid of the order of one square mile?

A3. Actually there is no limitation on the use of small time steps other than the computation overhead that any code would be subject to. MF-FMP is currently limited to simulating stress periods (time periods where user-specified inflows, outflows, or boundary heads are changing) of great than a week or two depending on the soil types. All other features can go down to hourly or daily time steps. While, future development of MF-FMP will include the option to simulate soil moisture that will address this potential limitation for some applications, MF-FMP is especially well suited for regional and subregional simulations that typically require stress periods of two weeks to a month in duration. In addition, MF-FMP now has multiple solvers and will be capable of using parallel computing and GPU solvers with ongoing upgrades, making it a very fast code.

Q4. Discuss any model specific pros and cons and inherent uncertainties in terms of model approaches related to underlying theory or solution technique(s)? Are there differing numerical solution options available to the modeler? Is there a class or classes of applications that are appropriate or inappropriate as related to the governing equations and/or numerical solution technique(s)?

This discussion is particularly relevant when the equations are nonlinear. If different solution options are available to solve the system of equations are there clear criteria when one technique should be used versus another? Is it simply a matter of numerical efficiency or also of accuracy of the solution?

A4. MF-FMP now has a wide variety of solvers including the principal conjugate gradient (PCG) solver, the nonlinear version of PCG (PCGN), PCG-Geometric Multi-Grid Solution Package (GMG), and Newton-Raphson Solver (NWT) that is especially well suited for dealing with the wet-dry problem or settings where large changes in inflows/outflows could create very nonlinear relations to head dependent flows or flow-dependent flows.

Q5. Does MODFLOW simulate groundwater flow and transport and, if so, are the governing equations coupled or is an iterative solution technique used?

My reading of MODFLOW documents indicates that the model can be coupled with a package to simulate groundwater flow and transport. The model does not have the capability to simulate biologic effect nor temperature dependent phenomena.

A5. MF-FMP can be coupled with advective transport through MODPATH (and MODPATH-OBS) and MT3DMS. Additional features for transport are available in the MODFLOW version called SEAWAT that does have the capability to simulate heat, dispersive transport, and multiple species. MF-FMP does simulate the water-production from ET so in a limited way it does simulate the consumption of water from biologic effects. Since MF-FMP includes more aspects of the distribution of vegetation (spatial and temporal changes in root depths, canopy, crop coefficients, submerged vegetation, etc.) it is unique in its abilities to capture the detail of changing biological landscape.

Q6. Are there known performance issues documented with respect to model scales, types of problems or *applications?*

Some methodologies used in MODFLOW limit its applicability to time steps shorter than a couple of weeks.

A6. As indicated in the similar question above (Question 3), the application of MF-FMP is especially well suited to subregional to regional scales. Some aspects of head or flow dependencies will slow down simulation with MF-FMP such as including a hundreds to thousands of MNW wells, or inclusion of complex canal systems, or complex unsaturated flow infiltration scenarios.

Q7. What are the types of boundary conditions that can be simulated? What types of monitoring data is required for the various boundary conditions? Are there unique or model specific treatments of boundary conditions in the numerical solution procedure?

MODFLOW can model the standard types of boundary conditions and treats them in a very standard way, i.e. coupling them within the system of equations to be used. However specially in the case of the stream-aquifer boundary condition the coefficient and the head difference appearing in the general head (also called Cauchy) type boundary condition are not necessarily correct.

A7. I don't agree with this. MF-FMP is correctly simulating and making approximations to unsaturated infiltration (UZF), including the potential for streamflow gains/losses above unsaturated zones (SFR2), canal flows (SWR1), and wellbore flows (MNW1/MNW2).

Q8. Have there been any peer review(s) or publications available on this model? If so, please document these references.

Please provide.

Groundwater Studies:

(1) Hanson, R.T., Schmid, Wolfgang, Faunt, C.C., and Lockwood, B., 2010, Simulation and Analysis of Conjunctive Use with MODFLOW's Farm Process: Ground Water Vol. 48, No. 5, pp. 674 - 689. (DOI: 10.1111/j.1745-6584.2010.00730.x)

(2) Porta, L., Lawson, P., Brown, N., Faunt, C., and Hanson R. 2011. Application of the Central Valley Hydrologic Model to Simulate Groundwater and Surface-Water Interaction in the Sacramento-San Joaquin Delta. Poster presentation at the California Water and Environmental Modeling Forum Annual Meeting. Pacific Grove, California.

(3) Dogrul , E.C., Schmid, Wolfgang, Hanson, R.T., Kadir, T.N., and Chung, F.I., 2011, Integrated Water Flow Model and MODFLOW-Farm Process: A Comparison of Theory, Approaches, and Features of two Integrated Hydrologic Models: California Department of Water Resources Technical Information Record, TIR-1, 80p. (http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/Publications/downloadables/Reports/IWFM%20and%20MF-FMP%20TIR-1%20(DWR-USGS%20Nov2011).pdf)

(4) Schmid, Wolfgang, Dogrul , E.C., Hanson, R.T., Kadir, T.N., and Chung, F.I., 2011, Comparison of Simulations of Land-use Specific Water Demand and Irrigation Water Supply by MF-FMP and IWFM: California Department of Water Resources Technical Information Record TIR-2, 80p. (http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/Publications/downloadables/Reports/IWFM%20and%20MF-FMP%20TIR-2%20(USGS-DWR%20Nov2011).pdf)

(5) Hanson, R.T., Flint, L.E., Flint, A.L., Dettinger, M.D., Faunt, C.C., Cayan, D., and, Schmid, Wolfgang, 2012, A method for physically based model analysis of conjunctive use in response to potential climate changes: Water Resources Research, Vol. 48, 23p., doi:10.1029/2011WR010774
(6) Liu, Tiegang, and Luo, Yi, 2012, An empirical approach simulating evapotranspiration from groundwater under different soil water conditions, Environ. Earth Sci., 11p., DOI 10.1007/s12665-012-1577-3
(7) Schmid, W., Hanson, R.T., Faunt, C.C. and Phillips S.P., 2008, Hindcast of water availability in regional aquifer systems using MODFLOW's Farm Process: Proceedings of Hydropredict 2008, Prague, Chec Republic, September 15 – 19, 2008, pp. 311-314
(8) Schmid, W., and Hanson, R.T., 2007, Simulation of Intra- or Trans-Boundary Water-Rights Hierarchies using the Farm Process for MODFLOW-2000, ASCE Journal of Water Resources Planning and Management , Vol. 133, No. 2, pp. 166-178 (DOI: 10.1061/(ASCE)0733-9496(2007)133:2(166))
(9) Schmid, W., King, J.P., and Maddock III., T.M., 2009, Conjunctive Surface-Water / Ground-Water Model in the Southern Rincon Valley using MODFLOW-2005 with the Farm Process, prepared for the Elephant Butte Irrigation District, Las Cruces, NM; New Mexico Water Resources Research Institute Completion Report No. 350.

Q9. How well have the models been tested? i.e., has there been formal validation studies performed on each model? Are the validation studies documented or included in or with the model documentation?

A **wrong** model with **wrong** parameters calibrated on **good** data and showing a good fit can give the impression that the model is adequate and "validated". Have there been studies done that partition the historical data in a "calibration" set and another "validation" set? The purpose being to test if the model has a good **predictive** capability particularly when studying different management strategies.

Also were the extreme data included in the calibration set or left in the validation set? Or also did the calibration set include the rather normal data while the validation set did on the contrary contain the more extreme historical data?

A9. Yes MF-FMP was evaluated with respect to HYDRUS2D in the development of it approximation to unsaturated infiltration through the soil zone (Schmid PhD Dissertation). Was evaluated with respect to this approximation of infiltration from lab experiments (Liu and Luo, 2012). Finally, the application of MF-FMP to Pajaro Valley (PVHM) has been the best validation of its ability to simulate pumpage within 10% using limited (multi-annual) land-use information (comparison with reported seasonal pumpage) and simulated supply-and-demand components with the ASR and Coastal Delivery System developed to replace some of the coastal pumpage (Hanson et al., in press, 2013).

Q10. What is the quality of model documentation for MODFLOW? Are model assumptions clearly defined and documented? Does the model's documentation effectively discuss how model assumptions can impact possible modeling objectives? Does each model's documentation clearly and effectively describe the uses, conditions, and types of applications that the model can be used for?

The documentation regarding assumptions used and how the assumptions can impact possible modeling objectives is fairly good, though the document about MODFLOW 2005 reads more like a user's manual than a text about the theoretical and physical basis of the model. The documentation does not stress the types of applications that the model can be used for. Did I miss something there? In which report and on which pages?

A10. The early manuals do not go into great detail regarding the theoretical development or guidelines for applications. However, more recent MODFLOW related manuals such as FMP1, FMP2, SFR2, UZF1, SWR1, MNW2 do an excellent job of describing the theoretical basis and giving guidelines for applications and analysis that also include meaningful example models that can be used as a starting point for developing real-world applications. Many manuals have compared against more detailed models (UZF1, SWR1) or analytical solutions (MNW2).

Q11. What are the pros and cons of the model in terms of accessibility of input and output data, the use of standardized data formats, and the availability of sample problems and user support?

A11. MODFLOW excels at this aspect with open source code with extensive in-line documentation, versioning, relevant example models, and extensive on line support as well as availability to the team of developers. Input and output data are well structured and accessible in GIS and ascii formats for many features of MODFLOW. We have developed free tools that allow the construction of these data sets with particular emphasis on complex temporal data sets that are difficult to construct with commercial GUI's. Most of the input instructions are also accessible through a publicly available web site supported by USGS.

(http://water.usgs.gov/nrp/gwsoftware/MODFLOW2000/Guide/index.html)

Q12. What are the capabilities for the modeler to customize or modify the model? Include a brief indication whether each model is open-source or proprietary.

MODFLOW is not proprietary but that does not make it open-source. It is not clear if the model's complete source code is available to the general public.

It is not clear in this question who the "modeler" is? MODFLOW staff or a general user not affiliated with the USGS? MODFLOW, it seems, would provide limited support to users and probably would not customize a model to suit the particular needs of a user, at least not for free.

A12. This response is completely incorrect. MODFLOW is the most widely used code in the world and has undergone more applications, testing and verification than any other code. Most of the MODFLOW developers were listed in my MODFLOW summary presentation slide 4) at the workshop. It is constantly being improved, expanded, and corrected if necessary. New versions are released frequently and come in a wide variety of versions to special considerations (http://water.usgs.gov/software/lists/groundwater/). MODFLOW and all of its source code is free, open source, and completely available to anyone. In addition, we collaborate and welcome collaboration with other groups that want to add or improve features within MODFLOW such as Riparian Evapotranspiration Package (RIP-ET) and FMP1 from University of Arizona, the new Seawater Interface (SWI) Package developed with Delft University of Technology and Waternet, Netherlands and Univ. of Geogia, MT3D application in SEAWAT with Chunmiao Zheng (Univ. of Alabama), and most recently the Unstructured Grid and NWT developed in collaboration with a consulting firm. An important requirement for adding new features to MODFLOW is that they are being applied to a real complex problem in conjunction with development (ex. FMP1). I gave this as part of my presentation on MODFLOW development at the workshop, so please refer to these presentations as well. We do provide support, but substantial support or modifications need to be part of funded projects since the USGS relies on external funding for much of its operational costs. No model will be modified for free…someone is always paying. MODFLOW is also intimately connected to parameter estimation software (UCODE, PEST, etc), linkage to other water allocation models (SWAT, WEAP, RiverWare, etc), and other features that allow visualization and analysis such as ZONEBUDGET, MODPATH/MODPATH-OBS, Groundwater management Process (GWM) (Optimization-allocation), Hydrologic Balance Analysis Program (HyBAP new tool), and others.

Model Implementation, Calibration/Validation, and Applications

Q13. Assess and discuss MODFLOW model's ability to simulate the following applications. As part of the discussion, please include past applications of the models to the California Central Valley as well as any other applications known prior to or brought about during this peer review related to California Central Valley water resources management. Wherever possible, relate the discussion to the aspects or features of each model; or indicate whether none of the three models are appropriate for a given application. Also, include in the discussion, any assumptions or necessary context with respect to monitoring data requirements. For prior applications and, if available, summarize the public's acceptance of model results.

e. *Aquifer Safe Yield: Can MODFLOW be used to quantify the limits where resource development will not lead to undesirable environmental effects? Describe the types of groundwater stresses that can be simulated (e.g., groundwater pumping or groundwater recharge projects)?*

The answer is yes to both questions. Both groundwater pumping or recharge can be simulated.

A13 a. "Safe Yield" is an unfortunate misnomer that is grossly complicated by the delay of multiple stresses and nonsteady conditions (ex. climate variability)….please refer to Brederhoeft's landmark paper and the follow up by Alley and Leake. More recently, the term "Sustainable Yield" has been used to describe these multiple limits. The definitions we use are:

Sustainability: Development and use of water in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences.

Conjunctive Use: Joint use and management of surface-water and groundwater resources to maximize reliable supply and minimize damage to the quantity or quality of the resource.

The secondary effects such as flows at the delta, streamflows requirements for environmental flows or water rights, land subsidence, water quality, pumping levels, etc. will dictate sustainability before overdraft becomes an issue (especially with correlative groundwater rights.

f. *Describe briefly how MODFLOW could be used in a conjunctive use modeling assessment?*

Answer is Yes. MODFLOW is primarily a simulation model. It does refer to an optimization capability. The procedure to find the optimal values of the decision variables is not specified. It seems that it is done by repeatedly simulating various strategies to manage surface and groundwater conjunctively and then select the better solution among the various candidates.

A13 b. Please refer to my two journal articles (Hanson et al., 2010 and 2012) for examples of conjunctive use analysis. Conjunctive use simulated in a physically-based simulation in a supply-and-demand context is the only way to analyze the complex interrelations and indirect influences of head and flow-dependent flows within complex and highly engineered systems such as the Central Valley. The secondary effects such as flows at the delta, land subsidence, deficit irrigation, and water quality are the types of secondary effects that may ultimately be the rate controlling features to sustainable use and development of the water resources in the Central Valley. Data requirements will heavily influence the skill of the simulation. Having data streams of streamflows, diversions, climate data, changes in land use and land ownership, priorities in water use, and changes in cropping attributes are all examples of data that really can improve the skill of the simulation with MF-FMP when available at every month (stress period).

In addition, MF-FMP can be linked with GWM to perform formal optimization of state variables (Q's) subject to constraints such as salt loads, streamflow requirements, hydraulic gradients, etc. MF-FMP can not only address constraining or optimizing urban pumpage but also agricultural pumpage separately with the additional feature of groundwater allotments for each "farm" and surface-water allotments for the entire model that are built in limits on the allocations of water to individual farms or the entire model. MF-FMP also has built in optimization options for operational drought scenarios for acreage optimization, water-stacking, or conservation pool. Finally, MF-FMP also has the ability to simulate deficit irrigation where demand is reduced to limited supply…this is critical for climate change and adaptation scenario modeling.

g. *Surface Water and Groundwater Interaction: What is MODFLOW's approach to surface water and groundwater interaction? Is the model fully integrated or would the groundwater model need to be combined with another surface water model?*

The model is fully integrated. However the approach used to describe the flow exchange between a stream and an aquifer when in hydraulic connection is not correct. It can be adequate through calibration. However the calibrated parameters cannot be used with a different grid system than the one for which they were calibrated.

A13 c. I don't agree with this. Please refer to the SFR2, NWT, UZF, and SWR manuals. If it's incorrect, please be specific. In addition, the SFR uses a streambed vertical hydraulic conductivity so the conductance is grid dependent but not the specified parameter.

h. *Land Subsidence: With respect to MODFLOW, can aquifer dewatering or subsidence be simulated and if so how is it treated in the model?*

It is treated in this model.

A13d. MF-FMP has some unique features including multiple ways to simulate subsidence (with and without delay, with geostatic loads, water-table adjustment of effective stress, and optional vertically deforming mesh that is linked to all other features).

i. *Land-use: What is MODFLOW functionality in incorporating and simulating differing land-use types and characteristics?*

MODFLOW can simulate differing land-use types.

A13 e. It can not only simulate different land-use types, it can simulate crop rotation, and changes in the extent and distribution of water-balance subregions ("farms"). Please see my comments about types of MODFLOW in previous questions.

f. Surface and Ground Water Quality: Specifically, which physical, chemical, and biological parameters and constituents can be simulated by MODFLOW, if at all? If the groundwater model does not allow water quality simulation, what options are available to the user? For example, are there companion models that can be used? With respect to each model, can salt (mass) flux be simulated in aqueous and/or solid phases? How well do the models' account for chemical and/or biological transformations and partitioning between soil, water, and air? How well do the models account for surface sources of contamination (*e.g.,* landfills, industrial waste sites, septic tank fields)?

MODFLOW has capability to simulate water quality through transport of dissolved substances in the groundwater but apparently not in streamflow. It does not model temperature or biologic effects.

A13 f. Please see my comments about types of MODFLOW in previous question.

g. Tile Drainage: Can the MODFLOW simulate different types of agricultural irrigation practices like tile drains, for example?

Yes it can.

A13 g. We also redirect returnflows to specific locations in the streamflow system.

h. Evapotranspiration: How are evaporative and transpiration losses treated in the model; i.e., are evaporative and transpiration losses lumped or are the components treated separately?
In MODFLOW the evaporation and transpiration losses are treated separately. However it is not clear that that separation is very useful in practice. After all bare soil can be represented as a weed crop with very limited root depth. Though with surface water bodies that approach would not work!
A13 h. I'm not sure what this last comment means, please clarify. The separation of E ant T is significant with different extinction depths, rates and behavior with depth. We also separate the E and T from precipitation, from irrigation, and from direct uptake of groundwater. These separations based, in part on the basal crop coefficient, provides additional insight into how water is being consumed, from what sources, and where.
Regarding the source of data for evapotranspiration:

We make ETo estimates from Hargrave-Semani approximation and from Presley-Taylor approximation of Pennman-Monteith eqn. We are also calculating actual ET from remotely sensed data using LANDSAT, MODIS with methods such as SEBAL and METRIC as well as developing canopy from NDVI estimates and crop coefficients from METRIC/MODIS estimates of ETo (not from NDVI such as Allen et al). We have published and used GCM estimates (Hanson et al., 2012). We have compiled extensive references of crop coefficients (beyond FAO and others) from many sources and continue to grow this compilation as well.

ii. Groundwater Optimization: Can each model determine the minimum number and optimum location of extraction wells for groundwater production or groundwater contamination remediation?

See Question Q13 b. The determination of "good" if not optimal extraction rates at wells existing locations can be done by repetitive simulation. MODFLOW can follow the path of dissolved contaminants in the groundwater but for existing wells. It does not optimize for optimal locations of wells. Placing wells at different locations and doing a number of runs one can assess which location is good and better than other locations. It is however not formally "optimal".

A13 i. This is incorrect. MF-FMP connected or used in concert with GWM can be used to identify optimal well locations using integer variables (see GWM documentation or publications). Also, as noted in previous question, MF-FMP can also perform optimization based on profit based on costs and yield for agricultural consumption.

j. Regulatory and Policy Aspects: If regulatory and policy aspects were a part of the model application, how well can MODFLOW address those aspects?
MODFLOW emphasizes meeting water needs and especially irrigation needs. It also includes water rights. It does not per se include environmental constraints.
A13 j. Environmental constraints could be implemented as groundwater allotments.

Q14. Are there any specific pros and cons with integration of monitoring data for model performance testing? i.e., model calibration and verification?

The USGS has done a superb job of developing a web site with data for the Central Valley. That is an extremely valuable tool for all who need to make studies in that area.

A14. We are also working on "self-updating models" that will integrate data input streams from land-based and remotely-sensed data streams such as streamflows, diversions, water levels, and changes in land use and cropping attributes.

Q15. Have post-simulation analyses been performed on applications of the three models to data for California or the Central Valley? If so, how well have the three models met their calibration targets?

No such analysis has been performed with MODFLOW. I'm not sure what your answer means, please clarify.

A15. We calibrate every model against thousands of observations such as CVHM.

Q16. How well does MODFLOW use the "range of error" in the model calibration in drawing conclusion about the model results?

A16. MODFLOW doesn't do this the modeler makes this a part of his analysis. This may occur with the help of parameter-estimation software such as UCODE or PEST which are run with MODFLOW embedded along with other evaluation and observation programs.

Q17. Does MODFLOW's output include a water budget? If so, is the model output clear and meaningful?

A17. Yes there are multiple water budgets that can be derived from MF-FMP. These include a summary groundwater budget, a detailed groundwater budget through use of ZONEBUDGET, several landscape budgets through FMP, Unsaturated flow budget from UZF, streamflow time series from HYDMOD and GAGE, streamflow budget information from SFR, and surface-water budget information from SWR.

Q18. Can the results from MODFLOW be readily represented to non-technical audiences either directly through its native interface or using associated software? Could this model be used to facilitate discussion in public forums?
A18. Yes we also distill this further down through our postprocessing tool HyBAP that allows automatic distillation and loading and graphing from access database to excel spreadsheets that can illustrate the results graphically and simply.

Conclusions and Recommendations
Q19. What are your recommendations for model uses or model improvements for each of the three models for the California Central Valley?

A19. Self-Updating modeling structures are a must for models this large and complex to systematize use, updates and analysis and to minimize costs of maintenance and operations. Ultimately, linkages to other types of models (biological, economic, watershed, reservoir operation, etc.), data input streams, Decision Support systems, Water Allocation models such as CALSIM or CALVIN, land use models, and climate modeling platforms will be needed to create a complete and integrated Decision Support System. MF-FMP also is the current choice of CVSALTS for the analysis of salts and nutrients throughout the Central Valley.

Q20. What do you consider to be this model's strongest/weakest capabilities?
It is its completeness because it deals with the important aspects of an integrated hydrologic model relevant to applications in the Central Valley of California. User is not confused with many options which are not of value to simulate what happens in the Central Valley. Yet it is fairly accurate in its representation of the major physical phenomena taking place in an essentially agricultural and flat domain. It is also fairly clear that when talking about the Central Valley one excludes the Sacramento San Joaquin delta, and associate bay, because MODFLOW does not have a capability to model salt water movement in a tidal context.
A20. Actually it will be able to in the future versions with the inclusion of the SWI package for groundwater saline intrusion and linkage of MT3D to SWR and LAK packages.

6.4 Appendix 4: Governing Equations and Definition of Terms

Authored by Hubert Morel-Seytoux

Conservation of mass for saturated groundwater flow

Case of a confined aquifer

In three dimensions in differential form the (classical) equation of conservation of mass combined with Darcy's law for a confined aquifer is:

$$S_s \frac{\partial h}{\partial t} - \frac{\partial}{\partial x}[eK_x \frac{\partial h}{\partial x}] - \frac{\partial}{\partial y}[eK_y \frac{\partial h}{\partial y}] - \frac{\partial}{\partial z}[eK_z \frac{\partial h}{\partial z}] + q_{ext} = 0$$

where S_s is a dimensionless positive coefficient (specific storage) that accounts for the compressibility of the aquifer rock formation and that of water, K is the hydraulic conductivity with principal axes aligned with the Cartesian horizontal coordinate directions x and y and the vertical coordinate z oriented positive upward and h is the head ($z + \frac{p}{\rho_w g}$). e is the saturated thickness of the aquifer. q_{ext} Is an external volumetric (algebraic) withdrawal rate per unit horizontal area, algebraically positive if indeed it is a withdrawal. If q_{ext} is positive h has to decrease to compensate and thus $\frac{\partial h}{\partial t}$ would be negative. With water withdrawal from the domain the pressure of water has to decrease. The product eK receives the name and symbol, transmisivity T. With that notation the equation takes the form:

$$S_s \frac{\partial h}{\partial t} - \frac{\partial}{\partial x}[T_x \frac{\partial h}{\partial x}] - \frac{\partial}{\partial y}[T_y \frac{\partial h}{\partial y}] - \frac{\partial}{\partial z}[T_z \frac{\partial h}{\partial z}] + q_{ext} = 0$$

Case of an unconfined aquifer

In the case of an unconfined aquifer it is most of the time customary to apply the Dupuit-Forchheimer (D-F) assumption that there is no vertical gradient of head within the aquifer and thus the head is also the water table elevation. In this case the differential equation takes the form:

$S_y \frac{\partial h}{\partial t} - \frac{\partial}{\partial x}[T_x \frac{\partial h}{\partial x}] - \frac{\partial}{\partial y}[T_y \frac{\partial h}{\partial y}] + q_{ext} = 0$ where S_y is a dimensionless coefficient known as "specific yield".

The value of the specific yield is lower than the porosity of the aquifer because some of the water is not mobile and cannot be removed from the formation simply by lowering the water table. Actually this equation is somewhat approximate and the IWFM and MODFLOW codes use various methods to compensate for that fact. For example typically the specific yield is assumed to be a constant. In fact when the water table drops not the full amount of S_y is drained instantaneously but a delayed yield occurs. Also when there is recharge to the aquifer from deep percolation less space is available for the rising water table to fill because the percolating water already is occupying some of the pore space and the value of this previously occupied fraction depends upon the recharge rate.

Conservation of mass for unsaturated water flow (flow in the "vadose" zone)

The (classical) governing equation in differential form is:

$$\frac{\partial\theta}{\partial t}-\frac{\partial}{\partial x}[k_{rw}K_x\frac{\partial h}{\partial x}]-\frac{\partial}{\partial y}[k_{rw}K_y\frac{\partial h}{\partial y}]-\frac{\partial}{\partial z}[k_{rw}K_z\frac{\partial h}{\partial z}]+q_{ext}=0$$

where the water content, θ, is defined as the volume of water per unit bulk volume. Naturally the maximum value of water content is the porosity of the soil. k_{rw} Is the relative permeability to water, a function of water content. Note that in this equation, q_{ext}, the external withdrawal rate is defined as a volumetric rate per unit bulk volume. In the unsaturated zone the water pressure is less than atmospheric and is a function of water content. Normalized water content is defined as: $\theta^*=\frac{\theta-\theta_r}{\theta_s-\theta_r}$ where θ_r is the "residual" water content (i.e. water that cannot be removed by mechanical processes but could be removed say in the laboratory by evaporating the water at high temperatures) and θ_s is the water content at saturation which is less than porosity because there could be entrapped air within the pore space. In terms of normalized water content relative permeability can be expressed algebraically in the form: $k_{rw}=(\theta^*)^p$ where p is a positive empirical exponent of low value (like say 2-3) for coarse material like coarse sand and of high value (like say 6-10) for tight material such as clay. One expression (Brooks-Corey) for capillary suction (capillary pressure expressed as an equivalent height of water, dimension of length) is: $h_c=h_{ce}(\theta^*)^{-M}$ where h_{ce} is the so-called entry pressure (head) and M is a positive empirical coefficient, with low values for coarse soils and high values for tight soils. Various suggestions exist to relate the coefficients p and M; the most common one is: p=2M + 3.

In the governing equation for unsaturated flow the expression of head in terms of capillary head is: $h=z-h_c$

Head (as defined for groundwater and unsaturated flow)

The forces that move ground-water are those of gravity and pressure. Per unit volume gravity is:

$\rho_w gz$ where ρ_w is the density of water, g is the acceleration of gravity and z is elevation.

Dividing by $\rho_w g$ the combined forces of gravity and pressure take the form, which defines head:

$z+\frac{p}{\rho_w g}=h$ the "head" which has dimension of a length.

Darcy's law

Darcy's law states that the discharge Q perpendicular to an area, A, is proportional to the drop in head Δh taking place over a distance Δz and the coefficient of proportionality is a characteristic of the ease at which the aquifer medium is able to transmit flow. That coefficient has the name "hydraulic conductivity", K. Symbolically then:

$$Q = AK\frac{\Delta h}{\Delta z}$$

Discrete form of governing groundwater equation (MODFLOW)

«Development of the ground-water flow equation in finite-difference form follows from the application of the continuity equation: the sum of all flows into and out of the cell must be equal to the rate of change in storage within the cell. Under the assumption that the density of ground water is constant, the continuity equation expressing the balance of flow for a cell is

$\sum Q_i = SS\frac{\Delta H}{\Delta T}\Delta V$ where□Qi is a flow rate into the cell (L3T-1);

SS has been introduced as the notation for specific storage in the finite-difference formulation; its definition is equivalent to that of Ss in equation 2–1—that is, SS is the volume of water that can be injected per unit volume of aquifer material per unit change in head (L-1);

ΔV is the volume of the cell (L3); and□Δh is the change in head over a time interval of length Δt.

The term on the right-hand side is equivalent to the volume of water taken into storage over a time interval Δt given a change in head of Δh. Equation 2–2 is stated in terms of inflow and storage gain. Outflow and loss are represented by defining outflow as negative inflow and loss as negative gain.» (MODFLOW, 2005)

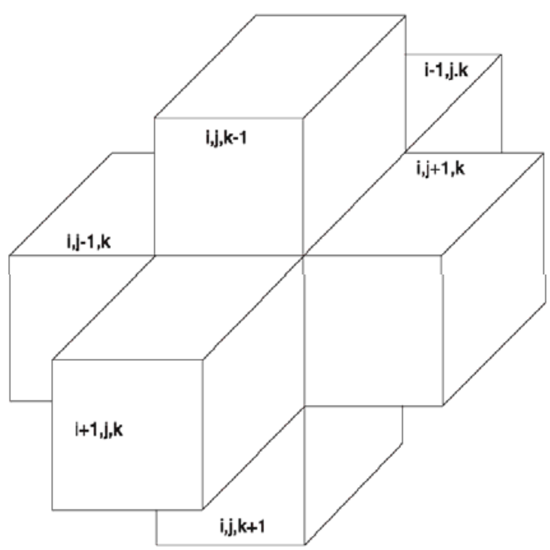

Figure 2–2. Indicies for the six adjacent cells surrounding cell i,j,k (hidden). (Modified from McDonald and Harbaugh, 1988.)

The determination of the discharges involves application of Darcy's law. It also involves a number of approximations, given that neither heads nor hydraulic conductivities are known continuously in space.

Capillarity

Capillarity is the force which by the action of the surface tension at the interface of two immiscible fluids (such as water and oil, or water and air) allows a fluid, such as water, that wets the walls of a conduit in a porous medium, such as a petroleum rock, to displace another fluid that does not wet the walls, oil, or simply air in a capillary tube.

Capillary fringe

In the literature this term refers usually only to the zone in the soil where the water content occupies the entire pore space even though the water pressure is less than atmospheric. In MODFLOW FMP it refers to the entire soil zone above the water table, saturated or not.

Manning's formula

That formula for the velocity of water, v, in a river states that the velocity depends on the following factors:

(1) the "hydraulic radius", which is the ratio of the wetted cross-section of the river divided by its perimeter, R_H. For a rectangular cross-section it thus would be: the area 2HW divided by the perimeter (2H + W), where H is the height of water in the river and B is the width of the cross-section
(2) the "friction slope", S_f, which for uniform steady flow is the slope of the river bed, and
(3) an empirical roughness coefficient called Manning's n, n_M .
The formula does not depend on these variables by direct proportion. Indeed it has the complex form: $v = \frac{C_U}{n_M}(S_f)^{\frac{1}{2}}(R_H)^{\frac{2}{3}}$ where C_U is a coefficient of value depending upon the choice of units used in the formula.

Surface flow equation (simplified one-dimensional description).

<u>Newton's law</u>

For a particle of water of mass m at time t the expression of Newton's law is:

$m\frac{\partial v}{\partial t} = F$ where F is the net force acting on the particle. The variation of the velocity v at a given location, $\frac{\partial v}{\partial t}$ is the acceleration.

<u>Motor force</u>

In hydraulics the total head is defined as the sum: $H = z + y + \frac{v^2}{2g}$

where the term z (the elevation) is the contribution of the potential energy (gravity), y represents the pressure energy, and $\frac{v^2}{2g}$ represents the kinetic energy. This head is an energy per unit weight and has dimension of length. Flow is in the direction of decreasing head. The motor force per unit weight is the negative of the head gradient that is: $-\frac{\partial H}{\partial x}$. This term is dimensionless and is called the energy slope and denoted S_e. An explicit expression for the energy slope is:

$S_e = -\frac{\partial H}{\partial x} = -\frac{\partial z}{\partial x} - \frac{\partial y}{\partial x} - \frac{v}{g}\frac{\partial v}{\partial x}$ or since $-\frac{\partial z}{\partial x}$ is the slope of the terrain S_o then:

$$S_e = -\frac{\partial H}{\partial x} = S_o - \frac{\partial y}{\partial x} - \frac{v}{g}\frac{\partial v}{\partial x}$$

De Saint-Venant equation

$\frac{F}{mg}$ is the net force per unit weight. This net force is the difference between the motor force and the resistance (friction) force. Substitution leads to the equation: $\frac{1}{g}\frac{\partial v}{\partial t} = S_o - \frac{\partial y}{\partial x} - \frac{v}{g}\frac{\partial v}{\partial x} - S_f$

where S_f is the friction slope per unit weight. Bringing the derivatives with respect to x on the left hand side one obtains De Saint-Venant equation: $\frac{1}{g}\frac{\partial v}{\partial t} + \frac{\partial y}{\partial x} + \frac{v}{g}\frac{\partial v}{\partial x} = S_o - S_f$.

Classification of solutions: the "kinematic wave" solution

The De Saint-Venant equation written in the slightly modified form is: $S_f = S_o\{1 - \frac{\partial y}{S_o \partial x} - \frac{v}{gS_o}\frac{\partial v}{\partial x} - \frac{1}{gS_o}\frac{\partial v}{\partial t}\}$

If on the right hand side only the first term is retained the solution is said to be the "kinematic wave" solution. In this case the movement of water is conditioned strictly by gravity and friction (method used in MODFLOW UZF for flow in the unsaturated zone of the soil where the friction term is expressed by Darcy's law).

The equation of conservation of mass is generally: $\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0$ where A is the flow cross-section and Q the discharge or $\frac{\partial A}{\partial t}+\frac{\partial (Av)}{\partial x}=0$. Combination of this equation with the De Saint-Venant equation will provide the solution.

Curve number method

This method is used to determine runoff resulting from a precipitation event. It was developed by the Soil Conservation Service. The equation for discharge, Q, expressed as a depth in inches is:

$Q=\frac{(P-I_a)^2}{P-I_a+S}$ where P is precipitation (in inches) for the event, I_a is an initial abstraction (infiltration, interception, depression storage) and S is storage. Usually I_a is chosen to be 0.2S. A curve number is defined as: CN = 1000/(100 + S). Tables then define the value of CN as a function of soil type, agricultural practices and soil conditions (moisture).

Cauchy boundary condition

On a boundary prevails a certain head, h_b. Inside and near the boundary another head prevails, h_{in}. The discharge across the boundary is proportional to that difference. The coefficient of proportionality, C, is called a conductance. Symbolically: $Q=C(h_b-h_{in})$. The discharge is toward the domain if the boundary head exceeds that in the interior.

Field Capacity

In the literature field capacity refers to the water content left in the soil after it has drained by gravity for a day or two. It is also defined at times as the water content corresponding to a capillary pressure of a third of an atmosphere.

Solver

Solver is the generic name given to methods by which a large system of algebraic equations with multiple unknowns are solved. It also refers to the codes that have been programmed to implement the technique on the computer.

Stream-groundwater interaction when stream and aquifer are in connection

That boundary condition states that the discharge, Q, taking place across an area of the interface between a river and an aquifer in hydraulic connection is proportional to the difference in head across the interface. The formula for the discharge is thus: $Q=\kappa_C(h_R-h_A)$ where κ_C is a measure of how easily or hard it is for flow to take place between the two components. In the three models this conductance has the formula: $\kappa_C=\frac{K_C LW}{d}$ where K is the hydraulic conductivity of the clogging streambed layer, L is the length of the reach, W is the cross-section wetted perimeter and d is the thickness of the clogging layer.

Stream-groundwater interaction when water table is below the streambed.

In all three models it is assumed that there is a clogging streambed layer. Pure gravity discharge through the streambed is given by Darcy's law in the form: $Q = KWL\frac{\Delta h}{d}$ where Q is the discharge through the streambed, K is hydraulic conductivity of the streambed, W is the cross-section wetted perimeter of the stream, L is the length of the river reach (segment), Δh is the head drop across the streambed and d is the thickness of the streambed. This is evaluated differently by IWFM and MODFLOW. For IWFM $\Delta h = s$ where s is the stream stage and for MODFLOW it is (d+s).

Runoff from irrigation

This is done in 2 steps. Two fractions are defined with symbols f. First an "initial" runoff as a fraction of the irrigation supply is defined. Then using a smaller fraction a return flow reuse is defined. The difference between the initial value and the reuse one becomes the final runoff.

$$R_{i-ini} = I \times f_r^{I-ini}$$

$$U_i = I \times f_u^I$$

$$R_i = I\left(f_r^{I-ini} - f_u^I\right) \quad ; \quad f_r^{I-ini} \geq f_u^I$$

Interflow (MODFLOW)

time series of user-specified losses (fractions of P-ET and I-ET,(Dogrul et al, 2001, p. 34); fractions apply to what's left over from precipitation and irrigation **after** computation of ET (hence, "interflow")

$$R_p = (P - ET_{p-act})f_r^{P-loss}$$

$$R_i = (I - ET_{i-act})f_r^{I-loss}$$

f can be user-specified or MF-FMP uses the slope to compute. Routed to user-specified stream or to nearest stream

Deep percolation below bottom of root zone to water table

Note that λ is the so-called pore size index

$$DP = K_u = K_s\left(\frac{\theta}{\eta_T}\right)^{\frac{2+3\lambda}{\lambda}}$$

or VanGenuchten equation (IDCv4 manual, p.19):

$$D^{t+1} = D_{rdc}^{t+1} + K_s \left(\frac{\theta^{t+1}}{\theta_T} \right)^{1/2} \left\{ 1 - \left[1 - \left(\frac{\theta^{t+1}}{\theta_T} \right)^{1/m} \right]^m \right\}^2$$

and

$$m = \frac{\lambda}{\lambda + 1}$$

$$D_{rdc}^{t+1} = \begin{cases} \theta^t \left(Z^t - Z^{t+1} \right) & \text{if } Z^t > Z^{t+1} \\ 0 & \text{otherwise} \end{cases}$$

This is solved iteratively as part of solving the mass balance for the root zone.

TIR2, p.13: "deep percolation is a function of soil moisture contributing to the crop-irrigation

Unmet demand that is the basis for irrigation water application computation (that is, if not user-specified)

In Version 3 of IWFM, the portion of demand not met by precipitation and soil moisture storage is:

$$I^{t+1} = \frac{\dfrac{\theta_f - \theta^t}{\Delta t} - \left(P^{t+1} - R_p^{t+1} - ET_{c-pot}^{t+1} - DP^{t+1} \right)}{1 - \left(f_r^{I-ini} - f_u^I \right)}$$

computed in each time-step using runoff fractions in lieu of irrigation efficiency; the fractions apply to the irrigation demand, defined as the sum of moisture depletion, runoff, deep percolation, crop ET minus precipitation. Driven by maximum allowable depletion (MAD), which is crop specific, but area-weighted average of MAD is used BY SUBREGION (see pages 35-36)

In Version 4 of IWFM (IDCv4.0 Manual, p.10) the computation is managed separately for each land-use in each cell:

$$\theta^{t+1} Z^{t+1} = \theta^t Z^t + \Delta t \left(P^{t+1} - R_P^{t+1} + A_w^{t+1} - R_f^{t+1} + G^{t+1} Z^{t+1} - D_r^{t+1} - D^{t+1} - ET^{t+1} \right) + \Delta \theta_a^{t+1} \quad (1)$$

For MODFLOW

The portion of demand not met by precipitation and groundwater extraction; implicit to the computation of ET_i-act:

$$CIR = ET_{i\text{-}act} = T_{i\text{-}act} + E_{i\text{-}act}$$

where CIR is crop irrigation requirement.

6.5 Appendix 5: Comments on March 15, 2013 Draft Report, Submitted by Dr. Sivakumaran with Reponse to Comments by the IWFM Team

6.5.1 Comments by Dr. Kumarswamy Sivakumaran

My observations from the workshop:

(a) The model developers are concerned that certain "unfavorable" comments may lead their management to find fault with them.
(b) The review has extensively covered the theoretical, numerical, and computational factors.

If I were a manager and would like to choose a model, I would like to have the following questions answered by the model developers:

Please answer the following questions for a hypothetical catchments or basin of area 500 square miles:

(i) What is the minimum qualification needed for a person to use the computer code?
(ii) What areas of expertise do the modelers need?
(iii) Do they need to be experts in Arc GIS?
(iv) Do they need prior experience in the models before using them? If so, how many years?
(v) If prior experience is not necessary, how much time will it take for someone to learn, knowing that people learn at different rates?
(vi) Does the modeler need any other support staff? If so, how many and what areas of expertise should they have?
(vii) How much time is needed to assemble the data for each of the models?
(viii) How much time needs to be spent on calibrating and verifying the model before it is used for predictions?

(Note: I am using the terms models and codes as synonyms)

6.5.2 Response to Comments provided by the DWR IWFM team.

DWR Responses to Questions by Dr. Kumarswamy Sivakumaran as Part of the 2012-2013 CWEMF Peer Review Process of Ground Water Models (7-5-2013)

We appreciate the questions raised by Dr. Sivakumaran as they point to many important issues related to use of computerized mathematical models to address real world water resources related management and planning issues. Our responses below will be limited and based on our own experiences with IWFM and its applications and hopefully provide answers sought to the questions asked.

How IWFM is used in a specific project is very much dependent on where the model is applied and what answers are being sought, and what options/capabilities within IWFM are used to obtain those answers. For example: is the application pure ground water flow? Are there streams and canals to consider stream/aquifer interaction? Are there agricultural and urban water demands? Are they processed elsewhere, or is IWFM used to develop land-use based water demands? Is IWFM being used for a historical simulation or a planning simulation? Is the model being used to balance supply and demand components? In the responses below it will be assumed that most of the capabilities of IWFM will be used including deriving agricultural/urban land-use based demands similar to many applications already under way in California and Oregon.

Two types of IWFM users will be considered:

- **User Type A** that develops an IWFM application from scratch, calibrates it, and uses it to develop scenarios to answer hydrologic questions.
- **User Type B** that obtains an already calibrated IWFM application and uses it to develop scenarios to answer hydrologic/management questions. Both of these user types are common in real-world and they need different qualifications to be able to use IWFM.

(i) What is the minimum qualification needed for a person to use the computer code?

User Type A:
Since IWFM is an integrated hydrologic model that simulates many components of the hydrologic cycle and the interactions between these components, it requires the user to have: a good background in surface water – ground water hydrology and modeling, and an in-depth knowledge on the dynamics of many runoff processes as well as the farming and irrigation practices and how these practices might affect the natural flow patterns. The input data development requires a moderate proficiency in ArcGIS, Excel and a sophisticated text editor such as Textpad. Knowledge of NRCS SSURGO soils database and on how to process this database will be needed in developing the parameters for the root zone flow processes. Calibration of an IWFM application can be done manually or automated depending on the number of parameters being calibrated. In general, knowledge of automated parameter estimation software such as PEST or UCODE will be useful.

User Type B:
A user who obtains an already calibrated IWFM application to do scenario runs needs to have a basic understanding of the dynamics of the hydrologic cycle and the interactions between its components. They also need to have an understanding of how farming and irrigation practices may affect the natural flow patterns. To be able to develop scenarios and interpret the simulation results, the user needs to know how to manipulate columnar text data and moderate Excel functionality. IWFM produces many optional output data that allows the user to analyze the simulation results without having to "intercept" the source code. Although knowledge of ArcGIS is useful, it is not required for User Type B.

(ii) What areas of expertise do the modelers need?

User Type A:
A good grasp of principles in surface water hydrology, ground water hydrology (hydrogeology), and numerical modeling is recommended, typically found in an engineering (water resources), or hydrological sciences academic background. A basic understanding of irrigation engineering

principals and soil science, expertise in software such as ArcGIS, Excel, Textpad, PEST or UCODE is highly desired.

User Type B:
A general background in surface water and ground water hydrology, a basic understanding of irrigation engineering principles, a grasp of basic numerical modeling concepts, and moderate ability to use software such as Excel and Textpad is recommended.

(iii) Do they need to be experts in ArcGIS?

User Type A:
No, but a basic knowledge of ArcGIS would be very useful.

User Type B:
No.

(iv) Do they need prior experience in the models before using them? If so, how many years?

User Type A:
A user with experience with any hydrologic modeling software can quickly pick up IWFM. Our experience in helping other users suggests that within a 2 to 4-week period users that have no knowledge of IWFM start using it effectively due to its intuitive input and output data file structure.

User Type B:
Similar to User Type A, User Type B will only need a 2 to 4-week period to get up to speed with IWFM.

(v) If prior experience is not necessary, how much time will it take for someone to learn, knowing that people learn at different rates?

Please see the response for item (iv).

(vi) Does the modeler need any other support staff? If so, how many and what areas of expertise should they have?

User Type A:
Since IWFM simulates many components of the hydrologic cycle as well as the farming and irrigation practices, it generally requires a multi-disciplinary approach, given that most modelers are not experts in all of these fields. Although a user can come up with an initial set of parameters during the calibration phase or the scenario development phase, at some point, it may be required to consult with experts in other fields. For instance, soil scientists can hone the soil parameters while irrigation engineers can perfect the parameters related to farming and irrigation practices. Experts in ArcGIS can develop necessary parameters speedily. Overall, however, if any support staff is required and how many depend on the qualifications and expertise of the individual modeler that is using IWFM.

User Type B:

Similarly, how many support staff, if any, is required depends on the specific scenario a user is trying to put together. A scenario can be as simple as turning off diversions and meeting the demand fully by pumping; such a scenario development requires no support staff. Another scenario can be very complex with new crops using different farming and irrigation schemes coupled with different precipitation and ET requirements. In this case, staff with different expertise can be required depending on the skills of the individual user.

(vii) How much time is needed to assemble the data for each of the models?

This is completely application specific. Utilizing the full capabilities of IWFM – aside from the temporal and scale issues □ can be data intensive including hydrological, land use, soils, and aquifer parameters and time series. The time required to assemble the data for a 500 square mile basin depends on the complexity of the stratigraphy, farming and irrigation practices (if any), number of crops being planted in the basin, grid resolution, etc. Depending on these factors, data development can take from a few days to several months.

(viii) How much time needs to be spent on calibrating and verifying the model before it is used for predictions?

Similar to item (vii) above, this is application dependent, regardless of the size of the model boundary. Calibration and verification of a model with little or no farming activity, fairly uniform soil and aquifer parameters, and a coarse grid may take a few weeks. A more complex model domain with high heterogeneity in the aquifer and the root zone parameters, many agricultural crops, complex farming and irrigation practices, and fine mesh may require several months for a proper calibration and verification. Use of automated approaches such as PEST greatly facilitate and streamline the process, but at greater cost in technical abilities and computational resources.

6.6 Appendix 6: Comments on March 15, 2013 Draft Report, Submitted by DWR

DWR Comments
On the March 15, 2013 Draft Report
Peer Review of Groundwater Models Used in California's Central Valley

By Emin C. Dogrul and Tariq Kadir
May 10, 2013

Note: Reviewers' comments are shown in blue.

The draft report titled *Peer Review of Groundwater Models used in California's Central Valley* dated March 15, 2013 is a well-written and an unbiased review of the three codes used for the modeling of the water resources of California. The report recognizes the difficulties associated with modeling the complex hydrology and water distribution system of California's Central Valley, and the dependencies between the two. At the same time the report is able to give valuable insight to the potential users of these codes about their strengths, weakness and possible applications and listing valuable suggestions to the codes' developers for further improvements. The DWR staff commends the efforts of the peer reviewers on examining these complex codes and putting together this valuable report. We look forward to carefully studying the recommendations for guidance in future enhancing our model development work and applications.

The following are DWR's comments on the report as it relates to IWFM:

1. The name of the code IWFM is misspelled as either IWMF or IFWM in several parts of the report.
Corrected.

2. **Page 15:** It is stated that *"… IWFM is not mathematically integrated: at the core, IWFM solves the groundwater flow equation to which the mathematical models represent sub-systems along the boundaries of the aquifer … Each system is solved separately and an iterative process, similar to that in MODFLOW is used to couple the various subsystems."*.
Response: We do not agree with this statement. The stream, lake and groundwater conservation equations are mathematically integrated (in other words they are fully coupled) and are solved simultaneously (as opposed to being solved separately, as indicated in the report). The peer reviewers are referred to Section 3.7 and Appendix A of the IWFM v3.02 Theoretical Documentation for a detailed representation of the set of equations that are solved simultaneously. Other components such as the root zone and the unsaturated zone (the vadose zone between the root zone and the saturated groundwater system) are also mathematically integrated to the groundwater component. However, IWFM assumes a one-way interaction between these components and the groundwater system. In other words, it is assumed that the flow can only be vertically downward from the root zone or the unsaturated zone into the saturated groundwater. This assumption means that flows from the root zone or the unsaturated zone into the groundwater only affects the right-hand-side of the matrix equation that is being solved and, therefore, the conservation equations for the root zone and the unsaturated zone components can be solved separately from the set of equations representing the coupled stream-lake-aquifer system. One can argue the applicability of the assumption of the one-way interaction

between the root zone/unsaturated zone and the groundwater (which the peer reviewers do) but this does not mean that these components are not mathematically integrated.

We clarified this in the text and also ascertained that this property is shared with MODFLOW. We clarified that this is matter of mathematical representation, not accuracy. For the practitioner, this argument is mostly a matter of semantics. If surface and ground water equations are solved separately as two systems of equations and then values from one system are passed to the other while iteration takes place until convergence is met, the problem is solved correctly. If the equations for surface and ground are solved as one system of equations (fully coupled system) but in the process of solution iteration is required then the problem is solved correctly but it is not superior to the other. Whether the fully coupled system or the partially linearized arrangement achieved by iteratively coupling multiple system equations provides faster convergence is highly case-specific.

3. **Page 24:** The draft report states *"… [w]hether IWFM would have matched the analytical solution if the time step had been 1 week … and the coordinate system used were a Cartesian one, as is commonly done, instead of radial one, was not determined during the verification process."*

Response: It is generally accepted that through the discretization of spatial and temporal domain, numerical models introduce an error into the solution of the conservation equations they are attempting to solve, hence the pixels-of-a-TV-screen analogy used in the draft report. The larger the size of the spatial and temporal grid spacing, the more erroneous the simulation results will be. It is also expected that the simulation results converge to the exact solution (if one can be found) as the spatial and temporal grids are refined. This is true for IWFM or any numerical model used in any scientific or engineering field. It is also guaranteed for IWFM and for MODFLOW, HGS or any other numerical model that the results will be less accurate compared to the exact solution if weekly or monthly time steps are used versus to 10 seconds or 10000 seconds. The purpose of performing verification runs for a model is to check if the numerical algorithm is implemented correctly and if the model results converge to the exact solution as the grid is refined. The 11 verification runs detailed in DWR's model verification documentation follow this recipe and show that the numerical algorithm used for the solution of groundwater equation is implemented accurately. The draft peer review report quotes DWR statement that *"as a full-blown integrated hydrologic model IWFM was designed mainly for large-scale applications where the use of large time-step (weekly or monthly) is more appropriate"*. Here, the key phrase is *"as a full-blown integrated hydrologic model"*. DWR's suggestion to use large time steps is due to the methods used to simulate hydrologic processes (e.g. stream flows and overland flow processes) other than the groundwater flow and due to the lack of availability of measured data at smaller time steps (e.g. stream flow diversions) in California, when IWFM is used as an integrated hydrologic model. However, IWFM can also be used as purely a groundwater model and the simulation of all other hydrologic components can be turned off. In this case, the user can implement much smaller time step lengths without any issues as shown in the 11 verification runs for IWFM.

As to the reviewers' comment on the use of radial coordinate system versus Cartesian coordinate system, it should be pointed out that it was the Cartesian coordinates used in the verification problems of IWFM. Although the model domain in some of the verification runs was described in radial coordinate terminology using angles, the resulting domain itself was still represented and discretized using Cartesian coordinates. IWFM only uses the finite element representation described in Cartesian coordinates. It utilizes linear triangular and bi-linear quadrilateral grid cells that are described in Cartesian coordinates. On the other hand, representation of the groundwater conservation equation and the model domain in radial coordinates would have resulted in curvilinear grid cells which cannot be used by IWFM.

We deleted the reference to radial coordinates and shortened the discussion to salient points.

4. **Page 26:** The draft peer review report states that *"MODFLOW provides one small example, while … IWFM provide[s] no examples"*.
Response: We do not agree with this statement. Every released version of IWFM comes with a sample model accompanied with all the input and output files, and its dedicated documentation. The sample model can be downloaded by visiting IWFM's global web page and by navigating to the desired IWFM version's dedicated page (please see http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/index.cfm). Most IWFM users start from the sample model and modify its input files to build their own applications. Additionally, templates for input files can be downloaded from particular IWFM version's dedicated web page. These template files are in ASCII text format and include built-in comments explaining each of the required input data.

We changed the text accordingly and included the link.

5. **Page 45:** It is stated that *"IWFM is … not as well suited for local scale site groundwater models encompassing less than a few thousand acres"*. **Response:** This statement might be correct (although there are no examples that backs this statement) if both groundwater and land-surface processes need to be modeled in an application. However, if only the groundwater component of IWFM is used, it can be applied at much smaller scales than the draft report suggests. In fact, some of the verification runs performed for IWFM (Verification Problems for IWFM, DWR 2006) had very small domains. For instance, Tests 2.a and 2.b successfully simulate groundwater heads at an observation location about 1200 ft away from a pumping well. Test 5 which had a model domain of only 61 acres accurately simulates the effect of pumping and recharge at two aquifer layers separated by a clay layer. Therefore, the scale of the model domain where IWFM can simulate flow processes accurately highly depends on the hydrologic components that need to be included in the application. DWR staff believes that this is also the situation with MODFLOW that is accurately pointed out by the peer reviewers.

We clarified this point.

6. **Page 73:** DWR's response (communicated to Dr. Morel-Seytoux by e-mail on 6/11/2012) to question 13.a is not included in the draft report.

This has been included in the proper place in Appendix 2. See Appendix 2.

7. **Page 77**: Harvey-Samani should read Hargreaves-Samani.

This has been corrected.

8. **Page 97:** The reviewers list two equations regarding the flow and water demand computations in the root zone component of IWFM and ask which equation is valid. Both equations are valid, but they represent two different versions of IWFM. The first equation is valid and used in IWFM v3.02. The second equation is also valid but used in IWFM v4.0 and the stand-alone root zone modeling component IDC v4.0.

Thank you for clarifying.

Mike Tansey from U.S. Bureau of Reclamation also raised a few questions regarding IWFM in connection to the peer review report (per Rich Satkowski e-mail of 4-16-2013). We would like to provide our own responses to the questions, as follows:

9. **Page 22:** *Mike Tansey asks if mass balance is maintained in the reviewed models and if it is reported*. The answer for both of these questions regarding IWFM is yes. IWFM maintains the mass balance for all modeled hydrologic runoff components and any mass balance error is reported in easy-to-read water budget outputs for each these components.

10. **Page 39:** *Mike Tansey asks if it is correct that IWFM uses future water content in routing soil moisture in the root zone.* The answer is yes. IWFM uses an implicit method to solve the non-linear moisture fluxes in the root zone. Here, the term "*future water content*" represents the unknown soil moisture content at the end of the current time step for which a solution is sought for (i.e. an implicit method), instead of linearizing the equation by using the known moisture content from the previous time step (i.e. an explicit method).

These two responses (9. and 10.) have also been addressed in the manuscript.

6.7 Appendix 7: Comments on March 15, 2013 Draft Report, Submitted by Jon Traum

To: California Environmental Modeling Forum
From: Jon Traum, PE (Civil Engineer / Hydrologic Modeler)
Date: April 15, 2013
Subject: Comments on draft report *Peer Review of Groundwater Models used in California's Central Valley*

I am writing this memo to provide comments on the draft report *Peer Review of Groundwater Models used in California's Central Valley* that was released by CWEMF on March 15, 2013. I am providing general comments on the review. I have also provided some additional insight into the strengths and weaknesses of IWFM and MODFLOW-FMP, which I have discovered through extensive experience in working with these two codes.

[From T. Harter and H. Morel-Seytoux:] These are extremely valuable comments that stand well on their own. Jon is sharing many of is own experiences on MODFLOW with the Farm process and on IWFM. We have incorporated some of these comments into the manuscript to the degree we felt that they added further clarification (e.g., the reference to the Farm process instead of the Farm package). Some concepts mentioned here have been helpful in editing the report, but have not been fully included (for example, we do not bring up the concept of "cousin models", which we feel is beyond the scope of this report, although it is a valid idea; instead, we clarified some salient points, e.g., that MODFLOW with the Farm process cannot be coupled to MT3D.)

Overall Comments on the Review

Editorial

The format of the Peer Review (Review) is somewhat confusing. In the "Model Evaluation" section, each topic has an introduction, which generally describes the model process and why it is relevant for models in California. Then the rest of the topic describes how the model process is simulated in the three models. I personally found myself skipping these introductions as I was only interested in the discussion on how the processes are simulated in the models. The Review could be organized better if the introductions were moved up to the "Introduction" section, and the "Model Evaluation" section discussed ONLY the model applications.

On page 35, it would be helpful to repeat the table header for table 2 at the top of each page when the table wraps over to the next page.

Recommendations

On page 2:

"The reviewers recommend that agencies (local, state or federal) consider the development of multiple groundwater models that are developed in parallel based on different model codes to evaluate potential errors associated with the different conceptual methods associated with each code."

This is a very idealistic recommendation as agencies will not have the time or budget to develop more than one model.

On page 56:

"It would be useful if some tests were performed that are designed by an independent party and run either by the model developers (if they have the time to do it) or run by other practitioners familiar with the codes"

Again this is a great recommendation, but it is something that model users just do not realistically have the time and budget to do.

Naming Conventions

For some model features, each model uses a different name to describe the same feature. In the Review, these names are sometimes used interchangeably, which leads to some confusion. To add to this confusion, two features with the same name can actually represent different features in each model (such as a stream reach). I suggest adding a table, which compares naming conventions for each model, and then try to be consistent throughout the Review.

For example:

IWFM	**MODFLOW-FMP**
Model Element	Model Cell
Stream Node	Stream Reach
Stream Reach (a group of stream nodes)	Stream Segment (a group of stream reaches)
Subregion	Farm
Deep Percolation of Irrigation	Return Flow
Return Flow	Runoff of Irrigation
Time Step	Stress Period (a "time step" is a subdivision of a "stress period")

Also, what the Review calls the "Farm package" is actually called the "Farm Process". What the Review calls the "STREAM package" is actually called the "Streamflow-Routing package" (SFR).

Cousin Codes

The Review does not clearly identify the fact that MODFLOW-FMP is a "cousin code" of MODFLOW-2005. This distinction needs to be made because there are some features available in MODFLOW-2005 (or in other MF-2005 "cousin codes"), which are not available in MODFLOW-FMP. It is true, that many of these features could probably be coded into MODFLOW-FMP with less effort than it would take to code them from scratch. However, it needs to be recognized that these features are not immediately available in MODFLOW-FMP.

Similarly, the Review does not identify the fact IWFM is a "cousin code" of IGSM. There are some features available in IGSM, which are not available in IWFM. Like with MODFLOW, these features could probably be coded into IWFM with less effort than it would take to code them from scratch, but the features are not immediately available.

In addition, on page 25 it is stated:

"For example in the journal article library "ScienceDirect" (http://www.info.sciencedirect.com) the term "MODFLOW" returns 1,280 publications, the term "HydroGeoSphere " 74. For the IWFM case neither the acronym nor the full name is representative of the publication"

Most of these "MODFLOW" results are not for MODFLOW-FMP but are for MODFLOW-2005 or a legacy version of MODFLOW. A search for IGSM and IGSM2 would give a better sense of the number of IWFM related publications. From the time that it was developed in the late 1970s, IGSM has always included land surface processes, whereas MODFLOW has only included land use processes (though FMP) in the last six years. There are actually more applications of IWFM than there are of MODFLOW when considering the simulation of land use processes.

Below are some examples of features of "cousin codes"

Water Quality

IGSM had a water quality module in Version 5 that is no longer maintained in IWFM. It could be brought into IWFM with some work.

MT3DMS is the water quality module for MODFLOW. Based on my limited testing, the MODFLOW-FMP code crashes when enabling the Link-MT3DMS Package, so it appears that MODFLOW-FMP is not currently setup to run with MT3DMS. It would take some work from the code developers to fix this link and to allow the user to specify chemical concentrations for FMP related sources of water in the Sink and Source Mixing Package.

Particle Tracking

Particle tracking is available for IGSM in Version 6. It could be brought into IWFM with some work.

Particle tracking is available for MODFLOW through MODPATH. MODPATH utilizes the head output and cell-by-cell output files from MODFLOW, which are in the same format for both MODFLOW-2005 and MODFLOW-FMP. Thus, MODPATH should work with MODFLOW-FMP although I have not personally tested it.

Reservoir Operations

IGSM allows the user to specify minimum flow requirements and simulates reservoir operations in order to meet these requirements. This feature could be brought into IWFM with some work.

Optimization

MODFLOW-GWM is another "cousin code" of MODFLOW-2005 which can be used to determine the optimal location and magnitude of groundwater pumping. MODFLOW-GWM has had very few practical field applications, and it is not yet coupled with MODFLOW-FMP.

Differences in Processes Simulated

This section provides some additional insight into some of the practical differences between the model codes. Some of the differences discussed might already be stated in the Review or in the model documentation. However, many of these intricacies are only discovered through extensive experience in working with the model codes.

There are some hydrologic processes that are available in one code but not the other. There are also some hydrologic processes where one code is more flexible or provides more options on how to simulate a process compared to the other. Examples are provided in the subsections below.

To be consistent with the Review, this section discusses processes as they are simulated in IWFM version 3 and MODFLOW-FMP version 2. Some of the items discussed may have been changed in IWFM version 4 or MODFLOW-FMP version 3.

Grid

IWFM uses a finite element grid whereas MODFLOW uses a finite difference grid.

A strength of a finite element grid is that it can be refined near a stress in order to more accurately simulate the groundwater levels in areas with high groundwater gradients. The finite difference grid can also be refined around a stress through telescoping, but this method requires all cells in the same row and same column to be refined throughout the model, even if they are far from the stress area.

A weakness of a finite element grid is the difficulty in generating the grid. DWR provides a free finite element mesh generator on their webpage, but it is somewhat limited (can only make triangular elements). A more complete finite element mesh generator is only available through commercial software.

Stream Depths and Widths

MODFLOW is more flexible than IWFM in how it calculates stream depths. IWFM only provides one way to compute streamflow depth from streamflow rates, which is through the use of a rating table for each stream node. Typically, to get rating tables at this scale, a surface water routing model (such as HEC-RAS) needs to be constructed outside of IWFM.

In contrast, the MODFLOW SFR package provides five different ways to calculate stream depth, which are specified depth, Manning's equation with rectangular channel, Manning's equation with irregular channel, power function, or rating table (see the ICALC flag in the SFR documentation). In absence of an external model to provide rating tables, one of the other four methods can be used.

In IWFM, stream widths (wetted perimeter) are defined once in the parameter file and are constant throughout the simulation. In MODFLOW SFR, stream widths are calculated and vary with streamflow (except for the "specified depth" and "Manning's equation with rectangular channel" calculation methods, where the widths are constant).

Subsidence

The MODFLOW Subsidence and Aquifer-System Compaction package can simulate both the instantaneous and delayed subsidence due to the release of groundwater from interbed storage. IWFM only simulates instantaneous subsidence. The simulation of delayed subsidence makes MODFLOW much stronger at simulating subsidence in areas with thick slow-draining clay beds, such as the Corcoran Clay in the San Joaquin Valley.

MODFLOW also has better subsidence output options. The user has the option to have MODFLOW split up total subsidence into elastic and inelastic (irreversible) subsidence.

Stream Aquifer Interaction

The finite element mesh used in IWFM can be refined along rivers in order to more accurately simulate the groundwater elevation below the river. This strength is especially important when simulating stream aquifer interaction because with large cell sizes, the average groundwater head throughout the cell can be much different than the groundwater head directly below the river.

One strength of MODFLOW is that the user specifies the length of each stream reach within a cell. In IWFM, the river length is automatically calculated as the distance between the two stream nodes. For meandering streams, IWFM will under represent the stream length (usually leading to an over estimation of the streambed K).

Small Watersheds

IWFM simulates small watersheds to estimate ungagged surface water and groundwater inflows into the model area. It also provides an output budget for the small watershed inflows.

In order to simulate small watersheds in MODFLOW, the flows would need to be estimated outside the model. The surface flows could be brought into the model using the SFR package and the groundwater flows could be brought into the model using the Flow and Head Boundary package.

Drains

In IWFM, water collected by tile drains can either be sent to the stream network or exported out of the model. It can't be used to recharge the aquifer.

In MODFLOW, water collected by tile drains can either be used to recharge the aquifer (though the Drain Return package) or exported out of the model. It can't be sent to the stream network.

Runoff

In IWFM, runoff is separated into direct runoff and indirect runoff. Direct runoff is calculated by the model using the CN method, or it automatically occurs in paved urban areas. Indirect runoff occurs if the soil moisture goes beyond field capacity (either by rainfall or excess irrigation). In this case the excess water can either be percolated or runoff based on a user specified soil K.

In MODFLOW-FMP, the user specifics a fraction of runoff for irrigation by crop type and a fraction of runoff for precipitation by crop type. The fraction method is very limiting, especially in regional models, since the user must use the same fraction for a crop no matter where it is located. For example, a pasture near Redding probably has much higher runoff fraction than a pasture near Dos Palos. In MODFLOW-FMP indirect runoff is not simulated, so once water is "on farm", it is either consumed by ET or percolated.

Also, a large storm will typically have a higher runoff fraction than a small storm, which the IWFM CN method takes into account. Higher runoff for some storms can be simulated in MODFLOW-FMP by specifying the runoff fractions for each stress period, but it would require doing the calculation of the runoff fraction outside of MODFLOW-FMP.

IWFM is also much more flexible compared to MODFLOW-FMP on how to specific the routing of runoff back to the stream network. In IWFM, the user provides a stream node where each model element drains to, which allows the user to accurately simulate a subregion with multiple drainage canals. In MODFLOW-FMP, runoff can either be "fully routed" where the model evenly divides the runoff to all streams within the subregion or "semi-routed" where the user can specific ONLY ONE stream reach where the entire subregion drains to.

Urban Water Use

IWFM breaks up urban demand into indoor and outdoor water use. The user can specify the return flow characteristics of urban water use, such as going to a septic system or being discharged back to the stream network (after treatment). IWFM also provides a water use budget for urban areas that is separated from the agricultural water use budget. It also better simulates runoff in urban areas by allowing the user to define the fraction of pervious area and separate curve number for urban land use.

MODFLOW-FMP only simulates the outdoor component of urban water use.

Diversions

In IWFM, diversions can be specified at any stream node, and the user specifies the amount diverted. One subregion can receive diversions from several stream nodes, and/or one diversion can be split up by fractions to different subregions.

In MODFLOW-FMP, the user can only define one diversion point per farm. In addition, diversion can only occur at the ends of stream segments. Furthermore, the user CANNOT specific the amount diverted, and the farm will take all the surface water that it needs to meet demand until the stream goes dry. So for example, if the user specifies a larger river (such as the Sacramento River) as the diversion point for a farm, the farm will never have to do any groundwater pumping since it can meet all of its demands from surface water. These limitations require the user to jury rig the model by making an artificially complicated streamflow network to get the correct diversions going to each farm.

In IWFM, the user can also specify conveyance losses for each diversion, including the amount and location of recoverable losses (seepage) and the amount of non-recoverable losses (evaporation) before the water reaches the subregion. In MODFLOW-FMP, the user specifies conveyance losses by crop type, and these losses are returned to the stream network.

One strength of MODFLOW-FMP is in simulation of diversions for local scale models, such as a model of operations within a water purveyor. MODFLOW-FMP supports "fully routed" deliveries (where farms automatically take water from adjacent canals which have flow), which is a feature not available in IWMF.

Artificial Recharge of Diverted Water

IWFM can directly simulate artificial recharge which is diverted from a stream by specifying most of the diversion as being a seepage loss.

In order to simulate artificial recharge from streams in MODFLOW, it needs to be simulated indirectly. For example, it could be simulated by diverting the surface water outside of the model and then importing it back in using the recharge package.

Specified Agricultural Demand

In IWFM, the user has the option to specify the agricultural demand rather than have the model calculate it. In MODFLOW-FMP, the only option is to have demand be calculated by the model.

Being able to override the model's demand calculation has many uses. For example, the model developer could have agricultural demand data from a different source. In addition, the model can be run once to calculate agricultural demands, and then the demands can be fixed at these values to improve model performance for subsequent runs. Also when generating water management alternative scenarios to compare to a baseline, it is sometimes helpful to fix agricultural demand so that changes in agriculture demand don't mask changes due to changes in the scenario.

ET

In IWFM, ET_p is defined by crop and region. For example all pasture in subregion 10 will have the same ET_p. This method supports tabular input data by crop type such as data in DWR Bulletin 113.

In MODFLOW-FMP, ET_o is defined spatially by cell. This method supports input data in a grid format such as what could come out of a climate model.

Evaporation vs. Transpiration

In MODFLOW-FMP, a time series of fraction of vegetative area for each crop is defined, and transpiration only occurs in vegetated areas. For example, a crop might have only 20% vegetative cover in April but might be 80% in August when the crop has grown. A time series of fraction of evaporation of irrigation water area is also defined (the fraction of land area that has standing irrigation water such as an irrigation furrow). This allows the user maximum flexibility when simulating evaporation vs. transpiration.

In IWFM, the user specifics an ET_p for bare soil which is usually set to about 50% of ET_o. When a crop is not active in a subregion and transpiration is zero, IWFM uses this soil ET_p value to determine evaporation. It is unclear in the model documentation about how to define when a crop is not active. I believe that it can be done by setting the ET_p for the crop to zero.

Crop Mix

In IWFM crop mix is defined at the subregion level. In MODFLOW-FMP each cell has one crop defined. Depending on the cropping patterns, either model can have difficultly correctly simulating crop mixes.

For example, take a FMP farm that is 20% cotton and 80% vineyard with small evenly scattered parcels (so that each cell has 20% cotton and 80% vineyard by area). In MODFLOW-FMP, each cell is typically assigned a crop based on largest area within the cell, so the FMP farm would be incorrectly simulated as 100% vineyard.

In contrast, take an IWFM subregion that is 20% cotton and 80% vineyard with all the vineyards on the east side of the district and all the cotton on the west side. In IWFM, the crops would be incorrectly simulated with the cotton and vineyards distributed evenly throughout the subregion.

In IWFM, crop mixes only have to be defined in years when data is available (such as when a DRW land us survey was performed). The model will automatically interpolate between years.

Simulation of Groundwater Wells

For groundwater wells in general, the MODFLOW MNW package provides more options than IWFM on how to simulate groundwater pumping. For example, one option is to have wells stop pumping if groundwater levels drop below a certain threshold. Many Groundwater Management Plans have BMOs which set long term drawdown limits, and these limits can be simulated easily using this MNW option.

One weakness in the link between the MODFLOW MNW package and the farm process is that only one FMP-MNW well can be assigned per model cell (and no other MNW wells can be in that cell either).

In MODFLOW, wells are defined for each stress period and can change as new wells are added and old wells are retired. In IWFM, well locations are defined once and are static for the entire simulation.

One strength of IWFM is that for element pumping, there is an option to distribute pumping in proportion to the agricultural area in each element. MODFLOW-FMP has a similar option (NOCIRNOQ) which turns off agricultural pumping in cells with zero agricultural demand; however, this option is less flexible since a cell with a small amount of demand will pump the same as a cell with a large amount of demand.

Well Screens

For wells screened across multiple layers, the MODFLOW MNW package automatically calculates how much pumping occurs in each layer based on parameters such as aquifer K. However, the user must define the layers in which a well is screened based on a calculation done outside of the model.

In IWFM, the pumping layers are calculated by the model automatically (for well pumping) based on where the well screens intersect the model layers. However, the amount of pumping that occurs in each layer is calculated using simple proportions rather than based on aquifer properties. For element pumping, the fraction for each layer is user defined.

The MODFLOW MNW package simulates interborehole flow. From the theory side, this is a strength, but from the practicality side, this can be a weakness, as interborehole flow can lead to long computation time and numerical instability.

Often the user will want to turn off the MNW interborehole flow. In fact, MNW facilitates turning off the interborehole flow by having the option to create an output file in the basic well file format, where each MNW well is split into several single-layer wells. This well file can then be used in a subsequent model run instead of the MNW package.

However, when dealing with agricultural wells in MODFLOW-FMP, this splitting approach doesn't work well. MODFLOW-FMP divides the pumping evenly between all wells within a subregion, and MODFLOW-FMP considers each split well as its own well. So for example, if one well is screened across three layers, FMP would assign three times the pumping rate compared to a well that is only screened in one layer.

Deficit Irrigation

MODFLOW-FMP has more flexibility than IWFM in how it simulates situations where crop demand exceeds available supplies. In IWFM, the shortage is reported, but it is assumed that the crops are supplied from another imported source (this is called the "zero scenario" in MODFLOW-FMP). In MODFLOW-FMP, five options are available, which are water stacking, deficit irrigation, zero scenario, acreage-optimization, and acreage-optimization with conservation (see the IDEFFL flag in the MODFLOW-FMP documentation).

Anoxia

MODFLOW-FMP simulates anoxia due to a shallow water table, which is not simulated in IWFM. From the theory side this is a strength; however, in California, most crops are well managed to avoid anoxic conditions.

Furthermore, during calibration, the simulation of anoxia introduces a positive feedback loop which can seriously mess up the calibration. For example, if depth to groundwater is too shallow (maybe due to poor initial conditions , ET_{actual} is reduced due to anoxia, leading to reduced crop demand, leading to reduced groundwater pumping, leading to even shallower depth to groundwater. I often turn off anoxia during calibration by setting PSI(1) and PSI(2) to unrealistically high positive values.

Simulating Agricultural Demand on a Daily Time Step

IWFM can simulate land use processes on a daily time step because it uses a soil moisture accounting method. When looking at the daily soil moisture output during the growing season, the soil moisture decreases each day due to crop ET. After a few days, it hits a user specified "minimum soil moisture requirement". At this point irrigation happens, and the soil moisture is filled up to field capacity. This method creates a situation that is like real life, where the crops are irrigated every few days.

However, since surface water delivery data is usually only available on a monthly basis, I have not experienced any benefit to simulating on a daily time step. Daily time steps also greatly increase the model's execution time.

Advanced Options

MODFLOW-FMP offers several advanced options that are not available in IWMF for simulate some processes. For example, there is an option to allow irrigation efficiencies to vary based on changing groundwater levels. There is also an option to have crop root depths vary based on changing climate. Many more advanced options exist (see model documentation).

For a theory side, these options provide the user more flexibility in how to construct the model. However, from a practicality side, there is usually not sufficient data to support constructing the model using these advanced options. In addition, for someone just learning to use MODFLOW-FMP, these additional options can just confuse the user.

Other Considerations

Input Data Formats

For an experienced modeler, input data format is not that important as we are experienced in fitting input data into whatever format it needs to be in. However for users who are not experienced at modeling (such as a manager who wishes only to extract pumping data from the model), the IWFM model input data format is generally more user friendly than MODFLOW.

One major strength of IWFM is that time series data, non-time series data, and specification data are split into separate model files. Input time series data and non-time series data are in column format and can generally be directly pasted right into the input files (from programs such as Excel) without the need for any pre-processing. IWFM also makes heavy use of unit conversion scale factors, so data in the model files does not need to be converted out of its native units. Furthermore, the times when time series data are specified do not have to match the time steps in the model. For example, the model input files can have monthly pumping data and daily streamflow data. If the model is run with monthly time steps, IWFM will automatically calculate average the streamflow for each month based on the daily streamflow data. If the model is run with daily time steps, IWFM will automatically interpolate the daily pumping rates based on the monthly pumping data. Additionally, time series data can be specified outside the dates when the model is run. With this flexibility, model simulation period can be extended without the need to add more data to the input files, or the model simulation period can be truncated without having to delete extra data from the input files.

MODFLOW data tends to be all lumped into one data file in a block format where each block represents one stress period. It usually requires a pre-processor to develop MODFLOW input files or to convert the data in MODFLOW input files back to a usable format.

The column format makes it much easier to develop simple scenarios in IWFM. For example, if a user wants to change the pumping data for a well in IWFM, all he has to do is find the time series column of pumping rates for the well, paste it into Excel, change the values, then paste it back into the model. To do the same thing in MODFLOW would require the user to find place in each block where the well is specified, and then change the pumping value on each line. For a transient model with many stress periods, it would not be feasible to do these modifications manually.

One strength of the MODFLOW file format is that features (such as a well) can be turned on or turned off just by not specifying them in the next block. In IWFM, a well is always turned on, and the user needs to specify zero pumping for the times when the well is not active. This can often make IWFM model files very large.

IWFM input files allow the user to add comment lines within the model file whereas MODFLOW usually only allows comments at the top of the files (end-of-line comments are also allowed in some files). The greater flexibility in commenting allows IWFM users to include more extensive documentation within the model files.

Output Data Formats

For hydrologic budgets (such as water use, groundwater, streamflow), both IWFM and MODFLOW-FMP generate text file budgets, which can easily be imported into other formats such as an Excel spreadsheet. IWFM budgets have headers and dates, which make the files easier to read in text format; however, these headers can actually be a burden, since they need to be stripped away when the file is brought into excel. DWR provides an Excel tool to strip the headers (but this is another post processing step and another tool the user has to learn).

For water use budgets, MODFLOW-FMP offers a “Compact Farm Budget” (which lumps some outputs into more general categories) and a “Detailed Farm Budget”. IWFM only offers one budget, which has some outputs lumped. This lumping can make it difficult to extract specific types of water use information out of the IWFM water use budget.

In MODFLOW-FMP and IWFM, water use budgets are provided for the farms (FMP) or subregions (IWFM). However, IWFM also provides a “sub group” budget which allows the user to generate a budget for groups of elements that are different than the subregions. This budget can be useful if the user wants to extract water budget information for an area smaller than a subregion or to automate the aggregation for many subregions into a macro region for reporting purposes.

IWFM water use budgets also provide land use areas, which allow the user to easily calculate water use rates in feet (acre-feet per acre). In MDOFLOW-FMP, the user has to go back to the input files to determine the agricultural area in each farm.

For groundwater budgets, both MODLOW (through ZONEBUDGET) and IWFM (though Z-Budget) allow the user to generate budgets for any group of elements. IWFM also provides a default groundwater budget for the subregions.

For streamflow budgets, IWFM provides a budget for each group of stream nodes (called a stream reach). In contrast, MODFLOW SFR package provides a budget for each cell (also called a stream reach) (note the discrepancy about what each model calls a stream reach). The SFR budgets give the user more information since they are at a more detailed level, but it can also result in very large files for models with lots of stream reaches.

For developing hydrographs, IWFM is easier to use as the user can input observation locations directly into the "Print Control File" using the XY coordinates that the model grid is developed in. In MODFLOW, through the Hydmod package, observation locations are input with respect to the corner of the model grid, which requires pre-processing.

For visualizing model results (maps and cross sections), both models export data in a gridded format that can somewhat easily be mapped onto a shapefile grid and displayed in GIS.

User Guides

MODFLOW has a very detailed, easy to use online user's guide. This guide is also updated regularly as new model features are added. Unfortunately, the guide does NOT yet include support for the farm process. The data input instructions for FMP are somewhat confusing to follow because there are many options, and many of these options are only used if certain flags are set. The description of the FMP variables is also grouped in the documentation by topic rather than by the order that they appear in the FMP file, which can lead to more confusion. The best way to develop an FMP file is to use an existing file as a guide (such as the CVHM FMP file).

IWFM provides a PDF user's guide. However, the template files are the best guide available for developing model files. DWR makes heavy use comment lines within the temple files, making them easy to understand and follow.

GUIs

Free GUIs are provided by DWR and USGS for their respective model codes. DWR's GUI requires ArcMap, which is not free, but most users today have access to ArcMap.

The USGS GUI, ModelMuse, is in an ArcMap-like format that is easy to learn. The GUI does an excellent job at visualizing output. The user can import a model, even if it was not developed with ModelMuse. It allows a user to export model results to CSV or shapefile formats to do further analysis or visualization outside of the GUI.

ModelMuse can also be used to develop model input files. However, ModelMuse is limited to only a few packages (CHD, DRN, GHB, HOB, RIV, and WEL) for which it can utilize imported time series data. For other packages, time series data needs to be input for each feature (which becomes unfeasible for models with more than 20 or 30 features). Furthermore, ModelMuse does not yet support the farm process, so it cannot be used to assist in the preparation of MODFLOW-FMP files.

One drawback to ModelMuse is that it uses a lot of computer resources when working with large regional models. For these models, ModelMuse might not be feasible to use for people with older computers. The 32-bit version of ModelMuse has a 3 gb ram barrier, and it is not uncommon for a large model to take up 6+ gb of ram in ModelMuse.

The IWFM GUI is based in ArcMap, so a user familiar with ArcMap can understand the GUI easily. The GUI is currently set up just to work with C2VSim and does not work with other IWFM models at this time. The GUI can be used to visualize model output but does not support input file development. The GUI is still in beta testing; the major functionalities work, but there are still a lot of bugs that need to be fixed.

Calibration

In MODFLOW, many parameters are defined in a pval file, which makes development of a PEST template file very straightforward. Also, the Observation Process provides the model output in a format that can be directly read by PEST without the need to make complicated PEST instruction files.

In IWFM, most datasets have a unit conversion scale factor at the top of the file, which is intended to be used for unit conversions; however, this factor can also be used as a parameter by PEST to scale entire matrices of input data. IWFM also allows parameters to be defined using a “parametric grid” which essentially internalizes the Pilot Point calibration method. There are also IWFM PEST utilities available for public download which aid in calibration using PEST.

After Thoughts

Hopefully, some of my comments will be useful in supplementing parts of the Review.

Overall, both models have areas where they either are more flexible or simulate a process more completely than the other model. Thus, for specific applications, one model might be a better choice than the other. However, for a regional model, the strengths and weakness will balance out such that there is no “winner”. Ultimately, modelers will chose the model that they are most comfortable using.