

FULLY-INTEGRATED SURFACE AND SUBSURFACE MODEL FOR CONJUNCTIVE ANALYSIS OF WATER SUPPLY RELIABILITY, WATER QUALITY AND ECOSYSTEM HEALTH

G. Matanga, Hydraulic Engineer, Reclamation, Sacramento, CA, gmatanga@mp.usbr.gov,
L.R. Gessford, Geologist, Reclamation, Sacramento, CA, lgessford@mp.usbr.gov,
K. Nelson, Hydraulic Engineer, Reclamation, Sacramento, CA, knelson@mp.usbr.gov,
D.T. DeMarco, Project Manager, HydroGeoLogic, Waterloo, Canada, ddemarco@hgl.com,
E.A. Sudicky, Professor, University of Waterloo, Canada, sudicky@sciborg.uwaterloo.ca,
R. Therrien, Professor, Laval University, Canada, rene.therrien@ggl.ulaval.ca
S.M. Panday, Research Director, HydroGeoLogic, Herndon, VA, spanday@hgl.com
R.G. McLaren, Hydrogeologist, University of Waterloo, Canada, mclaren@uwaterloo.ca

Abstract

In water resource management, there is an increasing emphasis on problems that require conjunctive analyses of surface/subsurface hydrologic and water-quality processes. Major issues of concern to water managers include water supply reliability, water quality, ecosystem health, and impact of climate change on water resources. In California, the most popular planning model is CalSim-II. In its current form, CalSim-II is not appropriate for studies related to impact of climate change on California's water supply reliability due to its reliance on a 73 year historic record of streamflows for its primary hydrologic input. There is a need to dynamically link CalSim-II with a robust fully-coupled hydrologic model, HydroGeoSphere (HGS) that uses meteorological data to drive the hydrologic simulations. The linked HGS-CalSim-II model will provide an improved modeling tool to the water resource managers for examining the interrelationships between water supply reliability, water quality, and ecosystem health under changing climatic conditions and different management scenarios. Ongoing work will demonstrate application and verification of HGS considering two case studies. The first case study is at a highly characterized small-scale field site (259 hectares) for evaluating a drainage-water re-use system. It is located at Red Rock Ranch in San Joaquin Valley. This study will demonstrate the utility of HGS for consideration of small-scale projects in which detailed scientific representations are essential. The results from this case study will be useful for the formulation of optimal design and management guidelines for the re-use systems aimed at salinity and agricultural drainage control. The second case study will focus on the San Joaquin River Basin or its sub-basin. This will be a watershed-scale study that will involve application of HGS and the linked HGS-CalSim-II models. One of the central hypotheses motivating this work is that climate change will necessitate an increased reliance on the subsurface storage of water. The model results from the watershed-scale study are expected to substantiate this hypothesis.

INTRODUCTION

In the management of water resources, there is an increasing emphasis on problems that require conjunctive analyses of surface/subsurface hydrologic and water-quality processes. For example, the conjunctive use of surface and subsurface water resources is increasingly becoming an important component of the optimal management of California's limited water resources (Lund, 2003). The potential impacts of long term phenomena, such as climate change greatly exacerbate

the challenges of sustainable water-resource management and also increase the necessity of conjunctive use strategies. For example, a recent study published in *Proceedings of the National Academy of Sciences* indicates that by the end of the century Sierra snowpack may be reduced by 30-70% under a low emissions scenario, or by 73-90% under a business-as-usual scenario (Hayhoe et al., 2004). It is also expected that the spring snowmelt will begin earlier in the year and that the ratio of winter runoff to total runoff will be increased (Dracup et al., 2004). California's surface reservoirs will not be able to compensate for all of the lost storage from the reduced snowpack. Consequently, a critical element in California's adaptation to these changes will be an increased reliance on artificial recharge of aquifers or water banking during the wet periods. With respect to climate change, impact analysis will require hydrologic and water-allocation models that are driven by meteorological data (e.g., temperature, precipitation). Furthermore, success of conjunctive analysis of surface and subsurface water regimes will depend on availability of robust fully-coupled surface/subsurface hydrologic numerical models that accurately account for flow and transport processes within and at the interface of surface and subsurface water regimes

CalSim-II is the most popular water-allocation or planning model in California for assessing water supply reliability under different management scenarios. However, it has been noted that while CalSim-II does contain adequate representation of operating rules of the California's Central Valley and State Water Projects, it is not suited for climate change studies due to its reliance on a 73 year historic record of streamflows for its primary hydrologic input (Dracup et al., 2004). It is therefore proposed to adapt CalSim-II for climate change studies by linking it to a robust fully-coupled surface/subsurface hydrologic model known as HydroGeoSphere (HGS).

HGS and the linked HGS-CalSim-II models will also be valuable for a critical group of problems that involves the transport of dissolved contaminants at multi-scales in surface and subsurface water. For example, a recent report (NSTC, 2000) has shown how nutrients, primarily nitrate and phosphate, transported from continental watersheds, can disrupt the ecology of near-shore ocean systems or bay/delta water bodies. Management of nutrient loads in rivers contributing to the surface-water bodies, such as California's Bay-Delta, may involve field and modeling studies which are capable of representing nutrient sources as well as key fate and transport processes. However, modeling has not yet captured nutrient fate and transport processes in a way that is satisfactory for management purposes. The ability to understand nutrient processes at the watershed scale is an emerging national and State need as federal and state agencies begin to address TMDL (Total Maximum Daily Load) issues in the river basins. These kinds of analyses will require comprehensive flow and transport simulators with appropriate schemes for loading digital information (DEMs, soil maps, land-use information).

Historically, each of the above processes of concern has been analyzed independently, with source/sink assumptions providing a lumped estimate of the water budget components that are not directly simulated. For instance, surface-water flow and transport models neglect or highly conceptualize the subsurface interactions, whereas subsurface flow and transport models are driven by groundwater recharge estimates and treat the surface features such as lakes and streams as input or discharge locations (boundary conditions) for water and contaminants. Snowmelt – runoff models generally neglect subsurface flow processes or ET from non-snow covered zones,

and sediment transport models often use highly simplified hydrodynamics. This is satisfactory for analysis of the individual regimes with specific goals such as flood management (surface-water flow model), well-field management (groundwater flow model), groundwater contamination and remediation studies (groundwater transport model), or water quality investigations (surface-water transport model). However, within the framework of conjunctive management of scarce water resources or of water quality impacts affecting multiple flow domains, an integrated model is required that accounts for all processes within all domains in a physically-based manner. A major step towards that end is the development of HGS as a joint undertaking between University of Waterloo, Laval University, the Bureau of Reclamation and HydroGeoLogic Inc.

With respect to water quality and ecosystem analysis, there is ongoing work at University of Waterloo and Laval University to enhance HGS by incorporating additional hydrologic and water quality processes into the model to facilitate combined analysis of the interrelationship among water supply reliability, water quality, and ecosystem health. The ongoing enhancements include incorporation of modules related to simulation of snowmelt, temperature, dissolved oxygen (DO), nutrients and erosion/sedimentation.

Reclamation is developing a Graphical User Interface (GUI) for HGS to facilitate its application by a large audience of water-resource professionals. Furthermore, Reclamation's ongoing project work will demonstrate application and verification of HGS considering two case studies. The first case is a highly characterized small-scale field site (259 hectares) for evaluating a drainage-water re-use system referred to as Integrated on-Farm Drainage Management (IFDM) system, located at Red Rock Ranch on the western side of the San Joaquin Valley. This test site will allow us to take advantage of the extensive and detailed site characterization data set that is already available, and provide a valuable demonstration of the model's capability to handle the small-scale field, at which scientific representation of the flow and transport processes can be critical. Additionally, the results from this study will contribute to improved design and management of IFDM systems in the San Joaquin Basin and other parts of the arid Western United States. The second case study will focus on the San Joaquin River Basin or its sub-basin. This will be a watershed-scale study that will involve application of HGS and linked HGS-CalSim model for the combined analysis of water supply reliability, water quality, ecosystem health and impact of climate change on California's water resources.

MODEL ENHANCEMENT AND APPLICATION

HydroGeoSphere Background and Existing Capabilities

This ongoing work is directed towards providing a practical tool for multi-scale simulation of conjunctive surface/subsurface flow, solute and heat transport, and sedimentation in California's river basins and the Bay-Delta system, and elsewhere. Numerical models currently available to water resource managers do not consider processes of surface/subsurface hydrology, water quality and erosion/sedimentation together in a fully-integrated manner. HGS is among a relatively small class of physically based, spatially distributed (PBSD) models designed to address groundwater flow and surface water flow and their interactions. Other examples of such models include IGSM2 (Kadir et al., 2003), the SHE (Système Hydrologique Européen) model

(Abbot et al., 1986) and its decedents; SWRRB (Simulator for Water Resources in Rural Basins) (Arnold et al., 1991); THALES (Grayson et al., 1992); InHMS (vanderKwaak and Loague, 2001); MODHMS (Panday and Huyakorn, 2004); and Basin-Scale Hydrologic Model (Yu and Schwartz, 1998). The most important features that distinguish HGS from most of these other models is that the surface and subsurface water equations are solved in a fully integrated, rather than sequential (linked) manner, and that it has capability to handle solute transport processes. This in turn greatly improves the ability of the model to accurately simulate the complex physics of hydrologic systems that have strong interactions between the surface and subsurface hydrology, and articulates itself in the disappearance of mass balance problems and much greater computational efficiency. HGS itself is the result of more than a decade of research and development work at University of Waterloo, Laval University and HydroGeoLogic (Forsyth and Kropinski, 1997; Huyakorn et al., 1986; Sudicky, 1990; Sudicky and McLaren, 1992; Therrien and Sudicky, 2000).

HGS is a comprehensive conjunctive surface-subsurface modeling tool and represents a state-of-the-art in conjunctive hydrologic modeling. However, this simulator requires further enhancement to facilitate its application to the specific water resource and water quality problems that are most relevant to the integrated management of water resources, and pilot application to demonstrate and validate its applicability to complex hydrologic and water quality problems.

Enhancement of HydroGeoSphere

The ongoing enhancements of HGS include incorporation of modules related to snowmelt, temperature (heat) transport, dissolved oxygen (DO) and nutrient (N, P) transport and reactions, and sediment transport. Incorporation of snowmelt-runoff processes into HGS will expand its capabilities to encompass all major components of the hydrologic cycle, and in combination with CalSim-II provide a complete simulator that is driven by meteorological inputs. Moreover, snowmelt processes through their impact on water temperature are important in addressing ecological impacts. Implementation of snowmelt-runoff processes into HGS is relatively straightforward, since snow-melt water availability at the land surface can be calculated via independent snow-melt generation modules which can be invoked at each land-surface node at the beginning of a time-step to provide the source conditions. Multiple modules will be developed to represent both temperature-index models as well as energy- and mass-balance models. This will provide flexibility in modeling snow-melt in cases with both limited and more extensive data, and is consistent with the state-of-the art in snow-melt modeling, e.g., the NWSRFS (National Weather Service Snow Accumulation and Ablation System) model for flood-forecasting. The modules will include flexibility to allow for melt factors to be constant or functions of the antecedent temperature or time of year. Refreeze, compaction, new snow deposition, rain deposition, snowmelt, and release of liquid water will be considered as dominant processes governing liquid water available at the land surface which is available for runoff and infiltration. The end-result will enable more accurate predictions of runoff as compared to most existing snowmelt models which generally do not account for soil moisture storage.

Incorporation of the energy (heat) transport equation into HGS will greatly expand its capability to address temperature sensitive issues such as health of fish and other ecological indicators. The

energy balance equation will also be coupled with the snowmelt equations to account for the effect of snowmelt on water temperatures. Mathematically, the energy transport equation takes the same form as the contaminant transport equation which is already in HGS and has been thoroughly tested. The work involves modification of HGS to accommodate temperature as a variable of solution and incorporation of appropriate boundary conditions, such as accounting for heat exchange with the atmosphere, including absorption of solar radiation.

Dissolved oxygen and major nutrients such as nitrogen and phosphate are among the most important water quality characteristics. The transport equations that describe the physical transport and mixing of these components are already in HGS. The ongoing work is therefore focusing on incorporating reaction modules that account for the biochemical interactions between the components, including denitrification, fixation/sequestration due to biological growth, and associated oxygen depletion. In the case of phosphate which is strongly sorbed to soil particles, the transport module will account for movement of phosphate adsorbed to sediment particles and linked to the sediment transport module. A general biochemical reaction module will be developed that can account for either equilibrium or kinetic reactions, with temperature-dependent rate constants linked to the heat transport module to account for the effect of water temperature on reaction rates.

To complete the HGS enhancement, sediment transport routines will be added to the model. Sediment transport follows the contaminant transport mass balance equation in that sediments are transported via the mechanisms of advection and dispersion. The transport equations in HGS will need only slight modification to accommodate transport of sediments. The source/sink terms for sediments (erosion and deposition), however, are functions of the flow velocity, turbulence, particle size and type. These functions will be included in the surface water flow (2-D) and channel flow (1-D) domains of HGS to accommodate interactions with a wide variety of cohesive and non-cohesive sediments within and among the surface-water regimes. Kinetic or equilibrium adsorption of contaminants to sediments will also be incorporated to include effects of adsorbed chemicals on the suspended sediment load as a dominant transport mechanism for contaminants. This enhancement of HGS will allow for rigorous simulation of complex interactions of chemicals as they are transported within surface and subsurface regimes, interacting closely with losing and gaining stream conditions and with other contaminants and sediments within surface and subsurface regimes, as well as at the interface.

Linkage of HydroGeoSphere to CalSim-II

Linkage of HGS to CalSim-II will be undertaken by Reclamation. Methodology for linking HGS to CalSim-II will be developed. The general approach is to replace the 73 year historic sequence of flows (that currently represent the primary hydrologic input for CalSim-II) with HGS computed flows (based on meteorological data). CalSim-II will then provide reservoir releases and allocated water at predetermined points, determined by its optimization engine and a given set of operating rules and constraints, as input to HGS. All routing of water through the system will be undertaken by HGS. Thus, the hydrology and hydrodynamics of the flow domain will be completely evaluated by HGS and the hydrologic/hydraulic conditions required for the water allocation decision-making process will be passed on to CalSim-II for the purpose of allocating

water.

Evaluation of hydrology and hydrodynamics will be handled by HGS by solving appropriate differential equations. Hence the temporal variability of hydrologic and hydraulic conditions will be governed by the time steps applied in HGS. These hydrologic and hydraulic conditions will be passed on from HGS to CalSim-II and the water allocation will be performed by CalSim-II in the next time step. The water allocation at each predetermined node will be passed on to HGS for specification of appropriate boundary conditions required to solve the differential equations in HGS. The water allocation decisions made by CalSim-II do not require as fine of a temporal resolution as do the hydrodynamic processes simulated by HGS. Therefore, the CalSim-II simulation will in general utilize coarser time steps than the HGS simulation. During the time steps when CalSim-II is not run, the water allocation rates determined from the most recent CalSim-II time step will remain constant.

HGS will require future time series of rainfall and temperature for definition of boundary conditions (flux and evapotranspiration) for surface water. These time series may be evaluated by means of statistical or stochastic approaches. This will render the HGS/CalSim-II linkage valuable for evaluating impact of climate change on the California's water resources, and will enhance the current form of CalSim-II.

Application of HydroGeoSphere

Reclamation is evaluating existing data, collecting new data and developing conceptual models for application of HGS to the two case studies for IFDM system and San Joaquin River Basin. The IFDM system is a sustainable option for management of salt-laden agricultural drainage water and controlling of contamination of the San Joaquin River Basin and the Bay-Delta system.

The IFDM system at Red Rock Ranch includes approximately 219 hectares of salt-sensitive crops. The drainage water from salt-sensitive crops is used to irrigate about 24 hectares of salt-tolerant crops/trees and 6 hectares of salt-tolerant grasses. Two hectares of trees are used to intercept the subsurface flow of water and salts. A shared drainage system exists for the 2 hectares of halophytes and the less than 0.8-hectare solar evaporator.

HGS will be applied to evaluate flow and transport in the IFDM system, as well as capability of the system to control drainage water and salinity at the site. This work will facilitate a thorough understanding of the flow and transport processes, and lead to optimal design of new IFDM systems and evaluation of effectiveness of existing systems to control drainage water and salinity in the San Joaquin Valley.

The large-scale case study will involve demonstration of HGS application to San Joaquin River Basin or one of its sub-basins and verification of the model against field data. Federal and state agencies have been in partnership with stakeholders and local water/irrigation districts in dealing with water supply, quality and management, environmental mitigation and other water related issues for the San Joaquin River and its tributaries. The requirements that need to be addressed in this work include water quality, dissolved oxygen (DO) and water temperature issues in the lower

portion of the San Joaquin River and its tributaries. The water quality issue is compounded by the salts in agricultural and refuge return flows and agricultural drainage from the north-western portion of the San Joaquin Valley. In this study, we will demonstrate application of HGS to undertake a comprehensive simulation of flow and transport at a large scale. The model will be used to quantify non-point agricultural source impacts on surface and subsurface water quality; analyze conjunctive use in the basin and investigate the effects of water supply and usage on the ecosystem in the basin. We will also demonstrate linkage of GIS tools to HGS to facilitate evaluation of the impact of land use changes on water management practices on an ongoing basis. Results of this work are expected to contribute to a thorough understanding of the surface and subsurface flow and transport processes, leading to optimal environmental mitigation, conjunctive use and planning by federal and state agencies and stakeholders.

CONCLUSION

In water resource management, there is an increasing emphasis on problems that require conjunctive analyses of surface/subsurface hydrologic and water-quality processes. Major issues of concern to water managers include water supply reliability, water quality, ecosystem health, and impact of climate change on water resources. HydroGeoSphere (HGS) is undergoing enhancement to increase its capacity to handle conjunctive analyses in problems related to water supply reliability, water quality and ecosystem health. A dynamic linkage of HGS and CalSim-II will render CalSim-II valuable for evaluation of impact of climate change on California's water resources. Data evaluation and conceptual model construction are current underway for application of HGS and HGS-CalSim-II for small and large scale case studies. The results from these model applications will be the basis for verifying HGS and the linkage of HGS and CalSim-II. In the presentation, status of the ongoing work and modeling approach will be discussed. Results of this work will be presented in a future paper.

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