DISSERTATION

GEOSPATIAL DECISION SUPPORT SYSTEM FOR AMELIORATING ADVERSE IMPACTS OF IRRIGATED AGRICULTURE ON AQUATIC ECOSYSTEMS

Submitted by

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ABSTRACT

GEOSPATIAL DECISION SUPPORT SYSTEM FOR

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Although irrigation is key to the success of agriculture in much of the western United States, the associated water resource demands are often at odds with the needs of aquatic ecosystems. The storage and redistribution of natural water supplies that is required to meet agricultural demands often disturbs the natural streamflow regime that is key to the stream ecosystem. In many cases the conflicts between agricultural and ecological demands have led to increased regulatory restrictions on agricultural diversions to protect instream flows. While the results of such policies can help mitigate the most severe impacts of stream diversions, these regulations often result in agricultural shortfalls while achieving suboptimal environmental benefits.

The Russian River basin in northern coastal California is a prime example of a region that is facing the challenges created by the often-disparate needs of agricultural and environmental interests. As the primary agricultural activity in the basin, wine grape cultivation is the largest water user in the basin with spring frost protection and summer irrigation constituting the bulk of those demands. At the same time, the Russian River and its tributary system have been identified by the U.S. Fish & Wildlife Service as critical habitat for the endangered coho salmon and the threatened Chinook salmon and steelhead trout, which rely on the highly stochastic and seasonal natural streamflow patterns of the system to support their life cycles. To reduce

disruption of the natural streamflow regime and protect instream flows in the critical habitat, the California State Water Resources Control Board (SWRCB) has imposed a series of regulations that limit diversions. While a variety of studies in the Russian River basin have focused on the impacts of tributary diversions on instream flows as well as the effects of environmental regulations on streamflows and agricultural security, there is a lack of research that incorporates hydrometeorological modeling into such studies. To address this research gap and further study the effects of agricultural diversions and environmental regulations, a geospatial decision support system (geo-DSS) that combines a gridded hydrometeorological streamflow model (HL-RDHM) with a GIS-based river basin management model (GeoMODSIM) was developed and applied within the Russian River basin.

In a proof-of-concept implementation, the geo-DSS is first applied to a representative tributary in the Russian River basin that has been categorized as critical fisheries habitat and supports viticulture. The geo-DSS incorporates unimpaired flow estimates from the fine-scale (1/4 HRAP or approx. 1km) gridded HL-RDHM model with GeoMODSIM, which evaluates water management impacts and uses a one-day timestep. The resulting model implementation is used to evaluate current agricultural water management practices, the effects of environmental regulations, and agricultural water management alternatives in the basin. The geo-DSS was shown to accurately represent the impacts of short-term spring frost protection demands and the continuing impacts through the summer irrigation season on instream flows, which can be detrimental to the threatened and endangered (TES) fish species in the region. Additionally, the implementation of minimum bypass flow environmental protections was shown to severely limit agricultural water supply. Finally, model results indicate that through the use of improved agricultural water management practices, such as off-stream ponds, overall system supplies are adequate to meet agricultural demands while satisfying environmental instream flow restrictions.

In a second study, the geo-DSS was applied on a larger scale to the Feliz Creek tributary system in the upper Russian River basin to assess baseline conditions that included appropriated water rights, minimum bypass flow restrictions, existing agricultural pond storage, and agricultural demands. The baseline model framework was run with 100 sets of hydrologic forcing data to assess system performance across a variety of hydrologic conditions that ranged from dry to wet. Baseline results indicate that even with environmental restrictions in place, the cumulative impacts of upstream diversions can still be significant during low flow periods and agricultural supply shortfalls were common throughout the system. In subsequent scenarios agricultural management alternatives were evaluated to improve overall system performance. Results of these scenarios demonstrate that the addition of supplemental agricultural pond storage can significantly reduce agricultural supply shortages while making significant improvements to instream flow conditions. Additionally, the allowance of carryover storage from year to year, which is currently restricted in the basin, was shown to result in even more significant improvements. Finally, the model was used to identify the optimal location and size of supplemental storage within the basin. Overall, this type of tool is key to achieving the environmental instream flow goals in the Russian River basin while maintaining and enhancing the agricultural industry of the region.

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I would like to thank my advisor, Dr. John Labadie, for his support, patience, and guidance throughout the pursuit of my doctoral degree, without which this may have taken another 10 years.

I would like to thank my family and friends for continuing to believe me when I told you I was close to finishing, or at least making it seem like you did. This time I really am!

And lastly, a sincere thank you to Jic Nimbo for all the laughs along the way.

DEDICATION

For Diana and the kids –

as much yours as mine.

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CHAPTER 1 – INTRODUCTION

1.1 Background

In arid and semi-arid regions irrigation systems are necessary for the success of agriculture; however, these systems can have a variety of corresponding impacts to the related stream ecosystem. (Khan et al., 2006) On the regional scale, large reservoir and irrigation projects have been used to transform entire river basins, often making significant changes to the environmental regime of the basin, both directly and indirectly. (Patten, 1998; Wohl, 2018; Graf, 1999; Kingsford, 2000) By altering a river system from its natural, unimpaired flow regime to create a system that is focused on providing irrigated cropland with a timely supply of water, many of the characteristics of the stream system can be negatively impacted. For example, channelization of rivers provides a more efficient conveyance of water but often eliminates wetlands and increases stream velocities and sediment erosion, thereby negatively impacting fisheries habitat and generally reducing the size, number, and diversity of native fish species. (Schoof, 1980) Additionally, the construction and operation of dams for irrigation interrupts a river's natural disturbance regime, which incorporates the geographic variability and time-varying streamflow conditions that support the stream ecosystem. (Poff et al., 1997) This homogenization of river dynamics has been shown to have impacts on regional, continental, and even global scales. (Poff et al., 2007)

While irrigated agriculture relies on the redistribution of natural streamflows through the implementation of water storage and irrigation projects, stream ecosystems depend on predevelopment patterns in both the timing and magnitude of flows in order to thrive. In areas where the water supply is constrained and is insufficient to meet all demands, disparities in the timing and magnitude of necessary flows creates conflicts between these and other uses. However, through the efficient, integrated management of reservoirs and water distribution components, regional irrigation and water supply systems can be operated to best meet the needs of a multiplicity of water uses (Labadie 2004).

While large-scale projects are used to meet water supply demands on a regional scale, water users near tributary streams frequently rely on smaller projects to meet localized needs for flood control, water supply, and water treatment. (Potter, 2006; Tiessen et al., 2011) And while significant research focus has been given to the coordinated operations of dams, canals, and irrigation systems on mainstem rivers and large-scale irrigation projects, smaller tributary systems have been often neglected. However, Bottcher et al. (2013) clearly demonstrate "the use and potential importance of small tributaries and their fragile habitats to endangered fishes."

Agriculture in smaller upstream tributary systems generally relies on direct stream diversions to meet real-time irrigation demands. However, since irrigation is most-needed during drier periods when the instream supply can be reduced or is intermittent in nature, these diversions are often supplemented through the use of agricultural ponds. Like reservoirs in large irrigation projects, agricultural ponds are used to redistribute system flows and deliver agricultural water when needed. Although the individual impacts of tributary diversions for irrigation supply and pond filling are not as significant as those on the river basin scale, localized and cumulative environmental impacts at the tributary level can still be substantial. (Smakhtin, 2001; Spina et al., 2006; Pringle, 2000; Deitch et al., 2013) Also, while large-scale system impacts such as reservoir and canal construction can change the physical environment of a region, tributary-scale project impacts are generally related to the alteration of the streamflow regime such as reduced downstream supply, increased frequency of low-flow events, and the alteration and attenuation of natural streamflow patterns. (Smakhtin, 2001; Rolls et al., 2012)

In the western United States, the importance of having available water supplies to satisfy the often-competing demands of agriculture and aquatic ecosystems cannot be overstated due to the seasonally dry climate that is prevalent throughout the region (Schaible and Aillery 2017). As an example, the wine country of northern California presents a prime example of the challenges created by the disparate needs of agricultural and environmental concerns. Ecologically, many of the coastal river systems of the region support threatened and endangered anadromous fish species. In particular, the Russian River basin and its tributaries provide critical habitat for the endangered coho salmon as well as the threatened Chinook salmon and steelhead trout. The region can be generally categorized as Mediterranean, with a climate characterized by high seasonality in both temperature and precipitation, and which supports and informs the variable lifecycle needs of the fish species. (Bonada & Resh, 2013; Lytle & Poff, 2004)

While being ecologically important, the Russian River basin is also home to a thriving agricultural community that is primarily focused on the production of wine grapes. The cool wet winters and warm dry summers provide the ideal growing conditions for grapes; however, while requiring less water than other common crops in the region, viticulture still requires irrigation during the extremely dry summer growing season. (Smith et al., 2004; Deitch et al., 2009b) Additional irrigation demands occur in the form of frost and heat protection, which requires the application of large volumes of water over a short duration and can rapidly deplete streamflows in nearby waterways. (Deitch et al., 2009b; Johnson, 2015) And while the vineyards in the region are spatially distributed, the demands are often temporally coincident, especially in the case of frost protection. Further exacerbating the situation is that return flows from vineyard irrigation are minimal given the proliferation of drip irrigation in the region, which typically operate with irrigation efficiencies near 90%, thereby precluding any positive return flow impacts to streamflows that could be realized. (Johnson, 2015; Pritchard, 2010) As a result, the associated short-term abstractions from the overall stream system can be so severe as to cause fatal stranding events among the threatened and endangered fish species where streamflows are rapidly depleted and fish are unable to survive in the low streamflow conditions. (SWRCB, 1997; Deitch et al., 2009a; Johnson, 2015) Overall, the impact of the stranding events has been significant enough that in 2008 the National Marine Fisheries Service (NMFS) coordinated a multi-group study among a variety of government and non-governmental stakeholders to investigate strategies that would mitigate future potential stranding events. (Johnson, 2015)

Subsequent to the 2008 study, the California State Water Resources Control Board (SWRCB) approved a pair of regulations aimed at protecting fisheries habitat in the Russian River basin by maintaining minimum instream flows (SWRCB, 2010) and limiting frost protection diversions (SWRCB, 2011). Historically, water rights development in the western U.S. has focused on the full appropriation of streams and often considered water remaining in the stream for other purposes to have been wasted (Boyd 2003). However, beginning in the late 1960's instream flows have been increasingly recognized as a beneficial use for the support of fisheries and aquatic habitat (Reiser, et al. 1989), which allows owners of appropriated water rights to leave the associated waters in stream for the benefit of aquatic and riparian ecosystems without the risk of losing their water rights. The policies adopted by the SWRCB are unique in that they aim to protect instream flow rates without the use of an appropriated water right (SWRCB, 2010) and would restrict the diversion of water for frost protection even among existing water rights holders. (SWRCB, 2011)

1.2 Project Need

The resulting system of ecological and agricultural demands that are subject to increasingly restrictive administrative constraints within a hydrologic setting that is highly seasonal and stochastic in nature presents water managers in the region with a complex challenge. Accordingly, the tributary systems in the Russian River basin have been the focus of a variety of studies since the agricultural impacts within were highlighted by the NMFS group in 2008. Temperature and streamflow gage data have been analyzed to document the connection between frost protection and streamflow impacts (Deitch et al., 2009b) and the individual and cumulative impacts of diversions on smaller tributary streams have been assessed. (Deitch et al., 2009a) Additionally, a GIS-based model developed by Merenlender et al. (2008) that scales streamflow gage data to estimate tributary flows has been extensively used to evaluate water supply and demand throughout the basin (Merenlender et al., 2008); to assess the impacts of environmental policies and evaluate off-stream storage options (Grantham et al., 2010); to evaluate the cumulative impacts of small reservoir storage projects (Deitch et al., 2013) and; to assess the impacts of environmental regulations on streamflows and agricultural water security. (Grantham et al., 2014)

A significant shortcoming of previous research is its reliance upon scaled streamflow data as its primary data source. While the SWRCB Policy for Maintaining Instream Flows in Northern California Coastal Streams (SWRCB, 2010) allows the use of scaled streamflow data for determining the minimum bypass flowrate and the unimpaired flowrate, this approach incorporates inherent errors into the data and consequently propagates these errors into subsequent model results. For instance, the gaged data used for the scaled approach already represents regulated flows that have been impacted by upstream agricultural operations.

Furthermore, this approach relies on the identification of an analog watershed within the basin that shares similar characteristics of the watershed in question. Such characteristics may include geology, soil type, topography, vegetation, land use, and precipitation runoff processes, among others. Naturally, these characteristics can vary significantly from one watershed to another as well as varying spatially within the watershed itself. As a result, the use of scaled data from an analog watershed fails to capture the effects that these variations have on flow estimates and will lead to further model inaccuracies.

As an alternative, the SWRCB policy also suggests the use of a precipitation-based streamflow model for the estimation of unimpaired flows. While technically more complex than the scaled data method, the use of a precipitation-based model would eliminate many of the assumptions required with the first method that lead to inaccuracies. Furthermore, incorporating such a method into a research platform would not only reduce inaccuracies in the overall model but would provide a tool for streamflow estimation that is in keeping with SWRCB policy. A decision support system (DSS) that incorporates a precipitation-based streamflow estimation model would be a useful approach to filling the gap in previous research while providing local stakeholders with a tool for decision making.

1.3 Study Purpose

In general, a DSS is comprised of components for data management and system modeling in addition to a user interface that together support complex decision making and problem solving. (Shim et al, 2002) One implementation of the DSS is the geospatial decision support system (geo-DSS), which incorporates geospatially-referenced aspects into the various components of the DSS, often through the use of geographic information systems (GIS) tools. This study focuses on the development and application of a geo-DSS to tributary systems within the Russian River basin that incorporates a gridded hydrometeorological streamflow forecasting model with a geospatial water management model.

The Hydrology Laboratory Research Distributed Hydrologic Model (HL-RDHM) was developed by the Hydrology Laboratory of the National Weather Service and incorporates the model elements identified by SWRCB as essential for a precipitation-based streamflow model. (NWS, 2009) Driven primarily by precipitation and temperature forcing data, HL-RDHM is a gridded implementation of the Sacramento Soil Moisture Accounting model that is combined with a flow routing model to produce streamflow estimates at any location within the modeled basin and can be referenced and displayed within a GIS interface. GeoMODSIM, a GIS-based implementation of the MODSIM generalized river basin network flow model (Triana and Labadie, 2012) provides data management, system modeling, and user interface aspects to the geo-DSS. The GeoMODSIM model uses connected GIS feature classes within an ArcGIS geometric network to create a geo-referenced river basin model to which agricultural diversions and use, water rights, and policy-based restrictions are added. By coupling the spatially-referenced unimpaired streamflow estimates from the HL-RDHM model with the GeoMODSIM framework a more holistic representation of the basin is achieved.

As a final step in the development of the geo-DSS, the coupled HL-RDHM/GeoMODSIM model structure is applied to support the decision-making process and present solutions to complex management challenges. Initially the geo-DSS is applied to gain an understanding of the baseline conditions in the basin, which typically represent either unimpaired (pre-development) streamflow conditions or existing conditions. Building on the initial baseline results, a variety of scenarios can be modeled to provide information on a variety of management alternatives. Using the results of these modeled scenarios, the feasibility and impacts of management options can be assessed to support the decision-making process. In this study, the geo-DSS is used to evaluate system impacts of traditional management strategies in the Russian River basin as well as the subsequent impacts of environmental policies on agricultural use. Furthermore, the geo-DSS is used to analyze agricultural irrigation performance and streamflow impacts across a variety of hydrologic conditions, and to determine the optimal management strategies to balance agricultural and environmental needs in the basin.

The study results have been organized into two chapters. In Chapter 2 the development of the geo-DSS is described and demonstrated in a proof-of-concept implementation on a representative tributary within the Russian River basin that is identified as critical habitat for threatened and endangered species and supports vineyard agriculture. Geo-DSS results show the impacts that traditional agricultural practices have on instream flow rates as well as the positive impacts that improved management practices may provide. Finally, results in this study indicate that overall water supplies are sufficient to satisfy both agricultural and environmental needs in the system.

Chapter 3 presents a broader application of the geo-DSS to the Feliz Creek watershed, a tributary in the upper Russian River basin. One hundred sets of synthetic hydrologic forcing data are utilized to evaluate the overall system across a variety of hydrologic conditions. Baseline conditions are evaluated along with a series of management scenarios that focus on off-stream agricultural storage. Results indicate that environmental restrictions can have severe impacts on the availability of agricultural supply. However, through the use of off-stream agricultural storage, excess flows can be captured during the wet season and used to satisfy subsequent agricultural demands. Finally, the geo-DSS was also used to determine optimal supplemental storage volumes and locations throughout the Feliz Creek basin.

Following Chapter 3, a collection of appendices is included that documents other research efforts that were instrumental to the geo-DSS design and implementation but were not included in the publications.

CHAPTER 2 – GEOSPATIAL DSS FOR MAINTAINING AGRICULTURAL DIVERSIONS UNDER ENVIRONMENTAL FLOW REQUIREMENTS[1]

2.1 Chapter Abstract

Competing demands for scarce water supplies in irrigated alluvial valleys can lead to conflicts between disparate uses, resulting in increased risk of restrictions on agricultural diversions. A tool for understanding the impacts of irrigation diversions on natural stream systems at the tributary scale is needed to evaluate solutions that protect environmental flow requirements for endangered and threatened aquatic species while maintaining irrigation water security. A geospatially referenced decision support system (geo-DSS) coupling a fine scale (1/4 HRAP or 1km) gridded hydrometeorological model (HL-RDHM) with a GIS-based river basin management model (GeoMODSIM) is developed for irrigated stream-aquifer systems. In this proof-of-concept implementation, the geo-DSS is demonstrated on a representative tributary within the Russian River basin in the Northern Coastal region of California with extensive wine grape vineyard acreage for an average water year using a daily time step. Results indicate that commonly used management practices that rely on direct stream diversions and on-stream ponds for irrigation can have severe negative impacts on instream flow rates by impeding the migration of endangered Coho salmon and other species. Through the application of the geo-DSS, improved management practices such as use of off-stream agricultural ponds are able to meet irrigation demands while satisfying minimum environmental bypass flow restrictions, along with determination of ideal sizes and locations for supplemental off-stream storage.

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2.2 Introduction

The importance of available water supplies to satisfy the often-competing demands for agriculture and aquatic ecosystems cannot be overstated, particularly in much of the western U.S. where seasonally dry climates are prevalent (Schaible and Aillery 2017). Irrigated agriculture relies heavily on water storage and irrigation projects for the redistribution of natural system flows to satisfy the demands. At the same time, stream ecosystems depend on predevelopment patterns of both the timing and volume of flows in order to thrive, thereby representing a nonconsumptive demand for maintaining flows in rivers and streams, in contrast with diverting for agriculture and other off-stream consumptive uses. In areas where annual water supply is insufficient to fully satisfy both agricultural and environmental flow requirements within a stream ecosystem, disparities in the timing and quantity of the required flows creates conflicts between these and other uses.

Historically, adjudication and permitting of water rights in the western U.S. has encouraged full appropriation of streams and often considered water remaining in the stream for other purposes to have been wasted (Boyd 2003). Beginning in the late 1960's, however, instream flows have been recognized as a beneficial use for the support of fisheries and aquatic habitat (Reiser, et al. 1989), allowing owners of appropriated water rights to leave the associated waters in stream for the benefit of aquatic and riparian ecosystems without the risk of losing their water rights. Recently, however, policies have been put in place by the State of California Water Resources Control Board (SWRCB) for the purpose of protecting instream flows for ecological/environmental purposes, but without requiring an appropriated water right (SWRCB 2010). In the Russian River Basin of Northern Coastal California, the SWRCB has imposed new regulations that would restrict the diversion of water for grapevine frost protection in vineyards (SWRCB 2011).

Irrigation projects are essential to agriculture in the western U.S. and are often associated with large dams and streamflow diversions. Through the efficient, integrated management of reservoirs and water distribution components, these systems can be operated to best meet the needs of a multiplicity of water uses (Labadie 2004). Oad and Kullman (2006) developed a linear programming-based decision support system to document the potential for enhancing environmental flows by reducing agricultural and municipal and industrial (M&I) diversions through upgrading of water infrastructure and improved water management practices in the Middle Rio Grande region of New Mexico, but without damaging these important water use sectors. While these studies focus primarily on coordinated operations in main-stem rivers and major tributaries where sufficient on-stream storage capacity is available, smaller tributaries are often neglected. Bottcher et al. (2013) clearly demonstrate "the use and potential importance of small tributaries and their fragile habitats to endangered fishes."

Agriculture in smaller upstream tributaries generally consists of direct diversions for irrigation, the timing of which often coincides with drier seasons of the year. Consequently, these diversions are often supplemented with use of both on-stream and off-stream agricultural ponds to redistribute flows and deliver agricultural water when needed. While both options provide the benefit of water storage for use during periods of reduced streamflows, on-stream ponds in particular can negatively impact flows downstream of the diversion during pond filling (Cox et al. 2008). Off-stream ponds have the potential for more flexibility in operation and can utilize variable diversion rates during filling, thereby allowing irrigators to schedule diversions during times of greater supply while attempting to minimize the negative effects of those diversions on the stream ecology. For these reasons, off-stream ponds are viewed as a desirable alternative in the management of smaller tributary systems (Potter 2006).

The general impacts of irrigation diversions on instream flows are well understood and preferred management alternatives such as off-stream agricultural ponds have been identified. There remains, however, the need for hydrometeorological modeling tools for estimation of surface and subsurface flows resulting from spatially distributed rainfall events, while accounting for management decisions at temporal and spatial scales appropriate for the typical flow rates and patterns of tributary systems. Hydrometeorological modeling systems are capable of generating streamflow estimates based on spatially discretized quantitative precipitation information (QPI) providing input to gridded hydrologic models (GHM) for estimation of unregulated flows at discrete locations along a stream segment and evaluation of a complete spectrum of hydrologic scenarios (Johnson et al., 2015).

The California Department of Water Resources has developed a series of modeling platforms for water resource planning in the state. However, none are ideally suited for application in the Russian River basin at the tributary scale. The Water Resource Integrated Modeling System (WRIMS) (CADWR, 2019) is intended for evaluation of management strategies within large complex river basins, while the Integrated Water Flow Model (IWFM) (Dogrul and Kadir, 2019) is focused on regional-scale processes and management. As an alternative, tributary-scale studies have been conducted using alternative platforms. Grantham et al. (2014) evaluated tradeoffs between securing agricultural water supply and satisfying environmental flow requirements for a tributary of the Russian River located in Sonoma County, California. In contrast with use of spatially gridded hydrometeorological modeling approaches, as presented herein, this model directly applies streamflow gage data scaled by catchment area and precipitation measurements for developing flow estimates in stream segments throughout the watershed. A drawback of the direct use of streamflow gaged data is that these data represent regulated flows that include the impacts of agricultural diversions. The hydrometerological modeling approach employed herein differs in that streamflow and precipitation data are primarily used for calibration and verification of the gridded hydrometeorological models used for generating unimpaired or natural streamflow datasets.

Although there are hydrologic models that utilize gridded meteorological datasets, few provide spatially distributed runoff output on a gridded basis. For instance, the Precipitation-Runoff Modeling System, Version 4 (PRMS-IV) (Markstrom et al., 2015) and the Coupled Ground-Water and Surface-Water Flow Model (GSFLOW) (Markstrom et al., 2008) employ gridded precipitation input datasets to determine flow estimates for a single basin outlet point. Other models, such as the Soil and Water Assessment Tool (SWAT) (Neitsh et al., 2011), use the concept of hydrologic response units (HRUs) to model multiple points and sub-watersheds within a drainage basin. According to Glavan and Pintar (2012), however, "the main weakness of the (SWAT) model is a non-spatial representation of the HRU inside each subcatchment…this approach ignores flow routing between HRUs."

A coupled modeling structure that takes advantage of the unique capabilities of each component can result in a more accurate and complete description of the overall system. A typical modeling framework consists of a spatially distributed hydrologic model for estimating unimpaired or natural system surface and subsurface flows for input into a river basin water management model. In many cases, the coupled models form a decision support system (DSS) for evaluating the impacts of a multitude of management scenarios within the modeled basin. There is a general absence, however, of model applications that combine gridded hydrometeorological surface and groundwater flow models with a basin water management model to evaluate streamflow management decisions in irrigated alluvial valleys.

Presented herein is a proof-of-concept implementation of a hydrometeorological modeling system that generates spatially distributed surface and groundwater flows resulting from gridded precipitation fields for estimating unimpaired or unregulated flows for input into a geospatial water management model. The goal is to realistically account for the temporal and spatial impacts of water management decisions for irrigation diversions and pond operations throughout the stream system that require flow estimations that are not confined to the basin outlet only. This is required for evaluating various scenarios on the number and placement of new irrigation ponds anywhere in the basin. The coupled models comprise a geospatial decision support system (geo-DSS) for evaluating alternative management strategies in the development and application of effective solutions toward reconciliation of conflicts between the water diversion needs of irrigated agriculture and instream flow requirements for sustaining aquatic ecosystems. The geo-DSS can also be a useful tool for aiding irrigators in meeting permitting requirements for agricultural pond construction by accurately determining minimum bypass flow conditions at points of diversion.

2.3 HL-RDHM Geospatial Hydrometeorological Model

The Hydrology Laboratory of the National Weather Service has developed the National Weather Service Hydrology Laboratory Research Distributed Hydrologic Model (HL-RDHM) (NWS, 2009). HL-RDHM is based on the original Hydrology Laboratory Research Modeling System (HL-RMS), which was developed to combine features of both lumped and distributed models into a single hydrologic modeling system by implementing the Sacramento Soil Moisture Accounting (SAC-SMA) model on a gridded (1/4 HRAP (Hydrologic Rainfall Analysis Project) or approximately 1 km) basis (Koren et al. 2004). HL-RDHM as a gridded hydrologic model (GHM) uses temperature and precipitation as the primary input forcings, relying on the SAC-SMA model to generate surface and subsurface flow estimates (Figure 1). Johnson et al. (2015) describe the application of advanced multi-radar/multi-sensor systems to the Russian River Basin of Northern California for development of quantitative Geostationary Operational Environmental Satellite (GOES) precipitation index (GPI) fields coupled to HL-RDHM grids for evaluation of unregulated or unimpaired streamflows at any grid location in the basin.

HL-RDHM provides high resolution modeling of the spatial variability of rainfall, surface runoff, evapotranspiration, soil moisture, infiltration, groundwater interflow, and groundwater base flow to streams (NWS, 2009), and is the model of choice at several National Weather Service River Forecast Centers (RFCs) and Weather Forecast Offices (WFOs) for prediction of flood events. Furthermore, HL-RDHM has proven effective for forecasting flows in basins where extreme runoff events are prevalent and stream gaging data are sparse (Reed et al, 2007). Fares et al. (2014) assert that HL-RDHM is one of the most highly regarded distributed hydrologic models for producing flow predictions that fit well with streamflow measurements, with the added advantage of offering well-validated methods for deriving HL-RDHM model parameters from soil and land use data where there is lack of proximate streamflow gages.

As described in Johnson et al. (2016), an extensive calibration process was applied to hydrometeorological modeling in the Russian River basin using HL-RDHM, resulting in a model that is considered to be valid for both peak flow and low flow predictions. Eleven months of six-hour data from a series of seven tributary streamflow gage locations, exclusive of stations along the highly regulated mainstem Russian River, were used to calibrate HL-RDHM. The highly

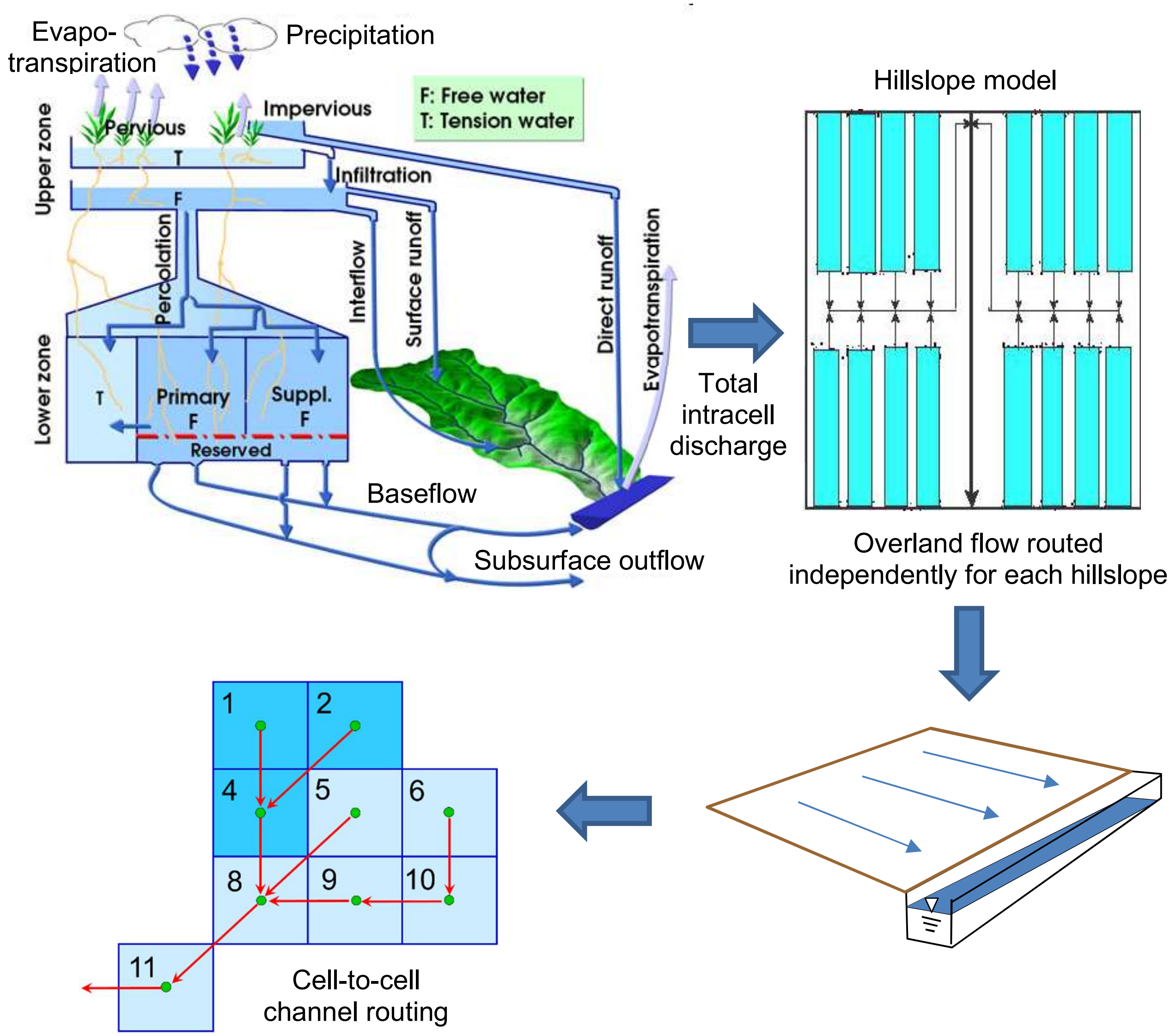

Figure 1. Schematic diagram of the Sacramento Soil Moisture Model and HL-RDHM Cell-to-Cell Routing Model (Clark, 2009)

variable short- and long-term streamflow rates prevalent throughout the region required separate calibration efforts for wet and dry periods and for each type of flow condition the dominant model parameters were identified and an explicit standardized approach was utilized to calibrate the 17 model parameters included in the SAC-SMA model. During dry periods, primary base flow components and basin response to precipitation events occurring under dry soil conditions dominate deep percolation rates and lower zone storage. During wet periods, the foremost model parameters are those governing surface runoff and interflow as well as upper zone storage parameters, interflow, percolation rates, and impervious area due to saturation.

The calibration process involved an iterative procedure focusing on maintaining both total water balance and matching measured peak flow discharge rates. A verification process using three subsequent months of data was performed with use of the Nash-Sutcliffe coefficient of efficiency (NSE), which represents how well the model predicts flows for all time steps (Nash and Sutcliffe, 1970). Calibration results for six of the seven gage locations had an average NSE of 0.75, where values exceeding 0.70 generally indicate good model performance. An independent verification was conducted for low flow conditions, which are of particular interest in the basin due to their impact on the life cycle of anadromous fish species, using a series of National Marine Fisheries Service (NMFS) low flow stream gages in Russian River tributaries that were not included in the calibration or verification process. Low flow model performance for these streams was considered satisfactory, with NSE values as high as 0.88 and average values of 0.82, indicating that a properly calibrated HD-RDHM model is capable of generating reasonably accurate unimpaired streamflow estimates for both peak flow and low flow conditions.

2.4 GeoMODSIM River Basin Management Model

2.4.1 Automated Construction of Georeferenced River Basin Networks

While HL-RDHM is effective for predicting unimpaired surface and subsurface inflows to a stream network as generated from gridded precipitation fields, it is incapable of modeling managed streamflows resulting from scheduling of irrigation diversions, as well as placement, sizing and operation of agricultural pond storage. For this purpose, HL-RDHM is coupled with GeoMODSIM, a GIS-based implementation of the MODSIM generalized river basin network flow model (Triana and Labadie, 2012). MODSIM, developed at Colorado State University (Labadie, 2012), is a license-free generalized river basin management software package that can be downloaded at http://modsim.engr.colostate.edu/ and has been extensively applied in the U.S. (e.g., Foti et al., 2014; Briand et al., 2008; Houk et al., 2007; Marques et al., 2006; and Flug and Campbell, 2005;), as well as many countries around the world (e.g., Berhe et al., 2013; Vaghefi et al., 2013; Shourian et al., 2008; Cheong et al., 2010; and de Azevedo, et al., 2000). GeoMODSIM is implemented as a custom extension in the ArcMap interface for Environmental Systems Research Institute, Inc. (ESRI) ArcGIS™ Desktop 10.x (ESRI, 2010), allowing geospatially referenced stream networks to be directly created in ArcMap from the USGS National Hydrography Dataset (Horizon Systems Corporation, 2014).

The custom ESRI GeoMODSIM Data Model is applied to developing georeferenced MODSIM networks in ArcGIS as generated by a geometric network constructed within the MODSIM feature dataset in a custom ESRI file geodatabase MODSIMNetwork.gdb. The geometric network MODSIM_Network_Net connects imported feature classes such as the NHD Plus v.2 stream and canal layers, reservoirs, gauging stations, diversion structures, agricultural and M&I demands, as well as ecological and environmental ecological and environmental flow requirements. Figure 2 displays the GeoMODSIM map overlays in ArcMap for a portion of the case study area of the upper Austin Creek tributary of the Russian River Basin of Northern California. GeoMODSIM allows full utilization of the available spatial data processing, display and hydrologic analysis tools available in ArcGIS in conjunction with the powerful MODSIM model functionality for integrated river basin management, with principle river basin features and infrastructure integrated into GeoMODSIM networks, including water rights and instream flow requirements.

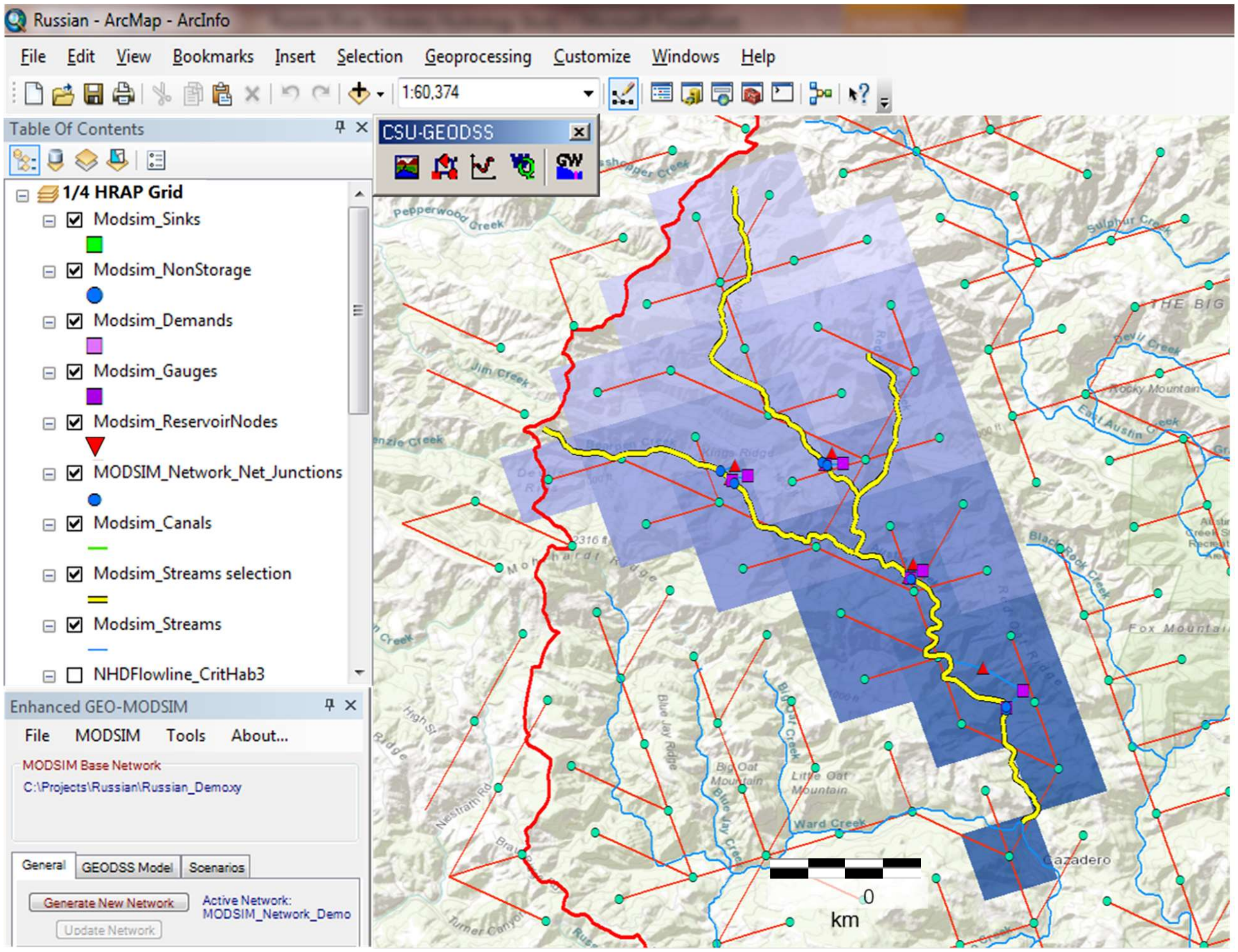

Figure 2. ArcMap display HL-RDHM grid cells and cell center connections overlain on GeoMODSIM network for upper Austin Creek in the Russian River Basin, California.

2.4.2 Coupling GeoMODSIM and HL-RDHM

A generalized approach to coupling the GeoMODSIM river basin network flow model with the HL-RDHM unimpaired flow network is to identify analogous points between the two networks by disaggregating HL-RDHM flow data at each time step for input into GeoMODSIM. To account for impacts of upstream management activities such as on-stream impoundments and diversions, flows at downstream nodes must be disaggregated into the various upstream components that are influenced by such activities. The various components of the total flow at a downstream node are abstracted to become inputs to GeoMODSIM at upstream nodes that correspond to locations of the management activities. The identification of analogous points in the two model networks is closely tied to the disaggregation process.

The confluence of two streams is an identifiable location in both models, allowing determination of corresponding geospatial relationships. Identification of locations in a stream reach lying between confluences is based on geographic proximity and use of the ArcMap interface. In some cases, the confluence of two stream reaches may be shifted to a node upstream or downstream of what would be a more geographically accurate location. Figure 3 provides an example of point correlation between the two models for the selected tributary of the Russian River which is utilized as the case study area for demonstrating application of the coupled models, as described subsequently. It can be seen by examining Pond 2 in Figure 3 in the GeoMODSIM stream network that the nearest HL-RDHM node on the main stream is 411971, but it also evident that node 411971 could represent a confluence. Since it would be inaccurate to include additional flows contributed from the other branch of the stream at the confluence, the next point upstream node (i.e., HL-RDHM node 411949) is used for Pond 2 input flow data.

2.4.3 Flow Routing and Disaggregation

Once the analogous points in the models have been identified, flow data from HL-RDHM are disaggregated for input into GeoMODSIM. Following the finite-difference approximation of the kinematic wave routing scheme as used by Koren et al (2004), the routing of flows from an upstream node to a downstream node for purposes of disaggregation is performed in HL-RDHM using Eq. 1:

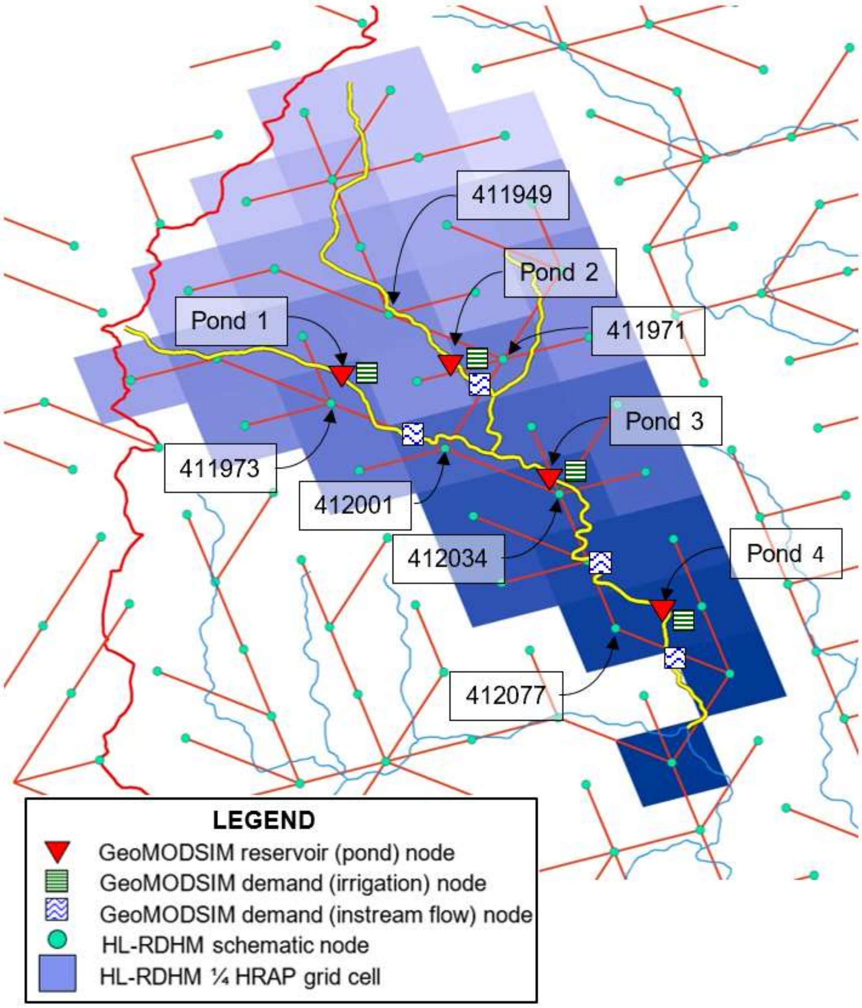

Figure 3. Coupled GeoMODSIM/HL-RDHM model for case study Russian River tributary showing HL-RDHM schematic node numbers and GeoMODSIM irrigation demand nodes associated with reservoir (pond) nodes 1, 2, 3 and 4.

$$Q_{i+1}^{j+1} = \frac{\frac{\Delta t}{\Delta x} Q_i^{j+1} + \left(\frac{1}{q_0}\right)^{\frac{1}{q_m}} \left(\frac{1}{q_m}\right) Q_{i+1}^{j} \left(\frac{Q_{i+1}^{j} + Q_i^{j+1}}{2}\right)^{\left(\frac{1}{q_m}-1\right)}}{\frac{\Delta t}{\Delta x} + \left(\frac{1}{q_0}\right)^{\frac{1}{q_m}} \left(\frac{1}{q_m}\right) \left(\frac{Q_{i+1}^{j} + Q_i^{j+1}}{2}\right)^{\left(\frac{1}{q_m}-1\right)}} \tag{1}$$

where Q_{i+1}^{j+1} = channel flow for node (j + 1) at time (i + 1); Δt = time step increment; Δx = distance between nodes j and j+1; q_0 = specific discharge; and q_m is an exponent parameter (NWS, 2009). As a reasonable approximation in most cases, HL-RDHM assumes that parameters q_0 and q_m are constant and determined from empirical relationships between discharge and channel cross-sections for each grid cell.

Application of the kinematic routing calculations of Eq. (1) requires that initial flows at time step i = 0 are given, but in fact are unknown. Three approaches were applied to estimating the initial flows at time step i = 0 by assuming different seed values for a preceding time step. Approach (a) assumes a seed value of 0 m^3/s; Approach (b) assumes a seed value equal to the subsequent model output for the pond, and; Approach (c) uses a linear extrapolation of model outputs for the pond from subsequent time steps to determine the seed value. Assuming that at least 10 previous time steps are required for convergence of the routed flows, calculations in Table 1(a) assume flows at previous time step i = -10 are 0 m^3/s, whereas in Table 1(b), the flow rate at time i = -10 is conjectured as 3.176 m^3/s which is the simulated HL-RDHM output for the pond, and is applied at the pond node as well as the downstream node. The final approach applies linear regression using flows at time steps i = -8 and i = -9 to extrapolate flows to time step i = -10, as shown in Table 1(c).

It can be seen in Table 1 that after 10 previous time steps, all three Approaches converge to the same estimated initial flows at time step i = 0 to three decimal place accuracy. This indicates that to in order to apply the disaggregation technique, HL-RDHM output data should include a sufficient amount of "spin-up" time prior to the period of interest, where the time span of the data set prior to the initial HL-RDHM simulation time step will vary with the downstream distance over which the flows are routed and disaggregated. By routing flows to downstream nodes, contributions of upstream nodes can be disaggregated from the HL-RDHM flow values at downstream input nodes, making it possible to account for management impacts on streamflows.

Table 1. Kinematic wave routing from node j (#411973) to node j+1 (#412973) using Eq. (1).

Time step i (hrs)	Approach (a)		Approach (b)		Approach (c)	
	Upstream flow at node j (m^3/s)[a]	Routed flow to node $j+1$ (m^3/s)[a]	Upstream flow at node j (m^3/s)[b]	Routed flow to node $j+1$ (m^3/s)[b]	Upstream flow at node j (m^3/s)[c]	Routed flow to node $j+1$ (m^3/s)[c]
-10	0.000	0.000	3.176	3.176	3.905	4.253
-9	3.176	1.934	3.176	3.176	3.176	3.544
-8	2.446	2.256	2.446	2.707	2.446	2.835
-7	1.650	1.879	1.650	2.043	1.650	2.089
-6	1.072	1.391	1.072	1.453	1.072	1.470
-5	0.698	0.986	0.698	1.011	0.698	1.017
-4	0.463	0.692	0.463	0.703	0.463	0.705
-3	0.316	0.490	0.316	0.494	0.316	0.495
-2	0.224	0.352	0.224	0.354	0.224	0.355
-1	0.166	0.260	0.166	0.261	0.166	0.261
0	0.128	0.197	0.128	0.197	0.128	0.197

Note: Kinematic wave routing from node j (#411973) to node $j+1$ (#412973) using Eq. (1):
[a] Initial flow rates at nodes j and $j+1$ for time step i = −10 set to 0 m^3/s.
[b] Initial flow rates at nodes j and $j+1$ for time step i = −10 set to flow at node #411973 for time i = −9.
[c] Linear extrapolation of flow rates at time steps i = -8 and -9 to time step i = −10.

In the network model shown in Figure 3, a portion of the unimpaired flow estimates from HL-RDHM for Pond 3 consist of flows from Ponds 1 and 2. Similarly, a portion of the unimpaired flow estimates from HL-RDHM for Pond 4 consist of flows from Ponds 1, 2, and 3. Therefore, it is necessary to disaggregate upstream flow components from the downstream input nodes, or ponds. The routing process continues downstream until an input node is reached, where in this case, the input nodes are each of the pond nodes, but could be any point of diversion or location of managed flow. Based on this process, routing Pond 1 flows downstream from HL-RDHM node 411973 to Pond 3 at node 412034) requires two disaggregation steps – first from HL-RDHM node 411973 to node 412001 and then again to node 412034. Likewise, routing Pond 2 flows downstream to Pond 3 requires three steps (i.e., from HL-RDHM node 411949 to node 411971 to node 412034). Finally, the routed flows are used to disaggregate Ponds 1 and 2 flows from the Pond 3 HL-RDHM model output.

2.5 Russian River Tributary Case Study

2.5.1 Viticulture Industry

The Russian River basin is located in the Sonoma and Mendocino Counties of Northern California, within which the case study tributary is selected for analyzing the relationship between agricultural diversions and the preservation of environmental instream flows (Figure 4).

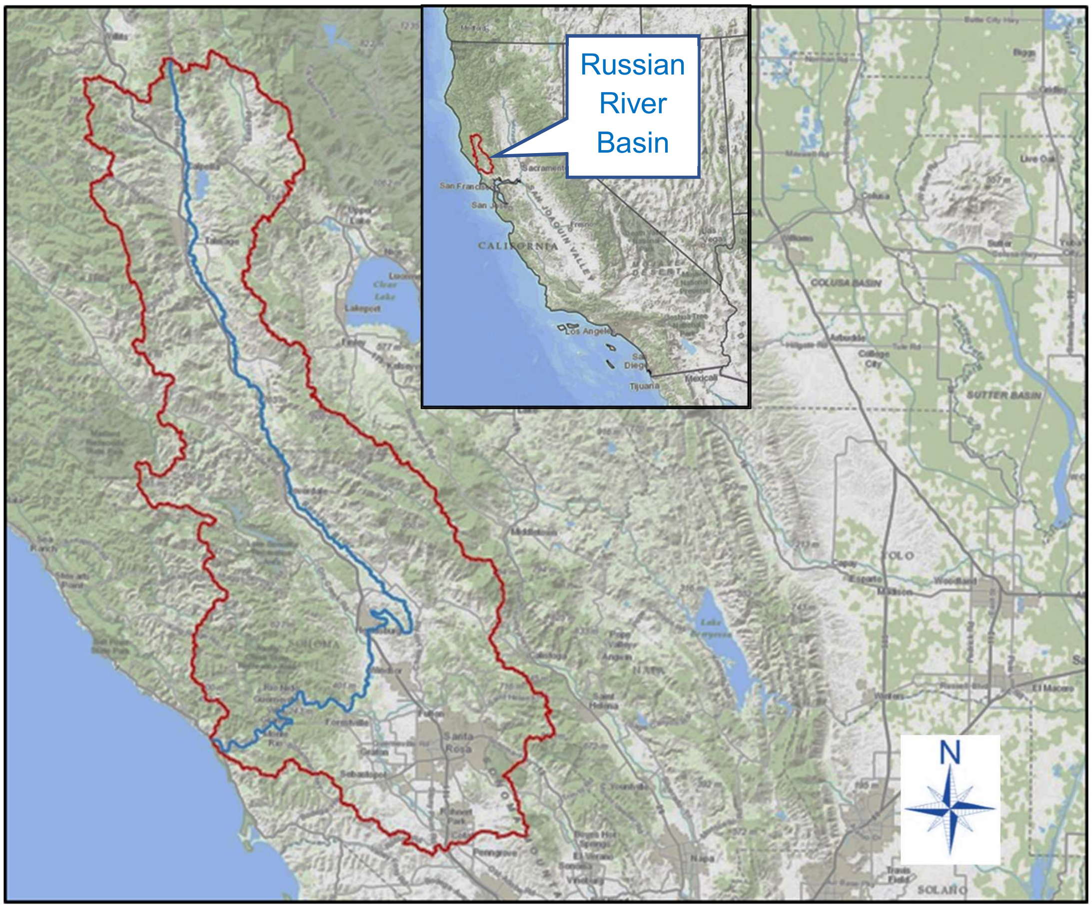

Figure 4. Location map for the Russian River Basin, Northern California

Recent trends in the Russian River basin include increased restrictions on agricultural diversions to enhance environmental flows for threatened and endangered fish species. Although legal proceedings surrounding these restrictions are ongoing, it is generally recognized by stakeholders in the region that there is a need for better understanding of the effects of agricultural activities on flows in salmon-bearing tributary streams. Agriculture in the Russian

River basin is dominated by viticulture, where, according to U.S. Department of Agriculture (USDA) data on land use, more than 25,100 ha (62,000 ac) of wine grapes were in production in 2013, accounting for approximately 6.5% of the basin area and 95.5% of all crops planted in the basin. While the soil and climate of the region is ideal for grape vine cultivation, irrigation is required to maximize the economic productivity of the crop (Smith et al. 2010). In general, irrigation in the basin is dominated by drip irrigation practices, which typically operate with irrigation efficiencies near 90%, thereby precluding any positive return flow impacts to the associated stream system. (Johnson, 2015; Pritchard, 2010)

The hydrometeorology of the Russian River basin is generally separated into distinct wet and dry seasons, where most of the precipitation occurring during the wet season (November to April) is driven by atmospheric river (AR) phenomena (Dettinger et al. 2011). Since the growing season generally coincides with the dry season (May-October), discrepancies in the timing of water supply and demand for irrigation water can have significant impacts on the tributary system. Direct diversions from tributaries and pumping from hydraulically connected aquifers for irrigation create immediate abstractions from the system during low flow periods, and the use of small on-stream agricultural ponds to store water during the wet season for use during the dry season can alter the natural flow patterns in the basin.

The impacts of irrigated agriculture on tributaries of the Russian River are not limited to summer growing season irrigation practices. Early in the growing season, after grapevine bud breaks have occurred, there is a risk of occurrence of damaging frost events. Vineyard growers utilize high rates of spray irrigation prior to the occurrence of forecasted hard frost events to form a protective layer of ice on the developing grapevine buds and canes. These intense rates of over-vine spray irrigation for short periods of time can significantly reduce flows in a stream segment.

2.5.2 Environmental Flow Requirements

In addition to supporting the economically significant wine industry in the region, the Russian River basin is also home to several threatened and endangered anadromous fish species. Currently, coho salmon are classified as endangered while Chinook salmon and steelhead trout are classified as threatened. In terms of water resources management, fishery demand is considered a non-consumptive demand within a stream system. For the anadromous fish in the Russian River, demand is quantified by the streamflow rate and varies in time according to natural or unimpaired streamflow conditions in the basin (SWRCB, 2010).

Dependence of endangered and threatened fish species on unimpaired streamflows serves multiple purposes. Under unimpaired flow conditions, sufficient flows early in the wet season signal the fish to begin their upstream migration, which also allows for passage of larger fish into the tributary system where coho salmon and steelhead trout prefer to spawn (NMFS, 2012). In contrast, reduced flows during the dry season support the early life stages when juveniles develop and emigrate downstream toward larger pools and streams (CDFG, 2004). In order to maintain instream flows for the protection of fishery resources, particularly threatened and endangered anadromous salmonids, the SWRCB has adopted new policies for appropriations in Northern California coastal streams, registrations for small domestic use and livestock stock ponds, and water right petitions. Additionally, further restrictions on diversions and groundwater pumping for purposes of frost protection were approved, including a policy of minimum bypass flows, which are instantaneous instream flow rates that must be satisfied at a point of diversion before water may be diverted (SWRCB, 2011). The policy prevents water diversions during periods when streamflow rates are at or below flow levels needed for spawning, rearing, and passage, including streamflow rates that naturally fall below the required minimum bypass flow rates (SWRCB, 2011).

2.5.3 GeoMODSIM Model of Upper Austin Creek

An upper portion of the Austin Creek tributary to the Russian River was selected for demonstrating the capabilities of the coupled GeoMODSIM/HL-RDHM models in evaluating strategies for accommodating both agricultural and environmental flow demands. Agricultural demands were quantified based on available USDA land cover data for vineyards within the drainage basins of the tributary system, which totaled 32.1 ha (79.4 ac). This total area was lumped into the four demand nodes located next to the four Ponds shown in Figure 3. Two types of agricultural water demands were developed for each demand node within GeoMODSIM: spring frost protection and summer irrigation demands. Using the vineyard cultivation area associated with each of the modeled demands, total water application rates were estimated based on average irrigation and frost protection demands within the basin.

Full irrigation of wine grapes in the Northern Coastal region of California requires approximately 39.6 cm (15.6 in) of irrigation per year (Pritchard, 2010). Assuming the irrigation season extends from May 1 to September 30 of any year, the average application rate is 0.3 L/s/ha (0.0043 cfs/ac). For each of the four demand nodes (i.e., vineyard enterprises) in the GeoMODSIM network, the average demand per unit area was multiplied by the total vineyard area to determine the irrigation demands (Table 2).

Frost protection demands within the basin are more erratic than irrigation demands, with the high-volume nature of the demands capable of causing rapid reductions in streamflow, which may lead to fish stranding events that are central to the continuing conflict between agricultural

Table 2. Estimated agricultural demands for irrigation and frost protection

Demand node	Total vineyard area (ha)	Total irrigation demand (m^3/d)	Frost protection demand per frost event (m^3)
1	3.4	88.8	571.1
2	2.9	74.0	477.4
3	11.6	301.0	1928.0
4	14.2	367.6	2358.4

and environmental concerns in the basin. While the demands can vary based on local conditions and duration, frost protection requires approximately 166 m^3/ha (2,272 ft^3/ac) of water for each frost protection event (Deitch et al. 2009). The timing of frost demands is also highly variable, and while there are typically four to six frost events per year, the number can be as high as twenty and as low as zero (Hines et al, 2009). To simulate demands for the prototype model, temperature data for the City of Santa Rosa were used to estimate the timing of frost protection demands in the basin. For the modeled period (2012 water year), five frost events were recorded in March and April, the months when grape buds are typically at risk for frost damage. Demands at each node are calculated by multiplying the frost protection application rate for a typical frost event by the total number of hectares of vineyard represented by the demand node (Table 2).

In order to focus on impacts that on-stream ponds may have on instream flow rates, agricultural ponds were modeled for three of the four demands, with the fourth demand used to demonstrate the influence of direct diversions for irrigation and frost protection on streamflows. Pond sizes of 6 x 10^3 m^3 (5 ac-ft) to 12 x 10^3 m^3 (10 ac-ft) were assumed, which is typical of the study area, and modeled based on the fill-and-spill mode of operations.

2.6 Management Scenario Results

Four management scenarios were evaluated to assess various conditions throughout the modeled stream system and demonstrate the capabilities of the geo-DSS – Scenario 1 represents existing conditions; Scenario 2 examines the effects of instream flow regulations on existing conditions; Scenario 3 evaluates off-stream ponds as a management alternative, and; Scenario 4 includes optimized off-stream pond sizes. The base GeoMODSIM streamflow management model included four agricultural demand nodes and associated stream diversions. On-stream ponds, instream flow demand nodes, and off-stream ponds are added to this base model as per the specific scenario descriptions that follow.

2.6.1 Scenario 1: Existing Conditions

This scenario is based on the assumed on-stream Ponds 1, 2, and 3 as being proximate to the three upstream vineyard enterprises, with the farthest downstream vineyard receiving direct diversions from the stream. The nonconsumptive instream flow demand nodes for maintaining minimum bypass flows, as shown in Fig 4, are assigned a low priority for this scenario, as compared with the agricultural demands, which results in minimum bypass flow requirements not being enforced. Typical agricultural demands for irrigation and frost protection are given in Table 2, with the ponds assumed to be drained at the beginning of the water year (Oct. 1 to Sep. 30), which is a common strategy for facilitating control of invasive bullfrog populations (Martz, 2014). Without imposition of minimum bypass flow requirements, Figure 5(a) shows that streamflows are sufficient to satisfy all agricultural demands. Additionally, this scenario demonstrates the general operation of fill-and-spill ponds where, although abstractions are made during frost events, the ponds refill shortly thereafter and remain full throughout the irrigation season.

During initial filling of the ponds under this scenario, as well as during frost events, streamflows downstream of the on-stream ponds are significantly impacted, as shown in Figure 5(b). Flowrates downstream of the agricultural diversions are reduced to levels below the minimum estimated summer unimpaired flowrate for a total of 269 days, including 45 days of zero flows where non-zero unimpaired flows had previously occurred. Additionally, flows downstream of Node 4 are similarly impacted, despite the absence of an on-stream pond. As seen in Figure 5(b), pond filling upstream of Node 4 beginning Dec. 1 reduces flows at Node 4 significantly, demonstrating the cumulative effects that multiple upstream diversions can have on downstream reaches.

2.6.2 Scenario 2 – Instream Flow Regulations

The streamflow impacts modeled in Scenario 1 are indicative of an important factor in the adoption of environmental flow protections. The potential for fish stranding events associated with significant short-term reductions in streamflow has led agencies such as the SWRCB to impose limits on streamflow diversions below a minimum bypass flow (SWRCB 2010). In the Russian River Basin, the minimum bypass flow requirement is determined based on upstream drainage area, and again, represents the streamflow rate below which no diversions are allowed. For diversion locations with upstream areas ranging between 2.6 and 830 km^2 (321 mi^2), minimum bypass flows are determined using the following empirical formula:

$$Q_{MBF} = 8.8 Q_m \left(2.6 DA\right)^{-0.47} \qquad (2)$$

where Q_{MBF} = minimum bypass flow (10^3 m^3/s); Q_m = mean annual unimpaired flow (10^3 m^3/s); and DA = upstream drainage area (km^2), with the calculated minimum bypass flows at each node location given in Table 3.

The GeoMODSIM model for Scenario 1 is modified for Scenario 2 to include nonconsumptive instream flow demands downstream of each diversion with priorities exceeding all agricultural diversions. Although inflexible fill-and-spill type operations are typical of

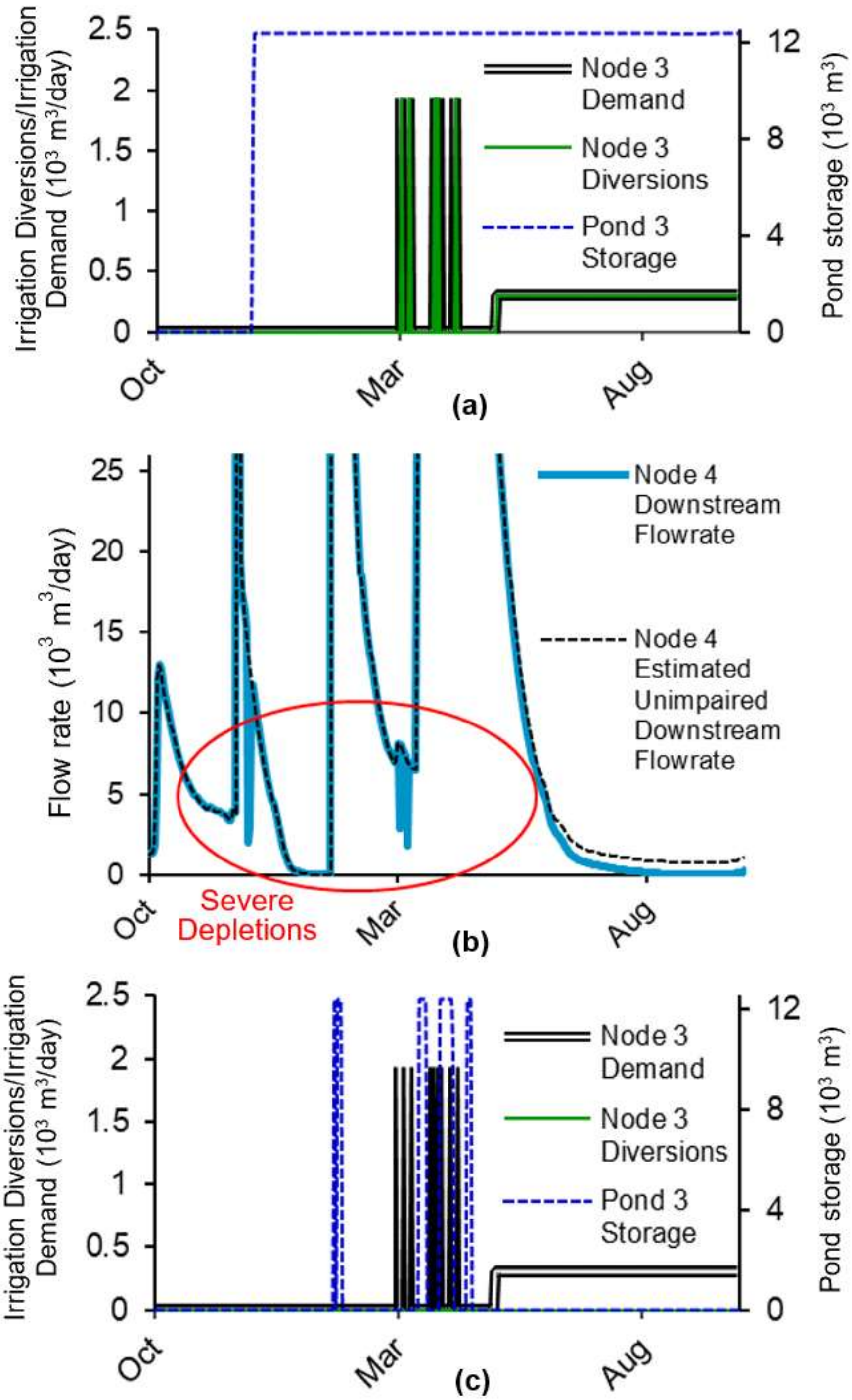

Figure 5. (a) Scenario 1: Node 3 (see Figure 3) diversions and on-stream ponds for existing conditions with no minimum bypass flows; (b) Scenario 1: downstream Node 4 (see Figure 3) impaired vs. unimpaired flows with on-stream ponds and no minimum bypass flows; (c) Scenario 2: Node 3 diversions with on-stream ponds and minimum bypass flow requirements.

Table 3. Minimum bypass flows determined according to the SWRCB policy for maintaining instream flows (SWRCB, 2010).

Demand Node	Upstream Drainage area (km^2)	Mean annual HL-RDHM modeled unimpaired flows (10^3 m^3/d)	Minimum bypass flows (10^3 m^3/d)
1	3.7	2.7	20.5
2	13.5	7.2	29.3
3	27.9	18.7	54.0
4	35.4	23.9	55.4

on-stream ponds, it is assumed that when the ponds initially fill during peak flow events, the storage must be released to satisfy the higher priority minimum bypass flow requirement downstream once the instream flow rate falls below the minimum instream flow rate. This essentially prevents agricultural users from making use of the on-stream ponds for irrigation diversions since the ponds must be full for spills to occur. As intended, the minimum bypass flow requirements serve to mitigate the negative environmental flow impacts of the diversions, but at the expense of preventing satisfaction of the agricultural demands.

Operationally, the impacts of minimum bypass flow restrictions in the model are reflected in Figure 5(c), showing the pond filling during peak flow events but emptying soon after due to the limited operational flexibility of fill-and-spill on-stream ponds. Downstream of Node 4, the minimum bypass flow limits alleviate the streamflow impacts that were evident in Scenario 1. A figure comparing unimpaired flows with impaired flows for this scenario is unnecessary since the hydrographs are exactly the same for low-flow conditions, where minimum bypass flow requirements prevent diversions for agriculture.

2.6.3 Scenario 3 – Instream Flow Regulations with Off-Stream Ponds

As detailed previously, off-stream ponds are a preferred alternative being considered for streamflow management and mitigation of the impacts of environmental flow restrictions on agriculture in the Russian River basin. An off-stream pond configuration allows for diversions to occur only when streamflow rates are greater than the minimum bypass flow limits but will allow for storage of those flows even when flow rates naturally fall below those levels. To accommodate the revised configuration, the GeoMODSIM model was modified by replacing the on-stream ponds at Nodes 1, 2, and 3 with off-stream ponds as well as adding an off-stream pond at Node 4 (see Figure 3). Initially, all pond sizes were unchanged from the previous scenarios to evaluate impacts of the use of off-stream pond operations. At Node 4, pond volume was initially set to zero to match existing conditions from Scenarios 1 and 2.

The initial results from Scenario 3 indicate that incorporation of off-stream ponds for agricultural use can have significant positive impacts on agricultural diversions in the context of increased environmental requirements for instream flows. As apparent in Figure 6(a), the off-stream ponds have the flexibility to fill during peak flow periods and provide a supplementary water source for agricultural demands later in the year. Diversions for pond filling only occur when the minimum bypass flows are satisfied, thereby minimizing low-flow impacts while maintaining the natural variability in the flow patterns.

When compared to the results from Scenario 2, the results of Scenario 3 show that off-stream ponds improve in agricultural diversion performance can be achieved despite the presence of environmental flow restrictions. However, it is also evident in Figure 6(a) that the previous storage volume of the ponds is insufficient to supply the total required irrigation needs at each node. After initially filling, the pond volume is significantly depleted during each frost protection event and is ultimately emptied early in the summer irrigation season.

2.6.4 Scenario 4 – Instream Flow Regulations with Optimized Off-Stream Ponds

Based on the results of Scenario 3, an iterative process was utilized in Scenario 4 to determine the necessary pond sizes that would be sufficient to supply the agricultural needs at each node in the system. The initial pond sizes of 6 x 103m^3 (5 ac-ft) to 12 x 10^3 m^3 (10 ac-ft) for Nodes 1, 2 and 3 were increased incrementally until shortages in the system were eliminated. Final pond sizes range from 15 x 10^3 m^3 (12 ac-ft) and 14 x 10^3 m^3 (11 ac-ft) for Ponds 1 and 2, respectively, to 49 x 10^3 m^3 (40 ac-ft) for Pond 3. The optimal Node 4 pond size was 62 x 10^3 m^3 (50 ac-ft).

Scenario 4 represents an optimized system capable of satisfying agricultural demands (Figure 6(b)) while sustaining minimum streamflow rates and maintaining the natural streamflow patterns that are a critical component of a healthy fisheries habitat (Figure 6(c)). Figs. 6(b) and 6(c) demonstrate typical pond performance in the optimized scenario with pond filling occurring during the first significant streamflow event after December 1st, with subsequent use of pond storage for frost protection and summer irrigation. As shown in Figure 6(b), and as is typical in the operation of off-stream ponds, there is some retention of water at the end of the irrigation season.

2.7 Summary and Conclusions

These results demonstrate the value of a geo-DSS based on a coupled modeling structure that more accurately and completely describes a tributary stream system that supports disparate consumptive irrigation demands, along with nonconsumptive environmental flow requirements. The distributed hydrologic surface flow model HL-RDHM provides unimpaired streamflow estimations at a fine scale (approx. 1 km) throughout the basin, while the GeoMODSIM streamflow management model considers the effects of stream management decisions on the

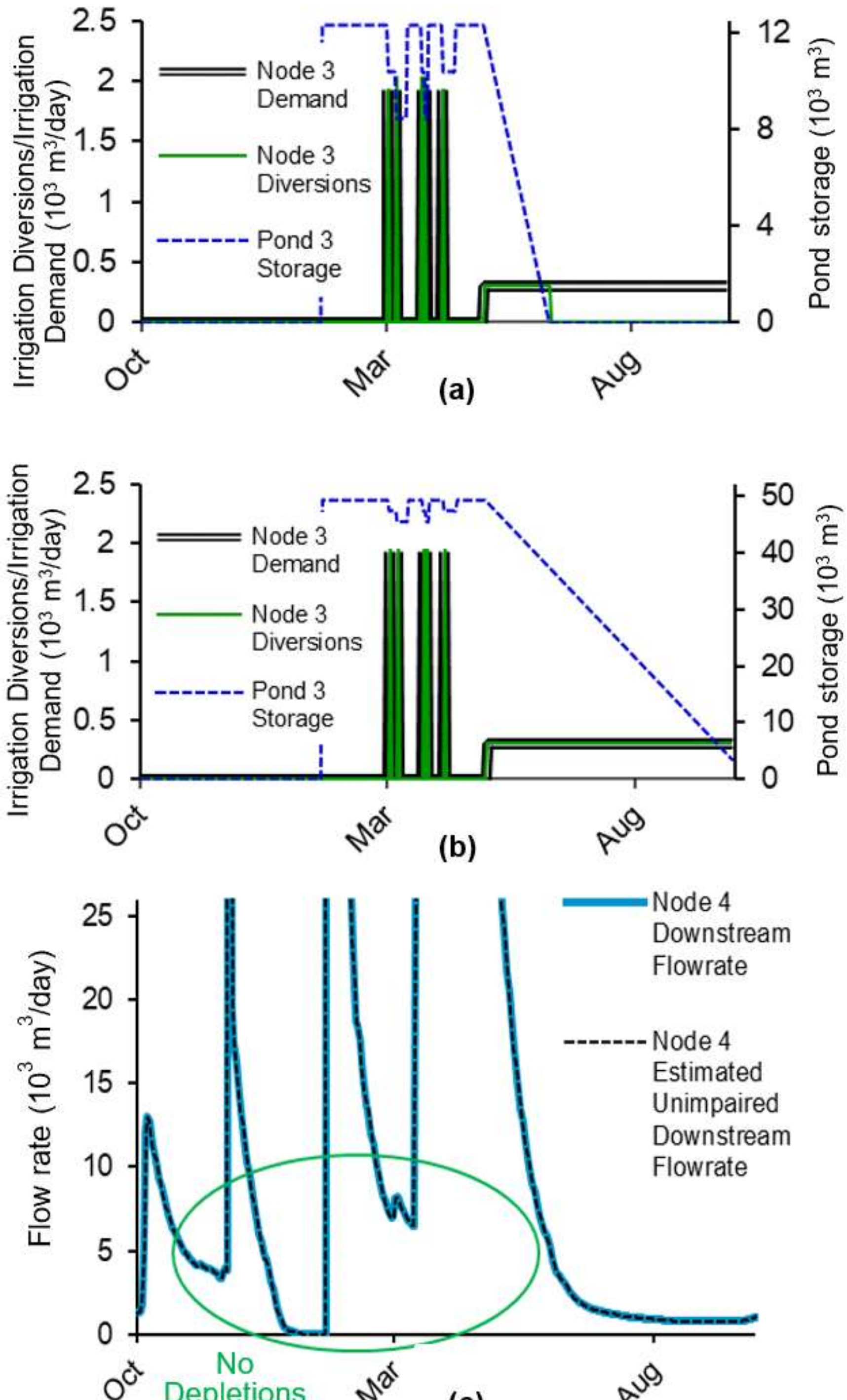

Figure 6. (a) Scenario 3: Node 3 (see Figure 3) diversions and off-stream pond storage with minimum bypass flows; (b) Scenario 4: Node 3 diversions and optimized off-stream pond storage with minimum bypass flows; (c) Scenario 4: downstream Node 4 (see Figure 3) impaired vs. unimpaired flows with optimized off-stream pond storage and minimum bypass flows.

natural flow regime. In the first scenario, the model describes the impacts of common agricultural practices on a natural stream system. The results of the model indicate significant streamflow impacts during periods of pond filling as well as diversions for agricultural demands, which is consistent with observed impacts on tributaries in the Russian River basin. However, by presenting the geo-DSS as an unbiased simulation of the stream system, it may be possible to develop additional support by local stakeholders for impact mitigation projects. Furthermore, an additional application of the HL-RDHM model is to provide estimates for unimpaired streamflows at ungaged tributary locations. Since many flow regulations are based on unimpaired streamflow estimates at the point of diversion, the model can provide the basis for minimum bypass flow rate calculations, which would be a valuable resource for appropriated agricultural water rights applicants.

In addition to demonstrating the impacts that stream diversions can have on the natural system, the geo-DSS is capable of illustrating the effect that environmental flow regulations can have on an existing agricultural system. The results of Scenario 2 indicate that the application of minimum bypass flow requirements on an existing system with primarily on-stream pond storage can significantly influence the ability to maintain agricultural diversions. While effectively eliminating the significant streamflow depletions evident in Scenario 1, these regulations, along with simplistic fill-and-spill operations for on-stream ponds, leave agricultural needs unsatisfied, as shown in Scenario 2.

The results of simulating the impacts of Scenario 3 in the geo-DSS show that simply replacing on-stream ponds with off-stream ponds of similar size can provide some benefit to irrigated agriculture while ensuring protection of fisheries habitat. While the smaller pond sizes are sufficient when utilizing an on-stream pond approach, they prove insufficient for agricultural supply when an off-stream pond configuration is used. For Scenario 3, which assumes the proposed off-stream ponds are of similar capacity to the on-stream ponds they are replacing, diversions for augmenting pond storage during the summer irrigation season would not be allowed since minimum bypass flow requirements would be violated due to low streamflow rates during the dry season and the insufficient capacity of the off-stream ponds.

Scenario 4 demonstrates the capability of the geo-DSS to perform iterative processes for determining the minimum off-stream pond capacities required for satisfying the summer irrigation demands utilizing the powerful spatial analysis tools available in the geo-DSS for informing pond siting and sizing decisions. Overall, it has been demonstrated through use of the geo-DSS that for this tributary system there is a sufficient water supply to meet both environmental and agricultural needs during a typical water year using appropriate management practices.

Tools that can be used to evaluate the various aspects of complex tributary hydrologic systems are essential for development of holistic solutions that are satisfactory to all stakeholders. The geo-DSS coupled model structure presented herein is capable of evaluating tributary systems at appropriate spatial and temporal scales that can consider a variety of scenarios including unimpaired conditions, the impacts of agricultural use and environmental restrictions, and future management alternatives. As applied to an example tributary stream system in the Russian River basin in Northern California, the model documents the harmful impacts of on-stream agricultural ponds and frost protection demands on instream flow rates and patterns, while also validating the potential for utilization of off-stream agricultural ponds for satisfying both agricultural needs and environmental flow requirements.

CHAPTER 3 – GEOSPATIAL DECISION SUPPORT SYSTEM FOR EVALUATING AGRICULTURAL SURFACE WATER MANAGEMENT STRATEGIES AND INSTREAM FLOW BENEFITS IN A TRIBUTARY SYSTEM[2]

3.1 Chapter Abstract

Tributary systems provide important ecological and agricultural benefits. However, agricultural water use near tributaries can have substantial negative impacts on critical ecosystems, and regulatory trends in many regions point to increased restrictions on agricultural flow diversions, which may lead to agricultural shortfalls while achieving suboptimal environmental benefits. A geospatial decision support system (geo-DSS) that combines a gridded hydrometeorological flow estimation model (HL-RDHM) with a GIS-based river basin management model (GeoMODSIM) is applied to the Feliz Creek basin, which is tributary to the Russian River in northern coastal California, to consider the impacts of agricultural water use and instream flow regulations, and to evaluate water management alternatives including supplemental agricultural storage and year-to-year carryover storage. The geo-DSS is applied on spatial (~1km grid) and temporal (one-day) scales that are ecologically relevant and accurately portray agricultural operations and water rights priorities. The geo-DSS utilizes one hundred sets of hydrologic forcing data that vary from dry to wet conditions to assess baseline conditions and to evaluate management alternatives. Baseline model results show that even with minimum bypass flow restrictions in place for instream flow protection, the cumulative effects of upstream diversions can still be significant during low flow periods. At the same time, the restrictions create significant agricultural irrigation supply shortfalls throughout the system. With the

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addition of carryover and supplemental storage, the number of agricultural shortages is reduced by 41 percent and the volumetric shortage is reduced by 48 percent. Single day improvements to instream flow rates average 39 percent by adding supplemental storage and average more than 100 percent when carryover storage is also included. Finally, supplemental storage locations are identified, and optimal volumes are more than double existing storage volumes. This type of tool is key to achieving environmental instream flow goals while enhancing the agricultural industry of the region.

3.2 Introduction

Agriculture in arid and semi-arid regions relies on irrigation to succeed, with varying corresponding impacts to the related stream ecosystem. (Khan et al., 2006) Large-scale reservoir and irrigation projects have been used to transform entire river basins, often making significant changes to the environmental regime of the basin, both directly and indirectly. (Patten, 1998; Wohl, 2018; Graf, 1999; Kingsford, 2000) By engineering a river system that is focused on providing irrigated cropland with the necessary water supply at the appropriate time, many of the characteristics of a natural stream system are negatively impacted. For example, channelization of rivers provides a more efficient conveyance of water but often eliminates wetlands and increases stream velocities and sediment erosion, thereby negatively impacting fisheries habitat and generally reducing the size, number, and diversity of native fish species. (Schoof, 1980) Additionally, the construction and operation of dams for irrigation interrupts a river's natural disturbance regime, which incorporates the geographic variability and time-varying streamflow conditions that support the stream ecosystem. (Poff et al., 1997) This homogenization of river dynamics has been shown to have impacts on regional, continental, and even global scales. (Poff et al., 2007)

As an alternative to large-scale projects that are used to meet water supply demands on a regional scale, water users near tributary streams frequently rely on smaller projects to meet localized needs for flood control, water supply, and water treatment. (Potter, 2006; Tiessen et al., 2011) While the effects of a single smaller project generally are not as significant on the river basin scale, localized and cumulative environmental impacts at the tributary level can still be substantial. (Smakhtin, 2001; Spina et al., 2006; Pringle, 2000; Deitch et al., 2013) Furthermore, these impacts are typically related to the alteration of the streamflow regime rather the modifications of the physical environment that occur with larger, centralized water supply projects. Commonly cited effects of small, localized storage projects and diversions include reduced downstream supply, increased frequency of low-flow events, and the alteration and attenuation of natural streamflow patterns. (Smakhtin, 2001; Rolls et al., 2012)

The wine country of Northern California presents a prime example of a region that is facing the challenges created by the often disparate needs of agricultural and environmental interests. Many of the coastal river systems in the region are inhabited by threatened and endangered anadromous fish species. In particular, the Russian River and its tributaries provide critical habitat for the endangered coho salmon as well as the threatened Chinook salmon and steelhead trout. The unique Mediterranean climate of the region, characterized by high seasonality in both temperature and precipitation, supports and informs the variable lifecycle needs of the fish species. (Bonada & Resh, 2013; Lytle & Poff, 2004) At the same time, the Russian River valley supports a thriving agricultural community that is primarily focused on the production of wine grapes. While generally requiring relatively lower quantities of irrigation than other common crops grown in the region, viticulture still requires irrigation during the extremely dry summer growing season. (Smith et al., 2004; Deitch et al., 2009b) Additionally, spray irrigation is often used as a means of protection against frost and heat damage; however, it requires the application of large volumes of water over a short duration and can rapidly deplete streamflow in the nearby waterways that are used for water supply. (Deitch et al., 2009b; Johnson, 2015) Despite being spatially distributed, vineyard demands, in particular those associated with frost protection, are often temporally coincident, which can lead to significant short-term abstractions from the overall stream system, and which may also contribute to fatal stranding events among the threatened and endangered fish species. (SWRCB, 1997; Deitch et al., 2009a; Johnson, 2015) In 2008, following one such event, the National Marine Fisheries Service (NMFS) led a multi-group effort among a variety of government and non-governmental stakeholders to investigate mitigation efforts that would avoid future strandings. (Johnson, 2015) In subsequent years, the California State Water Resources Control Board (SWRCB) approved a pair of regulations aimed at protecting fisheries habitat in the Russian River basin by maintaining minimum instream flows (SWRCB, 2010) and limiting frost protection diversions (SWRCB, 2011).

Key to these regulations are the estimation of diversion impacts on unimpaired streamflows and the consideration of cumulative impacts of diversions within a stream basin. Accordingly, the impacts of tributary diversions in the Russian River basin have been the focus of a variety of studies since being highlighted by the NMFS study group in 2008. Temperature and streamflow gage data have been analyzed to document the connection between frost protection and streamflow impacts (Deitch et al., 2009b) and the individual and cumulative impacts of diversions on smaller tributary streams have been assessed. (Deitch et al., 2009a) Additionally, a GIS-based model developed by Merenlender et al. (2008) that scales streamflow gage data to estimate tributary flows has been extensively used to evaluate water supply and demand throughout the basin (Merenlender et al., 2008); to assess the impacts of environmental policies and evaluate off-stream storage options (Grantham et al., 2010); to evaluate the cumulative impacts of small reservoir storage projects (Deitch et al., 2013) and; to assess the impacts of environmental regulations on streamflows and agricultural water security. (Grantham et al., 2014)

A key component that has not been sufficiently addressed in previous research is the incorporation of unimpaired streamflow estimations based on hydrometeorological modeling in the evaluation of water management impacts and alternatives. In this study, we employ a geospatial decision support system (geo-DSS) originally developed by Fields et al. (2018) that combines a gridded hydrometeorological model (HL-RDHM) with a GIS-based river basin management model (GeoMODSIM) to estimate the cumulative effects of agricultural diversions and environmental streamflow regulations on unimpaired streamflow conditions in the Feliz Creek basin, a tributary to the Russian River in Mendocino County. By analyzing agricultural irrigation performance and streamflow impacts across a variety of hydrologic conditions, the geo-DSS is also used to determine the most favorable sizes and locations for supplemental off-stream storage development within the basin. This type of analysis is key to implementing the goals of the SWRCB Policy for Maintaining Instream Flows, given its reliance on estimates of unimpaired streamflow for setting flow requirements. (SWRCB, 2010)

3.3 Methods

3.3.1 Study Area

3.3.1.1 Study Area – Feliz Creek Watershed

This study is focused on the Feliz Creek watershed in the upper Russian River basin in Mendocino County, in the Northern Coastal region of California. (Figure 7) The Feliz Creek basin extends generally west from its confluence with the mainstem Russian River near the town of Hopland and drains 108 km^2 (41.7 mi^2) of total watershed area. The climate of the region can be categorized as Mediterranean in nature and is characterized by cool, wet winters and hot, dry summers. (Gasith & Resh, 1999) As a result, both precipitation and runoff follow the similar patterns of greater magnitudes of rainfall and streamflows occurring during the wet season and little to no precipitation and diminishing runoff volumes characterizing the dry season. Additionally, precipitation events during the wet season are primarily driven by atmospheric rivers, which generate rainfall patterns that are highly variable in timing, duration, and intensity.

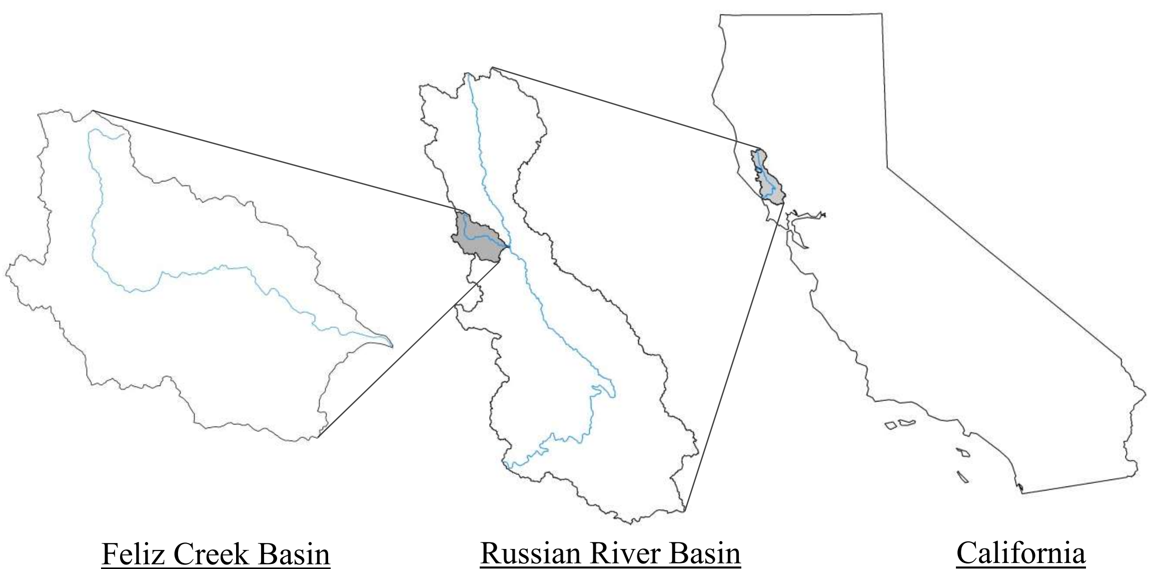


Figure 7. Study area - Feliz Creek and Russian River basin locations in northern coastal California

3.3.1.2 Study Area – Agricultural Setting

Agriculture in the Russian River and Feliz Creek basins is dominated by viticulture. According to 2017 U.S. Department of Agriculture data, approximately 90 percent of the cropland in the Russian River basin is devoted to grapevine cultivation; in the Feliz Creek watershed the percentage is similar – 91 percent of cropland (21.15 ha) was used for grapevine cultivation in 2017. Accordingly, vineyard-based agriculture is the largest water user in the Feliz Creek watershed, and given the absence of a centralized irrigation water supply project in the basin, water supplies are generally obtained from direct-runoff surface water sources. Many water users in the basin have developed small storage ponds that are typically less than 200,000 m^3 (100 acre-feet) in volume and are used to meet localized demands. These ponds are typically filled by either capturing direct surface runoff to the pond or through stream diversions during the wet season and are subsequently relied upon to meet frost protection and summer irrigation demands. (Grantham et al., 2014)

Viticultural irrigation demands can vary significantly depending on local conditions such as the hydrologic state, vine type, soil type, solar radiation level, humidity, and temperature, among other factors. (Pritchard, 2010) Furthermore, irrigation application rates can vary from full water use to some level of deficit irrigation water use based on localized demands and the irrigation strategy employed. In the absence of specific water use information for each irrigated vineyard parcel, an average annual summer irrigation demand of 39.6 cm (15.6 inches) is appropriate for the North Coast region of California. (Pritchard, 2010) In general, irrigation in the basin is dominated by drip irrigation practices, which typically operate with irrigation efficiencies near 90%, thereby precluding any positive return flow impacts to the associated stream system. (Johnson, 2015; Pritchard, 2010) Agricultural water demands for frost protection are generally inconsistent, with variation due to the number and length of the frost events and the required application duration for each. While the number of frost events in a particular season can fluctuate between as few as zero events or as many as twenty, there are typically four to six frost events in a given year. (Hines et al., 2009) Furthermore, the volumetric water demands associated with each frost event will also vary but can be approximated as 166 m^3/ha (2,272 ft^3/acre) per event. (Smith et al., 2004)

3.3.1.3 Study Area – Environmental Setting

Northern Coastal California provides essential habitat for a variety of threatened and endangered fish species. In particular, the Russian River and many of its tributaries have been listed as critical habitat for Coho salmon, chinook salmon, and steelhead trout since 2005, a designation that recognizes the region as having the physical and biological features essential to conservation of the species. (U.S. Congress, 1973) With respect to the anadromous fish species in the Russian basin, a key component of the critical physical environment is having a requisite amount of instream flows to support the various fish lifecycle stages. In recent actions to support this need, the SWRCB has placed particular emphasis on the restriction of streamflow diversions. In 2010, the SWRCB issued its Policy for Maintaining Instream Flows in Northern California Coastal Streams, which generally relies on a policy of diversion restrictions to maintain instream flows for the protection of fishery resources. (SWRCB, 2010) The essence of the policy is that streamflow diversions associated with new water rights applications are restricted in time, rate, and volume in order to mitigate their adverse impacts on instream flow rates. Furthermore, the SWRCB also adopted the Russian River Frost Protection Regulation in 2011, which restricts direct frost protection diversions unless included under an approved water demand management program regardless of the date of the water right. (SWRCB, 2011)

While the additional restrictions have been met with some resistance from agricultural users, it is generally recognized that there is a need for better understanding of the effects of diversions on instream flow rates as well as for a method of evaluating the available management alternatives within the basin. Moreover, an increasing number of more-senior water rights holders in the basin are beginning to adopt operational practices that are in accordance with the newer environmental flow policies. (Grantham et al., 2014) Given this trend, this study applies the diversion restriction policy set forth by the SWRCB as a method of quantifying the environmental streamflow demands. This policy determines a minimum bypass flow based on the mean annual unimpaired flow and the upstream drainage area at the point of diversion. (Table 4)

Table 4. Minimum Bypass Flow Formulas (SWRCB, 2010)

Drainage Area at Point of Diversion (POD)	**Minimum Bypass Flow Formula**
1 square mile or smaller	$Q_{MBF} = 9.0\ Q_m$
Between 1 and 321 square miles	$Q_{MBF} = 8.8\ Q_m\ (DA)^{-0.47}$
321 square miles or larger	$Q_{MBF} = 0.6\ Q_m$

Q_{MBF} = **minimum bypass flow** in cubic feet per second
Q_m = **mean annual unimpaired flow** in cubic feet per second
DA = the **watershed drainage area** in square miles

3.3.2 Model Framework

3.3.2.1 Model Framework – General Coupled Model Description

A key component of the SWRCB Policy for Maintaining Instream Flows is its reliance on unimpaired flow estimation for the determination of minimum bypass flow regulations (Table 4). Within the policy, two general methods for determining unimpaired flows are presented – an adjustment of streamflow records method and a precipitation-based streamflow modeling method. The adjustment of streamflow records method is based on the use of existing streamflow gage data from an analog watershed that shares characteristics of the watershed in question as the foundation for the analysis. The characteristics for comparison may include geology, soil type, topography, vegetation, land use, and precipitation runoff processes among other considerations. Once the streamflow data is obtained, it is then scaled based on the ratio of the upstream drainage area and average annual precipitation at the point of diversion to those at the gage site to obtain an estimate of the unimpaired flows. While this method is relatively straightforward, it relies on a series of assumptions regarding the watershed characteristics as well as the utilization of streamflow data that may already be considered impaired by upstream diversions and management decisions. As a result, the accuracy of the unimpaired flow estimations may be compromised.

The second method for the estimation of unimpaired flows suggested in the SWRCB policy is the use of a precipitation-based streamflow model. While more technically complex, this method eliminates many of the assumptions associated with the first method that may lead to inaccuracies. The policy specifies that such a model should be driven by precipitation data and should incorporate the same watershed characteristics that were considered in the first method for finding an analog watershed – geology, soil type, topography, vegetation, land use, and precipitation runoff processes among other factors. After development and calibration, a precipitation-based model would further offer the flexibility to not only determine minimum bypass flows but to also be used in conjunction with a watershed management model to create a more complete representation of the stream system.

The modeling framework used in this study combines spatially-distributed hydrometeorological modeling of unimpaired streamflows with a geospatial water management model to realistically account for the spatial and temporal impacts of water management decisions on instream flows. This coupled model structure, originally developed by Fields et al (2018), comprises a geospatial decision support system (geo-DSS) that can be further used to evaluate a variety of hydrologic scenarios and management alternatives within the watershed.

3.3.2.2 Model Framework – Hydrometeorological Model, Data Synthesis, and Flow Scenarios

The Hydrology Laboratory Research Distributed Hydrologic Model (HL-RDHM) was developed by the Hydrology Laboratory of the National Weather Service and, among other factors, incorporates the model elements identified by SWRCB as essential for a precipitation-based streamflow model. (NWS, 2009) At its essence, HL-RDHM uses precipitation and temperature as its primary model forcings and relies on a gridded implementation (1/4 HRAP or approximately 1 km) of the Sacramento Soil Moisture Accounting (SAC-SMA) model to generate estimates of surface and subsurface flows. These flows are then combined with a system of intracell and intercell flow routing methods to generate a network of unimpaired streamflow estimations throughout the modeled basin. The gridded nature of the model is advantageous for application within the policy structure of the SWRCB regulations given their basis on unimpaired flow estimations at diversion sites whose locations vary throughout a basin. While many traditional hydrologic models generate flow estimations at a single point, which is typically the basin outlet, HL-RDHM flow estimates are generated throughout a basin at each time step and can be correlated to the spatially-variable diversion point locations.

An HL-RDHM model has been developed and calibrated for use in the Russian River basin as part of the NOAA Hydrometeorology Testbed. The resulting model was shown to be capable of generating accurate unimpaired streamflow estimates for both peak flow and low flow conditions, which is of critical importance given the high flowrate variability in the basin. (Johnson et al, 2016) Furthermore, the HL-RDHM model captures the spatial and temporal variability in flows that are not reflected when applying a scaled-data approach to streamflow estimation. As described in its final report on the Russian River watershed, the Russian River Independent Science Review Panel (RRISRP) found that a variety of stream characteristics influences the rainfall-runoff response relationship in the basin. (RRISRP, 2016) Using these characteristics as a basis, Walls (2013) developed a stream typology that incorporates the geomorphological and hydrological aspects of the stream as well as the surface water-groundwater interactions in the system to categorize the various stream types found in the basin. (Figure 8a) When combined with typology data for the Feliz Creek basin, HL-RDHM streamflow data that has been normalized by upstream contributing area shows agreement between the two models and demonstrates the importance of using a precipitation-based streamflow model for flow estimation at points upstream of a basin outlet. In the streamflow model, stream reaches of the bedrock canyon typology exhibit above average responses to rainfall events and decreased normalized flows during periods of dryness, indicating reduced influence from groundwater on the stream baseflow. (Figure 8b) Conversely, modeled streamflows in alluvial-type stream reaches exhibit below-average responses to precipitation events but show increased normalized flowrates during dry periods, which indicates higher groundwater contributions to the baseflow in these reaches. (Figure 8b) Capturing these variations in streamflow response through the use of a precipitation-based streamflow model like HL-RDHM is essential for accurate flow estimations at points that are spatially distributed throughout a basin.

As applied in the Russian River basin, the HL-RDHM model has been used to generate streamflow forecasts in the basin based on observed precipitation and temperature data in the period since model development; however, the breadth of available data does not span the

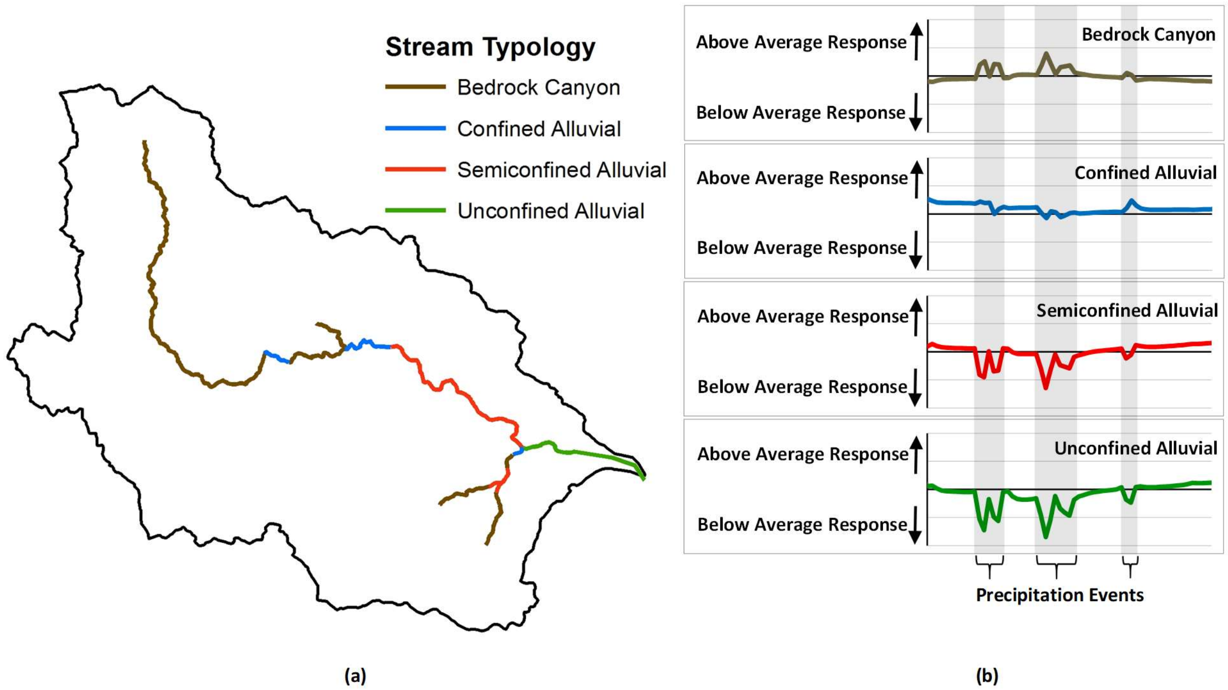


Figure 8. (a) Feliz Creek basin stream typology per Walls (2013). (b) Example HL-RDHM normalized flow (m^3/s per square kilometer) responses to a series of precipitation events demonstrating above average responses in bedrock canyon stream types and reduced/delayed responses in alluvial stream types

variety of hydrologic conditions required for this study. As an alternative for this study, synthetic HL-RDHM datasets were generated for the Feliz Creek basin based on historical Russian River flow data in order to obtain a wider range of water supply scenarios for analysis.

A statistical analysis of the HL-RDHM model output and corresponding stream gage data reveals that there is good correlation between the model results at gaged locations and observed gage data in the basin. (Johnson, 2016) Additionally, HL-RDHM flow estimations for cells upstream of the basin outlet can be correlated to the outlet flow estimations using a second-order polynomial relationship based on flow data normalized by upstream area. (Johnson, 2016) Using these relationships, synthetic HL-RDHM datasets can be generated using synthetic Russian River flow data as the primary input. (Figure 9)

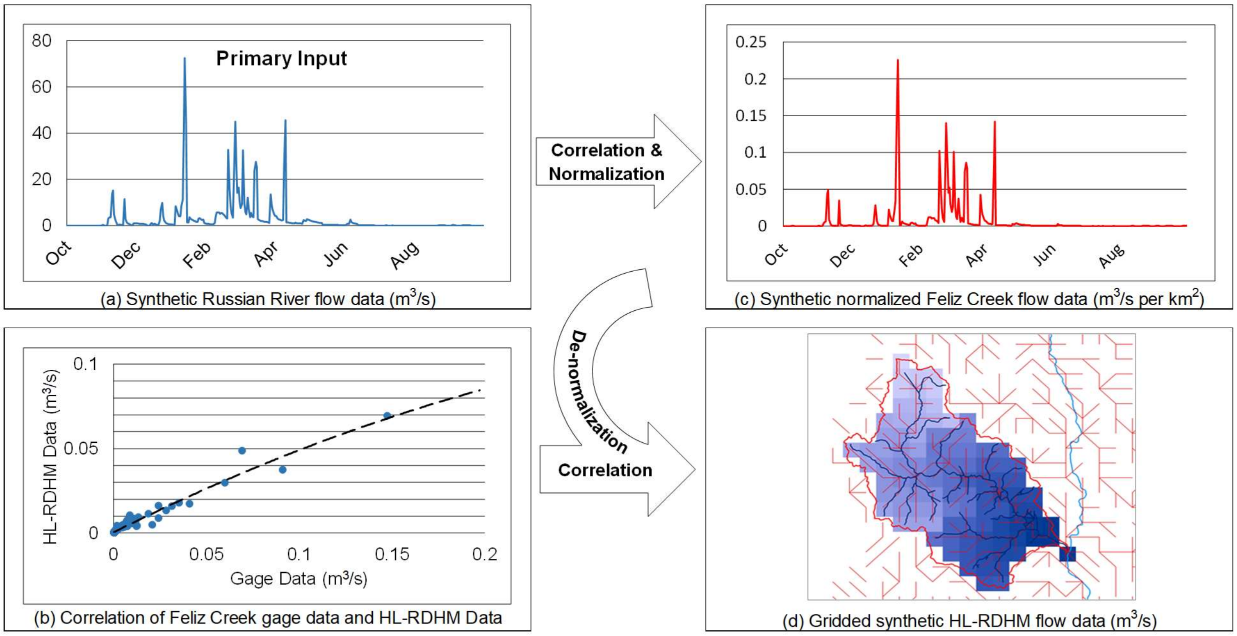


Figure 9. Synthetic HL-RDHM data creation. (a) Synthetic Russian River data is generated using a Markov Chain approach. (b) Synthetic normalized data is produced based on a correlation to the synthetic Russian River data. (c) A priori correlations between Feliz Creek gage data and HL-RDHM model data are combined with (b) to generate (d) gridded synthetic HL-RDHM datasets that are de-normalized for use as inputs to the GeoMODSIM streamflow management model.

Natural streamflow patterns in the Russian River basin are highly stochastic in nature. The basin hydrologic system is driven by atmospheric rivers, narrow bands of warm air and large water vapor content which generate intense precipitation events, resulting in runoff hydrographs characterized by intense peak flows followed by short recession curves. (Ralph et al, 2006) Furthermore, the basin hydrology can be divided into distinct wet and dry seasons, with nearly all precipitation occurring between December and May. Due to the extreme stochasticity and seasonality of the system, statistically-based models are generally unable to replicate the streamflow pattern characteristics in the basin. As an alternative, a Markov chain approach that retrieves Russian River gage data segments of variable length and combines them into a single synthetic streamflow record was employed to generate synthetic Russian River streamflow data. Using flow measurement data that is available since 1952 for the USGS Russian River gage at

Ukiah, a comprehensive set of flow scenarios can be generated that accurately recreate the stochasticity and seasonality of flow patterns prevalent in the basin. The resulting streamflow datasets can then be used to generate synthetic HL-RDHM datasets based on the approach detailed in Figure 9.

3.3.2.3 Model Framework – River Basin Management Model and Management Scenarios

While the HL-RDHM model provides unimpaired estimates of surface flows throughout the modeled basin, a more complete model of the Feliz Creek surface water system must include the impacts of water management decisions such as the location and magnitude of direct stream diversions as well as the location, size, and operation of distributed agricultural ponds. For this purpose, the HL-RDHM model is coupled with GeoMODSIM, a GIS-based implementation of the MODSIM generalized river basin flow model. (Triana and Labadie, 2012) Through the use of geospatially-referenced stream network data available from the USGS National Hydrography Dataset (http://www.horizon-systems.com/NHDPlus/NHDPlusV2_data.php) GeoMODSIM utilizes the geometric network construct within ArcGIS to create a geo-referenced river basin model. This network uses connected feature classes such as streams, canals, reservoirs/ponds, diversions, and consumptive use demands, as well as ecological and environmental instream flow requirements, to represent the stream system and model the effects of management operations. By utilizing HL-RDHM data as streamflow input at points throughout the stream network model and by accounting for water rights and policy-based restrictions on system operation, the GeoMODSIM model generates estimates of instream flows, flow diversions, and water use that accurately portray the temporal and spatial variability throughout the system. Given the use of drip irrigation throughout the basin, which typically operate with irrigation efficiencies near 90%, return flow impacts from management practices were assumed to be negligible. (Johnson, 2015; Pritchard, 2010; Dewandel et al, 2008)

Each GeoMODSIM model run is a unique combination of state variables, forcing data, and system management settings. In this model construct, state variables are used to define storage conditions in the basin by including carryover of existing storage as well as to define supplemental storage availability. For existing storage, the most conservative approach assumes that ponds are empty at the beginning of the water year. This is a common condition in the Russian River basin not only because stored water is often fully used for agriculture, but the emptying of ponds is commonly required under invasive species plans as regulated by the California Department of Fish and Wildlife to control bullfrog populations. (Deitch et al, 2013) For a basis of comparison, a second set of state variables was defined to include carryover storage of 50 percent in existing ponds at the beginning of the water year.

A key use of the model is to identify locations where additional storage can be accommodated and where it would be most beneficial within the overall system. Throughout the system, potential sites for supplemental storage were evaluated in seven regions of the basin that correspond to HL-RDHM grid cells. (Figure 10) Each of these regions supports agricultural use from direct runoff capture or stream diversions and may benefit from supplemental storage availability. Accordingly, two additional state conditions were defined that represent the availability of supplemental storage. Scenarios with no supplemental storage represent the system as currently constituted and scenarios with supplemental storage allow water to be stored and utilized to meet agricultural demands. Initial supplemental storage volumes were set to high values that effectively provided unlimited storage and final recommended volumes were determined using an iterative process. The resulting combinations of state variables result in four management scenarios, which are summarized in Table 5.

Subbasin	Number of Agricultural Demands	Area of Irrigated Agriculture (ha)	Existing Storage Volume (m^3)
1	1	15.4	2.2E+04
2	2	24.2	9.3E+04
3	1	7.3	3.2E+04
4	1	16.2	0.0E+00
5	1	6.9	4.1E+04
6	1	20.0	1.5E+05
7	3	107.5	2.3E+05

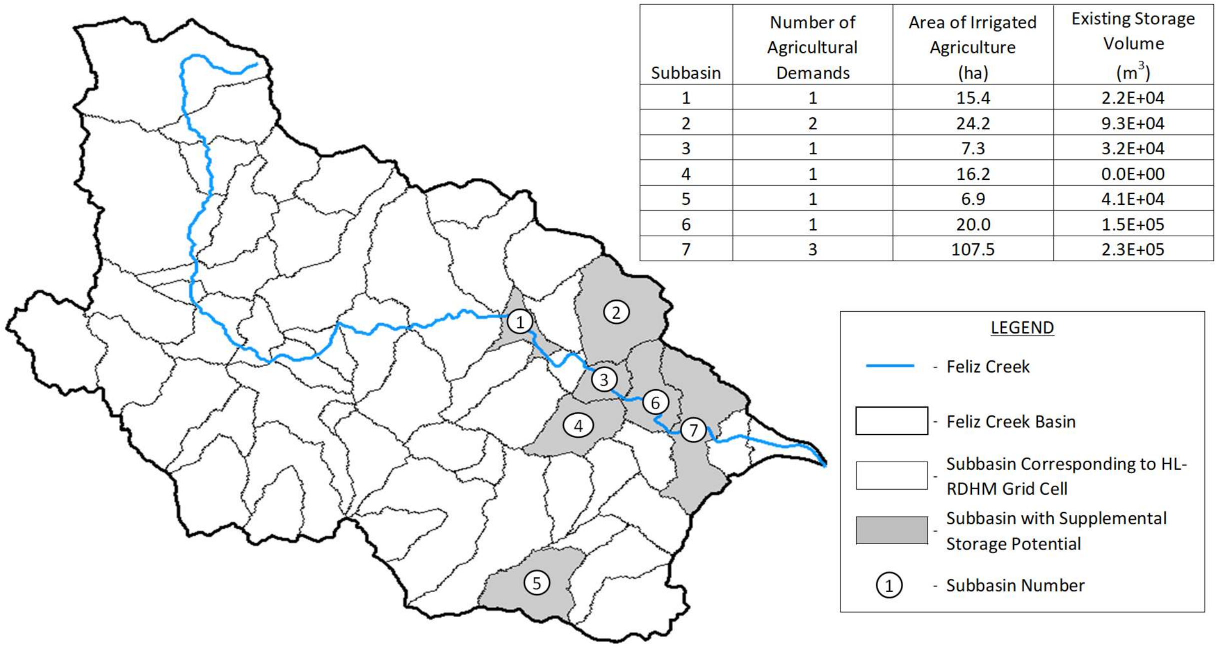


Figure 10. Feliz Creek basin map with subbasins corresponding to HL-RDHM grid cells. Highlighted areas identify subbasins where supplemental storage was evaluated as a management strategy for supporting agriculture and providing instream flow benefits.

Table 5. State variable scenarios defining pond conditions in each GeoMODSIM model run

	State Variable	
	Carryover Storage in Existing Ponds	**Supplemental Storage**
Pond Scenario 1	0%	NO
Pond Scenario 2	50%	NO
Pond Scenario 3	0%	YES
Pond Scenario 4	50%	YES

As previously described, the GeoMODSIM model forcing data is comprised of HL-RDHM output streamflow data for the Feliz Creek basin. Using the methods detailed previously and depicted in Figure 9, one hundred sets of synthetic flow data were generated to represent a wide spectrum of hydrologic scenarios. Three representative examples of synthetic Feliz Creek flow data are shown in Figure 11 and depict dry, average, and wet hydrologic conditions. As is evident in the figure, the use of Russian River gage data as the primary input for data synthesis results in the generation of datasets that capture the pronounced stochasticity and seasonality of the flow regime prevalent in the basin. Further, the graphs in Figure 11 demonstrate the extreme variability of water supply that can occur in the basin and the resultant need to consider a wide variety of scenarios in the evaluation of water management alternatives.

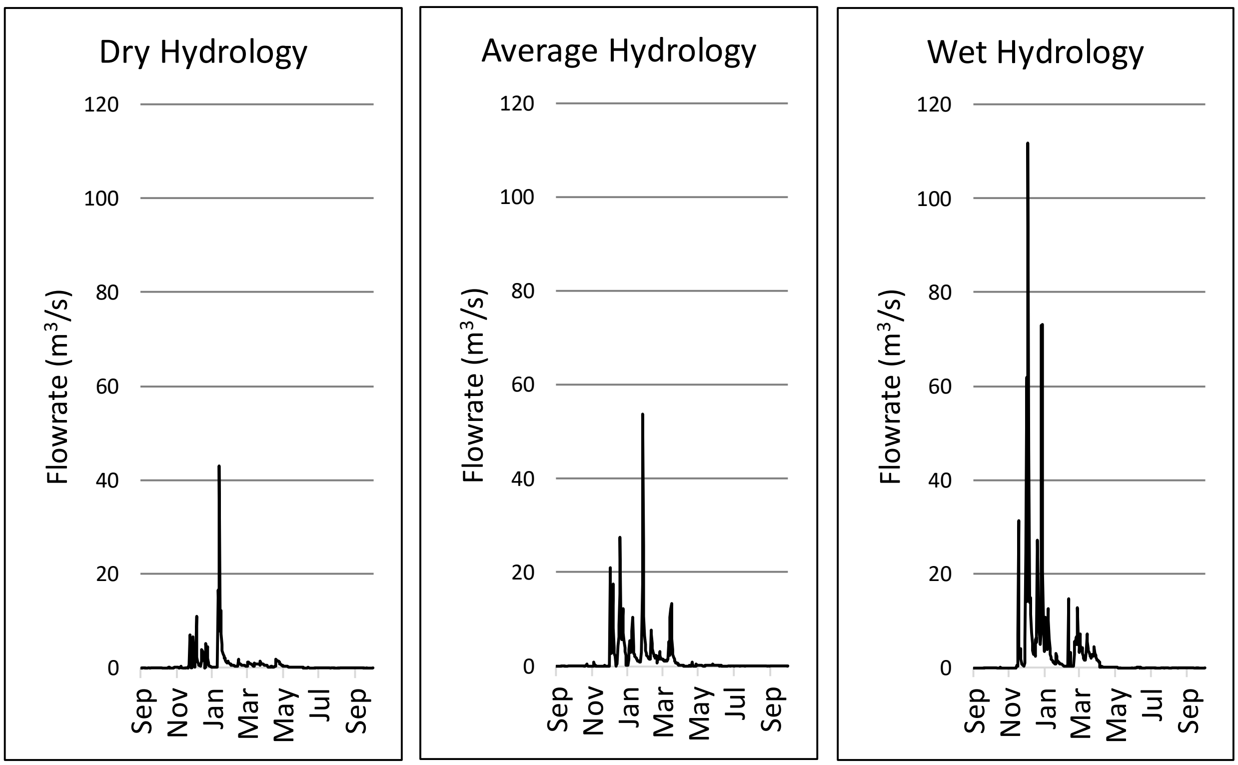


Figure 11. Synthetic flow data plots for Feliz Creek representing dry, average, and wet hydrologic conditions and demonstrating the typical stochasticity and seasonality of flows in the region.

Finally, system management settings include the model aspects that are consistent across all GeoMODSIM model runs. For example, agricultural use that includes summer irrigation and frost protection demands, water rights settings, and environmental flow requirements do not vary between model runs, which allows the focus of the model to remain on supplemental storage and carryover storage options, and the potential effects and benefits of each. Modeled agricultural demands, including frost protection and summer irrigation demands, were modeled per the assumed average values described the Agricultural Setting section. Similarly, environmental demands, in the form of minimum bypass flow restrictions, were modeled as detailed in the Environmental Setting section. Finally, water rights data from the California SWRCB Electronic Water Rights Information Management System (eWRIMS) including water rights locations, quantities, and priorities was incorporated into the GeoMODSIM model to inform the network flow optimization model and assure that flows are appropriately allocated per operational and water rights considerations.

3.4 Results

In the evaluation of system performance as well as management alternatives and their impacts, Pond Scenario 1 (see Table 5) represents a baseline for management conditions within the system, as it contains existing agricultural practices and minimum bypass flow criteria for environmental protections. As carryover storage and supplemental storage are included in the remaining three pond scenarios, the results of each scenario can be measured against the baseline conditions of Pond Scenario 1 to determine their overall impact on the system. The one hundred sets of synthetic flow data were divided into three hydrologic groups based on the overall average flowrate in each dataset for more detailed analysis – 33 dry datasets, 34 average datasets, and 33 wet datasets. Performance results for each pond scenario were evaluated across all hydrologic conditions for agricultural supply, instream flow impacts, and recommended supplemental storage size and location.

3.4.1 Results – Agricultural Supply

A simple and straightforward measure of agricultural supply system performance is a summation of the total number of agricultural demand shortage events observed throughout the system. While this measure does not quantify the magnitude of each shortage, it is generally indicative of the level of overall system inadequacies caused by a lack of available supply at the time of demand. In Figure 12, shortage counts are summarized as percentages of the total number of demand events for all hydrologic conditions as well as separately for dry, average, and wet hydrologic conditions. For the baseline Pond Scenario 1, agricultural demand shortages occurred at 69 percent of demand node timesteps for all 100 hydrologic datasets. This percentage stays relatively consistent regardless of the underlying hydrologic conditions – under dry conditions the percentage is slightly higher at 71 percent and under normal and wet conditions the percentage is falls to 69 percent and 67 percent, respectively. Results for Pond Scenarios 2, 3, and 4 show similar trends to the baseline scenario results with decreasing shortages as conditions vary from dry to wet; however, these are at reduced magnitudes from those in Pond Scenario 1. (Figure 12)

The relative results of the pond scenarios can be further compared within each set of hydrologic conditions and show that the trend for the total number of shortages remains consistent within each (Figure 12). As management strategies are implemented in Pond Scenarios 2, 3, and 4, (Table 5) the number of agricultural shortages decreases. Furthermore, a comparison with the baseline scenario demonstrates the relative effects of adding carryover storage and supplemental storage to the system. Results for Pond Scenario 2 (carryover storage included) indicate an overall shortage decrease of 13 percent across all hydrologic conditions from the baseline scenario and this improvement remains consistent when evaluated separately

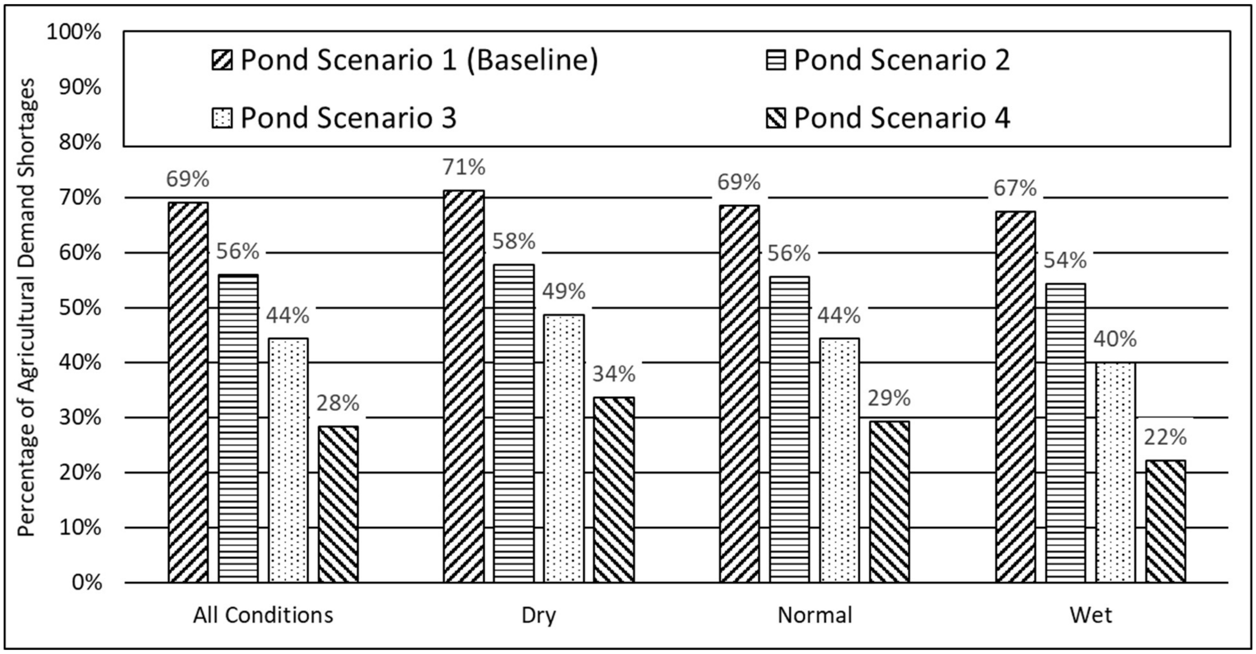


Figure 12. Agricultural demand shortage counts expressed as a percentage of total number of demand events across all pond scenarios and hydrologic conditions.

for dry, average, and wet conditions. Results for Pond Scenario 3 (supplemental storage included) indicate a 25 percent decrease in agricultural demand shortages for all hydrologic conditions and decreases of 22 percent, 25 percent, and 27 percent for dry, average, and wet conditions, respectively. Results for Pond Scenario 4 indicate that the combination of both management strategies can lead to even greater overall impacts. Across all conditions, Pond Scenario 4 led to a 41 percent reduction of agricultural demand shortages and for dry, normal, and wet conditions the reductions were 37 percent, 40 percent, and 45 percent, respectively.

An alternative method of measuring agricultural system performance is the summation of the total volumetric agricultural demand shortage observed throughout the system. By determining the overall volumetric shortage in each scenario, the impacts of management strategies can be more completely evaluated than by counting the number of shortages alone. In Figure 13, shortage volumes are represented as percentages of the overall agricultural demand for each pond scenario and are shown for all hydrologic conditions as well as for dry, average, and wet hydrologic conditions. For the baseline Pond Scenario 1, agricultural demand shortages totaled 83% of the total volumetric agricultural demand across all 100 hydrologic datasets. As was observed previously when assessing the number of shortages, the volumetric demand shortage stays relatively consistent when evaluated for specific hydrologic conditions – under dry conditions the percentage is slightly higher at 85% and under normal and wet conditions the percentage is falls to 83% and 81%, respectively. Results for Pond Scenarios 2, 3, and 4 show similar trends as volumetric shortages decrease from dry to wet conditions but with greater fluctuation and at reduced magnitudes from those in Pond Scenario 1.

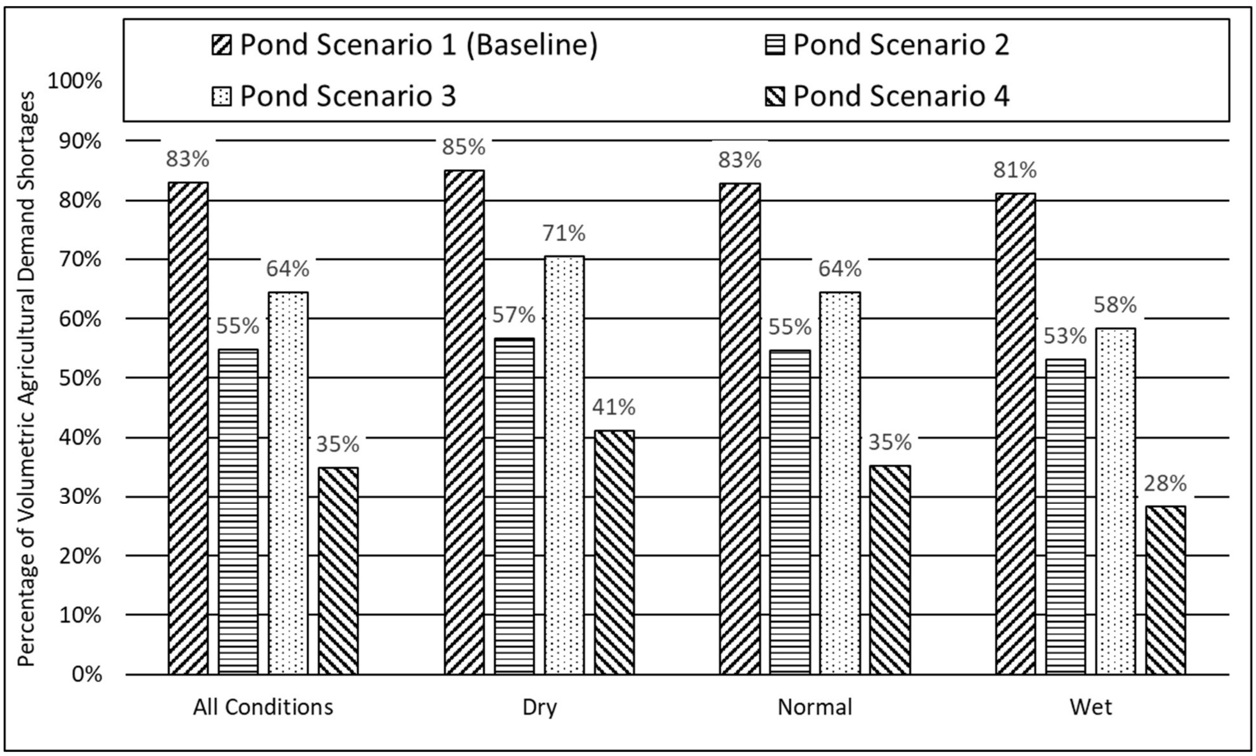


Figure 13. Volumetric agricultural demand shortages expressed as a percentage of total agricultural demand across all pond scenarios and hydrologic conditions.

As before, the relative results of the pond scenarios can be compared within each set of hydrologic conditions and the trends for the volumetric agricultural demand shortages are found to be consistent in each (Figure 13). As management strategies are implemented in Pond

Scenarios 2, 3, and 4 (Table 5) the volumetric agricultural demand shortage decreases. Furthermore, a comparison with the baseline scenario demonstrates the impacts of adding carryover storage and supplemental storage on volumetric agricultural demand shortages. With the inclusion of carryover storage (Pond Scenario 2) volumetric agricultural shortages decrease by 28 percent when evaluating all hydrologic conditions and this improvement is consistent when evaluated separately for dry, average, and wet conditions. Results for the inclusion of supplemental storage (Pond Scenario 3) indicate a 19 percent decrease in volumetric agricultural demand shortages across all hydrologic conditions and indicate decreases of 14 percent, 19 percent, and 23 percent for dry, average, and wet conditions, respectively. Finally, when both carryover storage and supplemental storage are included (Pond Scenario 4) results indicate that the combination of strategies has the greatest overall impacts. Across all conditions, Pond Scenario 4 led to a 48 percent reduction of volumetric agricultural demand shortages, and across dry, normal, and wet conditions the reductions were 44 percent, 48 percent, and 53 percent, respectively.

3.4.2 Results – Instream Flow Impacts

Within the Geo-MODSIM model priority structure, instream flow demand nodes equal to the minimum bypass flow were included immediately downstream of, and with a higher priority than, each agricultural point of diversion to ensure that minimum bypass flow restrictions were not violated. However, given the extreme variability and seasonality of the system, instream flow rates naturally fall below minimum bypass flow levels for over 90 percent of the modeled conditions. Of particular interest are agricultural instream flow impacts that occur during these periods of naturally low flow and the improvements that can be realized as management options are implemented.

Figure 14 shows an example of modeled flow conditions immediately downstream of an agricultural diversion with minimum bypass flow restrictions in place for both the baseline Pond Scenario 1 and Pond Scenario 3, where supplemental storage has been included. As shown in the figure, in Pond Scenario 3 supplemental storage fills early in the wet season when instream flow rates exceed the minimum bypass flow. Subsequently in the spring, supplemental storage throughout the system reduces the cumulative demand for direct stream diversions during frost events, thereby eliminating the severe drawdowns that occur in the baseline scenario during periods of naturally-low instream flow rates.

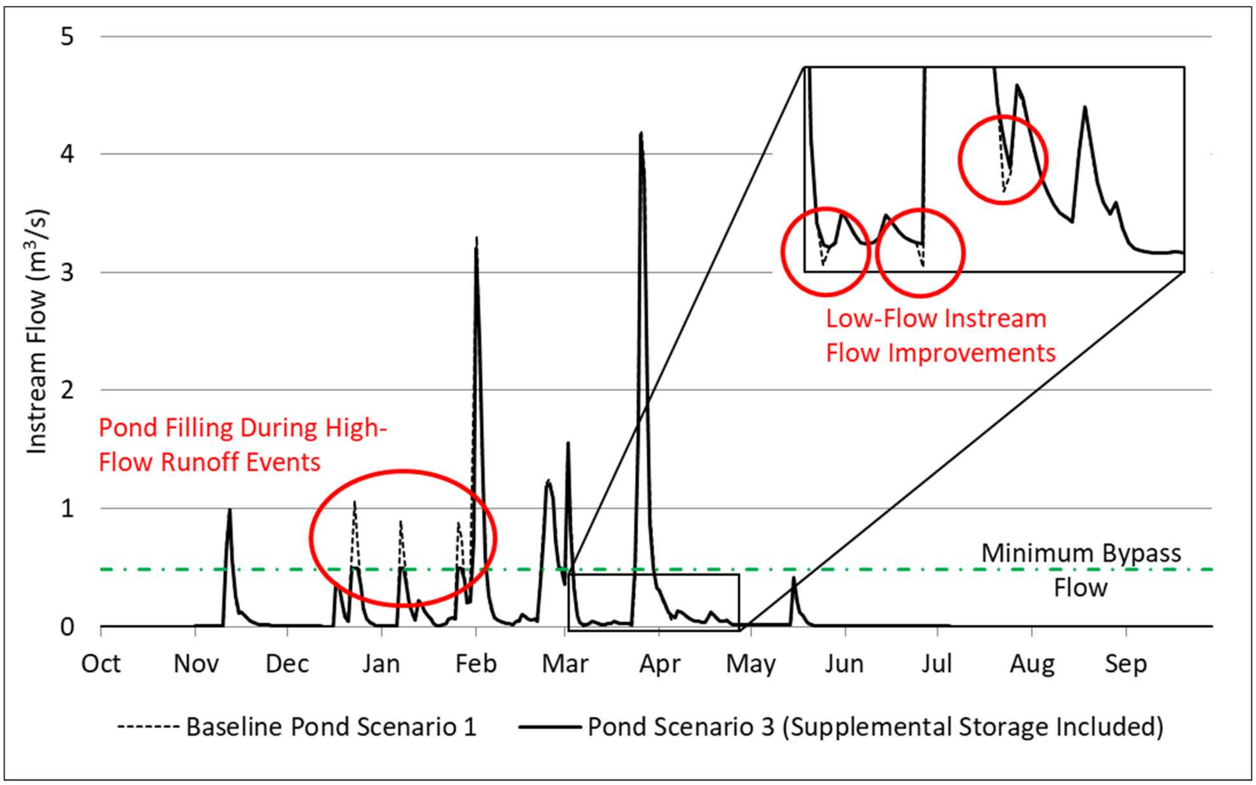


Figure 14. Modeled instream flow downstream of agricultural diversion and instream flow demand for the baseline Pond Scenario 1 and Pond Scenario 3 (Supplemental Storage Included). The modeled operations show the filling of supplemental storage during initial high-flow runoff events and improved instream flowrates during low-flow conditions related to frost protection demands.

In Figure 15, the overall number of instream flow improvements during periods of low instream flow conditions (below the minimum bypass flow) are presented. The overall number of instream flow improvements in each management scenario is summarized as a percentage of the total number of timesteps where low instream flow conditions were modeled in the baseline scenario. Results are summarized for all hydrologic conditions as well as separately for dry, average, and wet conditions. Pond Scenarios 2 and 4, which include carryover storage, exhibit similar trends with overall improvements averaging 25 percent and 24 percent, respectively. As hydrologic conditions vary, the overall number of improvements varies as well, with a greater number under dry conditions and fewer as conditions grow increasingly wetter. Results for Pond Scenario 3, which includes only supplemental storage, indicate overall improvement in only three percent of low-flow timesteps. However, as conditions range from dry to wet, the trend differs from that observed for Pond Scenarios 2 and 4, with the number of improvements increasing from one percent in dry conditions to a maximum value of five percent improvement observed in wet conditions.

As a quantitative assessment of the improvements to instream flow rates, each incremental flow rate improvement was calculated as a percentage of the baseline instream flow rate at the same time step. As an example, for a time step with a baseline instream flow rate of 0.1 m^3/s, an instream flow rate of 0.2 m^3/s in a managed scenario would represent a 100 percent improvement over baseline conditions. An overall summary of these results is presented in Figure 16. Results for Pond Scenarios 2 and 4 exhibit similar trends across all conditions as well as for dry, average, and wet hydrologic conditions. For all conditions, the average flow improvements for Pond Scenarios 2 and 4 were 99 percent and 104 percent, respectively, indicating that on average, where instream flow rates improved under managed conditions, the

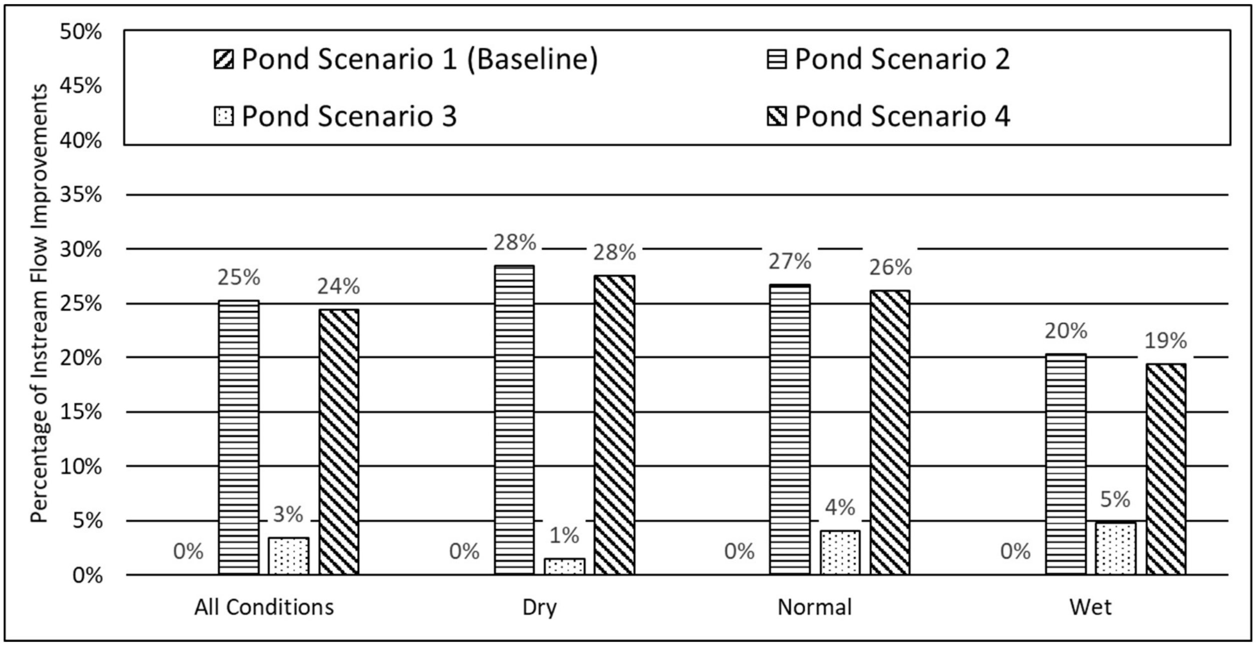


Figure 15. Number of instream flow improvements expressed as a percentage of the total number of timesteps with low instream flow conditions (below minimum bypass flow) across all pond scenarios and hydrologic conditions. For example, a value of four percent indicates that four percent of the timesteps with low instream flows observed in the baseline scenario were improved in the pond scenario.

resulting flow was approximately twice that of baseline conditions. Under dry and normal conditions these percentages were slightly lower but under wet conditions the improvements averaged more than a 100 percent improvement over baseline conditions. Results for Pond Scenario 3 indicate that improvements are significantly smaller in magnitude than those from the other management scenarios. For all conditions, instream flow rate improvements in Pond Scenario 3 averaged 39 percent over baseline conditions. This improvement was most significant under dry conditions where the average improvement was 48 percent. Under normal and wet conditions, the average improvement was 33 percent and 44 percent, respectively.

3.4.3 Results – Supplemental Storage

The usefulness of supplemental storage within a subbasin is tied to two primary factors. First, there must be a demand for extra storage created by agricultural shortages in the subbasin.

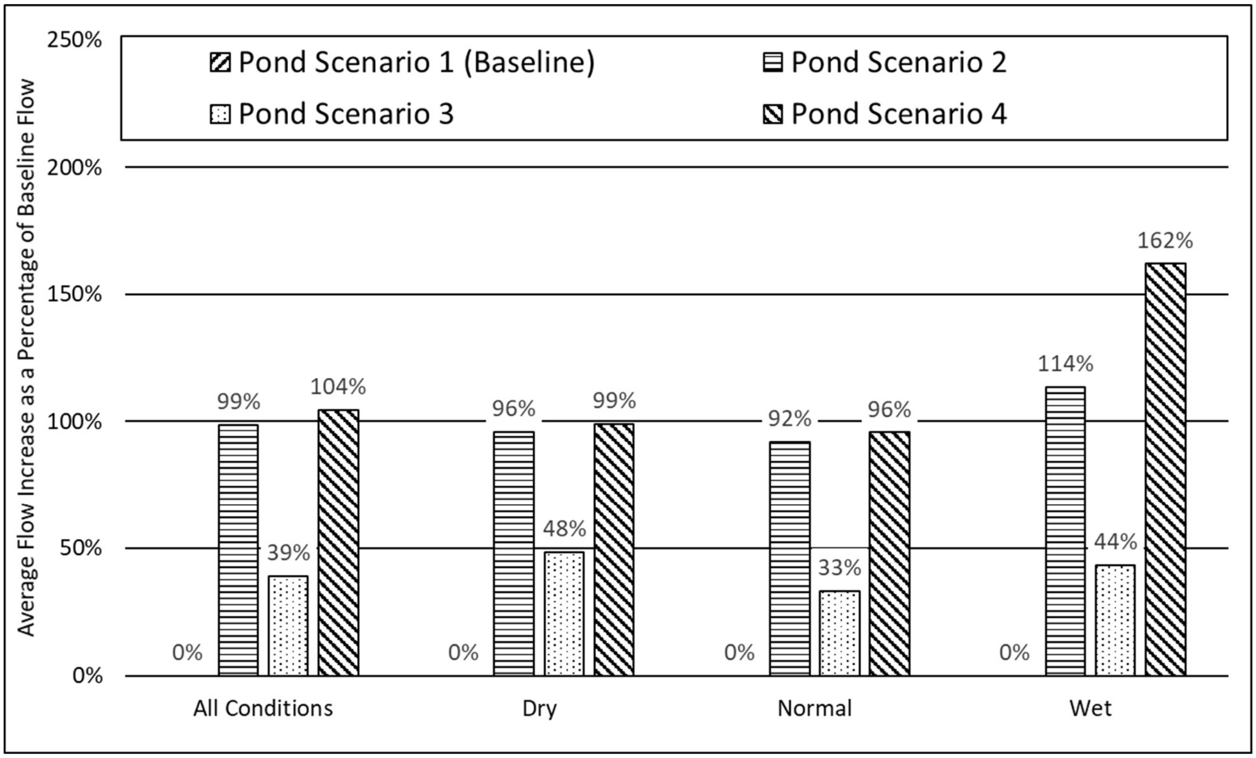


Figure 16. Average instream flow rate improvement expressed as a percentage of the baseline Pond Scenario 1 instream flow rate across all pond scenarios and hydrologic conditions. For example, a value of 104 percent indicates that where instream flow rate improvements were observed, on average the instream flow rate increased by 104 percent over the baseline instream flow rate for the pond scenario.

Second, local instream flow rates must have periods of sufficiently high flows to supply water to fill the supplemental storage. As shown previously in Figs. 6 and 7, agricultural shortages are prevalent throughout the system in the baseline scenario. However, the availability of water is more difficult to ascertain since an evaluation of available supply must include existing storage diversions and management impacts. In the GeoMODSIM model, supplemental storage nodes were added adjacent to existing storage and demand nodes. Within the model priority structure, supplemental storage was given a lower priority value than the associated instream flow demand node, the agricultural demand node, and the existing storage node, where applicable. In this way, the model guarantees that supplemental storage is only filled when instream flow rates are sufficiently high, agricultural demands are satisfied, and existing storage has already been filled.

Pond Scenario 3 was used to evaluate and calibrate supplemental storage options and did not include carryover storage as in Pond Scenario 4. Initially, all supplemental storage ponds were modeled with high storage volumes that effectively provided unlimited storage capacity, thereby allowing the maximum amount of storage to be retained in each pond when possible. Model nodes where supplemental storage was used represented locations in the system where additional storage could be considered and supplemental storage volumes were determined for each pond and for each of the 100 sets of hydrologic conditions by subtracting the final storage volume in a pond from the maximum storage volume attained throughout the water year. (Figure 17)

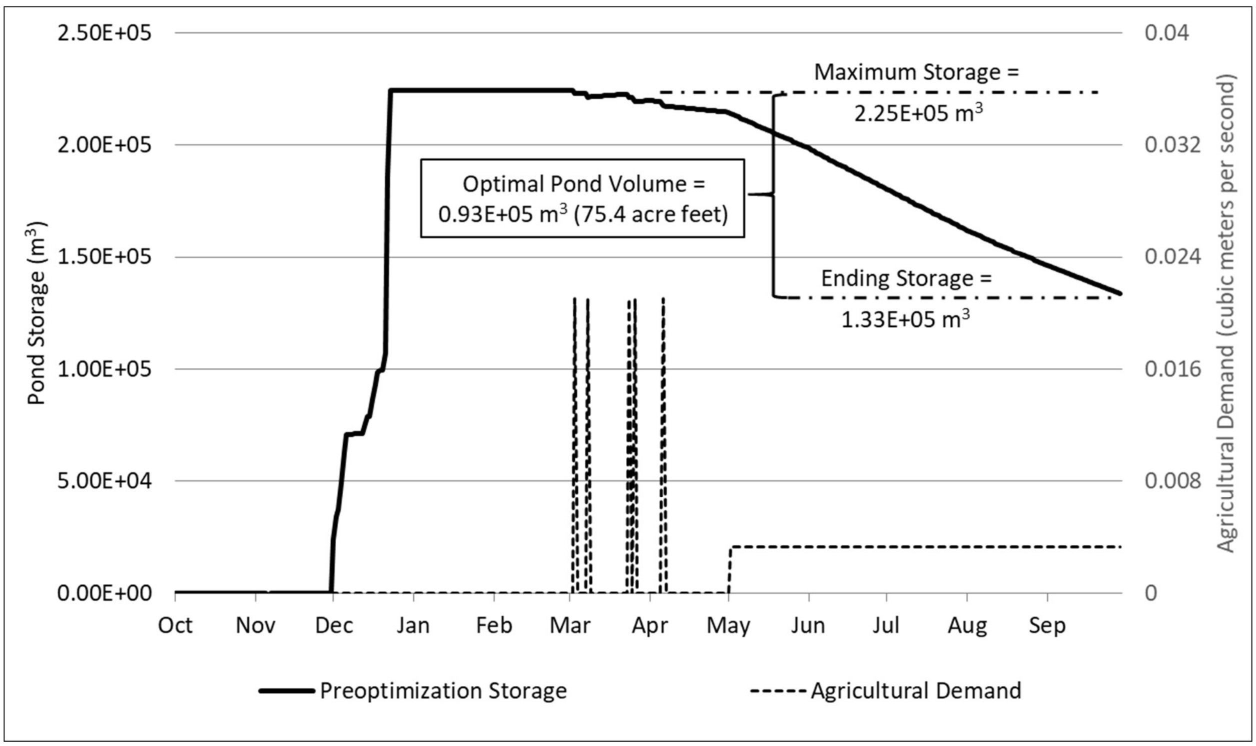
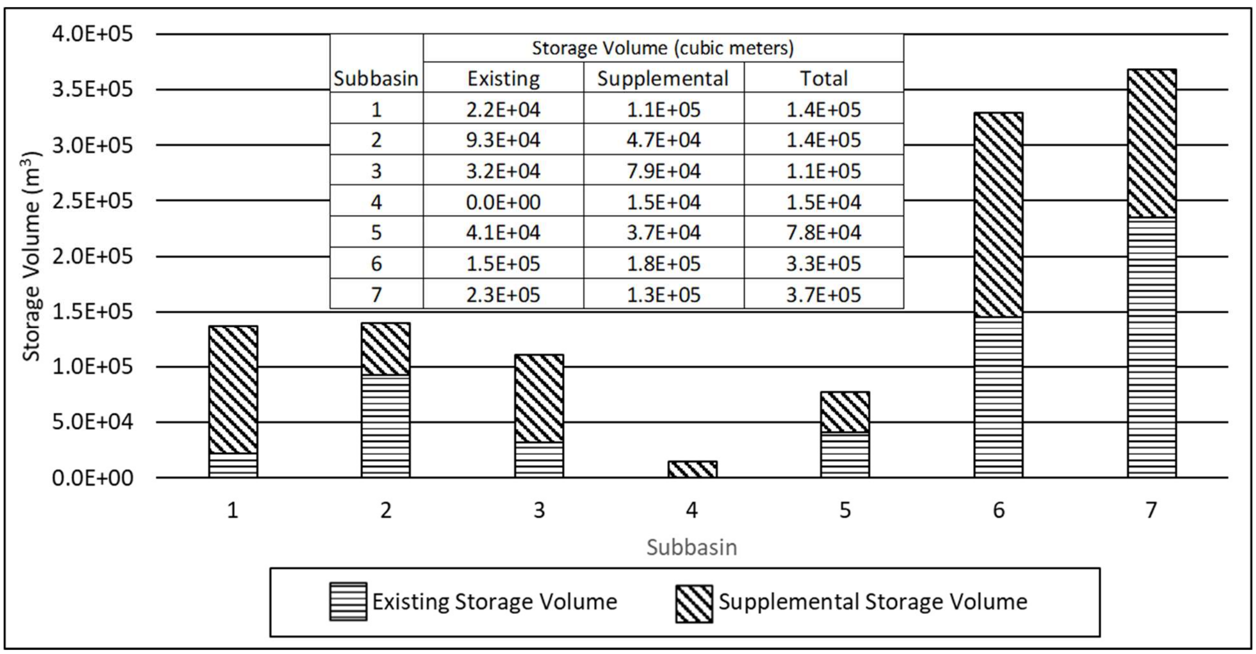


Figure 17. Example of supplemental storage pond operation and size calibration. The pond fills initially during large runoff events and storage is subsequently used to meet agricultural demands. Optimal pond volume is determined for each of the 100 sets of hydrologic conditions and the maximum of these volumes is applied as the final optimized pond volume.

Finally, a calibrated storage volume for each pond was determined as the largest supplemental storage volume determined across all pond conditions. These final calibrated storage volumes were used to determine final model results, as previously detailed.

Results indicate that all seven subbasins that were evaluated for supplemental storage potential (Figure 10) could benefit from and support additional storage. Optimal storage volume additions in each subbasin are summarized in Figure 18 and show that Subbasins 1, 6, and 7 can support the largest volumes of supplemental storage. However, when assessed as a percentage of existing storage, supplemental storage volume additions for Subbasins 1, 3, and 6 represent the largest fractional increases in storage over existing conditions, with increases of 522%, 246%, and 126%, respectively. Subbasin 4, which currently has no existing agricultural storage capacity, could benefit from 15,000 cubic meters (12.1 acre-feet) of supplemental storage.



Subbasin	Storage Volume (cubic meters)		
	Existing	Supplemental	Total
1	2.2E+04	1.1E+05	1.4E+05
2	9.3E+04	4.7E+04	1.4E+05
3	3.2E+04	7.9E+04	1.1E+05
4	0.0E+00	1.5E+04	1.5E+04
5	4.1E+04	3.7E+04	7.8E+04
6	1.5E+05	1.8E+05	3.3E+05
7	2.3E+05	1.3E+05	3.7E+05

Figure 18. Summary of existing storage, optimal supplemental storage, and total storage volumes by subbasin (Figure 10).

3.5 Discussion

3.5.1 Discussion – Agricultural Supply

The use of synthetic hydrologic datasets as the primary inputs to the coupled HL-RDHM and Geo-MODSIM model structure provides a tool to estimate the impacts of environmental regulations on agricultural surface water supply conditions and allows for the evaluation of management strategies for agricultural water supply across a wide range of hydrologic conditions. Results indicate that agricultural shortages are common throughout the system when environmental regulations that restrict diversions to periods of flow greater than minimum instream flow targets are employed. However, the number of agricultural supply shortages can be significantly reduced through the addition of supplemental agricultural storage ponds or by allowing carryover storage from the previous water year but is most significantly reduced by employing both strategies (Figure 12). The addition of supplemental storage and carryover storage extends storage reserves further into the summer irrigation season thereby reducing shortages associated with higher-frequency, lower-volume daily demands.

Volumetric agricultural shortages can also be addressed through the addition of supplemental storage and by allowing carryover storage from the previous water year. Contrary to the results for the number of agricultural shortages, the model indicates that carryover storage can have a greater impact on volumetric shortages than through the addition of supplemental storage (Figure 13). This discrepancy indicates that carryover storage helps to meet the high-volume demands associated with frost protection that occur earlier in the runoff season, thereby reducing the volumetric shortfall. When frost events occur prior to the significant runoff events that are needed to fill storage ponds, carryover storage provides a supply to meet these high-volume demands, which results in greater reductions of volumetric agricultural shortages.

Finally, the results indicate that, as modeled, agricultural shortages occur across all hydrologic conditions and for all management strategies modeled. While significant reductions of these shortages can be made through the addition of supplemental storage and by allowing carryover storage, additional management strategies are likely necessary to fully supply the agricultural demands of the system. Demand management strategies such as deficit irrigation and irrigation improvements are often used to bridge the gap created by limited water supplies and may a viable option in the Feliz Creek basin. Additionally, while the model indicates that the system is generally undersupplied as currently configured, it is likely that many of these strategies have already been employed to facilitate agriculture in the region. Further information on specific irrigation practices would reduce the assumptions needed to complete the model and would further close the gap between supply and demand.

3.5.2 Discussion – Instream Flow Impacts

As detailed throughout this study, natural instream flow rates in the Russian River and its tributaries, including Feliz Creek, frequently drop to levels below the minimum bypass flow. Consequently, these low flow periods are particularly susceptible to impacts due to local agricultural diversions as well as the cumulative effects of coincident upstream diversions such as those that commonly occur during frost events. While local diversion effects can be effectively mitigated through the use of environmental protections such as minimum bypass flow regulations, the cumulative effects of diversions further upstream can be more difficult to ascertain. The use of the coupled Geo-MODSIM/HL-RDHM model allows the effects of agricultural diversions on instream flow rates to be modeled across a broad set of hydrologic conditions and demonstrates the potential benefits that various management strategies can have on instream flow rates (Figure 14).

Model results indicate that improvements to low flow conditions can be realized through the use of supplemental storage as well as by allowing carryover storage from year to year. Overall, carryover storage provided the greatest benefits in both the number of instances where instream flow rates were improved (Figure 15) as well as the average quantitative instream flow rate improvement associated with each instance (Figure 16). The addition of carryover storage in Pond Scenarios 2 & 4 not only helps satisfy agricultural demands, thereby reducing instream flow impacts due to diversions, but it also increases the overall volume of water in the system from baseline conditions. This mechanism ultimately results in more instream flow rate improvements than what can be achieved with only supplemental storage across all hydrologic conditions. Not surprisingly, the benefits are greatest under dry hydrologic conditions. While the overall number of improvements to instream flows in Pond Scenario 3 (supplemental storage only) are not as significant as those seen in the scenarios that included carryover storage, the results can still be impactful. The Feliz Creek basin typically experiences low flow conditions (flow rates below the minimum bypass flow) for at least 90 percent of the year, regardless of overall hydrologic conditions. Based on this rate of occurrence, low flow improvements for three percent of these days would represent ten days a year of improved instream flow rates. As shown in Figure 14, these instream flow improvements can occur during extremely low flow periods and could be instrumental in avoiding potential fish stranding events.

Finally, the magnitude of the improvements made to instream flow rates were shown to be significant when evaluated as a percentage of baseline flows. Since most of the instream flow rate improvements are made during the dry season, these percentages represent relatively small volumes of water. However, as shown in Figure 14, these improvements often represent a restoration of instream flows to levels that are in line with natural flow rates that provide critical habitat for endangered fish. Overall, supplemental storage and carryover storage can have positive impacts to instream flow rates by providing supplies for upstream agricultural demands and reducing the cumulative impacts of diversions.

3.5.3 Discussion – Supplemental Storage

In the tributary systems of the Russian River basin, supplemental off-stream storage is commonly cited as a preferred management option for the mitigation of instream flow impacts associated with agricultural diversions. However, the viability of such options may be limited by agricultural demand constraints, instream flow availability, and operational impacts of upstream water use. By combining the distributed unimpaired flow estimates from HL-RDHM with the GeoMODSIM water management model, multiple options for supplemental off-stream storage ponds were evaluated and optimal sizes were determined at each location.

Within the seven subbasins identified for supplemental storage potential (Figure 10) thirteen different pond locations were evaluated as management alternatives. Of these thirteen, four locations were eliminated due to a lack of sufficient water supply for filling and the remaining nine were sized according to water availability and agricultural demands. Given their downstream location, Subbasins 6 & 7 generally have more available water supplies and support significant amounts of irrigated agriculture. Consequently, these two subbasins have the greatest potential for adding supplemental storage (Figure 18). Interestingly, the model results also indicate that Subbasin 1 can accommodate a significant amount of additional storage despite its upstream location. While the area of irrigated agriculture in Subbasin 1 is smaller than that found in more-downstream locations, existing storage in the subbasin is inadequate to meet the associated demands, creating the demand for supplemental storage.

As detailed, implementation of supplemental storage options in the Feliz Creek basin is dependent on water resource supply and demand limitations. However, there may be physical limitations on the feasibility as well. In the scope of this study, the supplemental storage management alternative may represent the construction of new off-stream storage but may also be accomplished through the expansion of storage in an existing pond.

3.6 Conclusions

As applied in the Feliz Creek basin, the coupled HL-RDHM/GeoMODSIM model structure demonstrated above provides an effective tool for evaluating overall system performance and water management options in a tributary-scale system that contains critical habitat for threatened salmonids and supports a thriving agricultural community. Driven by atmospheric river events, precipitation and runoff patterns in the basin are highly stochastic yet follow consistent seasonal patterns, which is key to the critical fisheries habitat of the basin as well as the ideal viticultural conditions of the region. Traditional agricultural practices that rely on direct stream diversions are shown to negatively impact instream flow rates during low flow periods while the complex regulatory structure in the region presents challenges for the implementation of irrigation water management alternatives such as the addition of supplemental storage. Furthermore, it was shown that restrictions on agricultural flow diversions to benefit environmental instream flows can lead to significant irrigation supply shortages.

Model results indicate that off-stream storage of water collected during periods of high flows can provide an impactful supply of water for spring frost protection as well as through the summer irrigation season. Even greater results can be achieved through the allowance of carryover storage from one year to the next. At the same time, instream flow conditions can be improved through the addition of supplemental off-stream storage, thereby providing environmental benefits to the system. During periods of low flow, instream flowrates were shown to improve significantly from baseline conditions when additional storage was included in the system. Finally, supplemental storage may not be a viable alternative in all areas due to a lack of adequate water supplies or insufficient demands in the area. The model provides a tool to identify the subbasins within the tributary system that would benefit from additional storage and determine the optimal storage volume at each location. While the final addition of supplemental storage in the system will be dependent on local factors such as water rights approvals and site suitability, this type of analysis is key to achieving environmental instream flow goals while continuing to support the agricultural industry of the region.

CHAPTER 4 – CONCLUSIONS

Water resource systems in arid and semi-arid regions face myriad challenges related to satisfying competing demands with limited water supplies. At the regional or river basin scale, these challenges are often met through the use of complex systems of reservoirs and water distribution facilities; however, at the tributary scale, management options may be more limited due to a lack of a centralized water management system. As an alternative, water users near tributary streams frequently rely on smaller projects to meet localized needs for water supply. Although the individual impacts of these smaller projects may be less significant than those of larger projects, localized and cumulative impacts can still be substantial.

The Russian River basin in Northern California is a region that is often strained by the competing interests of agricultural and environmental needs. The Mediterranean climate of the basin proves to be ideal for viticulture while at the same time providing critical habitat for a variety of threatened and endangered fish species. The disparate demands associated with agriculture, which relies on stream diversions for irrigation, and the stream ecology, which depends on a requisite amount of streamflows to thrive, has recently led to a series of events that indicate a need for better understanding of the stream system. Fish stranding events occur when streamflows are rapidly drawn down to levels that are insufficient for the fish to survive. The coincident nature of viticultural demands has been shown to contribute to such stranding events and as a result, restrictions have been imposed on agricultural diversions. While beneficial to the fisheries habitat, these restrictions can be particularly detrimental to agricultural water supplies. To achieve a better balance between the agricultural and environmental demands of the region, water managers need tools that provide a more complete understanding of the system and offer the ability to evaluate management alternatives.

A geospatial decision support system (geo-DSS) was developed to assess the impacts of agricultural use and environmental restrictions on tributary systems within the Russian River basin that are characterized by a highly seasonal and stochastic hydrology and are operated under an appropriated water rights system. Unimpaired flow estimates from the fine-scale (1/4 HRAP or approximately 1km grid) Hydrology Laboratory Research Distributed Hydrologic Model (HL-RDHM) were combined with GeoMODSIM, a GIS-based implementation of the MODSIM generalized river basin flow model. The resulting coupled framework combines spatially-distributed, precipitation-based, hydrometeorological streamflow estimates with a geospatial water management model that realistically accounts for the spatial and temporal impacts of water management decisions on instream flows. As a geo-DSS, the modeling structure is capable of assessing baseline conditions within the complex system and evaluating the overall impacts and benefits of management alternatives to guide the stakeholder decision-making process.

As a proof-of-concept implementation of the geo-DSS, the value of the modeling system was demonstrated on a representative tributary in the Russian River basin. In this application, baseline conditions were defined as including agricultural demands without the imposition of environmental flow restrictions and showed that significant streamflow impacts were evident during periods of pond filling and agricultural diversions, which is consistent with the observed impacts in the Russian River basin. A subsequent application assessed the impacts that minimum bypass flow environmental protections can have on the system. Results indicate that the restrictions improved instream flows during critical periods, as intended; however, agricultural needs were largely unsatisfied due to the regulations. In the final two scenarios, the advantages of replacing on-stream agricultural ponds with off-stream ponds were demonstrated and optimal pond sizes were determined. The overall results indicate that for an average water year, available water supplies are sufficient to meet the environmental needs of the system while ensuring adequate water supplies are available for the associated agricultural demands in the area.

A second implementation of the geo-DSS within the Russian River basin applied the model to the entire Feliz Creek tributary system to assess management impacts and alternatives across a wide range of hydrologic conditions. In this instance, baseline conditions were defined as those that include existing agricultural diversions and water rights as well as minimum bypass flow restrictions for environmental protection. Baseline conditions indicate agricultural supply shortages across all hydrologic conditions when minimum bypass flow restrictions are followed. Subsequent scenarios indicate that increasing off-stream water storage water during periods of high flows can significantly improve water supply availability for frost protection and summer irrigation demands. Even greater results can be achieved through the allowance of carryover storage from one water year to the next, a practice that is currently restricted in the region. Instream flow benefits were also realized when supplemental agricultural storage was included. During periods of naturally low flows, instream flow rates were shown to improve significantly from baseline conditions. As a final step, the geo-DSS was used to identify the subbasins within the tributary system that would benefit from additional storage and determine the optimal volume in each.

While these studies effectively demonstrate the benefits of a geo-DSS that combines the gridded hydrometeorological model HL-RDHM with the GeoMODSIM river basin flow model, the development process served to identify areas where additional improvements and advancements are possible. The coupling of HL-RDHM and GeoMODSIM was dependent on a series of manual operations and automated identification of analog points between the two models would increase efficiency and reduce potential for model inaccuracies. The disaggregation of HL-RDHM data could also be improved through an automated process that calculates the input flow datasets for the GeoMODSIM model from the base HL-RDHM data. Additionally, an alternate approach to disaggregation may be possible by using unrouted flow data from the HL-RDHM model as GeoMODSIM input and relying solely on the GeoMODSIM routing methodologies. The use of synthetic datasets was essential to analyze the system across a wide breadth of hydrologic conditions, however the use of actual HL-RDHM datasets generated from historical precipitation and temperature datasets would provide valuable insight to the system. Finally, while an interactive and collaborative interface was developed and implemented, there was a lack of stakeholder involvement. Additional direct input from stakeholders on management options and water use patterns in the basin would provide significant benefits by increasing credibility and acceptance by all interested parties and furthering the research applications of the geo-DSS.

REFERENCES

Berhe, F. T., Melesse, A. M., Hailu, D., and Sileshi, Y. (2013). “MODSIM-based water allocation modeling of Awash River Basin, Ethiopia, Catena, 109, 118-128.

Bonada, N., & Resh, V. H. (2013). Mediterranean-climate streams and rivers: geographically separated but ecologically comparable freshwater systems. Hydrobiologia, 719(1), 1-29.

Bottcher, J. L., Walsworth, T. E., Thiede, G. P., Budy, P., and Speas, D. W. (2013). “Frequent usage of tributaries by the endangered fishes of the upper Colorado River Basin: Observations from the San Rafael River, Utah,” North American Journal of Fisheries Management, 33(3), 585-594.

Boyd, J. A. (2003). "Hip deep: A survey of state instream flow law from the Rocky Mountains to the Pacific Ocean." Natural Resources Journal, 43, 1151-1216.

Briand, G., Schuck, E. C., and Holland, D. W. (2008). “Effects of flow augmentation in the Snake River basin on farms profitability,” Journal of the American Water Resources Association, 44(2), 360-366.

California Department of Fish and Game (CDFG) (2004). “Recovery strategy for California coho salmon: Progress report 2004-2012.” Report to the California Fish and Game Commission, Sacramento, CA.

California Department of Water Resources (CADWR) (2019). Water Resources Integrated Modeling System 2.0. Bay-Delta Office, California Dept. Water Resources, Sacramento, California, USA. ‹https://water.ca.gov/Library/Modeling-and-Analysis/Modeling-Platforms/Water-Resource-Integrated-Modeling-System›

California State Water Resources Control Board (SWRCB) (2010). “Policy for maintaining in-stream flows in Northern Coastal California streams.” SWRCB Division of Water Rights, Sacramento, CA.

California State Water Resources Control Board (SWRCB) (2011). Amendment to Division 3 of Title 23, California Code of Regulations §862, SWRCB, Sacramento CA.

Carlson, E. A., Cooper, D. J., Merritt, D. M., Kondratieff, B. C., & Waskom, R. M. (2019). Irrigation canals are newly created streams of semi-arid agricultural regions. Science of The Total Environment, 646, 770-781.

Cheong, T. S., Ko, I., and Labadie, J. W. (2010). “Development of multi-objective reservoir operation rules for integrated water resources management,” Journal of Hydroinformatics, 12(2), 185-200.

Clark, R. (2009). “DHM-frequency surface response supporting flash flooding decisions making.” Colorado Basin River Forecast Center, National Oceanographic and Atmospheric Administration, Salt Lake City, UT.

Cox, C., Schmidt. E., and Vendlinski, T. (2008). The Ponds Project: A summary and conclusions of a collaborative process for replacing summer stream diversions with winter diversions and off-stream storage ponds in San Mateo and Northern Santa Cruz Counties. Sustainable Conservation, San Francisco, CA ‹http://suscon.org/contact› (Jan. 10, 2018).

de Azevedo, L. G. T., Gates, T. K., Fontane, D. G., Labadie, J. W., and Porto, R. L. (2000). Integration of water quantity and quality in strategic river basin planning.” Journal of Water Resources Planning and Management, 126(2), 85-97.

Deitch, M. J., Kondolf, G. M., & Merenlender, A. M. (2009a). Surface water balance to evaluate the hydrological impacts of small instream diversions and application to the Russian

River basin, California, USA. Aquatic conservation: marine and freshwater ecosystems, 19(3), 274-284.

Deitch, M. J., Kondolf, G. M., & Merenlender, A. M. (2009b). Hydrologic impacts of small-scale instream diversions for frost and heat protection in the California wine country. River Research and Applications, 25(2), 118-134.

Deitch, M. J., Merenlender, A. M., & Feirer, S. (2013). Cumulative effects of small reservoirs on streamflow in Northern Coastal California catchments. Water Resources Management, 27(15), 5101-5118.

Dettinger, M. (2011). "Climate change, atmospheric rivers, and floods in California–A multimodel analysis of storm frequency and magnitude changes." Journal of the American Water Resources Association, 47(3), 514-523.

Dewandel, B., Gandolfi, J. M., De Condappa, D., & Ahmed, S. (2008). An efficient methodology for estimating irrigation return flow coefficients of irrigated crops at watershed and seasonal scale. Hydrological Processes: An International Journal, 22(11), 1700-1712.

Dogrul, E. C., Kadir, T. N., Brush, C. F., and Chung, F. I. (2016). "Linking groundwater simulation and reservoir system analysis models: The case for California's Central Valley." Environmental Modelling & Software," 77, 168-182.

Dogrul, E. C. and Kadir, T. N. (2019). "Integrated Water Flow Model IWFM-2015, Revision 828, Theoretical Documentation" [Technical Memorandum]. Bay-Delta Office: California Department of Water Resources. ‹https://data.cnra.ca.gov/dataset/iwfm-version-2015-0-828/resource/5c5f96ed-11af-4964-86cd-dbfec6d8bbbd› (July 18, 2019).

Environmental Systems Research Institute, Inc. (ESRI) (2010). ArcGIS Release 10. Redlands, CA.

Fares, A., Awal, R., Michaud, J., Chu, P-S, Fares, S., Kodama, K., Samira Fares, and Rosener, M. (2014). "Rainfall-runoff modeling in a flashy tropical watershed using the distributed HL-RDHM." Journal of Hydrology, 519, 3436–3447.Fernald, A. G., Baker, T. T., & Guldan, S. J. (2007). Hydrologic, riparian, and agroecosystem functions of traditional acequia irrigation systems. Journal of Sustainable Agriculture, 30(2), 147-171.

Fields, C. M., Labadie, J. W., & Johnson, L. E. (in press). GeoSpatial DSS for maintaining agricultural diversions under environmental flow requirements. Journal of Irrigation and Drainage Engineering.

Fields, C., Labadie, J., and Johnson, L. (2015). "Integrated hydrometeorological and water management modeling: Russian River tributaries project," CIRA Magazine, Cooperative Institute for Research in the Atmosphere, Colorado State University, CO, 42, 7-10.

Foti, R., Ramirez, J., and Brown, T. C. (2014). "A probabilistic framework for assessing vulnerability to climate variability and change: The case of the US water supply system." Climatic Change, 125, 413-437.

Flug, M., and Campbell, S. G. (2005). "Drought allocations using the Systems Impact Assessment Model: Klamath River." Journal of Water Resources Planning and Management, 131(2), 110-115.

Gasith, A., & Resh, V. H. (1999). Streams in Mediterranean climate regions: abiotic influences and biotic responses to predictable seasonal events. Annual review of ecology and systematics, 30(1), 51-81.

Glavan, M., and Pintar, M. (2012). “Modelling of surface water quality by catchment model SWAT.” Studies on water management issues, M. Kumarasamy (ed.), InTech, DOI: 10.5772/29581 ‹https://www.intechopen.com/books/studies-on-water-management-issues/modelling-of-surface-water-quality-by-catchment-model-swat› (April 4, 2018).

Graf, W. L. (1999). Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. Water resources research, 35(4), 1305-1311.

Grantham, T. E., Merenlender, A. M., & Resh, V. H. (2010). Climatic influences and anthropogenic stressors: an integrated framework for streamflow management in Mediterranean-climate California, USA. Freshwater Biology, 55, 188-204.

Grantham, T. E., Mezzatesta, M., Newburn, D. A., & Merenlender, A. M. (2014). Evaluating tradeoffs between environmental flow protections and agricultural water security. River Research and Applications, 30(3), 315-328.

Hines, D., Brian C., and Robert H. (2009). Scope of potential frost protection impacts on salmonids. Workshop on Frost Protection, California State Water Board, April 7, 2009.

HL-RDHM user manual v. 3.0.0. (2009). ‹http://www.cbrfc.noaa.gov/present/rdhm/RDHM_3_0_0_User_Manual.pdf› (Nov. 27, 2017).

Horizon Systems Corporation. (2013). NHDPlus Version 2 Dataset. ‹http://www.horizon-systems.com/NHDPlus/NHDPlusV2_home.php› (October 2014).

Houk, E. E., Frasier, M., and R. G. Taylor (2007). “Evaluating water transfers from agriculture for reducing water shortages in the Platte basin.” Journal of Water Resources Planning and Management, 133(4), 320-328.

Jakeman, A., Voinov, A., and Rizzoli, A. (2009). Environmental Modeling, Software and Decision Support, Elsevier.

Johnson, B. J. (2015). Reasonable Use on the Russian River: A Brief History of the Frost Protection Rule. Golden Gate U. Envtl. LJ, 9, 41.

Johnson, L., Cifelli, R., Chandrasekar, V., Halgren, J., Hsu, C., Hughes, M., Fields, C., Labadie, J., Wick, G. and Zamora, R. (2015). “Sea to summit to sea modeling for total water budget and decision support.” CIRA Magazine, Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, CO, 42, 1-6.

Johnson, L. E., C. Hsu, R. Zamora, and R. Cifelli (2016). Assessment and Applications of Distributed Hydrologic Model – Russian-Napa River Basins, CA. NOAA Technical Memorandum PSD-316, NOAA Printing Office, Silver Spring, MD, 101 pp. doi:107289/V5M32SS9.

Johnson, L. E. (2016) Distributed Hydrologic Model for Fishery Flows: Development of Flow Statistics. In progress.

Khan, S., Tariq, R., Yuanlai, C., & Blackwell, J. (2006). Can irrigation be sustainable?. Agricultural Water Management, 80(1-3), 87-99.

Kingsford, R. T. (2000). Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. Austral Ecology, 25(2), 109-127.

Koren, V., et al. (2004). "Hydrology laboratory research modeling system (HL-RMS) of the US national weather service." Journal of Hydrology, 291.3, 297-318.

Labadie, J. W. (2004). "Optimal operation of multireservoir systems: State-of-the-art review." Journal of Water Resources Planning and Management, 130(2), 93-111.

Labadie, J. W. (2012). “River basin management decision support system: User Manual and documentation.” ‹http://modsim.engr.colostate.edu› (Nov. 27, 2017).

López-Pomares, A., López-Iborra, G. M., & Martín-Cantarino, C. (2015). Irrigation canals in a semi-arid agricultural landscape surrounded by wetlands: Their role as a habitat for birds during the breeding season. Journal of Arid Environments, 118, 28-36.

Lytle, D. A., & Poff, N. L. (2004). Adaptation to natural flow regimes. Trends in ecology & evolution, 19(2), 94-100.

Markstrom, S. L., Niswonger, R. G., Regan, R. S., Prudic, D. E., and Barlow, P. M. (2008). "GSFLOW - Coupled ground-water and surface-water flow model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005)." U.S. Geological Survey Techniques and Methods, Book 6, Chapter D1, Washington D.C.

Markstrom, S. L., Regan, R. S., Hay, L. E., Viger, R. J., Webb, R. M. T., Payn, R. A., and LaFontaine, J. H. (2015). "PRMS-IV: The precipitation-runoff modeling system, Version 4." U.S. Geological Survey Techniques and Methods, Book 6, Chapter B7, Washington D.C.

Marques, G. F., Lund, J. R., Leu, M. R., Jenkins, M., Howitt, R., Harter, T., Hatchett, S., Ruud, N., and Burke, S. (2006). "Economically driven simulation of regional water systems: Friant-Kern, California." Journal of Water Resources Planning and Management," 132(6), 468-479.

Martz, J. (2014). "Management of Invasive Bullfrogs." Environmental Studies Undergraduate Student Theses. 134. ‹http://digitalcommons.unl.edu/envstudtheses/134›

Nash, J. E. and Sutcliffe, J. V. (1970). "River flow forecasting through conceptual models: Part I—A discussion of principles." Journal of hydrology, 10(3), 282-290.

National Marine Fisheries Service (NMFS) (2012). “Final recovery plan for central California coast coho salmon evolutionarily significant unit.” Southwest Fisheries Science Center, National Marine Fisheries Service, NOAA, La Jolla, CA.

National Weather Service (NWS) (2009). “HL-RDHM user manual v. 3.0.0.” [Technical Manual]. Hydrologic Sciences and Modeling Branch (HSMB), Hydrologic Laboratory (HL), Office of Hydrologic Development (OHB) – National Weather Service (NWS). ‹https://www.cbrfc.noaa.gov/present/rdhm/RDHM_3_0_0_User_Manual.pdf› (July 19, 2019).

Neitsh, S. L., Arnold, J. G., Kiniry, J. R., and Williams, J. R. (2011). “Soil and Water Assessment Tool: Theoretical documentation.” Technical Report No. 406, Texas Water Resources Institute, Texas A&M University, College Station, TX.

Oad, R., and Kullman, R. (2006). “Managing irrigation for better river ecosystems: A case study of the Middle Rio Grande.” J. Irrig. Drain. Eng., DOI: 10.1061/(ASCE)0733-9437(2009)135:2(177).

Patten, D. T. (1998). Riparian ecosystems of semi-arid North America: Diversity and human impacts. Wetlands, 18(4), 498-512.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E., & Stromberg, J. C. (1997). The natural flow regime. BioScience, 47(11), 769-784.

Poff, N. L., Olden, J. D., Merritt, D. M., & Pepin, D. M. (2007). Homogenization of regional river dynamics by dams and global biodiversity implications. Proceedings of the National Academy of Sciences, 104(14), 5732-5737.

Potter, K. W. (2006). Small-scale, spatially distributed water management practices: Implications for research in the hydrologic sciences. Water Resources Research, 42(3).

Pringle, C. M. (2000). Threats to US public lands from cumulative hydrologic alterations outside of their boundaries. Ecological Applications, 10(4), 971-989.

Pritchard, T. L. (2010). Irrigation management of winegrapes with a limited water supply. University of California Cooperative Extension, ‹http://ucmanagedrought.ucdavis.edu/ PDF/WINE-GRAPE% 20DROUGHT% 20LONG-1.pdf (2010)› (Nov. 27, 2017).

Ralph, F. M., Neiman, P. J., Wick, G. A., Gutman, S. I., Dettinger, M. D., Cayan, D. R., & White, A. B. (2006). Flooding on California's Russian River: Role of atmospheric rivers. Geophysical Research Letters, 33(13).

Reed, S. M., Schaake, J., and Zhang, Z. (2007). "A distributed hydrologic model and threshold frequency-based method for flash flood forecasting at ungauged locations." Journal of Hydrology, 337(3-4), 402-420.

Reiser, D. W., Wesche, T. A., and Estes, C. (1989). "Status of instream flow legislation and practices in North America." Fisheries, 14(2), 22-29.

Rolls, R. J., Leigh, C., & Sheldon, F. (2012). Mechanistic effects of low-flow hydrology on riverine ecosystems: ecological principles and consequences of alteration. Freshwater Science, 31(4), 1163-1186.

Russian River Independent Science Review Panel (RRISRP) (2016). Conceptual model of watershed hydrology, surface water and groundwater interactions and stream ecology for the Russian River watershed. <http://www.russianriverisrp.org/Downloads/ISRP_FINAL_REPORT.pdf> (April 12, 2019).

Schaible, G. D., and Aillery, M. P. (2017). "Challenges for US irrigated agriculture in the face of emerging demands and climate change." Chapter 2.2.1 in: Competition for water resources: experiences and management approaches in the US and Europe, J. Ziolkowska and J. Peterson (eds.), pp. 44-89, Elsevier, Amsterdam.

Schoof, R. (1980). ENVIRONMENTAL IMPACT OF CHANNEL MODIFICATION 1. JAWRA Journal of the American Water Resources Association, 16(4), 697-701.

Shim, J. P., Warkentin, M., Courtney, J. F., Power, D. J., Sharda, R., & Carlsson, C. (2002). "Past, present, and future of decision support technology." Decision support systems, 33(2), 111-126.

Shourian, M., Mousavi, S. J., and Tahershamsi, A. (2008). "Basin-wide water resources planning by integrating PSO algorithm and MODSIM." Water Resources Management, 22, 1347-1366.

Smakhtin, V. U. (2001). Low flow hydrology: a review. Journal of hydrology, 240(3-4), 147-186.

Smith, R. J., Klonsky, K. M., Livingston, P. L., & DeMoura, R. L. (2004). Sample Costs to Establish a Vineyard and Produce Wine Grapes: North Coast Region Sonoma County. University of California Cooperative Extension, Davis, California, USA.

Smith, R. J., Klonsky, K. M., and De Moura, R. L. (2010). "Sample costs to establish a vineyard and produce wine grapes: North Coast region, Sonoma County." University of California Cooperative Extension, Davis, CA.

Spina, A. P., McGoogan, M. R., & Gaffney, T. S. (2006). Influence of surface-water withdrawal on juvenile steelhead and their habitat in a south-central California nursery stream. California Fish and Game, 92(2), 81.

State Water Resources Control Board (SWRCB) (1997). Staff Report on the Russian River Watershed.

State Water Resources Control Board (SWRCB) (2010). Policy for maintaining instream flows in Northern California coastal streams.

State Water Resources Control Board (SWRCB) (2011). California Code of Regulations Title 23, § 862.

Tiessen, K. H. D., Elliott, J. A., Stainton, M., Yarotski, J., Flaten, D. N., & Lobb, D. A. (2011). The effectiveness of small-scale headwater storage dams and reservoirs on stream water quality and quantity in the Canadian Prairies. Journal of Soil and Water Conservation, 66(3), 158-171.

Triana, E., and Labadie, J. W. (2012). GIS-based decision support system for improved operations and efficiency conservation in large-scale irrigation systems. Journal of Irrigation and Drainage Engineering, 138(10), 857-867.

U.S. Congress, (1973). Endangered species act. US Code, 16, 1534-1544.

Vaghefi, S. A., Mousavi, S. J., Abbaspour, K. C., Srinivasan, R., and Arnold, J. R. (2013). "Integration of hydrologic and water allocation models in basin-scale water resources management considering crop pattern and climate change: Karkheh River basin in Iran," Regional Environmental Change, DOI 10.1007/s10113-013-0573-9.

Walls, S. (2013). A geomorphic typology to characterize surface-groundwater Interactions in the Russian River basin. Master's Thesis Graduate Division of the University of California, Berkeley.

Wohl, E., & Springer International Publishing AG. (2018). Sustaining River Ecosystems and Water Resources. Springer International Publishing.

APPENDICES

Appendix A Synthetic HL-RDHM Data Generation Using a Markov Chain Approach

Introduction

The geo-DSS developed for use in the Russian River basin is composed of two key components. The first is the GeoMODSIM river basin management software, which accounts for water management decisions and impacts such as the location and magnitude of direct stream diversions, water rights, and the location, size, and operation of agricultural ponds. The second component is HL-RDHM, which provides the primary forcing data for the GeoMODSIM model in the form of a distributed network of unimpaired streamflow estimations that is input at various points throughout the GeoMODSIM stream network. The distributed nature of this data is a key advantage of the coupled model approach to the geo-DSS structure and is a distinct advantage that HL-RDHM offers over the many other hydrologic modeling software options that produce streamflow estimations at a single point, which is often the basin outlet.

One shortcoming of the HL-RDHM model is that the breadth of available data for use in the geo-DSS is limited since its primary application uses real-time precipitation and temperature forcing data and has only been active since approximately 2011. As a result, the available distributed streamflow data set is comprised of only a narrow range of hydrologic conditions. A key feature of the geo-DSS is the ability to evaluate the impacts of management alternatives across a range of hydrologic conditions. By doing so, the geo-DSS can support decision making and build stakeholder confidence in the model and the results.

As an alternative to using HL-RDHM datasets generated from observed precipitation and temperature data, a method of generating synthetic HL-RDHM data was developed. Johnson (2016) performed an investigation of flow statistics for Russian River tributaries to support water managers efforts to make ecological improvements to stream systems. At its essence, this work establishes correlations between long-term Russian River flow data that is available for the period from 1953 to present and Feliz Creek gage data that is available between 1959 and 1966. From there the Feliz Creek gage data was correlated to the HL-RDHM model output at the gage location and which can again be correlated to upstream grid cells using area-normalized HL-RDHM data. Using this series of correlations, Russian River gage data was used to generate synthetic HL-RDHM data for upstream cells within the Feliz Creek basin and from these values flow statistics were generated.

Using the correlative approach detailed by Johnson (2016), a method of producing synthetic HL-RDHM data was developed for use within the geo-DSS is generally shown in Figure 1 and for which the steps are detailed below.

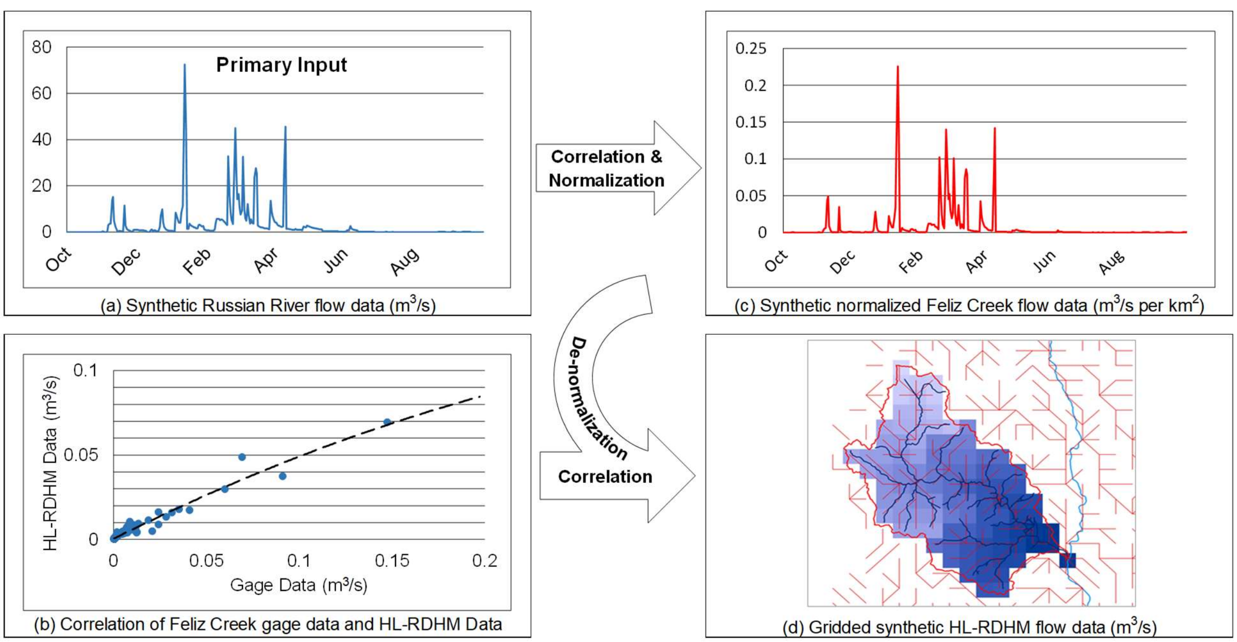


Figure 1. Synthetic HL-RDHM data creation. (a) Synthetic Russian River data is generated using a Markov Chain approach. (b) Synthetic normalized data is produced based on a correlation to the synthetic Russian River data. (c) A priori correlations between Feliz Creek gage data and HL-RDHM model data are combined with (b) to generate (d) gridded synthetic HL-RDHM datasets that are de-normalized for use as inputs to the GeoMODSIM streamflow management model.

Step 1 – Generate Synthetic Russian River Flow Data

The first step needed to generate synthetic HL-RDHM data is the generation of synthetic Russian River flow data. When properly applied, stochastic models can be used to represent hydrologic time series, such as the Russian River flow data, based on hydrologic series statistics. For time periods shorter than a year, hydrologic series can often exhibit shifts or trends in the data that are generally referred to as seasonality. Unimpaired flows in Russian River tributaries exhibit strong seasonality and stochasticity. The wet season, driven by atmospheric rivers and which generally extends from November through April, is characterized by intense precipitation events and correspondingly high peak flows in the stream system. Conversely, the dry season is characterized by a general lack of significant precipitation events and unimpaired stream flows that generally diminish from May to October. Statistical analysis of unimpaired flows in the Russian River basin (Johnson, 2017) confirms this seasonal variation. A variety of methods were investigated to generate synthetic streamflow data for the Russian River and are detailed below.

<u>AR Model</u>

A variety of stochastic models could be considered for representing hydrologic time series, but in general, autoregressive (AR) and autoregressive with moving average terms (ARMA) models are capable of accommodating most typical hydrologic cases. (Salas, 1993) However, AR models are more generally considered less flexible than ARMA models given that AR models depend on a single parameter while ARMA models depend on two parameters. Given this distinction, AR processes could be characterized as short-memory processes and ARMA processes as long-memory processes. Due to the "flashy" nature of flows in the Russian River basin as well as the fact that the model is being applied to smaller tributaries within the basin, the AR model was seen as a good option for modeling flows within the Russian River and Feliz Creek basins.

The AR(p) model defines a time series with the following equation:

$$y_t = \mu + \sum_{j=1}^{p} \varphi_j \left(y_{t-j} - \mu\right) + \varepsilon_t \qquad (1)$$

where:

y_t	=	Flow rate at time step t
μ	=	Mean flow rate
j	=	Correlated time step number
p	=	Total number of correlated time steps
ϕ_j	=	Parameter equal to the autocorrelation coefficient of time step j
y_{t-j}	=	Flow rate at time step t-j
ε_t	=	Uncorrelated random error term

After seasonal standardization, lower-order AR(p) models have been used for simulating daily flows and the AR(1) model takes on the form:

$$y_t = \mu + \varphi_1 (y_{t-1} - \mu) + \varepsilon_t \qquad (2)$$

where:

y_t	=	Flow rate at time step t
μ	=	Mean flow rate
ϕ_1	=	Parameter equal to the lag-1 autocorrelation coefficient
y_{t-1}	=	Flow rate at time step t-1
ε_t	=	Uncorrelated random error term

The use of the AR(1) model is predicated on the consideration of seasonality in the streamflow model. Partitioning the stream flow data into monthly segments can be used to account for seasonal variations in the mean and standard deviation.

To generate daily synthetic data, the lag-1 autocorrelation coefficient was determined from daily data. Also, it is reasonable to assume that flow patterns in the Russian River basin are similar throughout the basin. In the absence of long-term daily data throughout the basin, the daily lag-1 autocorrelation coefficients can be determined from daily Russian River gage data, preferably from the Ukiah gage since it is nearest to Feliz Creek.

The final key term in the AR(1) model is the error term, ε_t. This term must be an uncorrelated series that can be determined using the lag-1 autoregressive process.

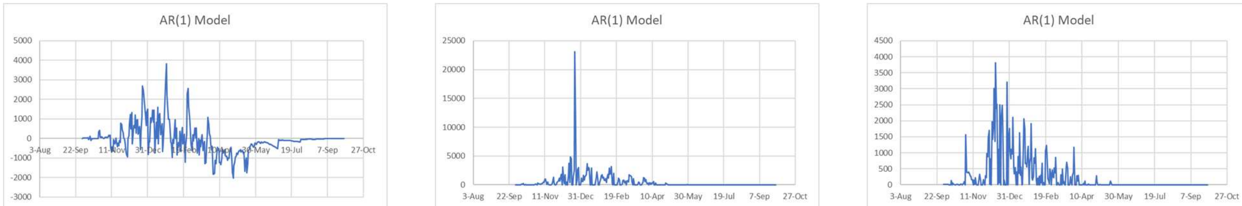
$$\varepsilon_t = y_t - \varphi_1 y_{t-1} \qquad (3)$$

where:

ε_t	=	Uncorrelated random error term
y_t	=	Flow rate at time step t
ϕ_1	=	Parameter equal to the lag-1 autocorrelation coefficient
y_{t-1}	=	Flow rate at time step t-1

By using equation (3), an uncorrelated series of error terms can be determined using the same daily Ukiah gage data that was used to develop the lag-1 autocorrelation coefficients. Based on this series, an error distribution can be developed for use within equation (2) that can be used for synthetic streamflow data simulation.

Results for the AR(1) approach to Russian River synthetic data generation were poor. The extreme stochasticity of the basin caused multiple errors in the synthetic data generation that were not realistic. Most evident, as seen in Figure 2(A), are the negative values generated by the model. The error distribution often resulted in negative error terms (ε_t) that exceeded the mean flowrate (μ) in magnitude, resulting in an overall negative flowrate. To correct this, minimum flow values were limited to zero in a subsequent implementation of the AR(1) model. As shown in Figure 2(B) and 2(C), this method eliminated the negative values and generated flows that were seasonal in nature. However, the inherent stochasticity of the model resulted in flow patterns that were inconsistent with natural flow patterns. Recession curves were often eliminated, zero flow conditions were prevalent, and the overall number of rainfall events indicated by the synthetic data was higher than is typical in the basin.



(A) (B) (C)

Figure 2. Example AR(1) synthetic data generation results. (A) High stochasticity results in negative error terms that are greater than the average flow rate and negative flows. (B) & (C) Model is constrained to a minimum flow value of zero and shows reasonable seasonality but exaggerated stochasticity and too many zero-flow days result in a poor representation of the basin conditions.

<u>PARMA Model</u>

The AR(p) model described above can be expanded to include the effects of variable average flows and periodicity in the flow data. While some methods of adjusting the model to include these effects were described above, the base AR(p) model can be amended to include terms to account for seasonality and moving averages. The periodic autoregressive moving average model (PARMA) is useful for modeling periodic hydrologic time series and is described by the following equation.

$$y_{\nu,t} = \mu_t + \varphi_{1,t}\left(y_{\nu,t-1} - \mu_{t-1}\right) + \varepsilon_{\nu,t} - \theta_{1,t}\varepsilon_{\nu,t-1} \quad (3)$$

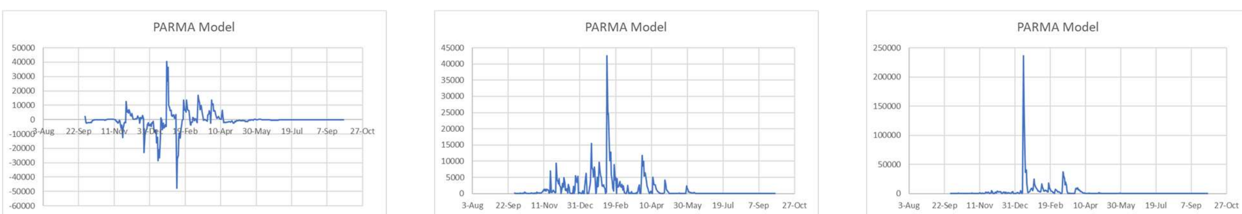
where:

$y_{v,t}$	=	Flow rate in year ν at time step t
μ_t	=	Mean flow rate for time step t
$\phi_{1,t}$	=	Parameter equal to the lag-1 autocorrelation coefficient for time step t
$y_{v,t}$	=	Flow rate in year ν at time step t-1
μ_{t-1}	=	Mean flow rate for time step t-1
$\varepsilon_{\nu,t}$	=	Uncorrelated random error term for time step t
$\theta_{1,t}$	=	Moving average parameter for time step t
$\varepsilon_{\nu,t-1}$	=	Uncorrelated random error term for time step t-1

The model can be applied seasonally, but the time step t can represent any period, including daily flows, without loss of generality in the equation. The mean flow for time step t (μ_t) could be either a daily or monthly value.

The lag-1 autocorrelation coefficient ($\varphi_{1,t}$) was computed on a daily basis using Russian River gage data from the Ukiah gage. The mean flow rate for the previous time step (μ_{t-1}) is the monthly or daily value, as previously discussed for the current time step average. The uncorrelated random error terms $\varepsilon_{v,t}$ and $\varepsilon_{v,t-1}$ are normal variables with mean zero and variance $\sigma_t^2(\varepsilon)$. The variance of the daily errors can be determined on a daily or monthly basis and corresponds to the average value convention used. The moving average parameter is determined by solving a system of simultaneous equations based on the seasonal mean, seasonal standard deviation, and the lag-1 season-to-season correlation coefficients.

Results for the PARMA model were slightly better than those of the AR(1) model, but not significantly. Similar trends associated with the error terms were evident – negative flowrates, excessive peak events, and a preponderance of zero-flow days (see Figure 3). Recession curves following high-flow events seemed to show improvement from the AR(1) model and warranted further investigation into the PARMA model.



(A) (B) (C)

Figure 3. Example PARMA synthetic data generation results. (A) High stochasticity results in negative error terms that are greater than the average flow rate and negative flows. (B) & (C) Model is constrained to a minimum flow value of zero and shows reasonable seasonality and improved recession curve patterns but retained exaggerated stochasticity and an excessive amount of zero-flow days.

<u>Statistical Model Refinements</u>

Subsequent efforts were made to refine the PARMA model implementation so that the effects of the error term would be mitigated. First, monthly averages for mean streamflow values were replaced with rolling averages, typically +/-7 days or +/-15 days. This was intended to transition smoothly between months in the model. As seen in Figure 4, the +/-15-day window results in a smoother curve but may remove some natural trends that are evident in the +/-7-day window.

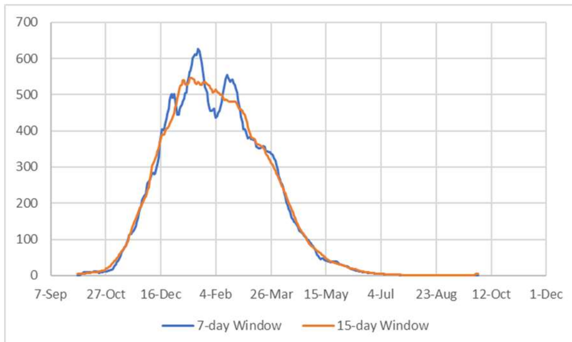
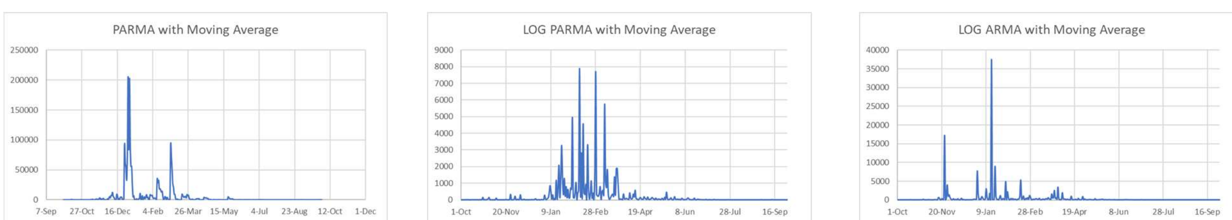


Figure 4. Moving-average flowrates using variable time windows

As seen in Figure 5 (A), the inclusion of a rolling average in the calculation appears to have improved the seasonality of the model but overall results were not significantly improved. Additional models implemented the model using a log-based approach, however these results also exhibited the same challenges seen in previous models (see Figure 5(B) and (C)).

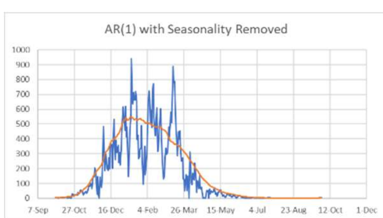


(A) (B) (C)

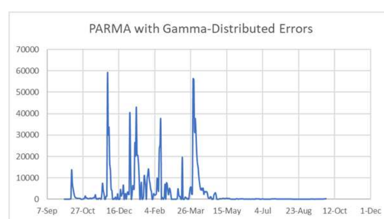
Figure 5. Example synthetic data generation results. (A) PARMA with +/-15-day rolling average (B) & (C) Log-PARMA and Log-ARMA models using a daily moving-average window of +/-15 days. Models exhibit reasonable seasonality but show exaggerated stochasticity and an excessive amount of zero-flow days.

Two subsequent attempts at creating synthetic data from a statistically-based model focused on the distribution of the errors. Errors in the AR(1) and PARMA models are assumed to be normally distributed, which is a primary reason that error terms frequently exceed the average flow term and negative flow values are modeled. To refine the error dataset into one that fits a normal distribution, Grubb's test for outliers was applied to the dataset to eliminate perceived outlying errors. The overall approach aims to remove seasonality in the dataset prior to fitting a normal distribution to the error dataset. The result of this approach was an overall flow pattern that overemphasized average flow value and muted the error terms. However, the occurrence of zero-flow days was greatly reduced (see Figure 6(A)).

The final approach focused on the use of a different distribution of the error terms. The previous approach indicated that the assumption of a normal distribution did not appear to be correct. As an alternative, a gamma distribution was applied to the error terms to reduce the number of negative or zero-flow values while maintaining the potential for peak flows in the model. While these model aspects were improved, the PARMA model with gamma-distributed errors typically exhibited many of the same problems as previous models – increased peak runoff events, a shortened or absence of a post-runoff recession curve, and excessive zero-flow days, despite an improvement from previous models.



(13)



(B)

Figure 6. Example synthetic data generation results. (A) AR(1) model with rolling average (orange line) and Grubb's Test applied (B) PARMA model with gamma-distributed error terms.

<u>Markov Chain Approach</u>

As shown previously, a variety of attempts were made to use a statistical model to generate synthetic flow datasets for the Russian River basin. However, none of the modeled datasets were able to encompass the stochasticity and seasonality of the system while generating representative streamflow patterns that include recession curves, non-zero minimum flowrates, and an appropriate level of peak flow events.

As an alternative, a Markov Chain approach that leverages on the extensive set of gage data available for the Russian River was developed. At its essence, this method begins with a general assumption that the record of over 60 years of daily streamflow data presents a wide array of information that, while not comprehensive, is broadly representative of the most prevalent streamflow conditions in the basin. With this assumption, it can be further surmised that by sampling data from various annual sets of data and combining them, a new, realistic set of data can be created. Using a Markov Chain approach, the individual sources of data can be determined, and an essentially unlimited number of datasets can be produced. The general approach is shown as a flow chart in Figure 7 and the steps are detailed below.

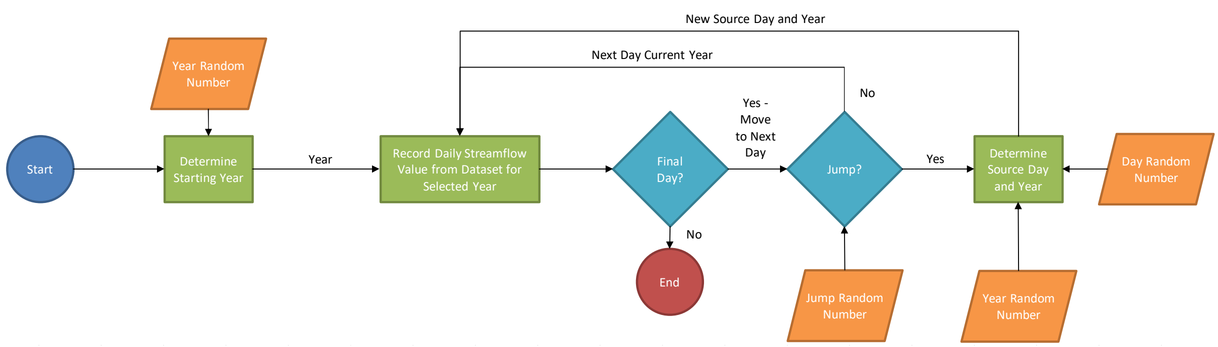


Figure 7. Flow chart for Markov Chain data generation.

Step 1 – Determine Starting Year. Based on a random number, select a year to begin data selection from and record this value from the source dataset into the destination dataset. Initial start day is October 1, the beginning of the water year.

Step 2 – Move to Next Day in Destination Dataset. As an example, in the second overall step this would be October 2. If the destination dataset day is September 30, process ends and synthetic streamflow data record is complete.

Step 3 – Determine Jump Status. Based on a random number, determine if the next value will come from existing year of data (90% probability) or a different year of data (10% probability). This is termed a "jump" to a different year.

- If no jump, record subsequent day of data from source dataset into the destination dataset and return to Step 2.
- If a jump, go to Step 4.

Step 4 – Determine Source Dataset Day and Year. Based on a random number, determine the year to jump to for the next source dataset. (This may be the current year.) Using another random number determine which day within the source dataset to jump to. Record this value and return to Step 2.

- The day to jump to can be within a +/-5 day window from the current destination dataset day. For instance, if the process is being used to fill in data in the destination dataset for November 10, the model may jump to a day in the source dataset between November 5 and November 15 and continue from there. This recognizes that conditions can vary within a certain period and ensures that peak flows will be prevented from occurring only on specific dates on which they have occurred in the past.
- The destination dataset day and the source dataset day will progress separately but will never be separated by more than 5 days.

The process is detailed in another way in Figure 8(A), where the following steps are evident –

- For March 5 in the destination dataset, the source dataset year is 1977 and the source dataset day is also March 5.
- For five days no jump occurs and consecutive days of data from 1977 are input in the destination dataset.
- For March 11 in the destination dataset, the model jumps to a different source year, in this case 1961. Additionally, the model jumps ahead by two days from the destination day so that the data source is March 13, 1961. Both the year and day jumps were determined randomly.

- For six subsequent days there is no jump and for March 11-17 in the destination dataset, the model data source is March 14-19, 1961.
- On March 18 in the destination dataset, the model jumps again, this time to March 14, 1992. This day is within the +/-5 day window specified previously. The model continues to select from 1992 data through the end of the example.

(A)

		Destination Dataset																
		5-Mar	6-Mar	7-Mar	8-Mar	9-Mar	10-Mar	11-Mar	12-Mar	13-Mar	14-Mar	15-Mar	16-Mar	17-Mar	18-Mar	19-Mar	20-Mar	21-Mar
		1560	739	543	3670	1310	675	217	192	182	168	156	140	132	79	75	80	680
Source Datasets	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	1959	2540	2680	1190	2590	1020	666	521	437	978	776	535	412	341	278	229	220	204
	1960	93	410	243	405	371	377	413	293	227	930	1810	1160	1340	794	695	574	448
	1961	1480	1930	1020	601	416	317	303	251	217	192	182	168	156	140	132	124	116
	1962	49	54	54	49	51	46	43	39	36	41	44	157	132	100	81	70	61
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	1975	304	223	170	139	117	99	86	74	64	57	53	50	45	42	46	55	43
	1976	6.6	6.2	5.8	5.5	10	22	14	12	13	11	87	142	87	58	38	25	20
	1977	1560	739	543	3670	1310	675	449	334	272	232	201	180	161	146	136	125	116
	1978	359	280	227	190	159	135	119	107	96	87	99	106	152	103	95	86	81
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	1991	114	368	235	195	158	134	116	103	92	84	125	1400	1570	771	465	331	262
	1992	137	126	115	106	98	90	84	79	76	79	75	80	680	551	316	217	170
	1993	89	85	73	66	60	56	53	49	45	42	39	38	35	33	30	27	27
	1994	85	77	64	600	5440	2650	2220	1320	2760	4500	1770	886	667	1220	688	2270	1350
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

(B)

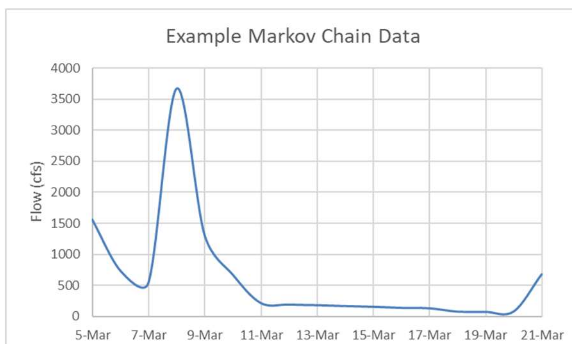


Figure 8. (A) Example Markov Chain data generation detailing “jumps” from one source dataset to another in order to create a single set of streamflow data. (B) Resulting Markov Chain dataset plot.

The resulting dataset from Figure 8(A) is plotted in Figure 8(B). As is evident, the resulting dataset appears realistic and seamlessly blends portions of multiple datasets into a single synthetic dataset. In Figure 9 four examples of complete datasets are presented. When compared to the stochastically-generated AR(1) and PARMA model results from earlier, the benefits of the Markov Chain approach are apparent. First, the seasonality and stochasticity of the natural system is maintained. Second, intermediary flows between peak runoff events as well as flows during the dry season return to normal levels and do not fall to zero as frequently occurred in the statistical models. Third, while it is possible for the Markov Chain approach to result in sharp drops from peak flows to low flows, recession curves following peak flow events are more-generally maintained with this approach. Finally, the number of peak flow events is more consistent with observed conditions in the basin. Overall, the Markov Chain approach for synthetic data generation performed best and was selected to generate the primary input for the synthetic HL-RDHM data generation process (Figure 1(a)).

Step 2 – Establish Intercell HL-RDHM Correlations

As first investigated by Johnson (2016), HL-RDHM flow patterns upstream of the basin outlet show similar trends in the flow data (e.g. corresponding peak flows) however flow response following precipitation events is dependent not only on upstream contributing area but on stream typology, as well (see Appendix B). Consequently, the correlation of HL-RDHM flows from the basin outlet to upstream cells would need to consider both sources of variation.

As detailed in Appendix B, area-normalized flows can be used to explain the variations in flow response seen in sections of differing stream typologies. Expanded to this application, area-normalized streamflow data can also be used to describe the relationship between flows at the basin outlet with flows at upstream grid cells. By developing correlations between points based on area-normalized flows, influences from stream characteristics such as typology will be captured (e.g. "flashy" responses to precipitation in bedrock canyon stream sections and delayed responses with increased groundwater contributions in alluvial-type stream sections during dry periods).

The HL-RDHM model for the Feliz Creek watershed includes 99 cells. For each of the 98 cells above the basin outlet cell, area-normalized HL-RDHM data was scatter-plotted against

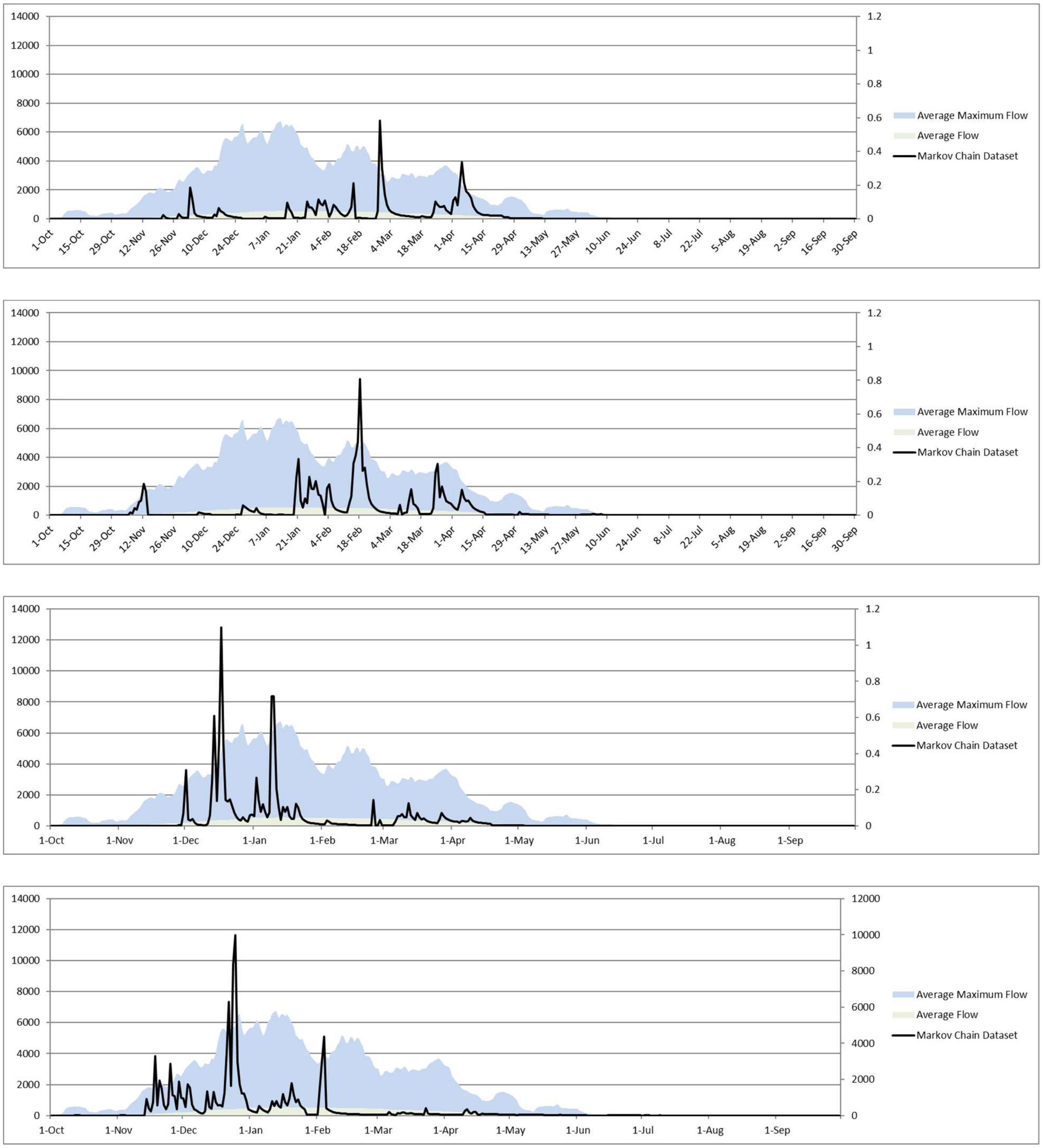


Figure 9. Four example Markov Chain-generated streamflow datasets for the Russian River at Ukiah. The synthetic datasets exhibit the seasonality and stochasticity of the natural system while maintaining accurate low-flow conditions between peak events and during the summer dry season.

that from the basin outlet. A second-order polynomial fit was then made to the data to establish a relationship that could be used to correlate basin outlet flow data to the upstream cell flow data (see Figure 10). Overall, R2 values for the polynomial fit averaged 0.89, which is considered very good, and ranged between a minimum value of 0.59 and a maximum value of 0.99.

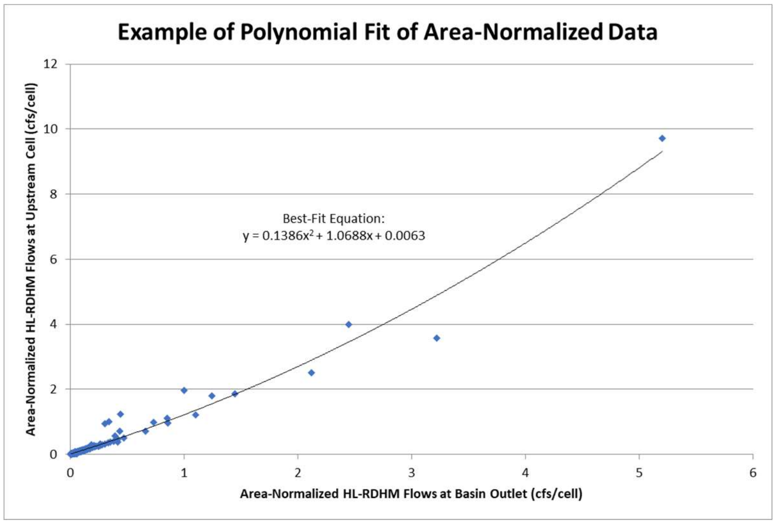


Figure 10. Example scatter plot of area-normalized data with second-order polynomial fit of data

Step 3 – Establish Correlation Between Russian River Flow Data and HL-RDHM Data at Feliz Creek Basin Outlet

As detailed in Step 1, a method has been developed to generate synthetic data for the Russian River at the Ukiah gage. As further detailed in Step 2, synthetic HL-RDHM data for upstream cells in the Feliz Creek basin can be generated from HL-RDHM data at the basin outlet. To allow for the generation of synthetic HL-RDHM data for the entire Feliz Creek basin, a correlation between Russian River gage data and HL-RDHM data at the Feliz Creek basin outlet is required.

As detailed by Johnson (2016), a USGS streamflow gage was in place at the Feliz Creek outlet for the period between 1959 and 1966 and correlations between the Feliz Creek gage and the Russian River gage is considered moderate to good in nature. To better describe the relationship, two correlations were made, one for low-flow conditions and one for all other conditions (see Figure 11).

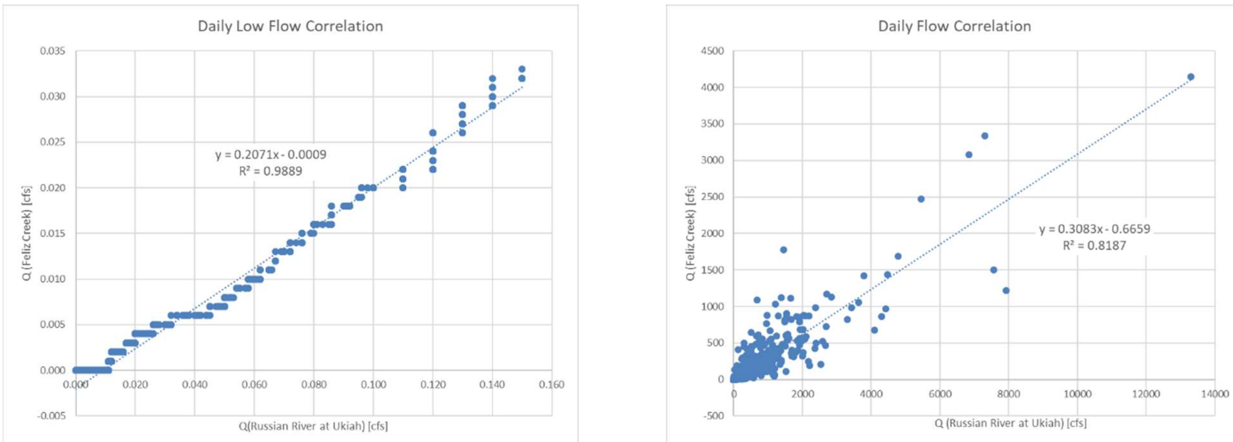


Figure 11. Correlations of Russian River gage data (Ukiah) with Feliz Creek gage data for daily low flow and normal conditions (per Johnson, 2016)

While HL-RDHM is used to estimate streamflows at the site of the Feliz Creek gage, a final correction is still necessary to estimate HL-RDHM data from Feliz Creek gage data inputs. In his work, Johnson (2016) observed a bias in the simulated data that pointed toward underestimation of flows by the HL-RDHM model. When compared to data collected from a National Marine Fisheries Service gage at the Feliz Creek basin outlet, HL-RDHM data for low

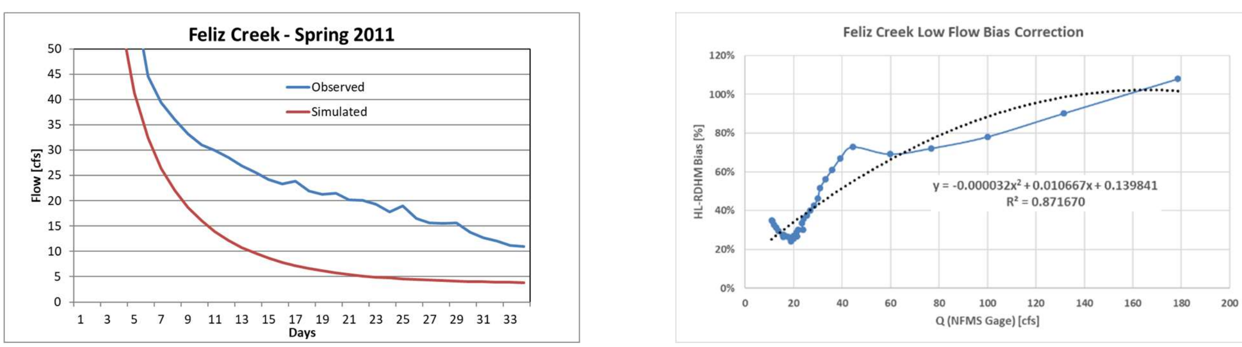


Figure 12. Bias correction for HL-RDHM data based on NMFS gage data (per Johnson, 2016)

flow conditions were consistently less than gaged flows. Consequently, for flowrates at or below 200 cfs, a bias correction was applied per Figure 12.

Combining the correlations shown in Figure 11 with the bias correction shown in Figure 12, an estimation of HL-RDHM flows at the Feliz Creek basin outlet can be determined from Russian River flow data.

Step 4 – Correlate and De-Normalize Flows

The final step in the synthesis of HL-RDHM data is the application of the correlations detailed in Steps 2 & 3 and de-normalization of the data into a distributed dataset of synthetic HL-RDHM data. From an initial set of synthetic Russian River streamflow data, area-normalized HL-RDHM data is generated using the series of correlations from Steps 2 & 3. These datasets are then de-normalized by multiplying the normalized values by the upstream contributing area for each cell. Figure 13 shows an example of synthetic Russian River flow data and the data generated for an HL-RDHM grid cell in the Feliz Creek basin.

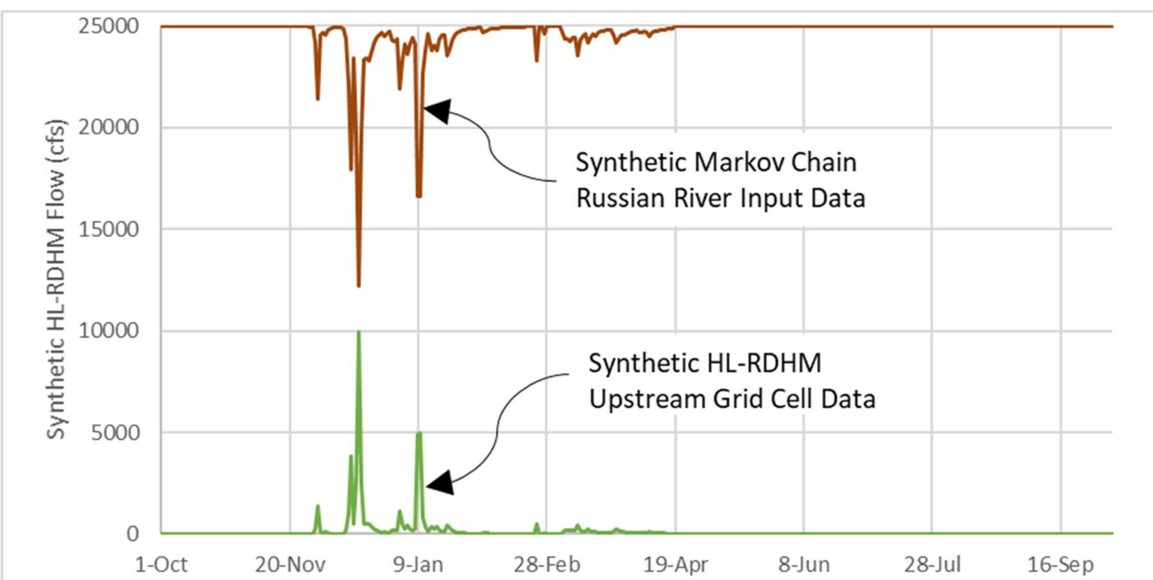


Figure 13. Example synthetic HL-RDHM data generated from synthetic Russian River gage data.

As is evident, the peak flow events and general flow patterns evident in the Russian River data are translated to the synthetic data for the HL-RDHM grid cell.

Summary

In order to support the decision process, the geo-DSS must be applied across a wide array of hydrologic scenarios to assess the system's operation in all conditions. However, HL-RDHM input data is only available for a limited window of time and does not encompass a comprehensive set of hydrologic conditions. As an alternative, a method of synthetic data generation was presented that uses an extensive set of streamflow data and a Markov Chain approach to produce synthetic Russian River data. By correlating this data to the HL-RDHM model cells in the Feliz Creek basin, it is possible to generate synthetic HL-RDHM datasets to represent a full range of hydrologic conditions and allow the analysis of the Feliz Creek system under any conditions.

Appendix References

Johnson, L. E. (2016) Distributed Hydrologic Model for Fishery Flows: Development of Flow Statistics. In progress.

Koren, Victor, et al. “Hydrology laboratory research modeling system (HL-RMS) of the US national weather service.” Journal of Hydrology 291.3 (2004): 297-318.

National Weather Service (NWS) (2009). “HL-RDHM user manual v. 3.0.0.” [Technical Manual]. Hydrologic Sciences and Modeling Branch (HSMB), Hydrologic Laboratory (HL), Office of Hydrologic Development (OHB) – National Weather Service (NWS). ‹https://www.cbrfc.noaa.gov/present/rdhm/RDHM_3_0_0_User_Manual.pdf› (July 19, 2019).

Salas, J. (1993). Analysis and Modeling of Hydrologic Time Series. In D. Maidment (Ed.), Handbook of Hydrology (Chap. 19). Vol. 9780070. New York: McGraw-Hill.

Appendix B Stream Typology

Gaining and losing stream reaches provide important habitat for the threatened and endangered salmonids that live in the Russian River basin. However, the identification of gaining and losing reaches can be difficult since it is dependent on a combination of both geomorphic and hydrologic conditions that can be highly variable throughout a stream system. If the locations of these reaches, particularly the gaining reaches, could be estimated, the results could be used to focus additional research or investigations as well as to guide habitat restoration efforts.

Geomorphically, channel conditions such as slope, confinement, and bed materials can influence whether a stream reach may have the potential to be gaining or losing. For instance, confined bedrock stream channels have little potential for gaining or losing flows to the surrounding substrate. On the other hand, a semi-confined alluvial channel may have the right characteristics for a gaining or losing stream. A stream typology developed and applied to the Russian River basin by Walls (2013) and further discussed by Marcus (2016) was used to classify streams based largely on the depth and type of alluvial deposits and the degree of natural channel confinement (see Figure 1).

While the initial classification of streams according to geomorphology is useful for providing qualitative information as to where potential gaining and losing reaches may occur, a true characterization of the streams as such requires input based on the stream hydrology and flow data. Typically, this requires detailed subsurface modeling, extensive streamflow gaging, or perhaps both to provide an indication of the surface water and groundwater interaction.

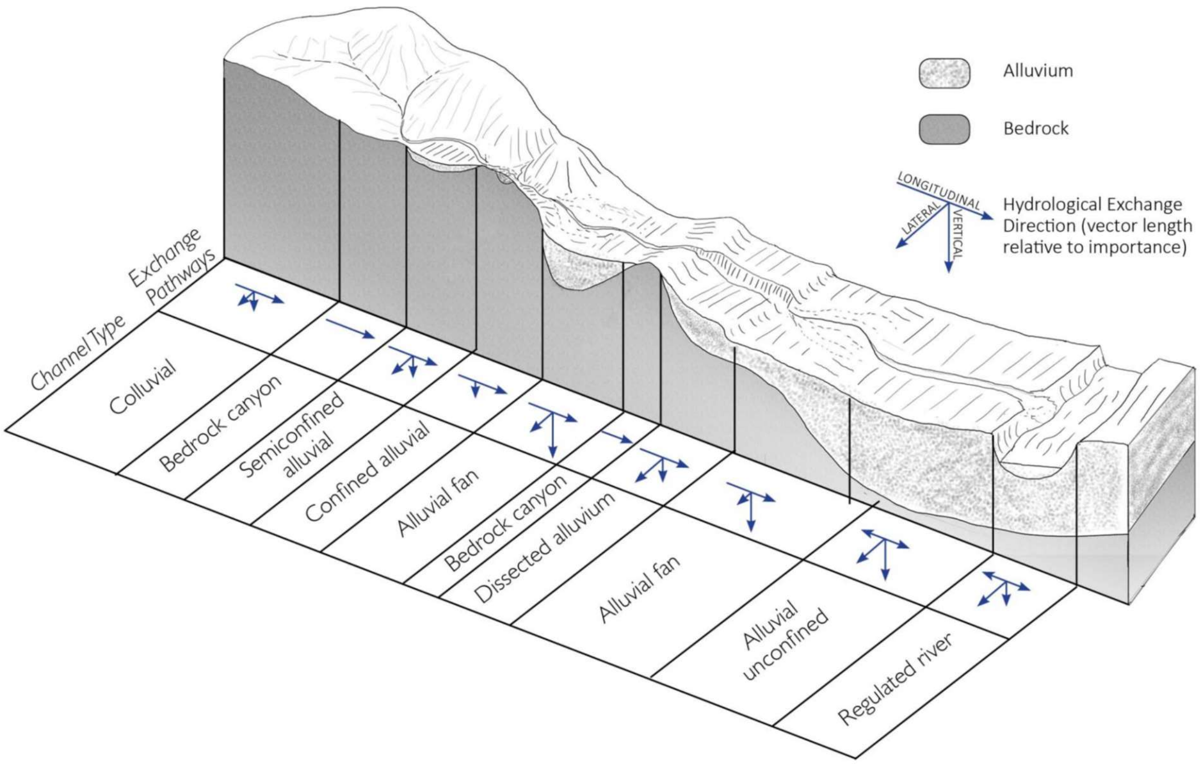


Figure 1. Generalized diagram of surface-groundwater interactions relating to geomorphic setting (Walls, 2013)

As an alternative to subsurface modeling and streamflow gaging, there is potential in using routed surface flow estimates from a well-calibrated distributed hydrologic model as a proxy for gage data in stream classification. A Hydrology Laboratory Research Distributed Hydrologic Model (HL-RDHM) of the Russian River basin has been calibrated to provide routed surface flow estimates of both peak and low flows for a one-kilometer gridded network. Combining the HL-RDHM flow estimates with the stream typology classifications will allow for further speculation on the nature of stream reaches as gaining or losing.

An initial investigation into combining the stream classifications with HL-RDHM flow data was performed for Feliz Creek in Mendocino County. Stream classifications according to Walls (2013) were added to a base GIS map of Feliz Creek (see Figure 2).

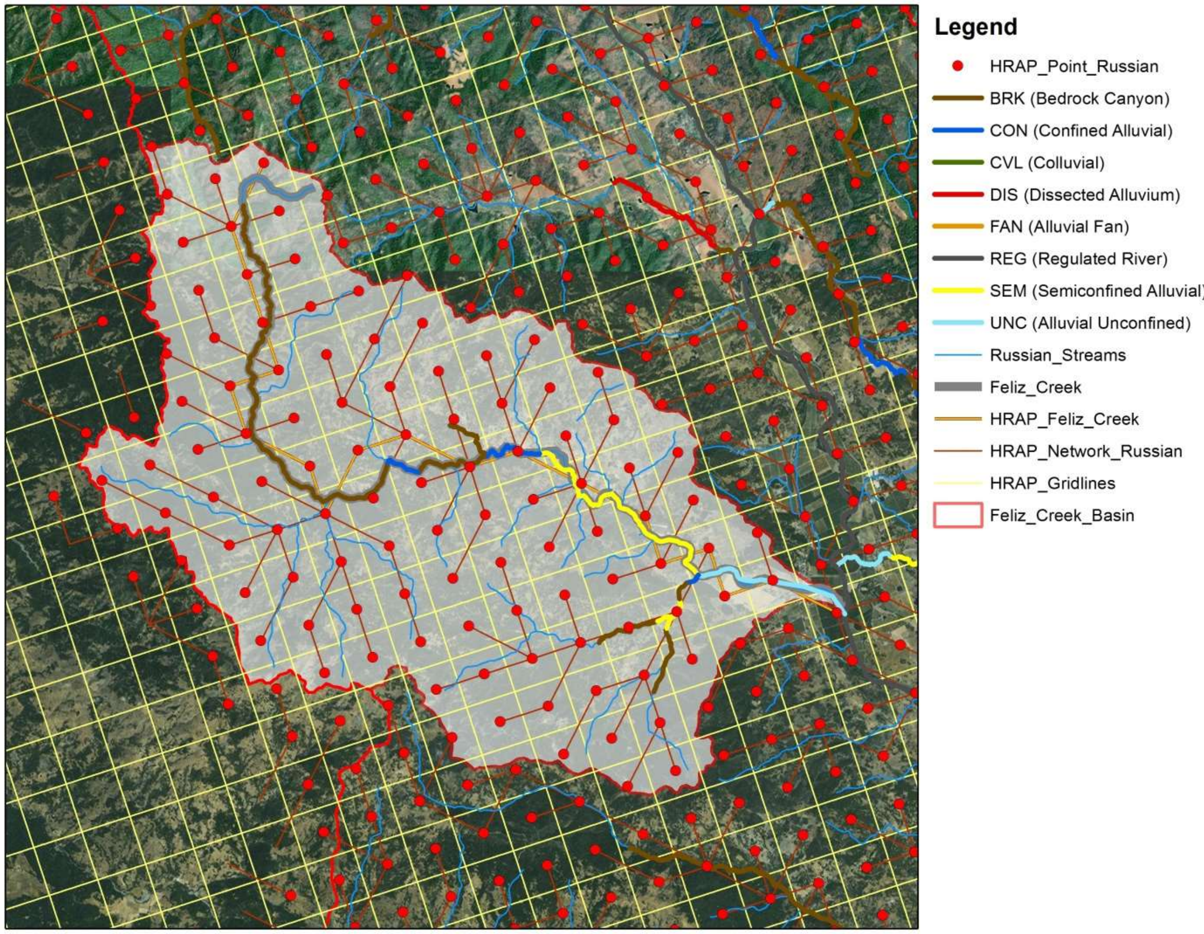


Figure 2. GIS map of Feliz Creek Basin showing typology and HRAP/HL-RDHM grid

Based on the overlay of the stream classifications with the HL-RDHM grid, each section of the conceptual channel for Feliz Creek was assigned a stream classification. As shown in Figure 2, the upper half of Feliz Creek is categorized as bedrock canyon. Moving downstream, the channel alternates between bedrock canyon and confined alluvial channel types. Next, the channel transitions to semiconfined alluvial and finally the channel is finally categorized as unconfined alluvium as it connects with the main stem of the Russian River.

Using the HL-RDHM model of the basin, estimated channel flow rates for each HRAP point were generated for a period between 01-Mar-2011 and 31-Dec-2012 on a 6-hour time step. The generated data can be used in a variety of ways. For instance, a traditional hydrograph can be developed for any location in the basin that shows flow rates over time (see Figure 3). The graph shows the characteristic wet and dry periods within the basin and the distinct peak flows and prolonged dry periods during those times.

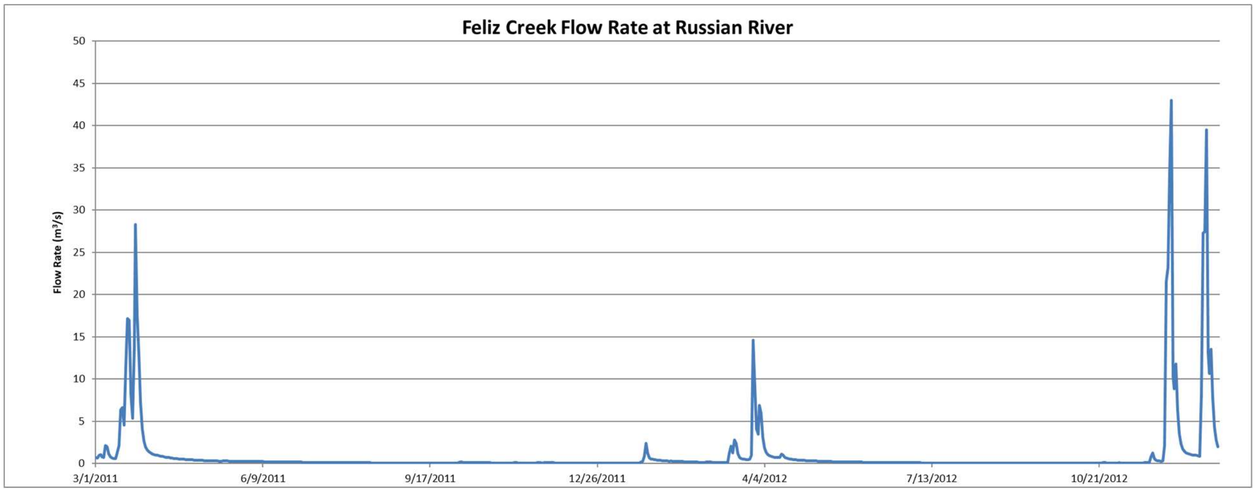


Figure 3. HL-RDHM-generated Feliz Creek flow rates at the confluence with the Russian River

Another way that the data can be used is to generate profiles of the stream that demonstrate how the flow rate varies as moving downstream from the headwaters to the confluence with the main stem. This type of data may indicate gaining or losing reaches within a stream by showing significant increases or decreases in flow along the channel. For example, Figure 4 shows the stream flow profile for Feliz Creek for the peak flow event on 28-Mar-2012. As shown, the flow rate initially increases at a relatively steady rate for the first 10,000 meters, then increases dramatically over the next 1,000 meters. While this could be an indicator of increased contributing flows from groundwater, it is actually the result of a significant increase in upstream contributing area, which nearly doubles over that span.

This data may indicate that downstream reaches lose flow to the substrate or that upstream reaches may be gaining flow from the surrounding water table. However, it is not possible to make any such conclusions after looking at the flow profile for a single day. For

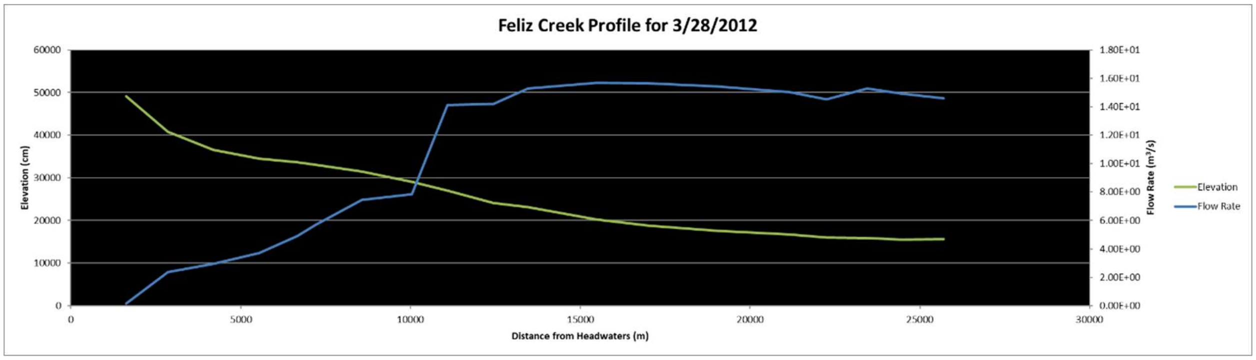


Figure 4. Example flow profile for Feliz Creek

To account for changes in total contributing area, flow rates can be normalized by the upstream contributing area of each cell. The resulting flow profile for the same date shows higher per-area streamflows in the upper portion of the basin with values decreasing toward basin outlet (see Figure 5).

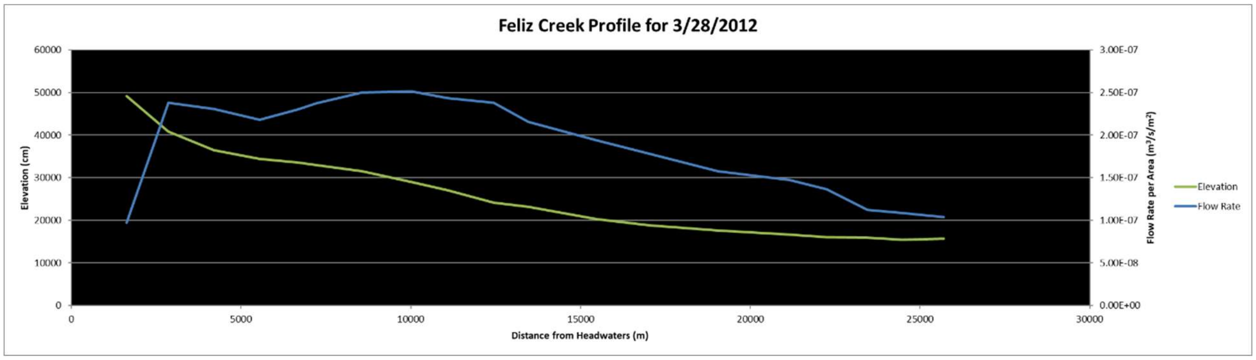


Figure 5. Example per-area flow profile for Feliz Creek (28-Mar-2012)

instance, one month later a completely different pattern is evident in the flow profile (see Figure 6). Where the profile in Figure 5 was for a peak flow event, Figure 6 shows the profile for a day during the recession curve leading into the dry season in the basin. Upper basin per-area flow rates are slightly lower than those for the earlier date but are comparable. However, lower-basin flow rates are significantly greater than those from the peak flow event, indicating a potential change in the nature of the surface-groundwater interaction.

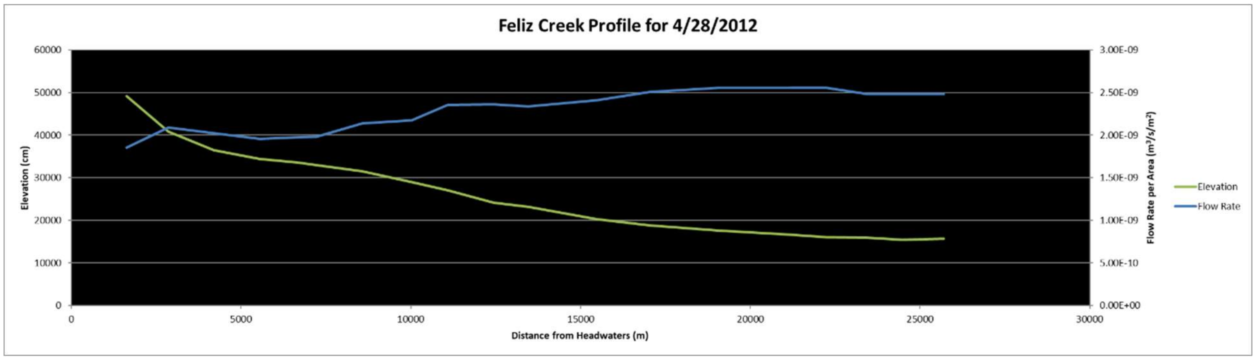


Figure 6. Example per-area flow profile for Feliz Creek (28-Apr-2012)

This type of analysis can be repeated for any time period of modeled data and may give an indication of gaining and losing reaches. However, a more complete characterization of the surface-groundwater interaction requires the consideration of the stream typology, as previously discussed. By adding stream typology information to the flow profiles, the flow patterns can be further enhanced.

Figure 7 shows the same profile as Figure 5 for the 28-Mar-2012 peak flow event but includes the stream typology data. The upper portion of the basin is comprised of bedrock canyon, which generally results in a flashier response to rainfall events and generates an above average streamflow response in the basin. The lower portion of the basin consists of more alluvial-type channels. Alluvial soils have higher infiltration rates and will generally have a slower response to precipitation than those of the bedrock canyon, especially when following a prolonged dry period. Both of these characteristics are evident in the Figure 7 profile.

The stream typology information was also added to the 28-Apr-2012 recession flow profile and is shown in Figure 8. In this graph, the bedrock canyon flow rates have decreased in magnitude while the flow rates for the confined, semiconfined, and unconfined alluvials increased significantly. This suggests that the faster response flows in the bedrock canyon are subsiding while the alluvial channels are beginning to experience increased contributions from groundwater.

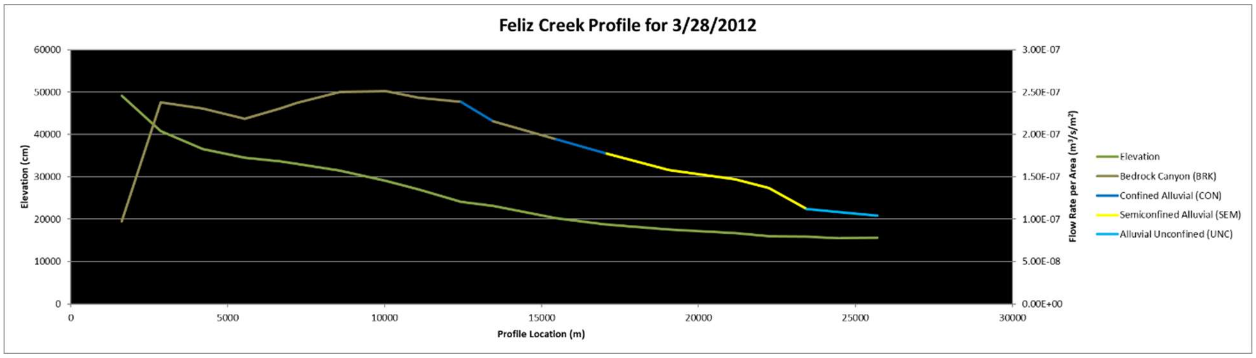


Figure 7. Example per-area flow profile for Feliz Creek with stream typology (28-Mar-2012)

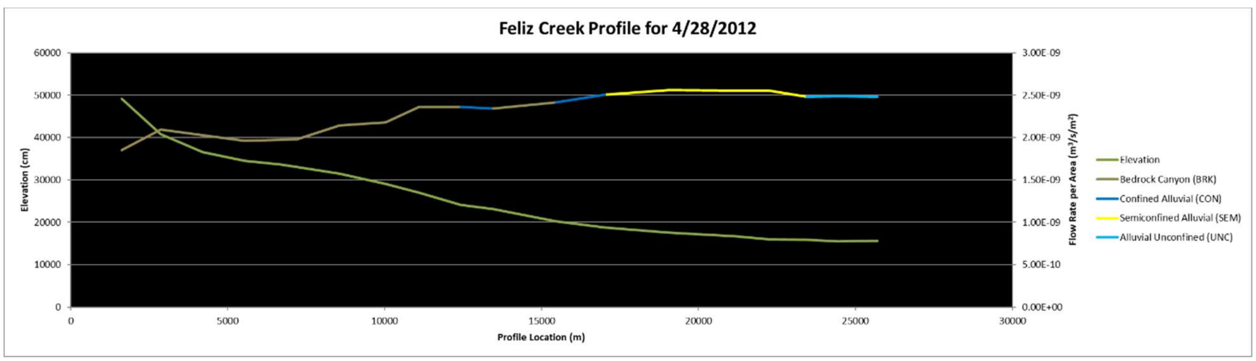


Figure 8. Example per-area flow profile for Feliz Creek with stream typology (28-Apr-2012)

While the flow patterns observed for these two example profiles support the general characterizations of bedrock and alluvial channel types, analysis of the flow profile over time may indicate if these patterns are consistent over time. Figure 9 includes a surface plot of the Feliz Creek flow profile over a two-month span that includes the profiles for the 28-Mar-2012 peak flow event as well as the 28-Apr-2012 recession. Evident in this plot is that the upstream (bedrock canyon) channels have much higher per-area response to precipitation events, not only for 28-Mar-2012 but also for another event that occurred on 01-Apr-2012. Further downstream (alluvial) channel responses to these events are consistently lower in magnitude.

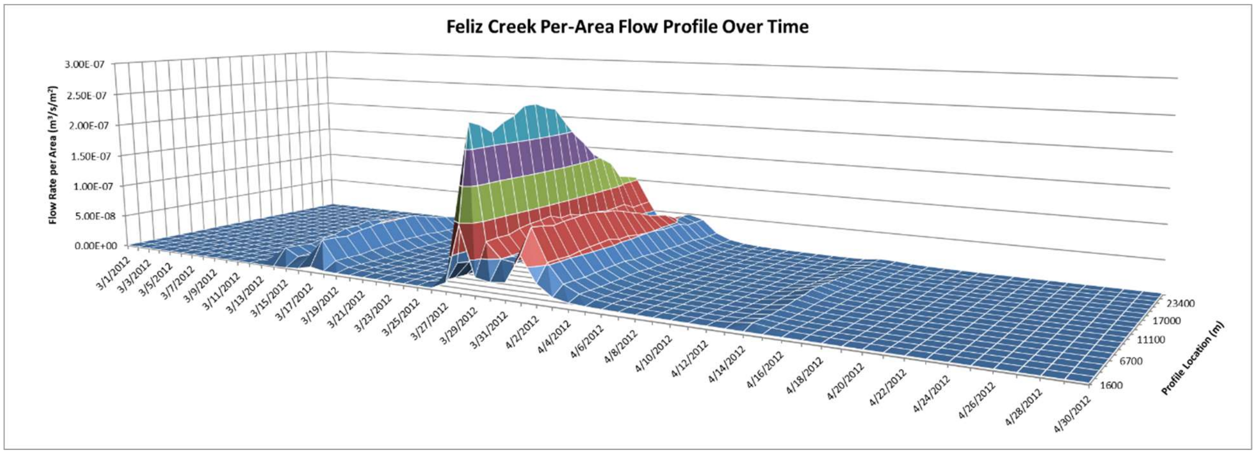


Figure 9. Feliz Creek per-area flow profiles over time (01-Mar-2012 thru 30-Apr-2012)

While the Figure 9 plot indicates that peak flow responses to precipitation events are generally consistent with the individual profiles shown in Figure 5 and Figure 7, the response during the flow recession is difficult to ascertain. The surface plot in Figure 10 was developed to provide additional detail to the recession flow profiles during the late spring and early summer months (01-May-2012 to 30-Jun-2012). In this plot, it is evident that per-area flow in upstream (bedrock canyon) channels is lower than the flows in downstream (alluvial) channels. As before, this general pattern is consistent with the individual profiles shown in Figure 6 and Figure 8 and indicates increased contribution to flows from groundwater.

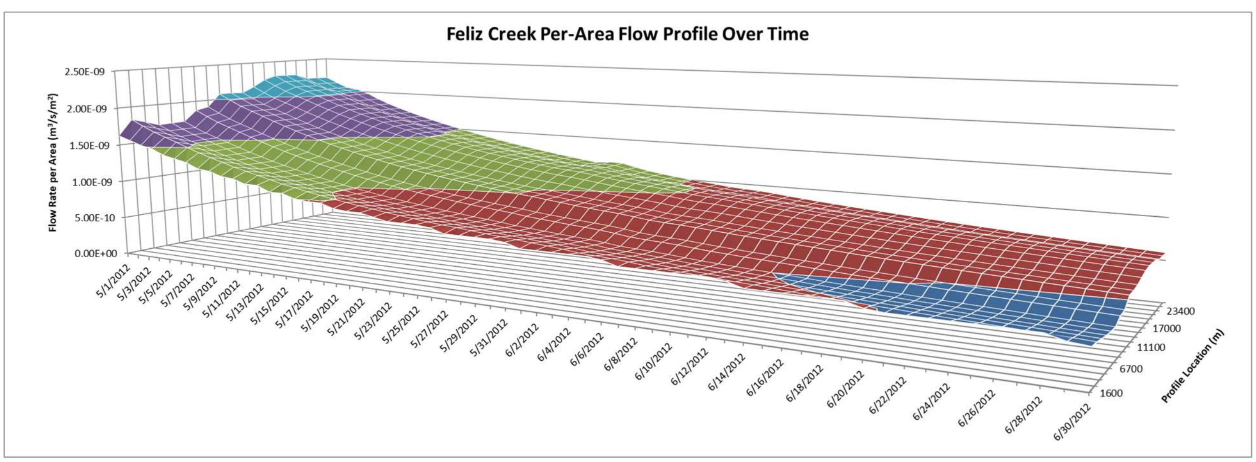


Figure 10. Feliz Creek per-area flow profiles over time (01-May-2012 thru 30-Jun-2012)

Figure 9 and Figure 10 demonstrate how the flow profile changes over time and given the distinct division between the bedrock canyon channel type of the upstream portion of Feliz Creek and the alluvial channel types of the downstream profile, it is evident that channel type and flow pattern are related. To further analyze this connection, the average daily flow per upstream contributing area was calculated across the entire profile on a daily basis. This daily average value was subtracted from the flow value for each segment, resulting in a deviation from average for each stream segment. Furthermore, these deviation values were averaged based on stream channel type. The resulting average deviation values, based on stream type, are shown in Figure 11.

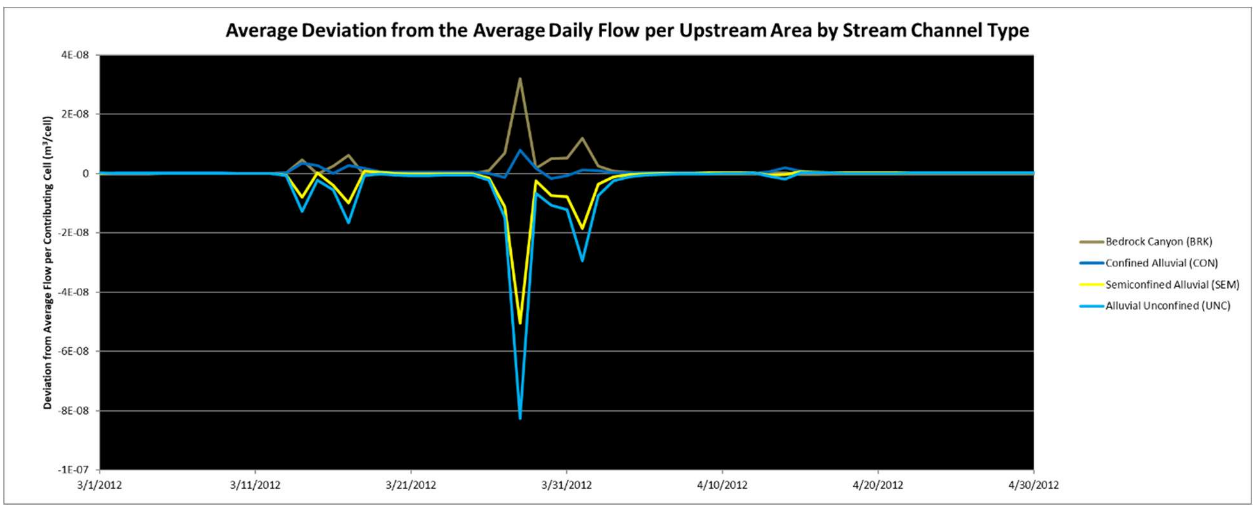


Figure 11 Average deviation from the average daily flow per upstream contributing area (01-Mar-2012 thru 30-Apr-2012)

What is evident in Figure 11 is that the average channel response for each channel type is consistent with the characterizations made in the Figure 9 analysis. On average, flow per upstream contributing area is much higher for bedrock canyon and confined alluvial channel types immediately following a precipitation event. Conversely, flow per upstream contributing area is below average in semiconfined alluvial and unconfined alluvial channels.

Figure 12 shows a similar plot to Figure 11, but for the recession curve during the late spring and early summer dry period. As was suggested by Figure 10, alluvial channels have higher than average flows per upstream contributing area, indicating higher amounts of baseflow contribution from groundwater. At the same time, bedrock channels experience below average flow per upstream area values, indicative of the lesser impact of groundwater contributions to base flow in these channels. Overall, the conceptual channel flow patterns generated by the HL-RDHM hydrologic model appear to support the stream typology characterizations for Feliz Creek.

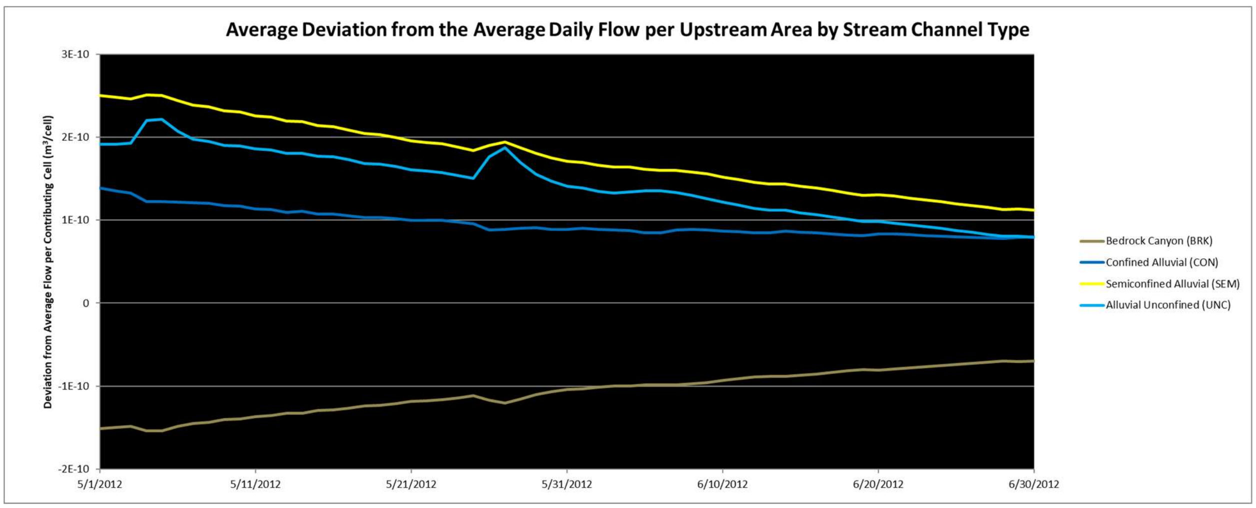


Figure 12 Average deviation from the average daily flow per upstream contributing area (01-May-2012 thru 30-Jun-2012)

Given that the average modeled streamflow patterns for each stream type are consistent with the expected flow patterns for each type, an analysis of the individual stream segments may provide an indication of where gaining or losing reaches may occur. For instance, if a particular stream reach has a significantly higher flow rate per upstream contributing area than the other stream reaches of the same type, this may indicate a gaining reach. Conversely, if the flow rate is significantly lower than average it may indicate a losing reach.

For Feliz Creek, confined and unconfined alluvium stream types comprise only two segments of the HL-RDHM hydrologic model. Because of the small sample size, it is not possible to determine the gaining or losing stream characteristics of these segments. Additionally, as shown in Figure 13, the flow rates per contributing area are very similar when compared to like stream types and the flow patterns are similar as well. There are some differences in magnitude for the confined alluvium flow rates but given the location of the confined alluvium stream segments in relation to other stream types (see Figure 2) the flows in these segments may be heavily influenced by the adjacent stream types.

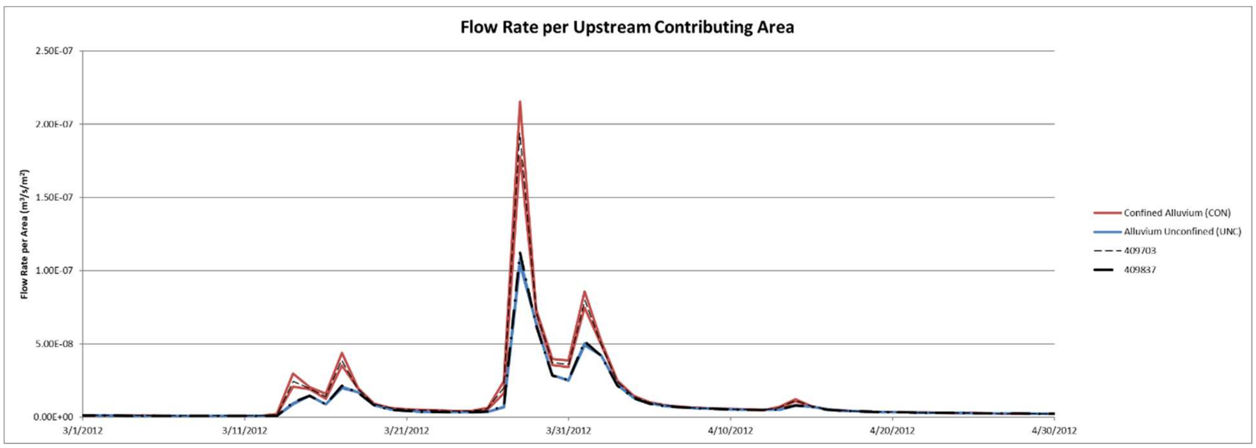


Figure 13 Flow rate per contributing area for confined alluvium (CON) and alluvium unconfined (UNC)

For the bedrock channel and semiconfined alluvium stream segments in Feliz Creek, an analysis of the flow rates for individual segments in relation to the average flow rate for the channel type was performed. In this analysis, the deviation from the average flow rate per upstream contributing area was determined for each channel type. For the bedrock canyon (BRK) channel type, most segments have above-average flow rates per area, as shown in Figure 14. However, for two stream segments, 409506 and 409203, the flow rates are significantly below average. This may be indicative of losing stream segments, perhaps related to fractured bedrock that can be found in the Russian River basin. However, further inspection reveals that Segment 409506 is the furthest upstream segment of Feliz Creek and has the smallest contributing area, which will tend to exaggerate any variations in the per area streamflow data. Segment 409203 is immediately adjacent, both upstream and downstream, to confined alluvium stream segments (see Figure 2). As previously discussed, this alluvial stream type generally has lower per area flow rates during and it is possible that these adjacent streams are influencing the behavior of this segment. In fact, as shown in Figure 13, the flow rate per area data for this segment lies between those of the two surrounding confined alluvium segments. This may indicate a mischaracterization of this segment as bedrock canyon that could require further investigation.

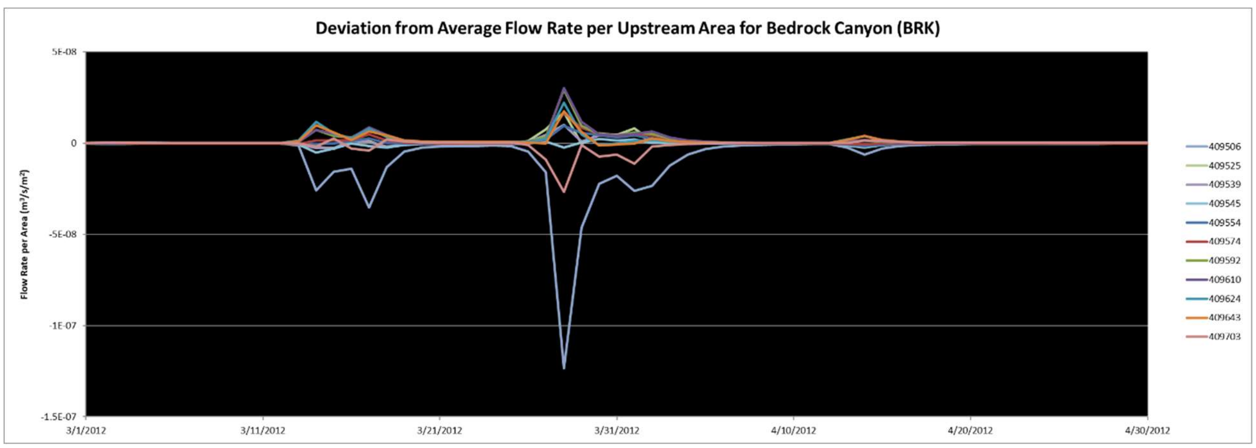


Figure 14 Deviation from average flow rate per upstream area for bedrock canyon (BRK) channel type

Semiconfined alluvium (SEM) consists of a four-segment stretch of Feliz Creek, just upstream of the unconfined alluvium that precedes the confluence with the Russian River (see Figure 2). Based on the comparison with the average per area flow rates shown in Figure 15, the most upstream segment (409763) has higher than average flow rates, which is a behavior similar to the adjacent confined alluvium stream type.

Also shown in Figure 15, the most downstream segment (409837) has below average flow rates, which is a behavior similar to the adjacent unconfined alluvium stream type. In both cases, the adjacent stream types may be influencing the behavior of the semiconfined segments. In fact, as shown in Figure 13, the flow rate per area data for this segment matches the two downstream unconfined alluvium segments. This may indicate a mischaracterization of this segment as semiconfined alluvium and could require further investigation.

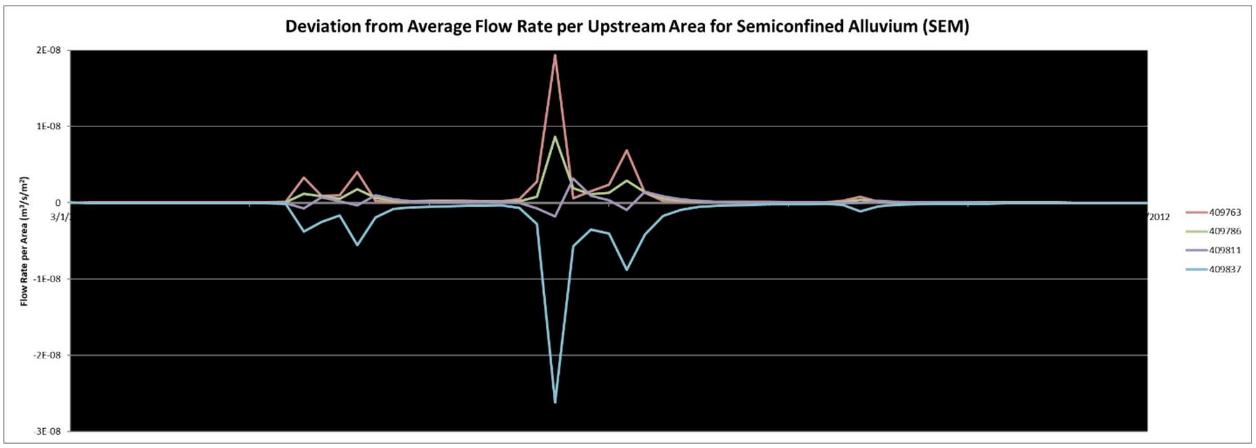


Figure 15 Deviation from average flow rate per upstream area for semiconfined alluvium (SEM)

Overall, there seems to be general agreement between the stream typology classifications and the RDHM estimated streamflows. The most uncertainty seems to lie in the transition areas between adjacent stream types. These areas often occur in the middle of an HL-RDHM cell and therefore may not be wholly attributable to only one stream type. Further refinement of how the HL-RDHM reaches are classified according the typology data is possible. Additionally, this review was performed for a single stream. The inclusion of additional stream segments in the basin may provide information on how streamflows vary with stream type. Finally, the inclusion of this type of analysis on a more well-calibrated stream than Feliz Creek may add further insight on streamflow variations as well.

Appendix References

Marcus, Laurel. Chapter 4 - Conceptual Model of Streamflow Processes, Russian River Independent Science Review Panel (2016). Conceptual model of watershed hydrology, surface water and groundwater interactions and stream ecology for the Russian River watershed. <http://www.russianriverisrp.org/Downloads/ISRP_FINAL_REPORT.pdf> (April 12, 2019).

Walls, Scott Porter. A Geomorphic Typology to Characterize Surface-groundwater Interactions in the Russian River Basin. Diss. University of California, Berkeley Spring 2013., 2013.

Appendix C Data Disaggregation

The Hydrology Laboratory Research Distributed Hydrologic Model (HL-RDHM) was originally developed by Koren et al. (2004) as the research modeling system (HL-RMS). The model uses kinematic wave routing for both overland flow and channel flow. For the purposes of disaggregating flows downstream of agricultural ponds, only channel routing was considered.

Two equations are used in kinematic wave routing:

Continuity

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = (q_{L_h} + R_g)\frac{f_c}{L_c} \qquad (1)$$

where:

A = Channel cross section
Q = Channel discharge
q_{L_h} = Routed overland flow
R_g = Slow runoff
f_c = Grid cell area
L_c = Channel length within grid cell

Momentum

$$Q = q_0 A^{q_m} \qquad (2)$$

where:

Q = Channel discharge
q_0 = Specific discharge (notation from HL-RDHM manual (NWS-OHD, 2009))
A = Channel cross section
q_m = Exponent parameter (notation from HL-RDHM manual (NWS-OHD, 2009))

Solving equation (2) for A gives:

$$A = \left(\frac{Q}{q_0}\right)^{\frac{1}{q_m}} \tag{3}$$

Taking the partial derivative of equation (3) with respect to t gives:

$$\frac{\partial A}{\partial t} = \left(\frac{1}{q_0}\right)^{\frac{1}{q_m}} \left(\frac{1}{q_m}\right) Q^{\left(\frac{1}{q_m}-1\right)} \frac{\partial Q}{\partial t} \tag{4}$$

Substituting equation (4) into equation (1) yields the continuity equation with a single dependent variable, Q.

$$\frac{\partial Q}{\partial x} + \left(\frac{1}{q_0}\right)^{\frac{1}{q_m}} \left(\frac{1}{q_m}\right) Q^{\left(\frac{1}{q_m}-1\right)} \frac{\partial Q}{\partial t} = \left(q_{L_h} + R_g\right) \frac{f_c}{L_c} \tag{5}$$

Per Koren et al. (2004) the following finite-difference approximation scheme was used to approximate the time and space derivatives of Q.

$$\frac{\partial Q}{\partial x} \approx \frac{Q_{i+1}^{j+1} - Q_i^{j+1}}{\Delta x} \tag{6}$$

where:

Q_{i+1}^{j+1} = Channel flow for (i + 1)th step on the x distance line and the (j + 1)th step on the t time line

Q_i^{j+1} = Channel flow for ith step on the x distance line and the (j + 1)th step on the t time line

Δx = Distance between nodes

$$\frac{\partial Q}{\partial t} \approx \frac{Q_{i+1}^{j+1} - Q_{i+1}^{j}}{\Delta t} \tag{7}$$

where:

Q_{i+1}^{j} = Channel flow for (i + 1)th step on the x distance line and the jth step on the t time line

$\Delta t =$ Time step length

$$Q \approx \frac{Q_{i+1}^{j} + Q_{i}^{j+1}}{2} \quad (8)$$

where:

Q_{i+1}^{j} = Channel flow for (i + 1)th step on the x distance line and the jth step on the t time line

$\Delta t =$ Time step length

Substituting equations (6), (7), and (8) into equation (5) yields:

$$\frac{Q_{i+1}^{j+1} - Q_{i}^{j+1}}{\Delta x} + \left(\frac{1}{q_0}\right)^{\frac{1}{q_m}} \left(\frac{1}{q_m}\right) \left(\frac{Q_{i+1}^{j} + Q_{i}^{j+1}}{2}\right)^{\left(\frac{1}{q_m} - 1\right)} \left(\frac{Q_{i+1}^{j+1} - Q_{i+1}^{j}}{\Delta t}\right) = (q_{L_h} + R_g)\frac{f_c}{L_c} \quad (9)$$

Solving equation (9) for Q_{i+1}^{j+1} yields:

$$Q_{i+1}^{j+1} = \frac{\frac{\Delta t}{\Delta x} Q_{i}^{j+1} + \left(\frac{1}{q_0}\right)^{\frac{1}{q_m}} \left(\frac{1}{q_m}\right) Q_{i+1}^{j} \left(\frac{Q_{i+1}^{j} + Q_{i}^{j+1}}{2}\right)^{\left(\frac{1}{q_m} - 1\right)} + \Delta t (q_{L_h} + R_g)\frac{f_c}{L_c}}{\frac{\Delta t}{\Delta x} + \left(\frac{1}{q_0}\right)^{\frac{1}{q_m}} \left(\frac{1}{q_m}\right) \left(\frac{Q_{i+1}^{j} + Q_{i}^{j+1}}{2}\right)^{\left(\frac{1}{q_m} - 1\right)}} \quad (10)$$

When applying equation (10) to disaggregate HL-RDHM output flows, the third term in the numerator, consisting of overland flow and slow runoff, can be ignored since intervening flows downstream of the agricultural pond should be kept separate from the routed flows from upstream of the agricultural pond.

However, intervening flows not only affect the cumulative runoff downstream of the pond, but they also have an effect on flow characteristics in the channel. This effect would typically be reflected in the specific discharge, q_0, which would, in general, increase with increased flow. Two methods of determining the routing parameters are presented in the HL-RMS model development. The channel shape method uses the Chezy-Manning approximation of a discharge and cross-section relationship to determine q_0 and q_m. The rating curve method uses an empirical relationship between discharge and cross-section to determine the same parameters. (Koren et al., 2004)

In the HL-RDHM model developed for the Russian River basin, the rating curve method was used to develop a raster grid of parameter values for the entire basin. The values for this grid do not vary with discharge but are instead assumed to be constant for all flow rates. For this reason, the effects of additional flows on the routing parameters can be ignored.

The HL-RDHM model generates channel flow estimations for each point in the gridded data model. Assuming that the effects of agricultural ponds will be most severe immediately downstream of the ponds, estimates of input flows are only needed at each pond. Input for ponds where there are no other ponds upstream can be retrieved directly from HL-RDHM results. For ponds downstream of other ponds, disaggregation is necessary to determine natural inflows.

The demo model is shown in Figure 1. In the demo model, four ponds were simulated. For each pond shown in Figure 1 a corresponding node from the HL-RDHM network (shown in light blue nodes and red links) was selected. As in the cases of Ponds 1 and 3, the pond was adjacent to the HL-RDHM node and within the same grid cell. For Ponds 2 and 4 the corresponding HL-RDHM node was not the closest node and required judgment by the modeler to determine the most appropriate node.

The next step was to extract HL-RDHM model output data for each node. For this example case, three days of one-hour data was used.

Once the extracted data was obtained, equation (10) was applied to rout flows downstream of each pond. In this case Δx is equal to the length of the diagonal of a grid cell

(1414.2 m) and Δt is 3600 s. The routing parameter q_m is equal to 1.333 for all points in the model and q_0 varies from point to point.

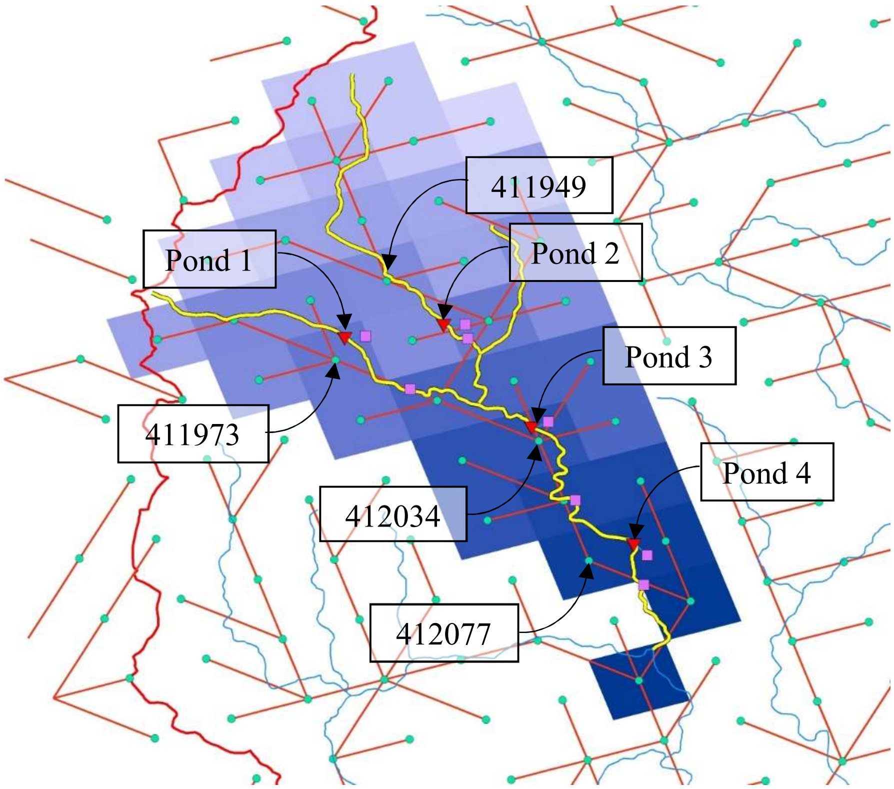


Figure 19. Demo Russian Tributary Model

Flows for each upstream pond were routed to any downstream ponds. In this case, flows for Ponds 1 and 2 were routed to Ponds 3 and 4, and the net flows at Pond 3 were routed to Pond 4. As necessary, flows were routed through intermediate points as well.

Sample calculations for Pond 1 flow routing are shown in Figure 2. For the sample calculations, the flow data for time steps 1 through 10 is output data from HL-RDHM, which comprises all Q_i values. Equation (10) is then used to calculate all values of Q_{i+1}.

		Pond 1	
	Point No	411973	412001
	q0		0.3034
	qm		1.333333
Time, t (hours)	0	0	0
	1	3.1757	1.934001
	2	2.4464	2.255772
	3	1.6496	1.879193
	4	1.0723	1.391319
	5	0.6977	0.986383
	6	0.4628	0.692426
	7	0.3163	0.489687
	8	0.2244	0.3524
	9	0.166	0.259667
	10	0.1283	0.196691

(a)

		Pond 1	
	Point No	411973	412001
	q0		0.3034
	qm		1.333333
Time, t (hours)	0	3.1757	3.1757
	1	3.1757	3.1757
	2	2.4464	2.70718
	3	1.6496	2.043387
	4	1.0723	1.453098
	5	0.6977	1.010759
	6	0.4628	0.702554
	7	0.3163	0.494116
	8	0.2244	0.354433
	9	0.166	0.260643
	10	0.1283	0.197178

(b)

		Pond 1	
	Point No	411973	412001
	q0		0.3034
	qm		1.333333
Time, t (hours)	0	3.905	4.252714
	1	3.1757	3.543757
	2	2.4464	2.834801
	3	1.6496	2.088908
	4	1.0723	1.470071
	5	0.6977	1.017424
	6	0.4628	0.705317
	7	0.3163	0.495322
	8	0.2244	0.354986
	9	0.166	0.260908
	10	0.1283	0.19731

(c)

- Q_i^j - Q_{i+1}^j - Q_i^{j+1} - Q_{i+1}^{j+1}

Figure 20. Sample Routing Calculations

One assumption was needed to enable the calculations. At time step t = 0, no flow data is known. Three assumptions were evaluated. As is shown in Figure 2(a), the first assumption was that flows at time step t = 0 were assumed to be 0 for ease of calculation. Figure 2(b) shows the assumption that at t = 0 the flow rate is equal to the first value of HL-RDHM output for the pond, 3.1757. This was applied at the pond node as well as the downstream nodes. The final assumption evaluated was a linear regression from points t = 2 and t = 1 to t = 0, as shown in Figure 2(c).

As is shown in the example calculations, by the 10th time step, the three methods are equal to three decimal places. Further calculations show that the difference between methods at Pond 4 (four points downstream of Pond 1) is less than one percent by the 15th time step. This indicates that to use this disaggregation technique, the HL-RDHM output data should include a sufficient amount of "spin-up" data prior to the period of interest. This length of data will vary with the length downstream that the flow is being routed and disaggregated.

The next step in disaggregation is to calculate the net flows at downstream Ponds 3 and 4. Pond 1 flows were routed two points downstream to Pond 3 and two additional points downstream to Pond 4, for a total of 4 downstream points. Pond 2 flows were routed three points downstream to Pond 3 and two additional points downstream to Pond 4, for a total of 5 downstream points. Routed flows were then subtracted from the HL-RDHM output data for downstream pond points to determine a net flow rate into each pond. This would be considered the natural intervening flow into a pond downstream of any upstream ponds and would be used as the input to the GeoMODSIM model. Sample calculations for Pond 3 are shown in Figure 3, and Figure 4 shows the disaggregation of the flows graphically.

		Pond 3 HL-RDHM	Routed Pond 1	Routed Pond 2	Net Pond 3
	Point No				412034
	q0				0.3034
	qm				1.33333333
Time, t (hours)	0				0
	1	7.471	1.120002	1.111778	5.23922007
	2	9.4823	1.815809	2.590584	5.07590662
	3	9.2003	1.854979	3.385202	3.96011858
	4	7.8157	1.572004	3.401286	2.84240996
	5	6.1736	1.222939	2.977531	1.97312975
	6	4.6872	0.916026	2.417726	1.35344742
	7	3.4904	0.677465	1.885225	0.92771002
	8	2.5829	0.50183	1.440663	0.64040719
	9	1.9165	0.375538	1.09243	0.44853161
	10	1.4351	0.285458	0.828363	0.32127833

Figure 21. Sample Flow Disaggregation Calculations for Pond 3

The calculations for Pond 4 were similar to those for Pond 3 with one exception. To account for management effects of Pond 3, the net flows, as calculated and shown in Figures 3 and 4, were routed downstream to Pond 4. Sample calculations for Pond 4 are shown in Figure 5, and Figure 6 shows the disaggregation of the flows graphically.

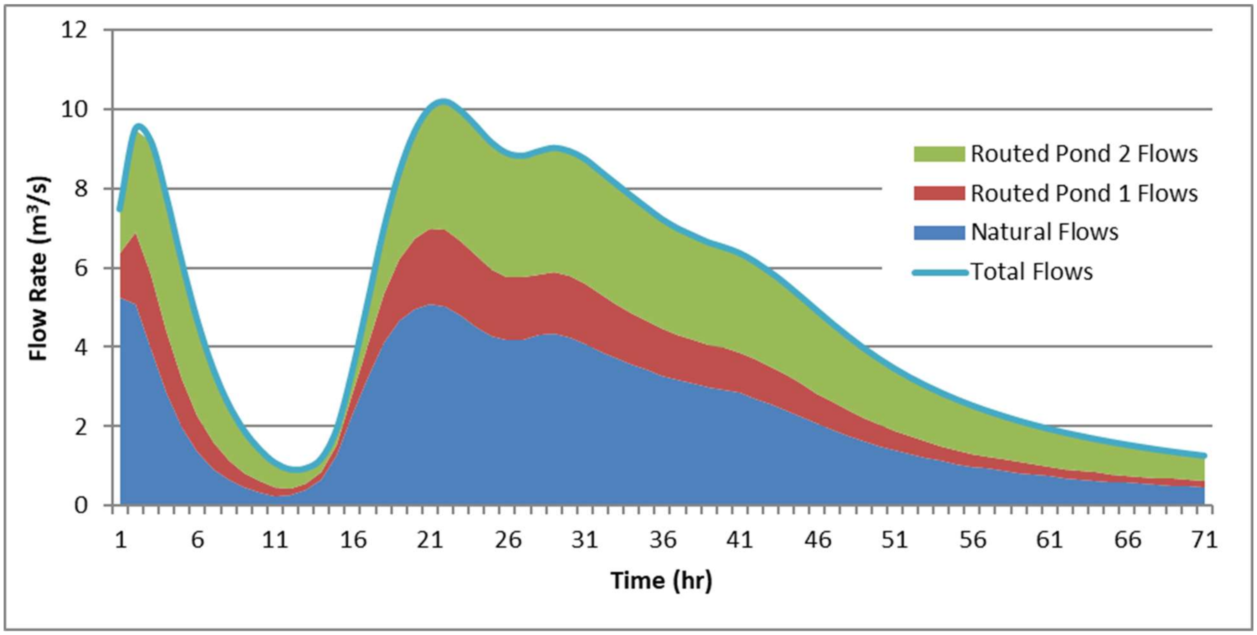


Figure 22. Pond 3 Disaggregated Flows

		Pond 4 RDHM	Routed Pond 1	Routed Pond 2	Routed Net Pond 3	Net Pond 4
Time, t (hours)	0					
	1	4.199	0.281067	0.278461	1.892371052	1.747101684
	2	6.7897	0.824429	1.103566	3.467940747	1.393764336
	3	8.2823	1.275016	2.089618	3.881236605	1.036429059
	4	8.4699	1.456784	2.746252	3.519560588	0.747303157
	5	7.7547	1.410603	2.930895	2.876217545	0.536984323
	6	6.6196	1.242488	2.761053	2.228192698	0.387865947
	7	5.4077	1.036578	2.410823	1.680812462	0.279486745
	8	4.3023	0.839293	2.010524	1.253617854	0.198865717
	9	3.3738	0.669636	1.632182	0.933248482	0.138733789
	10	2.6302	0.531648	1.305825	0.697916481	0.09481042

Figure 23. Sample Flow Disaggregation Calculations for Pond 4

In the final implementation into the GeoMODSIM model, the natural flows will be used as inputs to each of the agricultural ponds. For ponds without upstream management influences, this data can be directly determined from HL-RDHM output. For ponds with additional ponds upstream, these flows have been determined by disaggregating the flow rates estimated in the

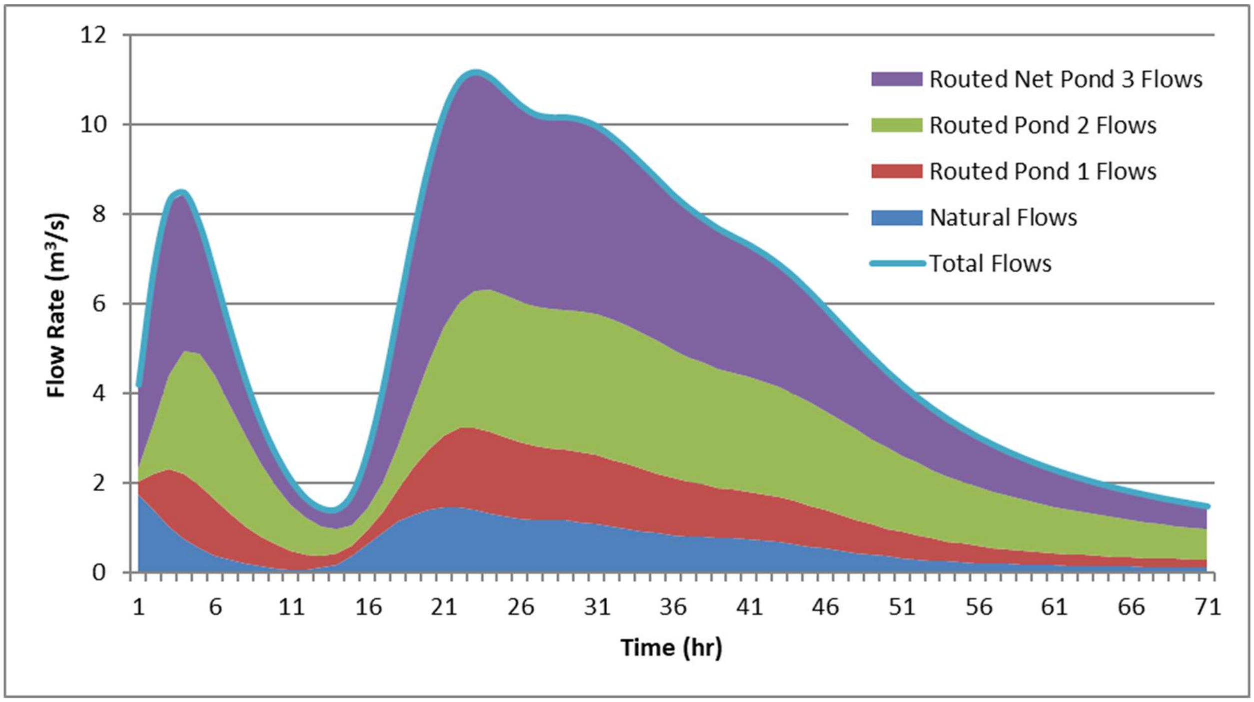


Figure 24. Pond 4 Disaggregated Flows

HL-RDHM model into the various components of upstream sources including other agricultural ponds and natural flows. Within the GeoMODSIM model, managed flows from pond releases will be routed downstream and combined with the natural flows to calculate a total input flow to downstream ponds.

Appendix References

Koren, Victor, et al. "Hydrology laboratory research modeling system (HL-RMS) of the US national weather service." Journal of Hydrology 291.3 (2004): 297-318.

National Weather Service – Office of Hydrologic Development (NWS-OHD), 2009: HL-RDHM User Manual v. 3.0.0. NOAA, Silver Spring, MD. 110 pp. http://www.cbrfc.noaa.gov/present/rdhm/RDHM_3_0_0_User_Manual.pdf

Appendix D Feliz Creek Basin Management Tool

Water resources engineers are often tasked with balancing multiple, competing interests within a single system. Hydrologic models, decision support systems, and multi-objective analysis are some helpful tools that are used in the development of water management strategies. However, while these strategies often seek balanced solutions, if the stakeholders are not directly involved in the modeling process, their needs and concerns may not be sufficiently addressed. To prevent this situation and to arrive at a more complete understanding of a watershed system, many water resource managers turn to a collaborative approach. In general, collaborative models are developed with input from various stakeholders and are essential for finding balanced solutions to management challenges.

Langsdale et al (2011) define collaborative modeling as "a process that engages stakeholders in the construction of computer models that support decision processes." Through the use of collaborative modeling, stakeholders are able to evaluate a model from diverse perspectives for transparency, validity, and equity of its impacts. (Reed and Kasprzyk, 2009) The authors continue to state that collaborative models "must provide a diversity of hypotheses and convey knowledge as broadly as possible to stakeholders, decision makers, scientists, and engineers." As a result, the science behind the model can better inform the decision making process, even given the extremely complex nature of human-natural systems. (Poff et al, 2003).

A common modeling choice for developing a watershed model is GIS, which, coincidentally, is also an ideal platform for building a collaborative model. The display properties of GIS combined with the spatial analysis tools that are available make it possible to include traditional modeling aspects with the ability to present the model results to stakeholders.

Additionally, authors such as Richter (2010) point out the need for hydrologic models that accurately model the spatial and temporal aspects of a watershed, including land use, diversions, reservoir operations, and unimpaired runoff estimations. Ramsey (2009) points out that spatial decision support systems should be designed to support the exploration of multiple alternatives instead of focusing on the solution of a single problem. By remaining flexible, the GIS-based tool can better support collaboration among the various stakeholders.

The Feliz Creek basin geo-DSS was developed to take advantage of the spatial information management and display capabilities of GIS by coupling of GeoMODSIM with the HL-RDHM distributed surface flow estimations. After initial model development, the GIS platform and display properties can provide useful tools for data dissemination and presentation to stakeholders. As part of the collaborative modeling approach, stakeholder input and response is an important next step in the model development and decision-making. In the Feliz Creek basin modeling process, the first such efforts involved presenting the model and results to a group of key stakeholders in the region and were accomplished via web-based conferencing. Feedback from the group was generally positive and all agreed that a platform that could make the model results accessible to a broader cross-section of stakeholders would be beneficial. Furthermore, a method of presenting the results in a neutral setting would encourage investigation of the model by stakeholders and facilitate the decision-making process.

The Feliz Creek Basin Management Tool was developed to be an interactive web-based display tool for model results. By overlaying GIS display elements into an internet-based web mapping application, information was presented in an environment that is familiar to internet and smart device users. Additionally, a feedback tool was implemented to provide users the opportunity to contact the developers directly with questions, suggestions, or concerns.

Individual aspects of the tool are described in more detail below. Through the use of tools such as the Feliz Creek Basin Management Tool, stakeholders can be given the opportunity to have significant impacts on water resource management decisions.

Tool Use and Description

- Website: http://wsnet2.colostate.edu/cwis170/Feliz/map.aspx
- Password: cafeliz12

Introduction Page

After logging into the website, the user is presented with a welcome message detailing the purpose of the tool and development information for the tool. It was especially important to convey to the user the impartiality of the information and to encourage individual exploration and consideration of the results.

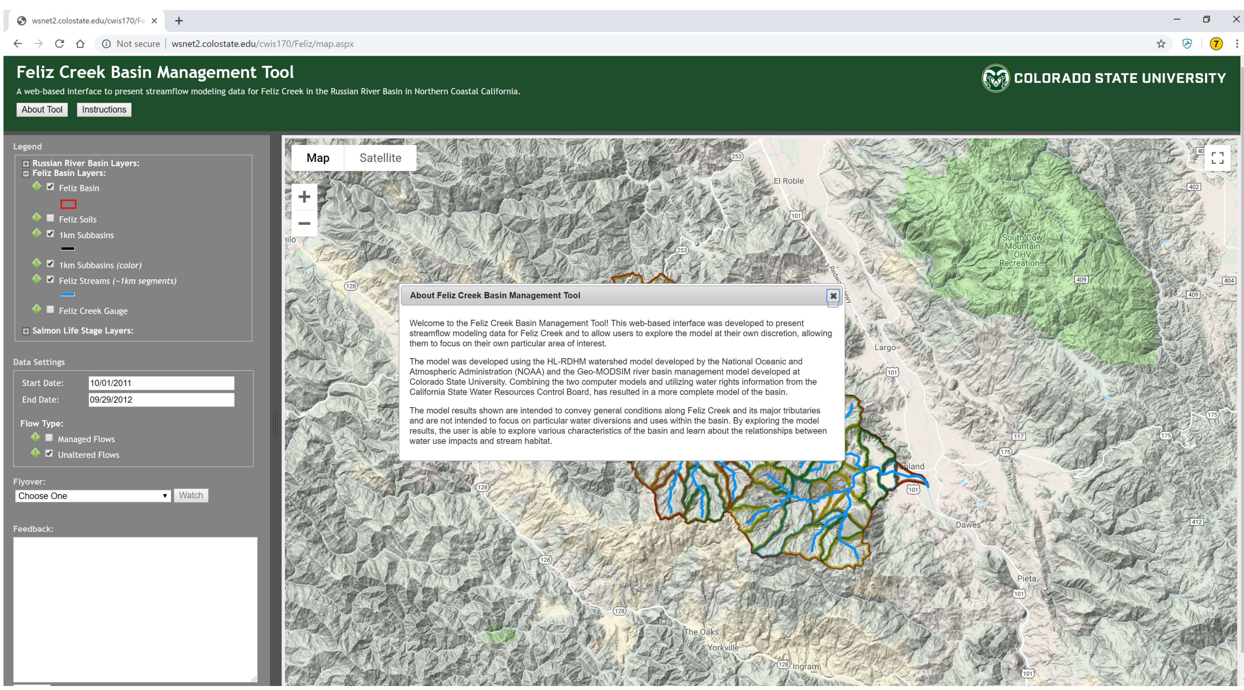


Figure 1. Introduction page that user is initially presented with after login.

Clicking the Instructions button at the top of the page will open the following window that contains a set of instructions to guide the user through the various options available to them.

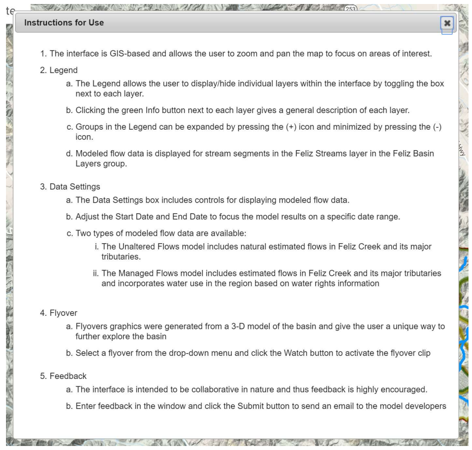


Figure 2. User instructions display.

Interactive Display

After closing the welcome message, the user is presented with an internet map display. The Feliz Creek tributary system is shown with subbasins outlined according to HL-RDHM grid cells. Google Maps was selected as the mapping application and the display can be switched between a standard map view (with or without terrain) and a satellite view.

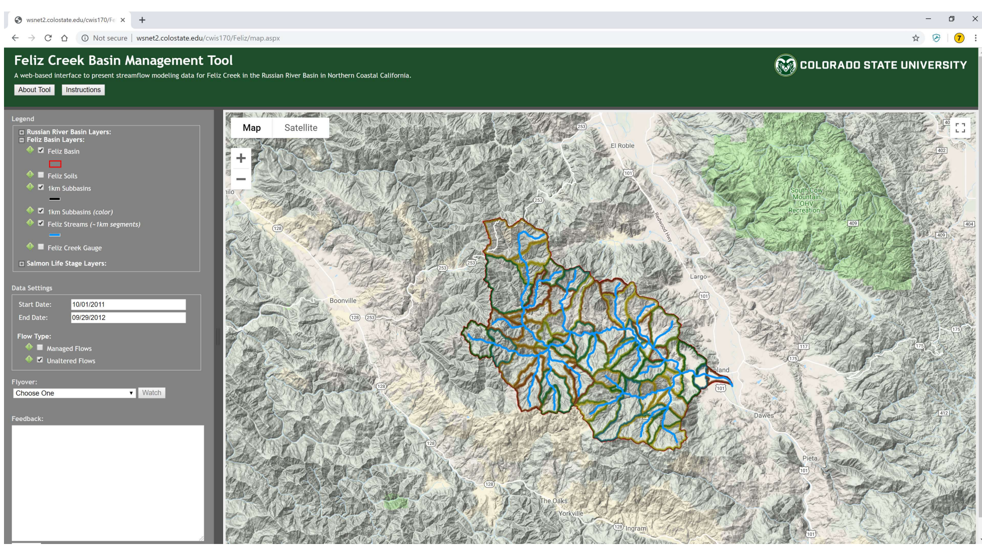


Figure 3. Interactive display showing map-based layout in Google Maps.

Legend and Map Display Options

The legend presents the user with a variety of options for layer display under headings for Russian River Basin Layers, Feliz Basin Layers, and Salmon Life State Layers. Each item in the legend is accompanied by an "About" button , which, when clicked, presents the user with information about the layer.

<u>Feliz Basin Layers:</u>

- Feliz Basin: Outline of Feliz Basin extents
- Feliz Soils: Hydrologic Soils Group classification throughout the basin
- 1km Subbasins: Subbasins corresponding to HL-RDHM grid cells approximately 1km square
- 1km Subbasins (color): Color version of 1km subbasins to help distinguish between subbasins
- Feliz Streams (~1km segments): Tributary stream system divided into segments that correspond to the HL-RDHM grid
- Feliz Creek Gauge: Shows location of Feliz Creek stream gauge

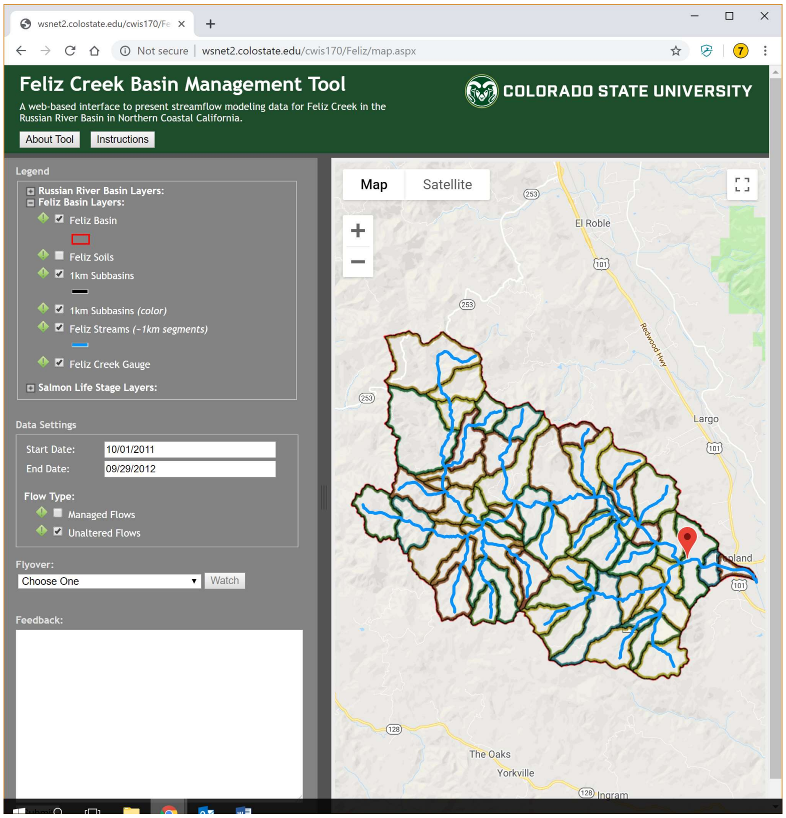


Figure 4. Detailed view of map legend and display options.

Russian River Basin Layers:

- HRAP Gridlines: Displays the HRAP gridlines, which correspond to the HL-RDHM grid
- Russian River Basin: Displays extents of Russian River basin
- Russian River: Displays mainstem of Russian River
- Russian Basin Streams: Displays main tributaries of the Russian River
- Stream Typology: Displays the stream typologies identified within the Russian River basin (see Appendix B)

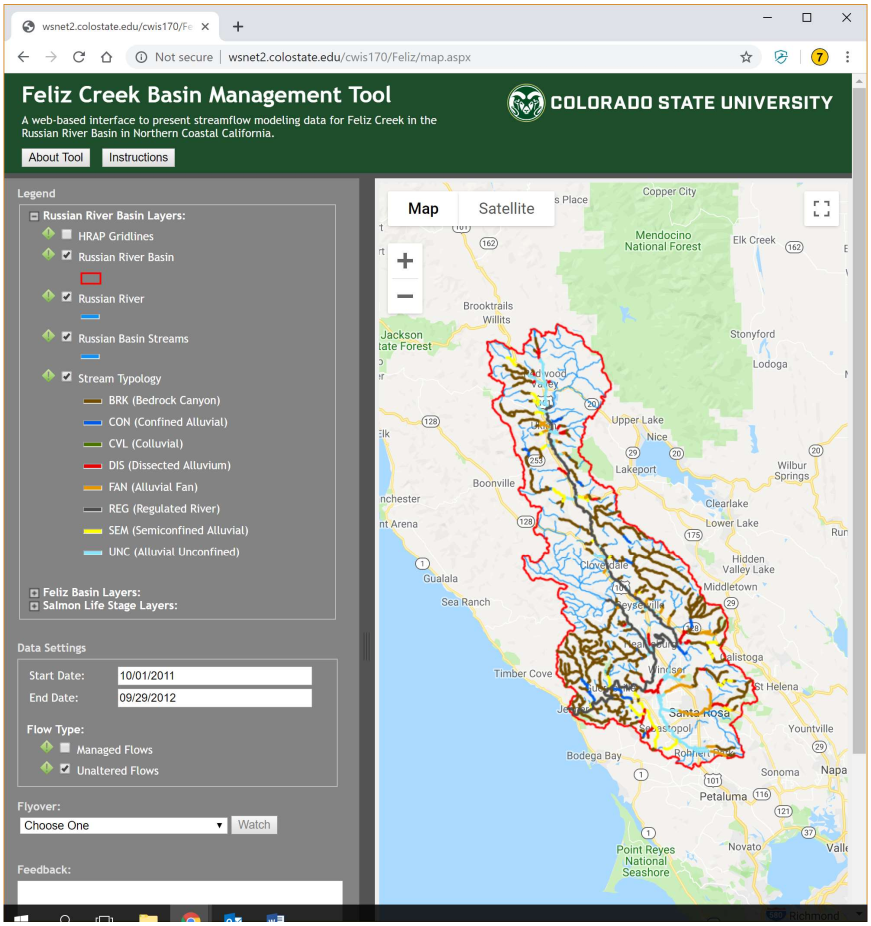


Figure 5. Russian basin stream layers with typologies.

Salmon Life Stage Layers:

An assessment of the Feliz Creek basin identified the stream reaches that were critical to the various life stages of the chinook salmon and steelhead trout. The National Marine Fisheries

Service categorized the streams based on their intrinsic potential for providing habitat. At its essence, intrinsic potential identifies streams as having the characteristics needed for fisheries habitat but do not necessarily identify streams where fish have been observed. This information is included as individual layers that can be displayed one-at-a-time.

- Chinook Salmon Life Stage Layers
  - November through January – Adult Migration
  - November through March – Spawning/Incubation/Emergence
  - January through May – Juvenile Seasonal Rearing/Migration
- Steelhead Trout Life Stage Layers
  - November through January – Adult Migration
  - November through March – Spawning/Incubation/Emergence
  - January through May – Juvenile Seasonal Rearing/Migration

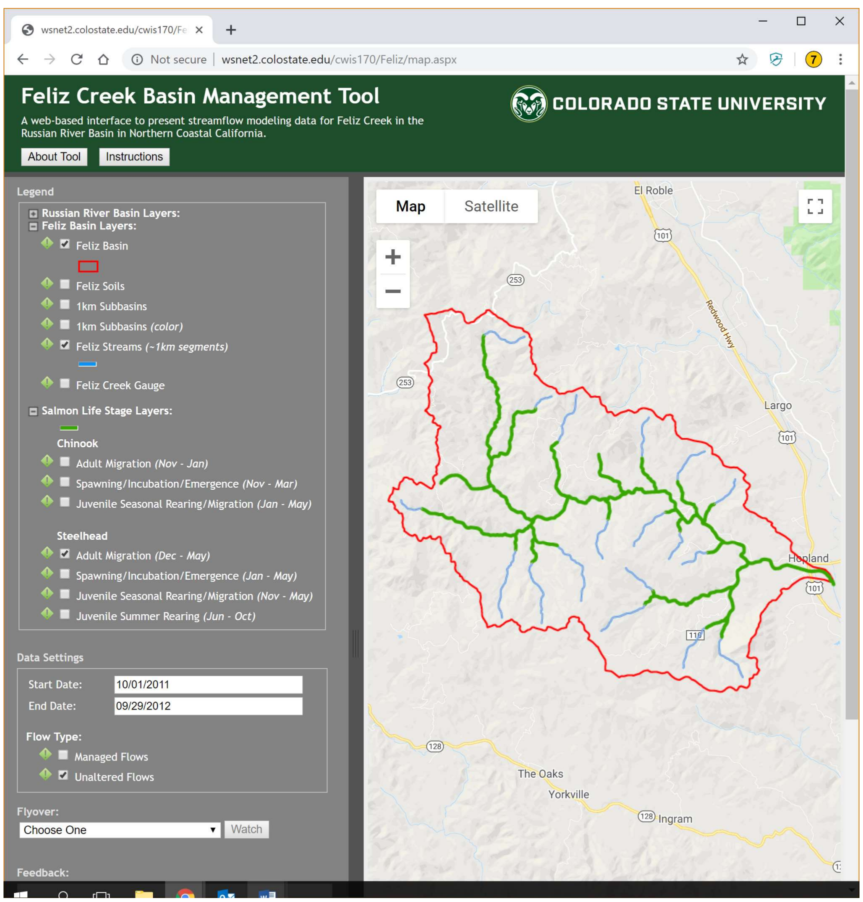


Figure 6. Feliz Creek basin with life state layers displayed.

Feliz Creek Model Results Display

For the Feliz Creek tributary system, streamflow model results can be viewed by clicking on a stream segment. The modeled year runs from October 1, 2011 to September 30, 2012 and represents a normal precipitation and runoff year for the basin.

Results of two scenarios are included – one for unaltered, or unimpaired, flows, and another for managed flows, which represents the stream system with water rights and agricultural diversions in place. The intent is to allow the user to compare and contrast streamflow conditions under the various scenarios.

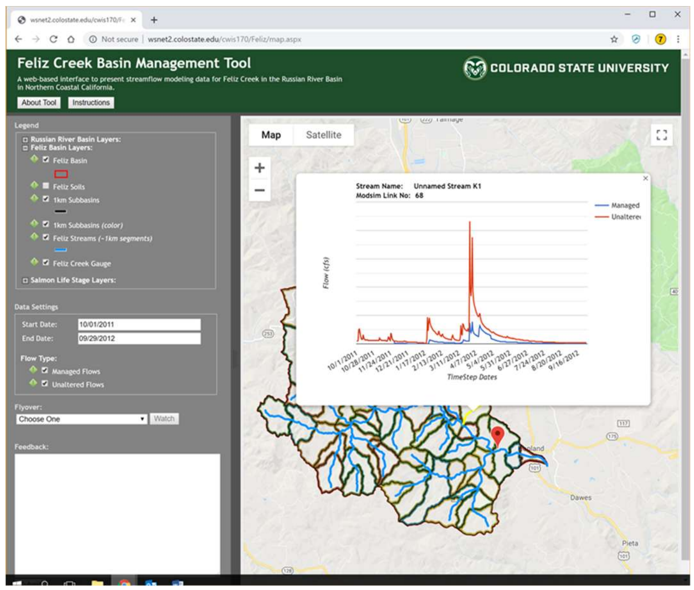


Figure 7. Example streamflow model results display.

The user can also specify the date range to be displayed. For instance, as pictured below, the spring frost season is a time of particular concern. By limiting the date range and zooming in on the hydrograph the impacts of frost protection diversions are evident.

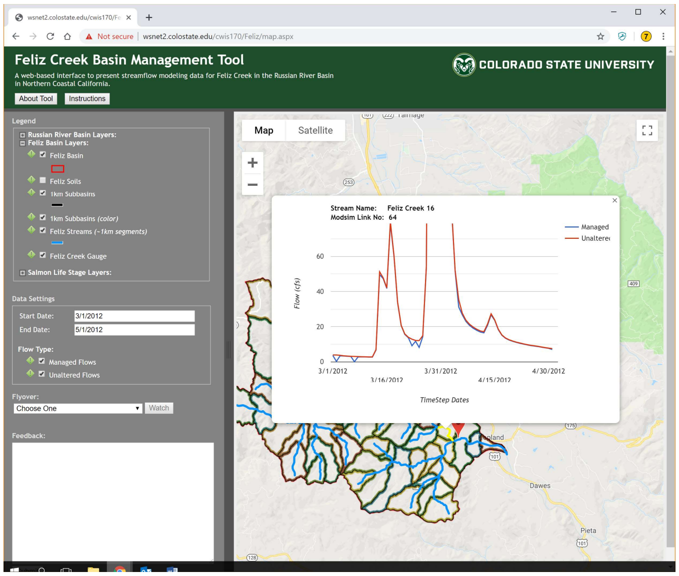


Figure 8. Example zoomed-in detail of streamflow model results display.

Stream Flyovers

As another example of the advantages that GIS presents the user, a selection of stream basin flyovers was created and are made available to the user. These flyovers offer another way to visualize the Feliz Creek basin that may encourage stakeholder interest in finding collaborative solutions. Information that is displayed in the flyover includes streams, subbasins, and vineyard locations with satellite imagery laid out on a 3D topographic display.

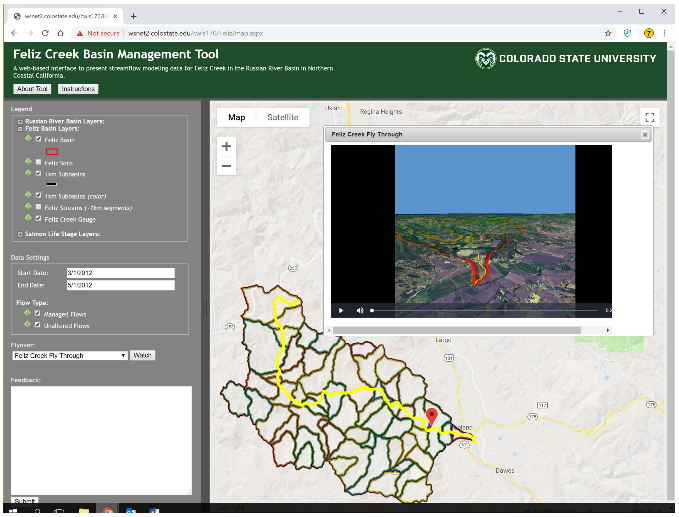


Figure 9. Stream flyover window.

Feedback Window

The collaborative process necessitates a feedback loop between the model developer and the stakeholders. At the lower left corner of the display a feedback window provides a tool for users to contact the developer with questions, comments, or suggestions. When the user submits the comment, an email is generated that is sent to the website manager and model developer. While the user may supply their contact information in the text of the feedback, the email can be sent anonymously. In this way, users can feel free to ask questions and explore the model at their own discretion, while focusing on their own particular area of concern.

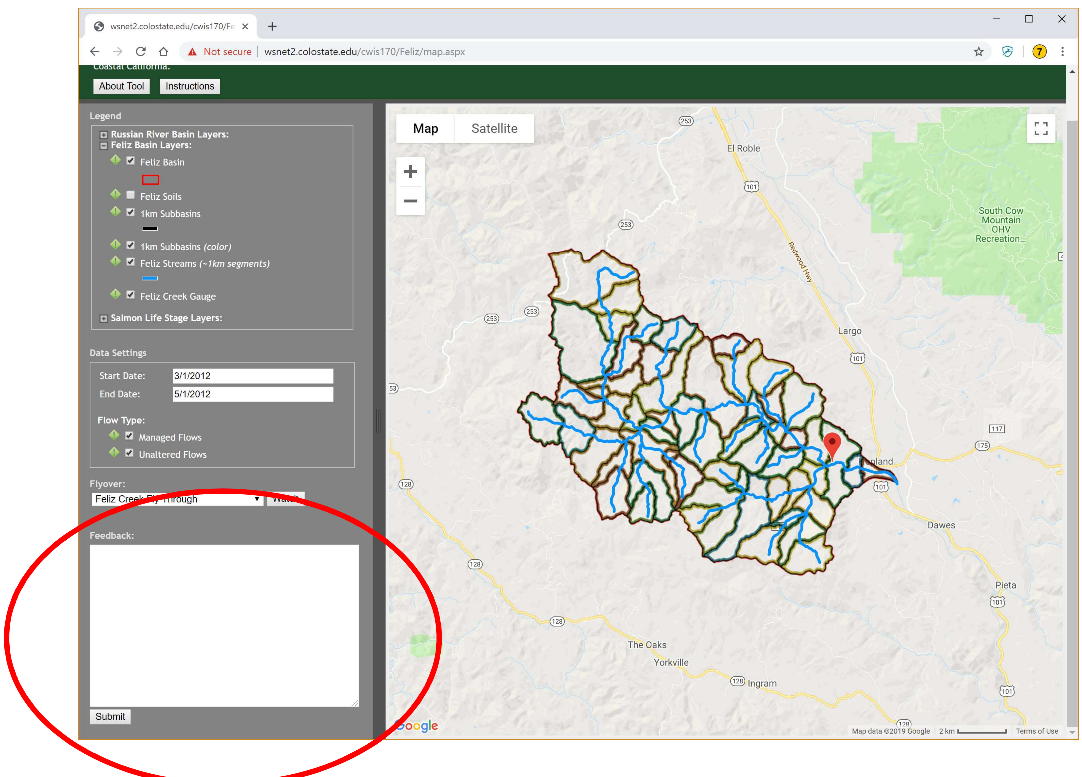


Figure 10. Feedback window for user feedback.

Future Development of the Feliz Creek Basin Management Tool

The initial implementation of the Feliz Creek Basin Management Tool was well-received and warrants further exploration as a collaborative modelling tool. Additional feedback would be beneficial to the model's development to add features that users would be interested in seeing and paring down features that are infrequently used. Most importantly, the model results shown in Chapter 2 of this dissertation could be added to allow the user to explore the 100 sets of hydrologic conditions as well as the four management scenarios. By presenting this information to the stakeholders in the region, a more complete model can be developed, management solutions can be developed, and the benefits of the collaborative process can be maximized.

Acknowledgement:

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Appendix References

Langsdale, S., A. Beall, E. Bourget, E. Hagen, S. Kudlas, R. Palmer, D. Tate, and W. Werick, 2011. Collaborative Modeling for Decision Support in Water Resources: Principles and Best Practices, Environmental Water Resources Institute, Reston, Virginia and Institute for Water Resources, Alexandria, Virginia.

Poff, N. LeRoy, et al. "River flows and water wars: emerging science for environmental decision making." Frontiers in Ecology and the Environment 1.6 (2003): 298-306.

Ramsey, Kevin. "GIS, modeling, and politics: On the tensions of collaborative decision support." Journal of Environmental Management 90.6 (2009): 1972-1980.

Reed, Patrick M., and Joseph Kasprzyk. "Water resources management: the myth, the wicked, and the future." Journal of Water Resources Planning and Management 135.6 (2009): 411-413.

Richter, Brian D. "Re-thinking environmental flows: from allocations and reserves to sustainability boundaries." River Research and Applications 26.8 (2010): 1052-1063.

Appendix E Literature Review

The following literature review was completed as an initial phase of the study to provide background information on key aspects of the study. Additional literature was reviewed subsequent to the preparation of this review and is referenced and included in the main body of the dissertation.

Coupling Spatially-distributed, Gridded Hydrologic and Water Management Models

As is typical in irrigated agricultural areas, the tributary systems in the Russian River basin are influenced by natural processes as well as management decisions. As such, an accurate portrayal of the tributary network stream flows must account for both natural and managed flows. This review focuses on previous efforts that couple gridded hydrologic models with river basin flow management models.

Depending on the particular characteristics of a basin that are of interest to the modeler, a variety of models and combinations of models are possible. By coupling physically-based gridded hydrologic models with network-based flow models, the unique capabilities of both models can be utilized. In this manner, highly specialized models can be combined to produce a more comprehensive and flexible model structure.

Gridded Hydrologic Models

The USGS model MODFLOW (Harbaugh, 2005) is a 3-dimensional finite difference groundwater model that can be used to model a variety of aquifer conditions. Additionally, since the model's introduction in 1988 (McDonald et al, 1988) dozens of specialized packages have been designed to work with the core MODFLOW software to detail individual aspects of the groundwater system. A number of these packages focus on the links between surface water and groundwater as well as the simulation of water management practices on the groundwater system. For instance, the RIV package (Harbaugh, 2005) simulates groundwater-surface water exchange and the SFR2 package (Niswonger and Prudic, 2005) can be used to simulate surface water transport in models. The WEL package (Harbaugh, 2005) simulates both extraction and recharge wells and the FMP2 package (Schmid and Hanson, 2009) can be used to model the redistribution of both surface water and groundwater resources for irrigated agriculture.

Given the variety of MODFLOW tools that are available, it becomes apparent to the user that MODFLOW can be used to develop a comprehensive hydrologic model using any combination of MODFLOW packages. MODFLOW models can also be run at a variety of time steps. However, given the generally slow-response times of groundwater flows, MODFLOW models are generally developed to use longer-term time steps, such as days, weeks, or months to reduce computation time. Additionally, while surface water flow simulation is possible using MODFLOW and its various components, the central focus of the model remains groundwater simulation. As such, short duration changes in channel flows such as the flood events common to the Russian River valley would generally not be well represented in the MODFLOW framework.

Also available from the USGS is the Precipitation-Runoff Modeling System, Version 4 (PRMS-IV) (Markstrom et al, 2015). Marksom et al (2015) describe PRMS-IV as a "deterministic, distributed-parameter, physical-process-based modeling system." PRMS-IV uses the concept of hydrologic response units (HRUs) to estimate the watershed response to climatic inputs such as precipitation and temperature. The watershed is divided into a collection of HRUs based on a variety of attributes such as elevation, vegetation, soil type, slope, and climatic patterns. Within each HRU the watershed response to climatic drivers is assumed to be uniform.

By calculating an area-weighted sum of all of the HRUs in a watershed, the total watershed response for a time period can be estimated.

PRMS-IV has also been combined with MODFLOW into the Coupled Ground-Water and Surface-Water Flow Model (GSFLOW). GSFLOW (Niswonger et al, 2008) takes advantage of the gridded input structure of both MODFLOW and PRMS-IV to create a comprehensive model of both surface water features and subsurface water features. By combining the two models, GSFLOW can consider the effects of climatic drivers such as precipitation, air temperature, and solar radiation as well as groundwater stresses on an entire watershed system. The GSFLOW model operates on a daily time step and is useful for evaluating the impacts of land-use and climate change as well as the effects of groundwater withdrawals over a wide range of drainage areas as well as time periods.

Although both PRMS-IV and GSFLOW utilize a gridded input system, basin responses and flow estimates are determined for a single basin outlet point. In the anticipated Russian River modeling framework, a key feature of the hydrologic model will be the capability to produce flow estimations for any grid cell within the system – most importantly for ungaged tributaries in the upper reaches of the watershed. PRMS-IV can be operated for time steps appropriate for analyzing flood patterns and the daily time step that GSFLOW uses would likely be sufficient for most flow analyses in the Russian River basin. However, in the case of irrigation diversions for protection from frost and heat events, which typically occur on a sub-daily timeframe, it would be important to be able to consider shorter time steps in the model. Additionally, real-time forecast information can be generated for a sub-daily time step as well, further emphasizing the need to accommodate shorter time steps in the model.

MIKE SHE (Abbot et al, 1986a & b) was originally developed based on the idea that the various flow processes within the hydrologic cycle can be physically modeled and incorporated into a comprehensive hydrologic model. MIKE SHE has been further updated since its original release by DHI Water & Environment to include a full suite of hydrologic modeling tools. (Graham and Butts, 2005) MIKE SHE uses a gridded format to model processes that include evapotranspiration, overland flow, unsaturated flow, and groundwater flow, and the model is able to produce gridded outputs for a wide variety of hydrologic states and processes. MIKE SHE is designed with a modular structure that allows it to be combined with other packages from DHI. One such package is the MIKE 11 river hydraulic program. By coupling MIKE SHE with MIKE 11 (Havnø et al, 1995), river network flow modeling and routing is possible that compliments the gridded output options of the MIKE SHE model alone.

One drawback of the MIKE SHE modeling system is the fully distributed nature that makes it such a useful tool. As is often the case with fully distributed models, a large amount of input data is required to build an accurate model. MIKE SHE does allow the user to vary the spatial distribution and complexity of each modeling component to suit the modeler’s purposes and the availability of data, as well as to reduce the computation time of the model. The coupling of MIKE SHE with MIKE 11 is not the optimal setup for a model of the Russian River tributaries. In order to model channel flow with the MIKE SHE/MIKE 11 coupling, stream channels must be explicitly modeled using a link and node system in the MIKE 11 river link network. While this can be accomplished, explicit modeling of a tributary network could prove prohibitive given the complexity of the system.

The USDA Agricultural Research Service has developed the Soil and Water Assessment Tool (SWAT) for modeling hydrologic systems on a variety of scales from a simple watershed to entire river basins (Arnold et al, 1998). The model is physically based and uses gridded input information regarding soil type, topography, vegetative cover, and land management practices to predict watershed responses to climatic information. SWAT uses the concept of hydrologic response units (HRUs) to subdivide the basin into areas that have similar hydrologic characteristics including land cover, soil, and management combinations. Surface water runoff from each HRU is routed to a main channel via smaller tributaries. Flow in the tributaries is not routed, but tributary length is used to determine time of concentration values for each HRU. Main stem flow is modeled using Manning's equation and routing is accomplished using either variable storage routing or the Muskingum river routing method.

The main purpose of the SWAT model is to predict the impact of land management practices on water with a particular focus on sedimentation and chemical loads in runoff. (Neitsch et al, 2009) The model is typically constructed to analyze changes in complex watersheds over longer periods of time. Key benefits of using SWAT are that the model structure allows the user to model watersheds without the benefit of stream gage data and that it has the capability of analyzing alternative management scenarios; both benefits could be applicable in the Russian River basin model.

While the SWAT model has capabilities that would be suitable for the purpose of modeling some aspects the Russian River basin, it would not be well suited for modeling the upper tributaries. While the input to the model can be developed from gridded coverage data, the hydrologic model and output data are based on the HRU concept. Applying the HRU modeling concept to the smaller basins of the tributaries would result in a complex model in order to route flows through the entire tributary system. Also, modeling the effects of agricultural ponds in the basin would require either explicit modeling of each pond as well as any proposed ponds or the creation of an HRU for each pond location to analyze management alternatives in a separate water resources management model.

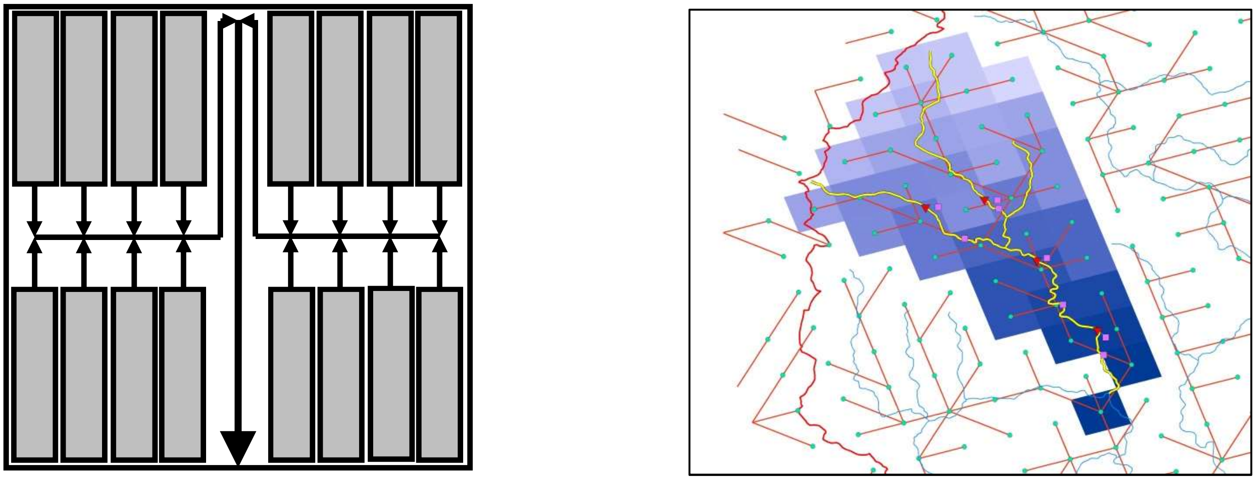
The Hydrology Laboratory (HL) of the National Weather Service (NWS) has developed the gridded rainfall-runoff model termed the Hydrology Laboratory Research Distributed Hydrologic Model (HL-RDHM). HL-RDHM is based on the original Hydrology Laboratory Research Modeling System (HL-RMS) (Koren et al, 2004) which was developed with the intent of combining features of both lumped and distributed models into a more efficient, yet still effective, hydrologic modeling system. This is achieved by applying the Sacramento Soil Moisture Accounting (SAC-SMA) model, which is a lumped hydrologic streamflow model, across a gridded surface to achieve a spatially distributed model.

Most gridded models, as previously detailed, are physically-based. The gridded structure allows the model to account for cell-to-cell fluxes, heterogeneities of model characteristics within the modeled stream basin, and the effects of spatially distributed inputs. This model structure also allows the modeler to use ever-finer resolution data to create more complex models in an attempt to fully describe the stream basin. However, in developing HL-RMS, Koren et al (2004) noted that "the use of more complex models does not necessarily result in better hydrograph simulation at the basin outlet." In an effort to simplify model development and reduce computational resource requirements while maintaining the key advantage of predicting interior point hydrology that distributed modeling presents, HL-RMS/HL-RDHM was developed to apply the lumped SAC-SMA model within each grid cell. Model development is further simplified by the option of estimating SAC-SMA parameters based on soil properties. (Koren et al, 2000)

The HL-RDHM model uses the Hydrologic Rainfall Analysis Project (HRAP) grid as the basis for its coordinate and grid system. The standard HRAP grid cell size is approximately 4km and varies slightly with latitude. The HL-RDHM model has been implemented on a variety of scales typically reported in relation to the standard HRAP grid cell size. For instance, ¼-HRAP grid cells are approximately 1km in size. The capability to use the ¼-HRAP grid allows the HL-RDHM model to generate streamflow estimates on the scale of the tributaries in the Russian River basin.

The HRAP grid is also used by the NWS River Forecast Center (RFC) multisensor precipitation estimate (MPE) system, which couples NEXRAD Doppler radar information with gage data for improved estimation of hydrologic system components such as spatially distributed, gridded precipitation estimates. (Young et al, 2000) Since the main driver of the SAC-SMA model is precipitation, the use of the HRAP grid system allows the HL-RDHM model to seamlessly utilize MPE data for runoff estimations. Additionally, both observed and forecast data are available for the HRAP grid, allowing the HL-RDHM model to operate in both forecast and estimation capacities.

For each model cell, the HL-RDHM model performs both runoff and routing calculations. Runoff calculations are based on the SAC-SMA model and include fast, medium, and slow response-type flows. Fast response flows include impervious, surface, and direct runoff and are routed through conceptual hillslopes (Figure 1(a)) before contributing to the main channel in each cell. The medium response interflow and slow response baseflow components are assumed to contribute directly to main channel flow. The combined fast, medium, and slow response flows are combined with channel flows from upstream model cells at which point cell-to-cell channel routing (Figure 1(b)) is applied to the aggregate flows.



(a) (b)

Figure 1 (a) HL-RDHM conceptual hillslope routing and (b) HL-RDHM cell-to-cell drainage network with stream network

By incorporating both rainfall-runoff calculations and routing operations into each cell, the HL-RDHM model allows for the estimation of streamflow runoff at any point within the stream network. By combining this capability with a smaller grid cell size, the HL-RDHM model can be used to estimate flows for points within the Russian River tributary network, most importantly ungaged stream locations. Additionally, the HL-RDHM model can be run at a variety of time steps, including daily and sub-daily durations. This option allows for more accurate modeling of frost and heat protection demands as well as more accuracy in flood flow routing through the system. Given the significant role that atmospheric rivers play in the Russian River basin, the ability to rout flood flows is key to fully describing tributary hydrology.

One key drawback of the HL-RDHM model is the representation of groundwater within the system. While soil moisture and groundwater are included in the SAC-SMA model, there is no cell-to-cell routing of groundwater between adjacent model cells. Instead, groundwater is assumed to contribute to channel flow within each model cell, where it is then routed downstream. This shortcoming would likely be most significant in lower reaches of modeled basins where increased baseflow may likely be generated by cumulative subsurface flows from upstream cells. (Reed et al, 2002) Fortunately, the effects of this model simplification would likely have a minimal effect on tributary flows in the upper reaches of the Russian River basin.

Coupled Hydrologic and Water Management Models

Coupling hydrologic models and water management models allows the modeler to take advantage of the unique capabilities of each model, resulting in a more complete description of the overall system. A typical coupled model structure consists of a hydrologic model estimating natural system flows for input into the water management model. In many cases, the final coupled model forms the foundation of a decision support system (DSS) and is used to evaluate decisions and scenarios within the modeled basin. Based on this literature review, MODFLOW is the most commonly used gridded hydrologic model for coupling with water management software. However, there have been a number of unique approaches to achieving this coupling, which are reviewed here.

A common application of coupled models is for regional-scale water planning and management. Boyle et al (2010) coupled three models to create a decision support tool to evaluate the effectiveness of using water rights purchases to supplement water deliveries to Walker Lake in Nevada. A MODSIM model was developed of the Walker River basin to include streamflow routing and reservoir operations. PRMS was used to model upstream contributing areas and estimate inflows to the study area in the MODSIM model. MODFLOW models were developed to represent the groundwater-surface water interaction in the agricultural regions in the Walker River basin and account for changes associated with water rights transfers and proposed irrigation changes in the region. The PRMS and MODFLOW outputs are used as one-time time series inputs to the MODSIM model, which then incorporates water rights and operations into a final stream routing model and decision support tool. The resulting decision support tool is capable of producing a reasonably accurate representation of the Walker River basin distribution system and an updated version has been used to evaluate long-term management scenarios in the basin. (Niswonger et al, 2014) However, although the PRMS model of upstream areas provides estimates of inflows to the study area, it does not fully represent both natural and managed flows throughout the system. While this may be suitable for the evaluation of long-term management strategies, this modeling system would not be well-suited for evaluating the short-term effects of diversions that are key in the Russian River basin.

Valerio et al (2010) coupled MODFLOW with the basin management software RiverWare (Zagona et al, 2001) to model environmental flows in the Colorado River basin. The resulting model performed a data exchange process between the coupled models on a once-per-time step frequency, which allowed the models to run in tandem rather than on a successive basis. The coupled model was not executed to an optimized solution, rather a trial-and-error approach was used to meet the flow targets. However, the general framework acknowledges the connection between groundwater and managed flows in a basin and the overall coupled model shows that return flows in the system may allow for improved reservoir operations when targeting minimum instream flow requirements. Dogrul et al (in review) led a similar effort in modeling the Central Valley of California. C2VSim (Brush et al, 2006), a finite-element representation of the groundwater and surface water system, was linked with CalSim (Draper et al, 2004), a water management model, to model a complex system of reservoirs, agricultural, and urban demands. The model was run for a period of 88 years on a monthly time step with data exchanged between the two models at each time step. While it was possible to iterate between the two models until the stream-aquifer interactions converged in successive iterations, memory issues and long execution times resulted in the use of only four iterations per time step, which was considered sufficient. The coupled model was used to analyze the long-term impacts of drought on pumping, surface water-groundwater exchanges, and groundwater storage.

Hadded et al (2013) used a coupling of MODFLOW with the WEAP water resources planning tool (Yates et al, 2005) to evaluate water management decisions in Tunisia. The North African country is extremely arid and has historically relied heavily on groundwater to satisfy municipal and agricultural demands, which has resulted in aquifer drawdowns measuring 22 meters. Recent water management strategies have included the addition of desalination plants to supplement water supply in 5 major cities in the southeastern region of Tunisia, which also rely on the same aquifer for groundwater supply. MODFLOW and WEAP were combined to model groundwater depletion and the impacts of desalination plants on a monthly time step over a 28-year period that included both historical modeling as well as the evaluation of future scenarios where the model acted as a DSS. Data was transferred on a monthly time step between MODFLOW and WEAP and the coupled model demonstrated the ability to simulate the changing aquifer and supply-demand conditions. A similar framework was developed by Droubi et al (2008) where MODFLOW and WEAP were coupled to analyze the water resources conditions in Syria. Heavy reliance on groundwater for municipal and agricultural supply makes it susceptible to system stresses such as population growth and drought. The resulting DSS was used first to model historic conditions and then to evaluate multiple management scenarios that included changes in both supply and demand. Data was transferred between the coupled models on a once per time step basis, with MODFLOW calculating groundwater heads, storage, and flow and WEAP calculating groundwater recharge, river stage, irrigation demand, and other water balance components. The coupling of MODFLOW and WEAP is useful for long-term planning and scenario evaluation, the modeling system would not be useful for analyzing the short-term impacts of diversions and precipitation events in the basin.

Sophocleous et al (1999) combined SWAT with MODFLOW to model the Rattlesnake Creek basin in south-central Kansas in an effort to include both water management and stream-aquifer interaction in a comprehensive model. The two models were run sequentially with data exchanged on a monthly time step. The model was developed based on 40 years of historical data and then was run for a 40-year future time period. A baseline case was compared to a variety of management scenarios as a demonstration of the potential impacts of management options rather than as a predictor of future conditions. Ramireddygari et al (2000) implemented the same model linkage structure to combine the Potential Yield Model, Revised (POTYLDR) (Koelliker, 1994) with MODFLOW in order to examine the effects that watershed structures such as irrigation ponds have on stream yield. POTYLDR is a surface water budget model that uses the Soil Conservation Service runoff curve number method (USDA, SCS, 1972) and is similar to SWAT in that it can account for changes in land use and climate in the runoff estimations. By comparing a base scenario with water management scenarios that included on-stream ponds, Ramireddygari et al (2000) showed that total streamflow from the basin was only slightly impacted by the inclusion of the ponds. However, the timing of streamflow was impacted in that peak flows were reduced and released more slowly downstream. The SWAT-MODFLOW coupling is intended to simulate long-term effects of management scenarios and would not be well suited to the evaluation of short-term impacts of management in the Russian River basin. Additionally, the HRU modeling concept that the SWAT model uses is not ideal for modeling tributaries in the Russian River system since it would generate estimated flows for individual outlet points rather than a gridded estimate of flows.

In another approach, the gridded MODFLOW model is not directly linked with the river management software but uses a proxy representation of MODFLOW instead. Fredericks, et al (1998) use response functions based on MODRSP (Maddock and Lacher, 1991) to estimate groundwater-surface water interaction in a MODSIM model of the South Platte River basin of Colorado. MODRSP is a modified version of MODFLOW that enables a linearized representation of the groundwater system. By using this system, Fredericks, et al (1998) were able to significantly reduce processing time and improve the accuracy of linear groundwater representation over other systems while evaluating the effectiveness of a long-term augmentation plan. Triana, et al (2010) used an artificial neural network (ANN) that was trained on high resolution MODFLOW model results to represent the groundwater-surface water interaction in the Arkansas River basin in Colorado. The ANN was then linked to a Geo-MODSIM river basin network flow model to evaluate water management alternatives in the region (Triana et al, 2009a; Triana et al, 2009b). As with the use of the MODRSP, the use of the ANN improves computation time. Additionally, the ANN gives the user the ability to estimate groundwater flows in areas that do not have a MODFLOW model. By using the same explanatory variables that the ANN was trained on and are readily available through GIS analysis, an estimate of the MODFLOW model can be made through the use of the ANN.

The SWAT model has also been used in conjunction with MODSIM to create a DSS for the Karkheh River Basin in Iran that not only evaluates changes in climate and cropping patterns, but also includes reservoir operations and hydropower generation in the system optimization. (Vaghefi et al, 2015) While SWAT is not a fully gridded model, it has the capability to produce flow estimations for a number of points throughout the basin for inclusion in the MODSIM model. Vaghefi et al used a twice-per-time step data transfer method that first runs the SWAT model with full water supply to generate agricultural demands. These demands were transferred to the MODSIM model to determine estimates releases and diversions that consider actual supply conditions. Finally, the MODSIM results were transferred back to SWAT to evaluate the final agricultural production. Using this approach, a variety of climate and crop pattern scenarios was considered and the combined effects on the multi-objective system were evaluated. However, this method would not be ideal for use in the Russian River basin. The SWAT model output for individual subbasins or HRUs would not be an efficient modeling approach for a tributary system.

PRMS uses a modeling approach that is similar to the SWAT model in that it uses continuous data to subdivide a basin into modeling response units (MRUs), which are analogous to the HRUs of the SWAT model. Using this system, PRMS can be used to generate surface flow estimates for points throughout a river basin, including ungaged locations, which can then be incorporated into a flow management model. One such application was made by Mastin and Sharp (2006) for the Yakima River basin in Washington State. Based on the model that was previously created for the Yakima River basin (Mastin and Vaccaro, 2002), a PRMS model and RiverWare were coupled using the USGS Modular Modeling System (MMS) to incorporate natural and managed flows into a single DSS. Management aspects within the river basin include irrigation demands as well as instream flow requirements for endangered salmonid species. The model was used to evaluate average historical conditions for comparison with historical drought years as well as estimated conditions based on a global climate change scenario. Results indicate that on average, for the Yakima River basin, there should be sufficient supply to meet both irrigation and instream flow requirements. However, future drought years are likely to result in irrigation and instream flow shortages. While the PRMS model was used to evaluate land use management scenarios as well as instream flow availability, the lack of a gridded hydrologic output limits the ability to evaluate a variety of management alternatives that may vary in both type and location.

Need for a Coupled HL-RDHM and MODSIM Model

Throughout the literature review there is a lack of coupled models that combine gridded-output surface water hydrologic models with water management models. While all of the hydrologic models that were previously detailed utilize gridded inputs to describe a watershed, most of the models provide output data on a watershed, sub-watershed, or hydrologic response unit basis. MODFLOW is first and foremost a groundwater hydrologic model that can generate estimates of surface water depth on a gridded basis. However, the surface flow routing of the streamflow routing package in MODFLOW does not account for flood wave routing and utilizes a link and node stream network representation that does not maintain the gridded output nature of the hydrologic model.

The literature review also reveals that there is a lack of coupled models that integrate a surface flow hydrologic model with a water management model in order to evaluate instream flows throughout a stream network while accounting for both natural and managed flows. Models that couple MODFLOW with management software are typically focused on the effect that water management decisions have on groundwater-surface water interactions and groundwater recharge. Other models that couple a surface water flow model with a management model generate results for a specifically modeled stream reach rather than for the entire stream network and are not flexible enough to evaluate many management options, such as agricultural ponds, without explicitly modeling them.

A model that couples HL-RDHM and MODSIM will serve to address these shortcomings. Similar to other hydrologic models, HL-RDHM uses gridded inputs for model development. However, HL-RDHM has the additional option of using precipitation and temperature forcing data, which can be from observations, such as radar information, or from precipitation and temperature forecast information. Furthermore, the gridded outputs that HL-RDHM generates make it possible to evaluate streamflow at any point within the basin. Additionally, the gridded streamflow estimates from HL-RDHM are correlated to the cell-to-cell drainage network for the basin, which is then used for kinematic wave streamflow routing that maintains the natural streamflow patterns within a basin. By creating an accurate MODSIM model that includes diversions, management structures such as agricultural ponds, instream flow requirements, and irrigation demands, and then combining it with the natural flow estimates from the HL-RDHM model, a more accurate representation of the total streamflow in a basin can be developed. Also, by combining the gridded HL-RDHM outputs with the flexibility of the MODSIM model, various management alternatives can be quickly evaluated without requiring explicit modeling in the hydrologic model. The coupled HL-RDHM–MODSIM model is expected to be a more accurate representation of the natural and managed flows as well as a flexible and useful tool for evaluating management options.

Russian River Tributary Models

The wide variety of stakeholders in the Russian River valley is emblematic of the high level of interest there is in understanding the hydrology of the basin. As such, a variety of models have been created for the Russian River basin that attempt to characterize one or more aspects of the watershed hydrology. By approaching this common goal from different perspectives, a more complete understanding of the multi-use system can be obtained. This review focuses on previously developed models of the Russian River basin and/or its tributaries.

Hydrologic Streamflow Estimation Models

A key aspect of fully understanding the Russian River watershed is the ability to estimate streamflows in the system. The hydrology of the basin is driven by atmospheric river phenomena coupled with orographic effects, which result in heavy rainfall events and frequent flooding during the winter wet season. However, for ecological and agricultural considerations, modeling of low flow periods during the summer dry season is equally, if not more, important. Flow estimation models can be generally grouped into two categories. In the first, models are developed to simulate flows at one or more points within the basin, which typically correspond to streamflow gage locations.

Miller and Kim (1995) applied the University of California Lawrence Livermore National Laboratory Coupled Atmosphere-River Flow Simulation (CARS) model to estimate Russian River flow responses to a series of significant rainfall events that occurred in the basin. The CARS model is a coupling of the rainfall prediction model Mesoscale Atmospheric Simulation (MAS) model (Kim and Soong, 1996) and the distributed hydrologic model TOPMODEL (Beven and Kirkby, 1976). The model was calibrated for the Russian River at the Hopland gage station and performed well for both precipitation and flood flow predictions. Kim et al (1998) present a similar model coupling named the Regional Climate System Model (RCSM). Similar to the CARS model, RCSM combines the MAS model with TOPMODEL to predict streamflows in the Russian River. However, RCSM also includes the Soil-Plant-Snow (SPS) model (Mahrt et al, 1984) to account for soil moisture, vegetative water content, and energy and snowmelt in the system. The results of the RCSM model of the Russian River basin were evaluated at the Hopland gage for the period from January 1, 1995 through March 15, 1995. The model performed well for flood prediction, but consistently overestimated streamflows during low flow conditions. Finally, the RCSM model was compared to two versions of the lumped Sacramento model that were developed for the Russian River watershed: the National Weather Service/River Forecast Center model (Burnash et al, 1973) and the Hydrologic Research Center (Georgakakos, 1986). All three models performed well for flood prediction and all three models over-estimated recession flows following the flood peaks. In another application of the RCSM model Kim et al (2000) used the model to estimate streamflows in the Russian River basin at the Hopland gage station as part of the evaluation of a downscale method for a general circulation model (GCM) that simulates climate data on a coarse (2.5° x 2.5°) resolution. The model was used to evaluate a hindcast scenario as well as observed data. In both cases, the TOPMODEL streamflow estimations were generally high for low flow conditions while flood event prediction was reasonably accurate. While these models are helpful for predicting the streamflow responses to precipitation events for a variety of points in the basin, they do not allow for the gridded streamflow estimates that allow for consideration of multiple management options.

Finally, Zhang et al (2010) applied the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) (Feldman, 2000) to the Russian River watershed. The model was developed based mainly on GIS-based information and is primarily driven by meteorological data. A preliminary calibration process of model parameters was based on streamflow data from six USGS streamflow gages within the basin. The model was then evaluated for a five-day period from December 12 to 16, 2002 for which precipitation and streamflow data was available for a significant storm event. The model demonstrated a reasonable level of skill in predicting peak flow timing but generally over-predicted the magnitude of the peak flows. Additional calibration was deemed necessary to improve results.

The second type of hydrologic model that has been developed has the capability of producing results on a gridded basis, thereby providing streamflow estimates for any point within the watershed. The Basin Characterization Model (BCM) (Flint and Flint, 2007) has been applied to the State of California to simulate hydrologic information on a fine (270m) spatial grid at a monthly time step (Flint et al, 2013). The model can then be used to estimate historical basin responses or predict future responses under a variety of climatic scenarios. The Dry Creek watershed in the Russian River basin was used as one of the calibration watersheds for the model development. While streamflow routing is not explicitly included in the model, a transformation was developed to convert recharge and runoff data to timeseries data that can be compared with gage data. Results for the Dry Creek basin indicate a high correlation between modeled and streamflow gage data.

The BCM was applied to the entire Russian River basin by Flint et al (2015) to generate simulated datasets for more than 100 years of historical climate data as well as 100 years of future data based on four climate projections. The model was updated to include a daily time step and was calibrated at 6 different gage locations throughout the basin. While a wide variety of hydrologic data is generated on a gridded basis, routed unimpaired streamflow estimates were produced for 12 points throughout the basin using the calibrated water-balance model and a post-processing routine. The model performance at these 12 points was reasonably accurate, with the best results demonstrated for streams that are relatively unimpaired by dam operations. While gridded hydrologic outputs are available from the BCM model, gridded routed flow estimates are not. To obtain routed flows at a location within the model, an additional transformation calculation is required.

HL-RDHM has been used to develop a gridded hydrologic model of the Russian River basin that characterizes the natural unimpaired flows within the basin. (Johnson et al, 2014) The model is based on the Sacramento Soil Moisture Accounting model and includes a cell-to-cell routing structure for estimation of spatially distributed runoff at any location within the basin. The model is capable of producing a variety of gridded hydrologic data and was originally developed to use a 4-km grid and 6-hour time steps. The model has been further refined to use a 1-km grid and 1-hour time steps (Johnson et al, 2014). Initial results of the model demonstrate reasonably good performance for both low flow and peak flow estimation.

Hydrologic System Modeling

Hydrologic system modeling, in the scope of this literature review, includes models that attempt to characterize more than just streamflows within the Russian River basin. In general, hydrologic system models recognize that streamflow diversions and management decisions may impair the natural flows within the system, creating the potential for imbalances within a multiuse system. The redistribution of flows in the Russian River watershed through the use of ponds and reservoirs has the potential to create environmental flow shortages in the system, but at the same time has provided the potential to operate the system to achieve a maximum benefit. Of course, system optimization is not new nor is it unique to the Russian River valley. Authors such as Labadie (2004) provide a background on operating multi-reservoir and multi-objective systems to achieve balanced results, while Richter et al (2007) investigated the restoration of environmental flows through the modification of dam operations. This review includes models that were developed to analyze the Russian River system as a multi-objective system.

Merenlender et al (2008) developed a GIS-based analytical tool for evaluating water supply and demand for use within the Russian River basin. Water supply estimates were calculated by scaling streamflow gage data for the modeled stream. For each point in the stream network, total unimpaired flows were approximated by scaling historic streamflow gage data based on the upstream contributing area and mean annual precipitation data at the point. Environmental instream flow diversion limits were based on the California State Water Resources Control Board (SWRCB) policy for maintaining instream flows (SWRCB, 1997), agricultural demands were estimated based on vineyard area, and rural demands were included for outdoor water use. The method was applied to two streams in the Russian River basin. In the Dry Creek watershed, the model was used to evaluate the impacts that the proposed SWRCB diversion regulations would have on agricultural diversions. Results indicate that 92% of the drainage network would be restricted to less than 33 days of surface water diversions per year. An additional analysis estimated levels of flow impairment due to small agricultural ponds in the watershed during normal and dry conditions. In the Pena Creek watershed, the model was applied to estimate the benefits associated with the construction of off-stream agricultural ponds. The GIS tool allowed for visual display of the results for decision support within the Russian River basin.

Grantham et al (2010) utilized the model and methods developed by Merenlender et al (2008) for the analysis of a small (16 km^2) catchment in the Russian River basin. Of interest were the effects of small fill-and-spill type agricultural ponds on streamflows throughout the year. In the first scenario, three hypothetical ponds of the same size were simulated within the basin. Results indicated that pond location can have a significant effect on the impacts to streamflows. Additionally, the cumulative effect of the simultaneous operation of all three ponds is more significant than the sum of the effects of the individual ponds. A second analysis included 14 hypothetical ponds that were sized according to the surrounding vineyard area. By evaluating the impacts and benefits of each pond, the management options could be ranked, thereby providing decision support for storage implementation. The final analysis focused on the same 14 alternatives but evaluated pond performance in accordance with the SWRCB environmental flow policies (SWRCB, 2010). The results indicated that only 3 of the 14 ponds would fill in an average year and surface water diversions would be required to meet 40% of the irrigation demand during the summer.

The tradeoffs between environmental instream flows and agricultural water security for Maacama Creek in the Russian River basin were studied by Grantham et al (2014). Based on the model by Merenlender et al (2008), agricultural water demands and environmental flow policies were modeled for a range of hydrologic conditions (dry to wet) and over a range of environmental flow policies (no regulation to strict regulation). Results indicated that while environmental flow policies did serve to protect instream flows, the ecological benefit was not always proportional to the detrimental effects on agricultural supply. Additionally, the effect of instream flow regulations is also dependent on the timing of precipitation events as well as diversion location. Finally, the study indicates that for this particular watershed, natural supplies were sufficient in most years for meeting water storage needs regardless of policy restrictions. During drought years conflicts were more common, indicating that management policies should be developed with a focus on drought years.

Merenlender (2008), Grantham et al (2010), and Grantham et al (2014) all utilize the model developed by Merenlender (2008) to evaluate various hydrologic aspects of the Russian River basin. However, a hydrometeorological modeling system that estimates streamflow based on either measured or forecast gridded precipitation estimates rather than scaled gage data would be able to evaluate a more complete spectrum of hydrologic scenarios.

The last study considered was the application of the European Water Framework Directive (WFD) to the Russian River basin (Grantham, 2008). The WFD seeks to balance the ecological health of a river while continuing to provide water for human needs. By using a basin-scale approach, management effects on a system are evaluated on a much broader scale than is typical in the United States, where there are often multiple agencies with overlapping jurisdiction for a single river or body of water. The study seeks to evaluate the Russian River basin in the context of the WFD by considering current river administration, characterizing the current environmental aspects of the various water resources within the basin, evaluating the various pressures and impacts of human influences on the river system, and establishing an economic profile of the basin to help develop water management strategies. Three key components were identified for the development of a sustainable water management plan under WFD guidelines. They include a basin-wide administrative body, a comprehensive ecological analysis of basin waters, and the development of economic and environmental criteria that measure the effectiveness of management decisions.

Management Impact Evaluation

While the previous section focused on models of the Russian River basin that evaluated hypothetical management scenarios, some studies are focused on characterizing the effects of current management strategies within the basin. By using empirical data on streamflows and demands within the basin, the impacts of streamflow diversions can be estimated. These estimates can then be used to guide the implementation of future management strategies.

Deitch et al (2009a) used a simplified water balance model to explore the impacts of instream diversions on streams within the Russian River basin. The simple model had three components: input, storage change, and output. Historic streamflow data from a year of average precipitation was used as the input streamflows. These historic flows were considered a more natural flow pattern as compared to more recent impaired flows. For the storage change variable, the model assumed that permitted instream diversions were the only abstraction from the stream. By calculating the difference between the input flow and the storage change, the expected output flows could be determined. The model was applied to six gaged streams in the Russian River basin. Results indicated that winter flows are likely unimpaired by diversions but in the spring and summer flows have a higher potential for ecological impairment or premature intermittency. The model was then applied to a series of 13 ungaged tributaries using a flow-per-area method of approximating streamflows. Similar results were reported, however impairment occurred earlier in watersheds with higher demands-to-runoff ratios. Overall, the study presented a straightforward approach to studying the potential impacts of instream diversions on streams based on historic and current data on streamflows and diversions. However, the model is unable to quantify the impacts or to evaluate specific management strategies in the basin.

In another example, Deitch et al (2013) uses a water balance model to estimate the impacts of small agricultural ponds on tributary streams within the Russian River basin. A GIS-based model of a portion of the basin that included a drainage area of 743 km^2 and 438 small on-stream ponds that use a fill-and-spill type operation was developed. By scaling historic streamflow data based on drainage area and precipitation, estimated streamflows were calculated for all points within the stream network. Ponds were modeled based on aerial imagery and volume-area relationships within the basin. The agricultural pond impacts were evaluated during the initial filling stages for a normal-type and a dry-type year. Impacts were evaluated based on location and duration for all points downstream of each pond. Cumulative impacts were also estimated by summing the total impact of each pond on all downstream points in the stream network. Overall, the cumulative impacts of small agricultural ponds are most significant on early-season flows and diminish with time. While the mass balance approach demonstrated the distributed impacts of multiple agricultural ponds in the Russian River basin, the method is restricted by its use of scaled gage data to estimate streamflows rather than the use of a hydrometeorological model.

Another approach to evaluating the impacts of instream diversions was applied by Deitch et al (2009b) where the hydrologic impacts of frost and heat protection were assessed through analysis of streamflow gage and temperature data. Streamflow gages were installed along three different streams in at least two locations per stream – one with a significant amount of upstream vineyards and one further upstream where there was insignificant vineyard acreage upstream. By comparing temperature data for the region with recorded streamflows, it was evident that temperature extremes were typically accompanied by significant decline in streamflows for gages with upstream vineyards, while gages without upstream vineyards remained unaffected. This empirical evidence suggests that instream diversions for frost and heat protection have a direct and significant impact on streamflows and future management strategies will likely need to include the improved operation of small ponds.

Another analysis of streamflow data was performed by Deitch and Kondolf (2012) to evaluate proposed instream flow requirements along a longitudinal gradient. Streamflow gages were installed at eight locations within the Maacama Creek watershed, and at each location the minimum instream flow was determined based on flow depth and channel geometry. Measured streamflow patterns were similar for all locations; however, it was noted that for locations with smaller upstream drainage areas peak flows were disproportionately higher and base flows lower when compared with flows for locations with greater upstream drainage areas. This was significant in that periods of diversion were substantially reduced for upstream points, which may then have a sizable impact on streamflow management within the basin.

Need for a Russian River Tributary System Model

Throughout the literature reviewed there has been a lack of Russian River tributary models that provide a comprehensive model of the streamflow hydrology. Many of the models seek to estimate streamflows for the basin on a watershed scale for individual storm events. While this can lead to a better understanding of the underlying hydrologic characteristics of the basin, it does little to inform management decisions. The BCM model (Flint et al, 2007) has the ability to produce gridded estimates of a variety of hydrologic variables, however a special transformation is required to estimate routed streamflows at a particular point in the system. The HL-RDHM model of the basin (Johnson et al, 2014) provides routed system flows, but, as detailed in the previous review section, it does not account for the effects of instream flow diversions and management decisions.

The literature review also indicated that there is a need for comprehensive modeling of the managed Russian River tributary system. While many of the reviewed models consider a variety of management scenarios, they are often compromised by the use of proxy streamflow data. Most commonly, gage data from the basin is scaled according to contributing area and/or precipitation depth. However, Deitch and Kondolf (2012) noted that while streamflow patterns remain similar throughout the basin for a storm event, the magnitude of the response is not always proportional to contributing areas. Additionally, the temporal scale of the current management system models is often insufficient to capture flood routing and the short-term effects that management decisions can have on the stream network.

In the evaluation of management impacts on the tributary system, the literature review reveals that many of the current models rely on model simplifications to describe the watershed. For instance, a simple water balance model was used by Deitch et al (2009a) and Deitch et al (2013) to estimate effects of instream diversions and ponds, but the instream diversions lacked a spatial distribution and the pond effects did not include irrigation patterns or withdrawals. Other models examine the implied impacts of diversions and environmental regulations but lack an appropriate structure in which to evaluate alternative scenarios and more specifically model streamflows within the system.

The development of a coupled HL-RDHM and MODSIM model will address the deficiencies of previous models in the Russian River basin. The combination of the HL-RDHM model with MODSIM will allow for detailed modeling of both unimpaired natural flows as well as managed flows on the tributary scale in the basin. HL-RDHM has the capability of estimating flows for historic periods using estimated precipitation from radar data as well as utilizing forecast data and simulated precipitation to analyze future hydrologic scenarios. The coupling will also allow the evaluation of a variety of management scenarios using estimated streamflows at appropriate temporal scales rather than scaled gage values. Through this model development, a more comprehensive analysis of management effects that includes an accurate portrayal of diversions and pond operations as well as the ability to consider a variety of environmental flow scenarios will be possible.

Collaborative Modeling in the Russian River Basin

Water resources engineers are often tasked with balancing multiple, competing interests within a single system. Hydrologic models, decision support systems, and multi-objective analysis are some helpful tools that are used in the development of water management strategies. However, while these strategies often seek balanced solutions, if the stakeholders are not directly involved in the modeling process, their needs and concerns may not be sufficiently addressed. To prevent this situation and to arrive at a more complete understanding of a watershed system, many water resource managers turn to collaborative modeling. This section of the literature review focuses on collaborative modeling and its applicability to the Russian River basin.

Collaboration in Water Resources Planning and Management

Collaboration has become an accepted and even expected practice in almost any modeling effort in the realm of natural resources planning and management. (Voinov and Bousquet, 2010) Also referred to as partnerships, consensus groups, community-based collaboratives, and alternative problem-solving efforts (Conley and Moote, 2003), Schuett et al (2001) defined collaboration in natural resources as "people working together, sharing knowledge and resources, to ensure sustainable ecological systems and communities." By including stakeholder input in the management process, resource managers not only seek to develop an optimal solution that benefits both the regional ecology and economy, but they also seek to build trust among opposing interest groups. (Cestero, 1999)

While collaboration has become a fairly typical approach to natural resources planning and management, the success of a project is not guaranteed by simply using collaborative methods. Schuett et al (2001) performed a survey of collaborative participants and summarized the keys to successful collaboration which included development, information exchange, organizational support, personal communication, relationships and team building, and accomplishments. To evaluate the overall success or failure of a project, Conley and Moote (2003) suggest that an evaluation of any collaborative effort be performed and describe a variety of approaches, standards, and methods that can be used. Cestero (1999) listed eight indicators of constructive collaboration:

1. Get meaningful projects implemented
2. Establish credible monitoring programs
3. Develop an open, permeable process
4. Foster broad and inclusive participation
5. Seek local, regional, and national participation
6. Engage the diversity of the group
7. Learn from each other
8. Craft innovative projects

By including these key features, "constructive collaborations work toward improving conservation and finding creative ways to meet local economic and social goals."

In general, collaboration in water resources planning and management is commonly associated with the incorporation of differing values and ideas in the development of goals and strategies for watershed management. A key component of the collaborative management framework is collaborative modeling. Richter et al (2006) present a collaborative approach to determining environmental flows that includes quantitative modeling, qualitative modeling, or both. In another study, Richter et al (2003) include modeling for the development of hydrologic simulations that can estimate the impacts of water management decisions as well as to explore management alternatives. Finally, Liu et al (2008) proposes a 9-step generic framework for effective natural resources decision support that includes modeling for the underlying natural processes as well as for scenario analysis. In any case, collaborative models are developed with input from various stakeholders and are essential for finding balanced solutions to the management challenges.

Collaborative modeling is synonymous with Shared Vision Planning, Cooperative Modeling, Computer Aided Negotiation, Mediated Modeling, Group Model Building, and Participatory Modeling (Cardwell and Langsdale, 2011). Furthermore, Langsdale et al (2011) define collaborative modeling as “a process that engages stakeholders in the construction of computer models that support decision processes.” Through the use of collaborative modeling, stakeholders are able to evaluate a model from diverse perspectives for transparency, validity, and equity of its impacts. (Reed and Kasprzyk, 2009) The authors continue to state that collaborative models “must provide a diversity of hypotheses and convey knowledge as broadly as possible to stakeholders, decision makers, scientists, and engineers.” As a result, the science behind the model can better inform the decision making process, even given the extremely complex nature of human-natural systems. (Poff et al, 2003).

While the use of collaborative modeling is widely accepted as a valuable tool in water resources planning and management, it is a relatively new process that is still evolving. As such, authors have begun to document some common components that collaborative modeling efforts have included. Voinov and Bousquet (2010) include 12 lessons learned that include both the social aspects of collaborative modeling as well as aspects of the modeling methodology. Langsdale et al (2013) reported the results of a task committee sponsored by the Environmental Water Resources Institute of the American Society of Civil Engineers and U.S. Army Corps of Engineers’ Institute for Water Resources that developed a set of Principles and Best Practices for collaborative modeling in water resources. The eight principles are:

1. Collaborative modeling is appropriate for complex, conflict-laden, decision-making processes where stakeholders are willing to work together.

2. All stakeholder representatives participate early and often to ensure that all their relevant interests are included.

3. Both the model and the process remain accessible and transparent to all participants.

4. Collaborative modeling builds trust and respect among parties.

5. The model supports the decision process by easily accommodating new information and quickly simulating alternatives.

6. The model addresses questions that are important to decision makers and stakeholders.

7. Parties share interests and clarify the facts before negotiating alternatives.

8. Collaborative modeling requires both modeling and facilitation skills.

In another observation, Rhoads et al (1999) point out that while watershed management is dependent on scientific modeling, many of the management decisions are social in nature. As such, effective communication between modelers and stakeholders is critical to management success. Similarly, Liu et al (2008) observe that a lack of communication is a common complaint of both decision-makers and modelers alike within water resources management, and that a collaborative modeling framework can be an effective solution to this problem.

A common modeling choice for developing a watershed model is GIS, which, coincidentally, is also an ideal platform for building a collaborative model. The display properties of GIS combined with the spatial analysis tools that are available make it possible to include traditional modeling aspects with the ability to present the model results to stakeholders. Additionally, authors such as Richter (2010) point out the need for hydrologic models that accurately model the spatial and temporal aspects of a watershed, including land use, diversions, reservoir operations, and unimpaired runoff. The geo-spatial decision support system (GeoDSS), as developed by Triana et al (2009a) for the Lower Arkansas River in Southeast Colorado is an example of just such a system. Ramsey (2009) points out that spatial decision support systems should be designed to support the exploration of multiple alternatives instead of focusing the solution of a single problem. By remaining flexible, the GIS-based tool can better support collaboration among the various stakeholders.

As with the general principles of collaborative modeling, there have also been efforts to outline the steps to collaborative model development. Voinov and Gaddis (2008) provide the most comprehensive guidelines for collaborative model development as a set of 12 lessons learned from the review of example collaborative modeling projects. The first five steps are devoted to identifying, engaging, and learning about the stakeholders to establish trust and identify conflicts. The remaining steps involve building and refining a model with stakeholder input, presenting and interpreting results to gain stakeholder acceptance and trust, and developing scenarios and management ideas with stakeholder input. Overall, the collaborative nature of the process is emphasized above the modeling aspects. Liu et al (2008) include many similar aspects into a multi-resolution, multi-disciplinary framework for collaborative modeling. In their system, models are developed at multiple scales in order to address management issues from a fine scale to a coarse, basin-wide scale. Finally, Palmer et al (1999) provide a list of the objectives of collaborative modeling, which include defining objectives, characterizing the physical and administrative features of a basin, evaluating alternatives, and comparing scenarios. These objectives are met by developing models that are relevant, valid, transparent, flexible, and accessible.

The final step to a collaborative modeling process is the evaluation of the modeling outcomes. Often, this step becomes more implicit rather than explicit in the development and implementation of a modeling system. However, Michaud (2013) developed an evaluation framework consisting of 36 evaluation measures that are designed to assess the effectiveness of the planning process, stakeholder participation, the modeling process, and modeling and planning outcomes. Through the use of such measures, the collaborative modeling process can be refined and participation can be improved in a way that can have more significant impacts on water resource management decisions.

Examples of Collaborative Modeling in the Russian River Basin

There is a wide variety of stakeholders concerned with water resources planning and management in the Russian River basin. The list includes agricultural users who depend on the river and its tributaries for irrigation supply, municipalities for whom the Russian River system provides the majority of water supply, and environmental groups whose primary concern is the habitat that the river and its tributaries provide for threatened and endangered fish species. Furthermore, within each of these categories there are numerous groups with more specialized interests that add even more complexity to the stakeholder framework of the basin.

Not surprisingly, conflicts have developed over water use in the Russian River basin, creating an environment where collaborative modeling could be used to develop acceptable management solutions. The National Oceanic and Atmospheric Administration (NOAA) Fisheries division has selected the Russian River basin as the first Habitat Focus Area and collaboration with community partners is recognized as a key feature of the research effort. (Fisheries, 2015) While a number of modeling efforts that could benefit from a collaborative approach have been undertaken in the Russian River basin, few examples of collaborative modeling have been found.

Merenlender et al (2008) describe a collaborative conservation process in the Russian River valley that is aimed at improving communication among stakeholders in northern Sonoma County with the purpose of habitat restoration for endangered fish species. Collaborative modeling efforts include the supply of agricultural water management information and data collection. Through these efforts, the coalition hopes to improve flow estimations for ecological and agricultural needs. Results of this continuing effort are not yet final, but the project is an indication that local stakeholders are interested in collaborative conservation in the basin that may be applied to the development of a comprehensive hydrologic model of a tributary.

One key area where collaborative modeling could offer significant improvements is in the area of agricultural data. Grantham et al (2010) developed a DSS that was capable of evaluating the effects of small agricultural ponds within a small watershed in the Russian River basin, Grantham et al (2014) developed a model that was focused on the links between environmental flow protections and agricultural water security, and Deitch et al (2013) modeled the effects of small agricultural ponds on streamflow. In each of these cases, agricultural pond volumes were estimated based on aerial photography. In other cases, agricultural water use was approximated based on a per-acre water use rate (Grantham et al, 2010; Grantham et al, 2014; Deitch et al, 2009). These are key areas where the use of collaborative modeling would yield more accurate models since using stakeholder input would reduce or eliminate the need to approximate agricultural pond sizes and diversions. In fact, Grantham et al (2010) and Grantham et al (2014) point out that the ultimate success of their models will depend on the use of collaborative modeling techniques.

Collaborative modeling could also be used to enhance models in the area of environmental flow requirements. While the California State Water Resources Control Board recently issued guidelines for maintaining instream flows for ecological benefit (SWRCB, 2010), alternatives to these guidelines, which are generally regarded as strict, should be evaluated as part of a comprehensive model. Richter et al (2006) set forth a 5-step process for determining environmental instream flows that relies on sound science, flexible management options, incremental changes, and public participation. This or another collaborative approach could be applied to enhance models such as those developed by Grantham et al (2010), Deitch and Kondolf (2012), and Grantham et al (2014), to provide additional management options to the stakeholders.

Need for a Collaborative Modeling Approach in the Russian River Basin

Throughout the literature reviewed there is wide base of support for collaboration in water resources planning and management. In fact, collaborative strategies have become the expected strategy for the development of management options throughout natural resources planning and management. Given the significant amount of conflict within the Russian River basin that exists between groups with opposing interests, collaboration can offer a variety of benefits such as finding a balanced solution as well as building trust among these groups. While far from being a standardized process, a collaborative effort should be focused on engaging the stakeholders and ensuring active communication among all interested parties.

The literature review also included a significant amount of information on collaborative modeling within water resources planning and management. Collaborative modeling is generally included a component of the overall collaboration process. Collaborative modeling focuses on building models that are based in science but are developed in conjunction with stakeholder input. By including them in the model development and maintaining open communication throughout the process, stakeholders are more likely to understand and trust the model results. The ultimate goal of collaborative modeling is to evaluate a wide range of relevant management alternatives and inform the decision-making process. Finally, the literature review of collaborative modeling also revealed that water resources system modeling must include both the spatial and temporal aspects of a watershed and GIS is an ideal tool for developing this type of model.

The literature review of collaborative modeling within the Russian River basin revealed that there is a general lack of collaborative models that have been developed within the basin. Many of the hydrologic models reviewed had the potential for improvement through the use of collaborative methods but they were not implemented. While collaboration is being used by conservation groups within the basin, collaborative modeling has been mostly ignored.

Overall, there is a general lack of examples of collaborative modeling within the basin. Through the use of collaborative modeling principles, the development of a coupled HL-RDHM and MODSIM model within a GIS platform will be greatly enhanced. Collaboration with stakeholders will allow for more accurate modeling of agricultural demands, pond operations, and diversions, and alternative environmental instream flow management options can be explored. Additionally, the use of an interactive, web-based tool will allow for the dissemination of model results to stakeholders in a way that allows for individual exploration of model scenarios and management alternatives. This approach will encourage dialog between stakeholders and model improvement, in keeping with collaborative modeling principles. By approaching the model from a scientific point of view and incorporating the collaborative principles and best practices outlined by Langsdale (2013), a comprehensive management model can be developed to address the water resources concerns within the Russian River basin.

Appendix References

Abbott, Michael B., et al. "An introduction to the European Hydrological System—Systeme Hydrologique Europeen,“SHE”, 1: History and philosophy of a physically-based, distributed modelling system." Journal of hydrology 87.1 (1986): 45-59.

Abbott, M. B., et al. "An introduction to the European Hydrological System—Systeme Hydrologique Europeen,“SHE”, 2: Structure of a physically-based, distributed modelling system." Journal of hydrology 87.1 (1986): 61-77.

Arnold, Jeffrey G., et al. "Large area hydrologic modeling and assessment part I: Model development1." (1998): 73-89.

Beven, K. J., and M. J. Kirkby. "A physically based, variable contributing area model of basin hydrology/Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant." Hydrological Sciences Journal 24.1 (1979): 43-69.

Boyle, Douglas P., et al. “Development of a decision support tool in support of water right acquisitions in the Walker River basin.” (2010).

Brush, C. F., et al. "Modeling The Evolution Of A Regional Aquifer System With The California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM)." AGU Fall Meeting Abstracts. Vol. 1. 2006.

Burnash, R., R. Ferral, and R. McGuire, 1973: “A generalized streamflow simulation system—Conceptual modeling for digital computers." Joint Federal–State River Forecast Center Tech. Rep., Department of Water Resources, State of California and National Weather Service.

Cardwell, Hal E., and Stacy Langsdale. "Collaborative Modeling for Decision Support–Definitions and Next Steps." Proceedings of the World Environmental and Water

Resources Congress, RE Beighley II and MW Kilgore (Editors). ASCE, Reston, Virginia. 2011.

Cestero, Barb. Beyond the hundredth meeting: A field guide to collaborative conservation on the West's public lands. Sonoran Institute, 1999.

Conley, Alexander, and Margaret A. Moote. "Evaluating collaborative natural resource management." Society &Natural Resources 16.5 (2003): 371-386.

Deitch, Matthew J., G. Mathias Kondolf, and Adina M. Merenlender. "Surface water balance to evaluate the hydrological impacts of small instream diversions and application to the Russian River basin, California, USA." Aquatic conservation: marine and freshwater ecosystems 19.3 (2009a): 274-284.

Deitch, Matthew J., G. Mathias Kondolf, and Adina M. Merenlender. "Hydrologic impacts of small-scale instream diversions for frost and heat protection in the California wine country." River Research and Applications 25.2 (2009b): 118-134.

Deitch, Matthew J., and G. Mathias Kondolf. "Consequences of variations in magnitude and duration of an instream environmental flow threshold across a longitudinal gradient." Journal of Hydrology 420 (2012): 17-24.

Deitch, Matthew J., Adina M. Merenlender, and Shane Feirer. "Cumulative effects of small reservoirs on streamflow in Northern Coastal California catchments." Water resources management 27.15 (2013): 5101-5118.

Dogrul, Emin C., Tariq N. Kadir, Charles F. Brush, and Francis I. Chung. “Linking Groundwater Simulation and Reservoir System Analysis Models: The Case for California’s Central Valley.” Environmental Modelling & Software (in review).

Draper, Andrew J., et al. "CalSim: Generalized model for reservoir system analysis." Journal of Water Resources Planning and Management 130.6 (2004): 480-489.

Droubi, A., et al. "A Decision Support System (DSS) for Water Resources Management,–Design and Results from a Pilot Study in Syria." Climatic changes and water resources in the Middle East and North Africa. Springer Berlin Heidelberg, 2008. 199-225.

Feldman, Arlen D. Hydrologic modeling system HEC-HMS: technical reference manual. US Army Corps of Engineers, Hydrologic Engineering Center, 2000.

Fisheries, NOAA "Habitat Blueprint: A framework to improve habitat for fisheries, marine life, and coastal communities: NOAA Fisheries." (2015).

Flint, Lorraine E., and Alan L. Flint. "Regional analysis of ground-water recharge." Ground-water recharge in the arid and semiarid southwestern United States (2007): 29-59.

Flint, Lorraine E., et al. "Fine-scale hydrologic modeling for regional landscape applications: the California Basin Characterization Model development and performance." Ecological Processes 2.1 (2013): 1-21.

Flint, L.E., Flint, A.L., Curtis, J.A., Delaney, C., and Mendoza, J., 2015, Provisional simulated unimpaired mean daily streamflow in the Russian River and Upper Eel River Basins, California, under historical and projected future climates: U.S. Geological Survey Data Release, doi.org/10.5066/F71C1TX4

Fredericks, Jeffrey W., John W. Labadie, and Jon M. Altenhofen. "Decision support system for conjunctive stream-aquifer management." Journal of Water Resources Planning and Management 124.2 (1998): 69-78.

Georgakakos, Konstantine P. "A generalized stochastic hydrometeorological model for flood and flash-flood forecasting: 1. Formulation." Water Resources Research 22.13 (1986): 2083-2095.

Graham, D.N. and M. B. Butts (2005) Flexible, integrated watershed modelling with MIKE SHE. In Watershed Models, Eds. V.P. Singh & D.K. Frevert Pages 245-272, CRC Press. ISBN: 0849336090.

Grantham, Theodore E., Adina M. Merenlender, and Vincent H. Resh. "Climatic influences and anthropogenic stressors: an integrated framework for streamflow management in Mediterranean-climate California, USA." Freshwater Biology55.s1 (2010): 188-204.

Grantham, T. E., et al. "Evaluating tradeoffs between environmental flow protections and agricultural water security." River Research and Applications30.3 (2014): 315-328.

Grantham, T., Christian-Smith, J., Kondolf, G. M., & Scheuer, S. (2008). A fresh perspective for managing water in California: insights from applying the European water framework directive to the Russian River.

Hadded, R., et al. "A decision support system to manage the groundwater of the zeuss koutine aquifer using the WEAP-MODFLOW framework." Water resources management 27.7 (2013): 1981-2000.

Harbaugh, Arlen W. MODFLOW-2005, the US Geological Survey modular ground-water model: the ground-water flow process. Reston, VA, USA: US Department of the Interior, US Geological Survey, 2005.

Havnø, K., et al. "MIKE 11-a generalized river modelling package." Computer models of watershed hydrology. (1995): 733-782.

Johnson, L.E., C. Hsu, R.J. Zamora, and R. Cifelli. Distributed Hydrologic Modeling for Water Management Decision Support in the Russian River Basin, California. Presentation at American Meteorological Society (AMS) 28th Conference on Hydrology, February 2, 2014. Atlanta, GA.

Kim, Jinwon, and S. T. Soong. "Simulation of a precipitation event in the western United States." Regional Impacts of Global Climate Change (1996): 73-84.

Kim, Jinwon, et al. "River flow response to precipitation and snow budget in California during the 1994/95 winter." Journal of Climate 11.9 (1998): 2376-2386.

Kim, Jinwon, et al. "A seasonal precipitation and stream flow hindcast and prediction study in the western United States during the 1997/98 winter season using a dynamic downscaling system." Journal of Hydrometeorology 1.4 (2000): 311-329.

Koelliker, J. K. "User's manual for POTential YieLD model Revised (POTYLDR)." Civil Engineering Department, Kansas State University, Manhattan, KS (1994).

Koren, V. I., et al. "Use of soil property data in the derivation of conceptual rainfall-runoff model parameters." 15th Conference on Hydrology, Long Beach, American Meteorological Society, Paper. Vol. 2. 2000.

Koren, Victor, et al. "Hydrology laboratory research modeling system (HL-RMS) of the US national weather service." Journal of Hydrology 291.3 (2004): 297-318.

Labadie, John W. "Optimal operation of multireservoir systems: state-of-the-art review." Journal of water resources planning and management 130.2 (2004): 93-111.

Langsdale, S., A. Beall, E. Bourget, E. Hagen, S. Kudlas, R. Palmer, D. Tate, and W. Werick, 2011. Collaborative Modeling for Decision Support in Water Resources: Principles and

Best Practices, Environmental Water Resources Institute, Reston, Virginia and Institute for Water Resources, Alexandria, Virginia.

Langsdale, Stacy, et al. "Collaborative modeling for decision support in water resources: principles and best practices." JAWRA Journal of the American Water Resources Association 49.3 (2013): 629-638.

Liu, Yuqiong, et al. "Linking science with environmental decision making: Experiences from an integrated modeling approach to supporting sustainable water resources management." Environmental Modelling & Software 23.7 (2008): 846-858.

Maddock, Thomas, and Laurel J. Lacher. MODRSP A Program to Calculate Drawdown, Velocity, Storage and Capture Response Functions for Multi-Aquifer Systems. University of Arizona, Department of Hydrology and Water Resources, 1991.

Mahrt, Lawrence, and H. Pan. "A two-layer model of soil hydrology." Boundary-Layer Meteorology 29.1 (1984): 1-20.

Maidment, David R. Arc Hydro: GIS for water resources. Vol. 1. ESRI, Inc., 2002.

Markstrom, Steven L., et al. PRMS-IV, the precipitation-runoff modeling system, version 4. No. 6-B7. US Geological Survey, 2015.

Mastin, M. C., and J. J. Vaccaro. Watershed models for decision support in the Yakima River Basin, Washington. No. USGS-OFR-02-404. DEPARTMENT OF THE INTERIOR WASHINGTON DC, 2002.

Mastin, M.C. and Sharp, W., 2006, “Comparison of simulated runoff in the Yakima River Basin, Washington, for present and global climate-change conditions,” in Third Federal Interagency Hydrologic Modeling Conference, Reno, Nevada, 2006, Proceedings: Reno, Nevada, Subcommittee on Hydrology, a subcommittee of the Advisory Committee on Water Information.

McDonald, Michael G., and Arlen W. Harbaugh. "A modular three-dimensional finite-difference ground-water flow model." (1988): A1.

Merenlender, Adina, M. Deitch, and Shane Feirer. "Decision support tool seeks to aid stream-flow recovery and enhance water security." California Agriculture62.4 (2008): 148-155.

Michaud, William R. "Evaluating the outcomes of collaborative modeling for decision support." JAWRA Journal of the American Water Resources Association 49.3 (2013): 693-699.

Miller, Norman L., and Jinwon Kim. "Numerical prediction of precipitation and river flow over the Russian River watershed during the January 1995 California storms." Bulletin of the American Meteorological Society 77.1 (1996): 101-105.

Neitsch, Susan L., et al. Soil and water assessment tool theoretical documentation version 2009. Texas Water Resources Institute, 2011.

Niswonger, Richard G., and David E. Prudic. Documentation of the Streamflow-Routing (SFR2) Package to include unsaturated flow beneath streams--A modification to SFR1. US Department of the Interior, US Geological Survey, 2005.

Niswonger, Richard G., et al. "GSFLOW, Coupled Ground-Water and Surface-Water Flow Model Based on the Integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005)." (2008).

Niswonger, Richard G., Kip K. Allander, and Anne E. Jeton. "Collaborative modelling and integrated decision support system analysis of a developed terminal lake basin." Journal of Hydrology 517 (2014): 521-537.

Palmer, Richard N., et al. "Modeling water resources opportunities, challenges and trade-offs: The use of shared vision modeling for negotiation and conflict resolution." Proc. of the Water Resources Planning and Management Conference. 1999.

Poff, N. LeRoy, et al. "River flows and water wars: emerging science for environmental decision making." Frontiers in Ecology and the Environment 1.6 (2003): 298-306.

Ramireddygari, S. R., et al. "Development and application of a comprehensive simulation model to evaluate impacts of watershed structures and irrigation water use on streamflow and groundwater: the case of Wet Walnut Creek Watershed, Kansas, USA." Journal of Hydrology 236.3 (2000): 223-246.

Ramsey, Kevin. "GIS, modeling, and politics: On the tensions of collaborative decision support." Journal of Environmental Management 90.6 (2009): 1972-1980.

Reed, Patrick M., and Joseph Kasprzyk. "Water resources management: the myth, the wicked, and the future." Journal of Water Resources Planning and Management 135.6 (2009): 411-413.

Reed, Seann, et al. "Distributed modeling for improved NWS river forecasts. "Proc. the Second Federal Interagency Hydrologic Modeling Conference, Las Vegas, NV. 2002.

Rhoads, Bruce L., et al. "Interaction between scientists and nonscientists in community-based watershed management: Emergence of the concept of stream naturalization." Environmental management 24.3 (1999): 297-308.

Richter, Brian D., et al. "Ecologically sustainable water management: managing river flows for ecological integrity." Ecological applications 13.1 (2003): 206-224.

Richter, Brian D., et al. "A collaborative and adaptive process for developing environmental flow recommendations." River research and applications 22.3 (2006): 297-318.

Richter, Brian D., and Gregory A. Thomas. "Restoring environmental flows by modifying dam operations." Ecology and society 12.1 (2007): 12.

Richter, Brian D. "Re-thinking environmental flows: from allocations and reserves to sustainability boundaries." River Research and Applications 26.8 (2010): 1052-1063.

Schmid, Wolfgang, and R. T. Hanson. The Farm Process Version 2 (FMP2) for MODFLOW-2005: Modifications and upgrades to FMP1. US Geological Survey, 2009.

Schuett, Michael A., Steve W. Selin, and Deborah S. Carr. "Making it work: Keys to successful collaboration in natural resource management. "Environmental Management 27.4 (2001): 587-593.

Sophocleous, M. A., et al. "Integrated numerical modeling for basin-wide water management: The case of the Rattlesnake Creek basin in south-central Kansas." Journal of Hydrology 214.1 (1999): 179-196.

SWRCB Staff Report on the Russian River Watershed. SWRCB Division of Water Rights. Sacramento, CA. (1997)

SWRCB. Policy for Maintaining In-stream Flows in Northern Coastal California Streams. SWRCB Division of Water Rights. Sacramento, CA. (2010).

Triana, Enrique, John W. Labadie, and Timothy K. Gates. "River GeoDSS for agroenvironmental enhancement of Colorado’s Lower Arkansas River Basin. I: Model development and calibration." Journal of water resources planning and management (2009a).

Triana, Enrique, Timothy K. Gates, and John W. Labadie. "River GeoDSS for Agroenvironmental Enhancement of Colorado’s Lower Arkansas River Basin. II:

Evaluation of Strategies." Journal of Water Resources Planning and Management (2009b).

Triana, Enrique, et al. "Neural network approach to stream-aquifer modeling for improved river basin management." Journal of hydrology 391.3 (2010): 235-247.

USDA, SCS. "National Engineering Handbook, Section 4: Hydrology. "Washington, DC (1972).

Vaghefi, S. Ashraf, et al. "Integration of hydrologic and water allocation models in basin-scale water resources management considering crop pattern and climate change: Karkheh River Basin in Iran." Regional Environmental Change15.3 (2015): 475-484.

Valerio, Allison, Harihar Rajaram, and Edith Zagona. "Incorporating Groundwater-Surface Water Interaction into River Management Models." Groundwater 48.5 (2010): 661-673.

Voinov, Alexey, and Erica J. Brown Gaddis. "Lessons for successful participatory watershed modeling: a perspective from modeling practitioners. "Ecological modelling 216.2 (2008): 197-207.

Voinov, Alexey, and Francois Bousquet. "Modelling with stakeholders. "Environmental Modelling & Software 25.11 (2010): 1268-1281.

Yates, David, et al. "WEAP21—A demand-, priority-, and preference-driven water planning model: part 1: model characteristics." Water International 30.4 (2005): 487-500.

Young, C. Bryan, et al. "Evaluating NEXRAD multisensor precipitation estimates for operational hydrologic forecasting." Journal of Hydrometeorology1.3 (2000): 241-254.

Zagona, Edith A., et al. "Riverware: A Generalized Tool for Complex Reservoir System Modeling1." JAWRA Journal of the American Water Resources Association 37.4 (2001): 913-929.

Zhang, Zhonglong, and Billy E. Johnson. HEC-HMS Development in Support of Russian River Watershed Assessment. No. ERDC/EL-TN-10-3. ENGINEER RESEARCH AND DEVELOPMENT CENTER VICKSBURG MS ENVIRONMENTAL LAB, 2010.