2010

An integrated surface water-groundwater interaction model for the Carmel River

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An Integrated Surface Water-Groundwater Interaction Model for the Carmel River

A Capstone
Presented to the Faculty of Science and Environmental Policy
in the
College of Science, Media Arts, and Technology
at
California State University, Monterey Bay
in Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science
by

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Spring 2010

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Abstract

The Carmel River supplies fresh water to the residents of the Monterey Peninsula within the water district served by the California American Water company (Cal-Am). The State Water Resources Control Board, in 1995, ordered that Cal-Am reduce their annual diversions from the Carmel River Watershed to within legal right (3,376 acre-feet per year). An alternative water source to the Carmel River has yet to be determined, and as a result, Cal-Am must continue to divert more water than their legal entitlement. The current magnitude of diversions has a negative impact on the spawning and migrating habitat of Steelhead (*Oncorhynchus mykiss*). Existing software in the Tarsier Environmental Modeling Framework was used to model the spatial distribution of surface water along the Carmel River. The model simulated the flow of water downstream from catchment area to the Pacific Ocean. The river channel was represented by a network data set comprised of links, representing individual reaches of the river, connected by nodes. Prior to my work, systematic error in the model was thought to be partially the result of the model lacking a simulation of the interactions between the surface water and the underlying aquifer. A groundwater sub-model was developed to correct for the systematic error. The groundwater sub-model simulated the movement of water between the river channel and the aquifer. Stock variables representing a shallow and deep aquifer were added to each link of the network data set. Simulated water in the surface water stock of each link percolates to these aquifer stocks until the groundwater reaches aquifer capacity, allowing surface water to continue flowing downstream. The model also allows the lateral flow of groundwater according to Darcy's Law. Quantitative and qualitative analysis of model output compared to observed data showed an increase in model accuracy. Quantitatively, a Nash-Sutcliff Coefficient was improved from 0.88 to 0.97 with the addition of the groundwater model. Qualitatively, a visualization of the longitudinal profile of the river system showed the simulated aquifer controlling the surface flow. A hypothetical application of this model is presented where reducing the pumping rate from the aquifer allowed the wetted river channel to increase by 2.5 km. Future work on the model should include a reservoir sub-model and accounting for spatial variability in the precipitation throughout the catchment area. With these improvements it will be possible to improve predictions of the spatial distribution of surface water along the Carmel River given hypothetical scenarios such as the rate and spatial distribution of pumping from the Carmel Aquifer. Using these simulations to inform decisions of river management could benefit all stakeholders of the river.

Introduction and Background

The Carmel River is the main fresh water Supply for residents of the Monterey Peninsula within the water district served by the California American Water company (Cal-Am). In an average year Cal-Am diverts over 10,000 acre-feet of water from the Carmel Valley basin to supply its customers with fresh water. In the 1990s complaints were made by four major stakeholders that the diversion directly results in significant harm to the local ecological system, as a result the State Water Resource Control Board (SWRCB) in 1995 has ordered Cal-Am to divert no more water from the Carmel River than the 3,376 acre-feet per year (afy) of which they have rights (SWRCB 1995). The most significant ecological harm is an adverse effect on the Carmel River riparian habitat and the migration patterns of Steelhead (*Oncorhynchus mykiss*) (SWRCB 1995). Overdraft has caused de-vegetation of the riparian zone by lowering the water table, which decreased bank stability, and in effect, geomorphic changes of the river channel (Kondolf and Curry 1986). The bank stability has been improved by restoration efforts emphasizing re-vegetation which requires irrigation as the water table is often below a level which can support vegetation (Kondolf 1995).

With no immediate alternative water sources to the Carmel River, Cal-Am has no choice but to continue diverting 7,000-10,000 acre-ft of water to which they have no legal right. This un-lawful diversion continues without legal action in this situation, because of case-law precedent set during Lukrawka v. Spring Valley Water Company (1915) in which it was determined that a water purveyor is required to furnish pure water at reasonable rates to any persons within their service area. By this precedence, clean potable water must be supplied to the Monterey Peninsula by its water purveyor Cal-Am. Until an alternative is found the water supply must continue to come from the Carmel River.

Several potential alternatives to continued diversions from the Carmel Aquifer have been considered. Cal-Am developed a project to build a new dam on the river just upstream from the current Los Padres Dam. A small group of outspoken individuals brought the end to the new dam project by objecting on account of the possibility of harm to areas sacred to indigenous descendents and the local ecology (Moore 1998). Other alternatives that have been proposed include a recycled water project, exploitation of another river, and aquifer storage and recovery (ASR). A combined ASR, recycling, and desalination project known as the "Coastal Water Project" has been proposed by Cal-Am as an alternative water supply, for which a final environmental impact report was published October 2009 (CPUC 2009).

Steelhead

Oncorhynchus mykiss is a salmonid species native to North America which migrates between the Pacific Ocean and freshwater streams. Typically this fish species uses fresh water streams for spawning. Ideal spawning habitat for Steelhead is moderate flowing water with gravel bar substrate in upper reaches of streams, commonly upper tributaries (Boughton et al. 2008). After the spawning season, steelhead returns to the Pacific Ocean. Post juvenile steelhead adapt between fresh and saltwater in lagoons during high surf before storm water runoff creates free access from the stream to the ocean (Hardy 2002).

Steelhead fish populations of the South-Central California Coast have declined significantly, in part as a result of manmade alterations to the discharge patterns of the rivers in which the fish spawn (NMFS 1996). The decline in population has raised concern from many groups and individuals because steelhead plays a critical role in river ecology. The protection of steelhead is important to biodiversity and to human culture as a source of food and recreation. The decline in population has prompted protection by the federal Endangered Species Act (ESA) (Busby et al. 1996). It is of legal importance to prioritize a solution to any problem threatening the population of any species protected under the ESA. The South-Central California Coast steelhead's status as threatened was most recently reaffirmed in 2006 (NOAA 2006). The status of threatened is given to a species that is deemed "likely to become endangered" in the near future (USFWS 2004). Under the ESA, management practices must be made to protect the abundance of this fish.

The diversions of water by Cal-Am from the Carmel River have a tendency to reduce the discharge of water in the river channel (Sophocleous 2002). Not only can low discharge kill fish outright, a reduction in stream flow can be a condition that directionally selects fish within a population shifting unique traits that a species carries (Matthews 2003). Reduction in streamflow by the impacts of diversions is especially true when surface flow is driven by groundwater seepage into the river channel, also known as base flow conditions. A smaller volume of water in the river causes the water temperature to rise, which can harm Steelhead habitat. Even though drought is a natural disturbance to which fish populations must adapt, the unnatural drying of rivers can cause a shift in a system's equilibrium resulting in a reduction in fish population (Dekar and Magoulick 2007, Magoulick & Kobza 2003). In addition to reducing the mobility of fish, low discharge can kill fish by altering the distribution of algae (Power et al. 1985).

Pumping

It is well known that the groundwater supply directly under a river system is in direct connection with the flowing surface water (Krause and Bronstert 2007, Newman et al. 2006, Anderson 2005, Langhoff et al. 2006). It is generally the natural condition of streams in similar climate as the Carmel to fill the bank alluvium with water during high flow events (Kondolf et al. 1987). The ground water is then able to supply the vegetation in the riparian zone of a stream with water allowing for a rich abundance of life along a river. As the stage of the river drops below the level of the water stored in the bank alluvium, the stream gains water from the groundwater providing a base flow allowing fish to continue their natural migration. Base flow is usually dependent on the water stored in the bank alluvium of a channel (Kondolf et al. 1987). By pumping water from the bank alluvium on the Carmel River Cal-Am is competing with base flow discharge, steelhead habitat and a healthy riparian zone.

Pumping groundwater from the aquifer affects the surface flow in a complicated manner. Some parameters that influence the interaction include the amount of water pumped, the storage capacity of the aquifer and several complex patterns of hydrological parameters such as hydraulic conductivity and spatial characteristics (Krause and Bronstert 2007). With knowledge and understanding of the study site, predictions can be made of the impacts of groundwater diversion on surface flow through simulation modeling. A few attempts have been made to simulate the Carmel Valley system. The most notable attempt was the Carmel Valley Simulation Model (CVSIM) (Mintler et al. 1990). This model used the standard continuity equation to simulate storage of the aquifer (Christianson 2003). As CVSIM was simply a water budget model, there is still a need for future work on simulation models specific to the Carmel River with the capability to simulate flow of both surface water and groundwater and its resulting impact on the spatial distribution of surface water. Work on such a model could be used in determining the best management plan for the river. Computer simulation models have been use for management of rivers by assisting in the study of human impacts on rivers and determining minimum flow requirements for ecological purposes (Richter 2003). This is especially relevant with the undetermined future of Carmel River management including the removal of the San Clemente Dam (Cal-Am 2010).

The local system

The Carmel River drains 650 km^2 of the Santa Lucia and the Sierra de Salinas mountain ranges into the Pacific Ocean via the Carmel lagoon (Fig. 1).

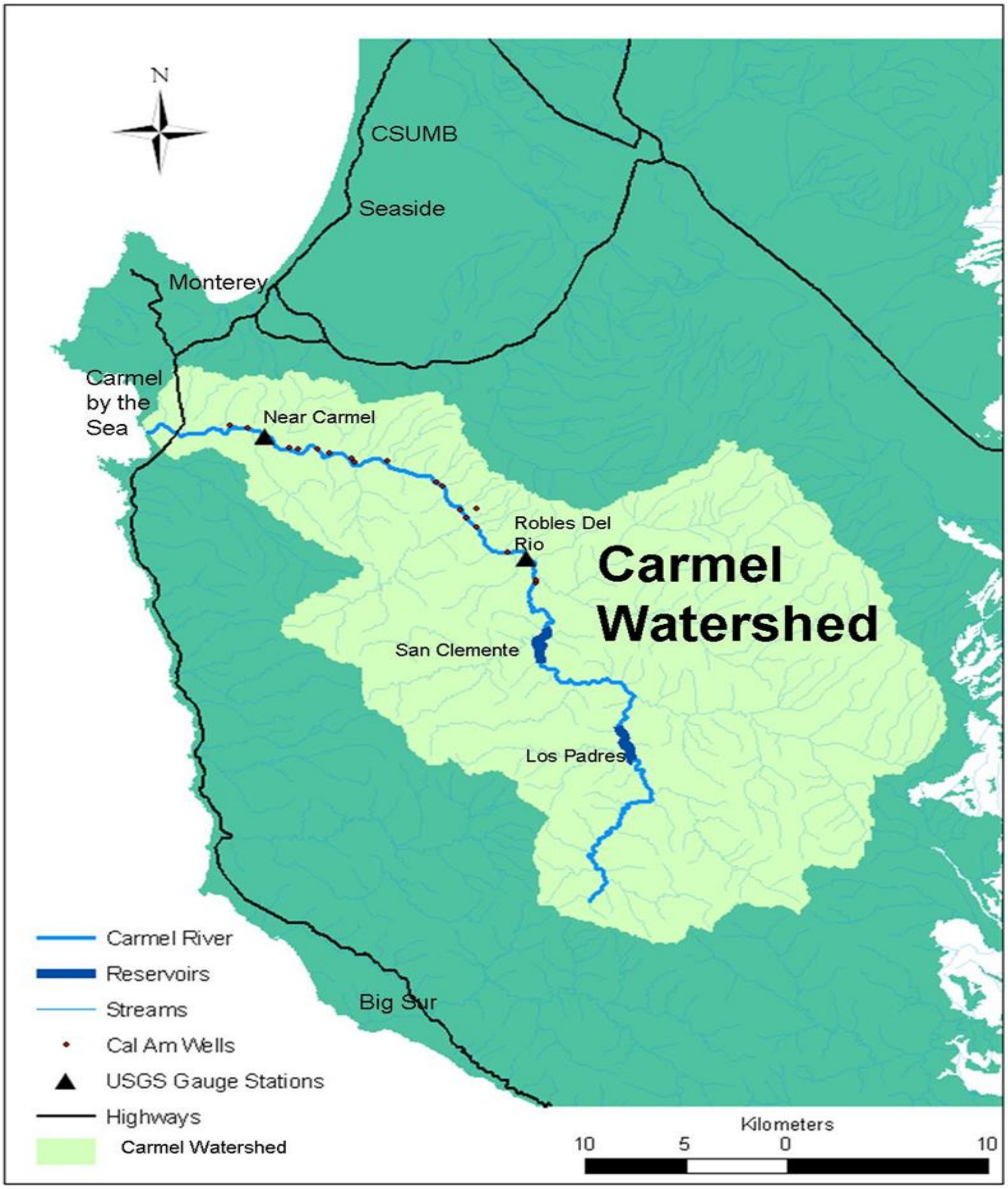

Figure 1. Map of the Carmel Watershed. Shows the main Catchment area of the Carmel Watershed, as well as major sub-catchments. Cal-Am production well locations from SWRCB permit of diversion #21080 of 2000.

The river flows 43 km to the Pacific Ocean with a relief of about 400 m making its average grade roughly 1%. The many small streams within the watershed that are tributaries to the Carmel River make its Strahler stream classification of 7th order (Smith et al. 2004). Most reaches of the Carmel River channel are well defined ranging from 6 to 45 meters in width (Kapple et al. 1984). The river has an area-normalized mean discharge rate for its drainage area with a mean at about 0.0044 $m^3/s/km^2$ (0.4 $ft^3/s/mi^2$) (Kapple et al. 1984). The watershed experiences a Mediterranean climate making the sporadic high rainfall events of great importance to the watershed ecology (Kondolf and Batalla 2005). The river tends to gain from groundwater during the first half of the year and lose its water to infiltration during the second half of the year (Kapple et al. 1984). The gaining and losing characteristic of the river can be monitored using the two United States Geological Survey (USGS) operated gauging stations along the river at Esquiline Road (referred to as "Robles de Rio") and Via Mallorca Road (referred to as "Near Carmel"). Figure 2 shows the average difference in observed discharge between the two USGS gauging stations sampled from 1980 to 2002.

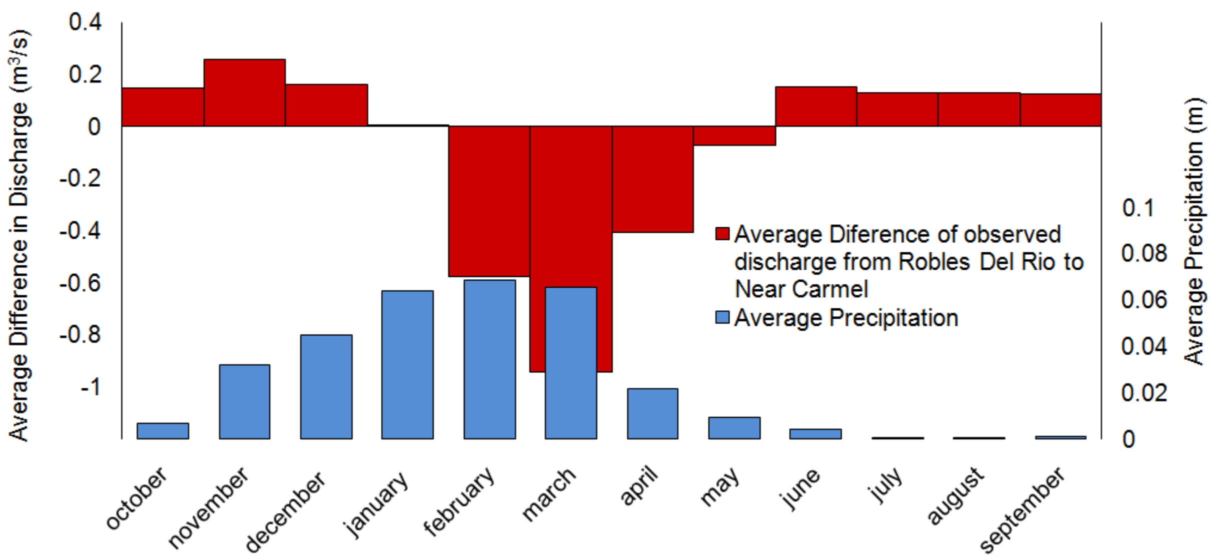

Figure 2. The average difference in discharge between the USGS gauge at Robles Del Rio and the gauge near Carmel Road (sampled from 1980 to 2002). Where the value is negative, the stream is gaining water between gauges. The river loses water, on average, from June to December. The river gains water, on average, between the two gauges from February until May.

Directly underlying and adjacent to the river is a highly permeable layer of alluvial sediment that stores the Monterey Peninsula's water supply. To supply fresh water to the

Monterey Peninsula, the California American Water (cal-am) diverts about 10,000 acre-feet of water annually from the Carmel River. Cal-Am has been handed down 1,137 afy of appropriative water rights acquired by several companies before 1914, including: C.P. Huntington, Pacific Improvement Company, Monterey County Water Works and California Water and Telephone Company. California American Water also has a right to divert water from the Los Padres reservoir. In total Cal-Am has a right to 3,376 afy of water from the Carmel River. (SWRCB 1995)

Marmoset

Marmoset is a watershed runoff and streamflow routing model developed within the Tarsier Environmental Modeling Framework (Watson & Vertessy, 2001; Vertessy et al 2002; Watson & Rahman, 2004). Marmoset was used to simulate the discharge of the Carmel River. The inputs to the model include a network data set of links and nodes representing the river channel, precipitation and temperature data, and landscape maps such as terrain and land cover. The model simulates the generation of watershed runoff from precipitation, and the routing of runoff downhill and downstream through the stream network. The nodes include landscape statistics from their respective catchment areas to determine the amount of runoff from each rain event. Once the simulated runoff enters the network data it is transported downstream between links and nodes. The simulated discharge information at each link can be recorded as time series data.

Aim of Research

This aim of this project was to increase the accuracy of a spatially distributed model of surface runoff along the Carmel River. To achieve an increase in accuracy, an integrated surface water and groundwater interaction model was added to Marmoset. Analysis was done to determine if the groundwater addition to the surface runoff model improved the ability of Marmoset to simulate the spatial distribution of water in Carmel Watershed system.

Postulate

I postulated that with the addition of the surface-ground water interaction sub model to the existing watershed runoff model the accuracy of simulated runoff from the Carmel Watershed system will be improved. I evaluated this postulate qualitatively by visualization of the model output and quantitatively by using an objective statistical metric of model accuracy. This metrics was computed both with and without the inclusion of the groundwater interaction sub-model, with all parameters calibrated to maximize model accuracy. I looked for evidence of significant improvement of model performance with the inclusion of the sub model to support this postulate.

Purpose

There is a conflict of interest between the habitat that is dependent on the Carmel River and the Monterey Peninsula residents that need a fresh source of water to maintain their health and livelihood. If threats to the South-Central California Coast Steelhead habitat are not addressed quickly then this listed evolutionarily significant unit (ESU) can be lost to extinction. The Carmel Watershed is a tremendous source of fresh water that has been harnessed by the Monterey residents for over one hundred years. Potential alternative water sources, while they would be great for the river ecosystem, would be extremely costly to the residents. Great benefit to all stakeholders of the Carmel River system would come from a way to harness the watershed as a water supply while maintaining the health of the ecological system dependent on the river.

The interests of Monterey Peninsula residents are represented by several agencies and organizations, including Cal-Am, the Monterey Peninsula Water management District, the Carmel Steelhead association, Water for Monterey County and the Citizens for Public Water. If the postulate is correct, the model would improve the predictability of the surface runoff in the Carmel River. The results of this project could serve as a tool for educating stakeholders, and/or informing decision makers by simulating potential management practices. Testable scenarios include the effects of enforcing pumping limits or altering spatial distribution of pumping rates on the availability of steelhead habitat. A reliable model of groundwater and surface water interactions could also increase the ability of policy decisions to be based on sound scientific data. With a flexible model it may be possible to simulate the reaction of the river to alterations made to the watershed system.

Methods

Data Sources

Spatial data was the foundation of the Marmoset watershed model. A 10 meter resolution (1/3 second) Digital Elevation Model (DEM), which was downloaded from the National Elevation Dataset's Seamless Data Distribution System (USGS 2010) in a proprietary binary format. The file was then converted into the Tarsier raster format. For the model to work properly each cell in the DEM must have a neighboring cell with equal or lesser value for water to drain. Processing must be done to the DEM to achieve this hydrologic continuity. The DEM was modified manually and automatically using the Pit Filler tool in Tarsier. This tool uses an algorithm to find places in the DEM which water cannot be routed from. The algorithm then fills these pits by a specified fill amount. The tool repeats this until each cell of the DEM has an adjacent downhill cell.

A network data set representing the river channel was created using the Watershed Analysis tool in Tarsier. From the DEM this tool creates rasters of watershed characteristics such as aspect, upslope area, stream channel location and catchment boundaries. These rasters were all used to create the network data comprised of a series of links and nodes from the river outlet to the headwaters. Within this network data were variables that the model used to transport water. The network data were created representing Carmel Watershed rivers with a minimum catchment area of $1\cdot10^8$ m^2.

Precipitation and temperature data were downloaded from the California Irrigation Management Information Systems within Department of Water Resources (CIMIS 2009). These data was recorded from Station 210 near the city of Carmel California at 36°32'27"N, 121°52'55"W.

Evaluating Model Efficiency

A Nash-Sutcliffe model efficiency coefficient (NSC) was calculated for the model (Nash & Sutcliffe 1970). The NSC, a common metric for evaluating model effectiveness, allows for an objective quantitative analysis of the model performance where Q_0 is the observed discharge and Q_m is modeled discharge.

$$NSC = 1 - \frac{\sum_{T=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{T=1}^{T}(Q_o^t - \overline{Q_o})^2}$$

An NSC value of one is a perfect prediction of runoff. A value of zero or less indicates a prediction no better than the average discharge.

Initial model runs

When the Carmel River was modeled using this typical watershed runoff model, the model predicted an overestimation of discharge for the first half of the rainy season. At some critical point during the water year (e.g. 2/16/2009) accuracy of model predictions increased. This was a systematic error that happened almost every year (Fig. 3).

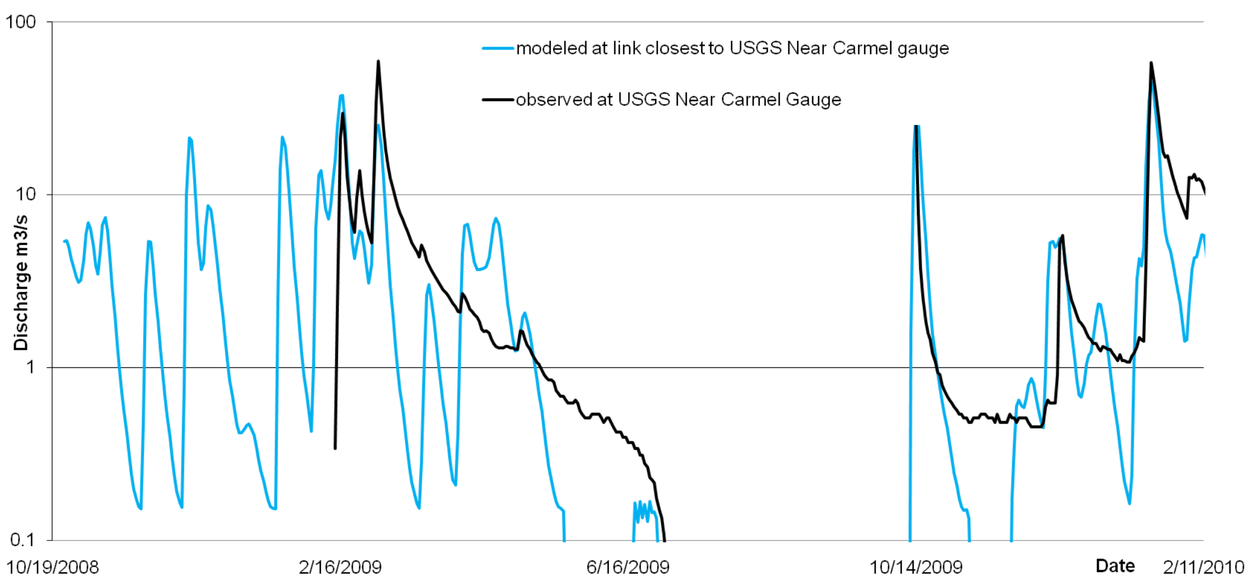

Figure 3. Comparison of predicted runoff with observed runoff. It is shown that the model over predicts runoff from rain events in the early water year. Beginning in February the model becomes more accurate, but continues to make inaccurate predictions. Vertical axis in meters cubed per second (1 m^3 = 47 ft^3).

A Nash-Sutcliffe Coefficient of 0.44 was calculated from October 24 2008 to March 1 2010. The result shows that the existing model was a better predictor than the average discharge at the Near Carmel USGS gauge station, but not accurate enough to make predictions of discharge based on given inputs. The large error in this model was, in part, due to the lack of representation of the Los Padres Reservoir. The Los Padres Reservoir collected upstream surface water runoff which otherwise would flow through the river, causing error in the model predictions until the reservoir was full and passing all streamflow directly to the reach downstream of it.

To correct for error caused by the reservoir, the model was altered such that simulations made above the Robles Del Rio gauge were removed and replaced by observed runoff data from the Robles Del Rio that was directly used as an input to the stream channel. This eliminates erroneous influences from the model anywhere upstream from the Robles Del Rio station. Inflow from the watershed between the two flow gages was modeled, and added to the predicted flow at the downstream gage (Fig 4).

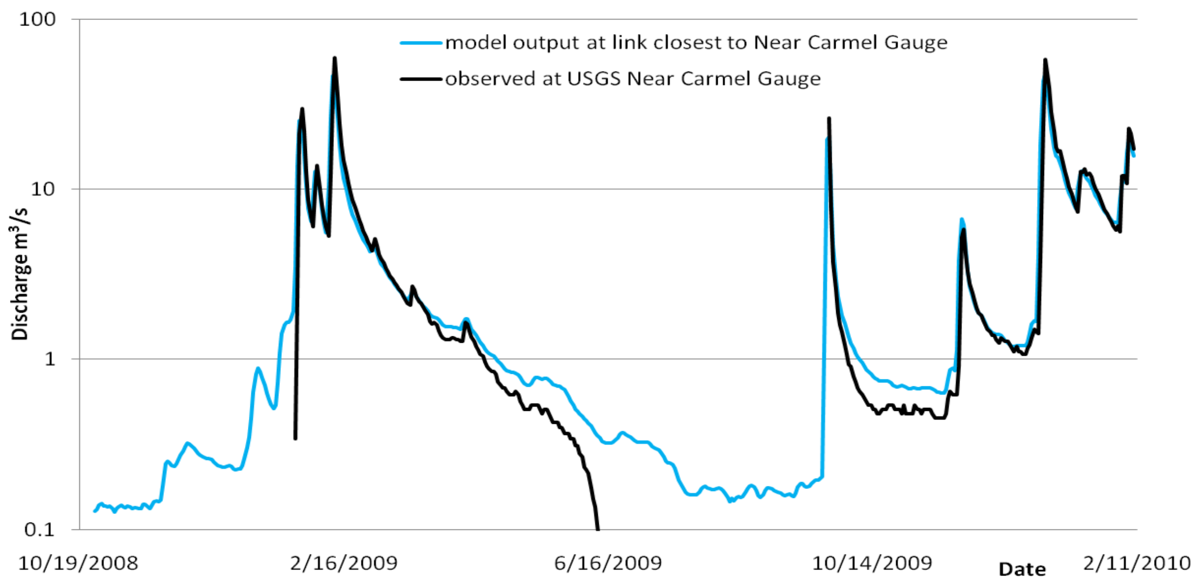

Figure 4. Comparison of predicted streamflow compared with observed data at the Near Carmel USGS gauge. The model used observed data from the Robles Del Rio USGS gauge as an input, replacing simulated runoff upstream from Robles Del Rio.

Although the accuracy of the model increased with the addition of the upstream direct gage data input (Nash-Sutcliff coefficient of 0.88), the overestimation of discharge before and after high rainfall events was still present in the model output. Without influence from the reservoir, this predictive error can be contributed to the lack of interactions with the aquifer.

Development of groundwater sub-model: Aquifer Geometry

To incorporate groundwater interactions with the surface water, a representation of an aquifer was added to the model. Two state variables were added to each link of the network data structure, one representing the shallow aquifer portion immediately adjacent to and beneath the stream, and one representing the deeper portion of the aquifer (down as far as the presumed location of bedrock) (Table 1).

Table 1. A list of all constants and variables used in the surface water / groundwater interaction model.

A_{aq}	Cross sectional area of the aquifer	m^2
A_{fp}	Estimated floodplain area of river reach	m^2
A_{gw}	Cross sectional area of phreatic zone	m^2
C_{aq}	Aquifer Capacity	m^3
C_{ns}	Capacity of near surface storage	m^3
D_{aq}	depth from the floodplain to the bottom of the aquifer	m
D_{gw}	depth to bedrock from water table	m
D_s	Depth of near surface storage (universal parameter)	m
GW	volume of goundwater	m^3
K	Hydraulic conductivity	m/day
L	Length of river reach	m
P_{aq}	Percolation rate from near surface to deep aquifer	m^3/day
P_{max}	Maximum percolation from surface to near surface storage	m^3
P_{ns}	Percolation from surface to near surface storage	m^3/day
S	Slope of river reach	
T	Model timestep	day
V_{ch}	Volume of water in the river channel	m^3
V_{gw}	Volume of ground water	m^3
V_{ns}	Volume of water stored in the near surface aquifer	m^3
W_{fp}	Average floodplain width of river reach	m
W_{gw}	width of the water table	m
β	Percolation weight (universal parameter)	
δ	Slope weight (universal parameter)	
θ_{hs}	Slope of adjacent hills (universal parameter)	
phi	Porosity (universal parameter)	
∇_{gw}	Hydraulic gradient	
Ψ	percolation from shallow to deep aquifer (universal parameter)	

The total Carmel Watershed aquifer system was thus represented as a set of discrete segments corresponding to the overlying stream segments (links). Connectivity between adjacent aquifer segments corresponded directly to connectivity between inter-connected stream links. This topology is reasonable for the Carmel Watershed, which has a longitudinal structure with minimal lateral heterogeneity that does not correlate with the stream network. Other watersheds with more complicated aquifers may require more complicated model spatial structures.

To estimate the volume of the aquifer corresponding to each stream reach, some terrain analysis was necessary. The aquifer was assumed to be dependent on the floodplain width, and slopes of the adjacent hills. An algorithm was developed to estimate the floodplain of the river based on a uniform flood height. The recursive algorithm, directed by the aspect raster, visited all upstream cells of the DEM from the cell closest to the stream outlet of the river channel network data (Fig. 5).

Figure 5. An image of the Carmel Valley from the National Agricultural Imagery Program (NAIP) with an overlay of the floodplain algorithm output at 1m (blue).

A similar algorithm starting at each node of the network data was developed to calculate the floodplain surface area for each node. The volume of the aquifer was estimated assuming a triangular geometry whereby the surface hill slopes on either side of the floodplain were assumed to be projected beneath the floodplain until they connect forming an impermeable barrier at the base of the aquifer (Fig. 6).

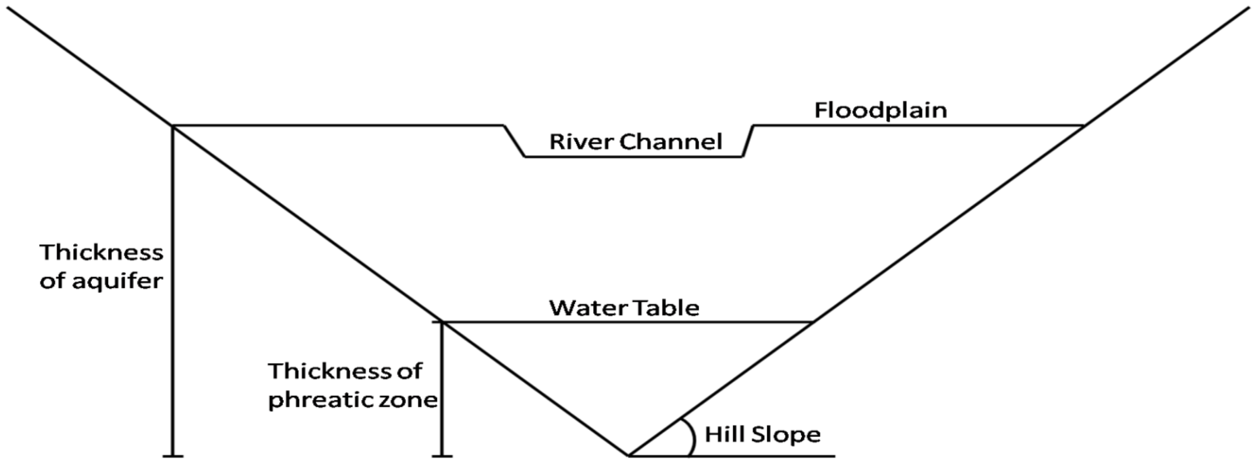

Figure 6. A representation of the assumed aquifer. With the width of the floodplain and the hill slope parameter, the aquifer and phreatic zone geometry was estimated using this assumption.

As each link of the network has a value for length and floodplain area. The average width W_{fp} (m) was calculated as the floodplain area A_{fp} (m^2) divided by the length of each river reach L (m).

$$W_{fp} = \frac{A_{fp}}{L}$$

According to the assumed geometry in figure 6, the depth from the floodplain to the bottom of the aquifer D_{aq} can be estimated with the width of the floodplain area and a hill slope parameter θ_{hs} (degrees).

$$D_{aq} = \frac{1}{2} W_{fp} \tan \theta_{\mathrm{hs}}$$

The aquifer cross sectional area A_{aq} (m^2) corresponding to a particular link was estimated using the width and thickness of the estimated aquifer.

$$A_{aq} = \frac{1}{2} W_{fp} D_{aq}$$

The aquifer capacity C_{aq} (m^3) for each link then became the area multiplied by the length of the link and a porosity parameter ϕ.

$$C_{aq} = A_{aq} L \, \phi$$

Development of groundwater sub-model: Ground Water Geometry

The geometry of the phreatic zone was used to model the movement of the groundwater. The cross sectional area of the phreatic zone A_{gw} (m^2) was found as a function of the given volume of groundwater V_{gw} (m^3), the length and the porosity ϕ of the aquifer.

$$A_{gw} = \frac{V_{gw}}{L\ \phi}$$

The width of the water table W_{gw} (m) and depth to bedrock from water table D_{gw} (m) can be found as a function of the area of the phreatic zone and the hill slope.

$$W_{gw} = \sqrt{\frac{A_{gw}}{\tan \Theta_{hs}}}$$

$$D_{gw} = \frac{A_{gw}}{W_{gw}}$$

The elevation of the water table at each link was estimated by adding the thickness of the phreatic zone to the aquifer elevation.

Development of groundwater sub-model: Percolation

During simulations, water was removed from the (surface) Water Stored variable in the links during routing to represent percolation. There was assumed to be a maximum volume that can percolate per day controlled by a near surface storage. The near surface storage capacity C_{ns} (m^3) is the product of the floodplain area, near surface storage depth parameter D_s (m) and the porosity of the aquifer.

$$V_{ns} = A_{fp} D_s \phi$$

The water percolating out of the channel was added to the shallow aquifer. Near surface percolation P_{ns} (m^3/day) was estimated to be a function of total water in the link V_{ch} (m^3) and of the slope of the river reach, with dimensionless parameters for percolation β and slope δ.

$$P_{ns} = \frac{\beta\, V_{ch}}{\delta\, S\, +\, 1}\, T$$

The maximum volume that can percolate P_{max} (m^3) was the volume of the near surface storage minus the near surface water stored V_{ns} (m^3).

$$P_{max} = T\,(C_{ns} - V_{ns})$$

A second percolation parameter Ψ (m/day) determined the rate (m^3/day) at which water was transported from the shallow to the deep aquifer P_{aq}.

$$P_{aq} = T\,\Psi\,A_{fp}$$

Development of groundwater sub-model: Ground Water Budget

The flow of groundwater was modeled by moving simulated water between variables within the network data set. As water was routed down between links and nodes the surface water and groundwater interact in a coupled system represented by the surface and subsurface storage variables (Fig. 7).

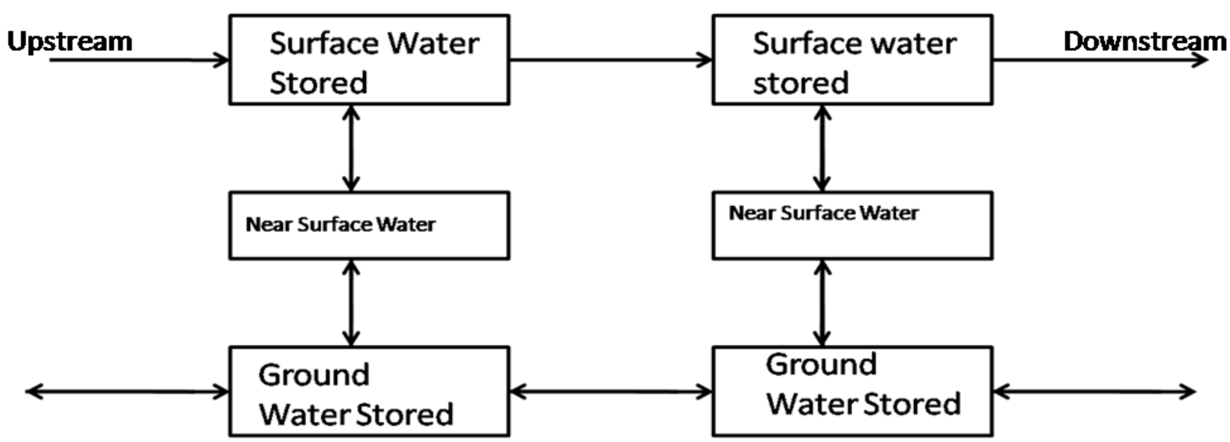

Figure 7. Illustration of the model structure for routing water downstream between the links and nodes of the network data and the transport between surface and subsurface variables.

The lateral flow of the ground water was modeled using a simple version of Darcy's law. The movement of water was the product of hydraulic conductivity, the pressure head and the cross sectional area of the ground water where GW_{flow} (m^3/day) is the subsurface lateral discharge of groundwater, K (m/day) is the hydraulic conductivity of the aquifer substrate, and $\bigtriangledown_{gw}$ is the dimensionless groundwater gradient. If lateral flow exceeds the capacity of the adjacent aquifer the leftover water exfiltrates into the surface runoff.

$$GW_{flow} = T\ KA_{gw} \bigtriangledown_{\mathrm{gw}}$$

Using the continuity equation the change of ground water was the inputs minus the outputs.

$$\Delta\mathrm{GW} = GW_{inflow} + P_{aq} - GW_{outflow} - ET - Pumping$$

The ground water budget was estimated by a difference equation adding the change of groundwater to the current groundwater, where *t* denotes the simulation timestep.

$$GW_t = GW_{t-1} + \Delta\mathrm{GW}$$

Results

A quantitative analysis was made of the model's effectiveness by comparing the model output data to observed data using the Nash-Sutcliffe Coefficient. The model was more accurate before and after big precipitation events with the addition of the groundwater sub-model (Fig. 8).

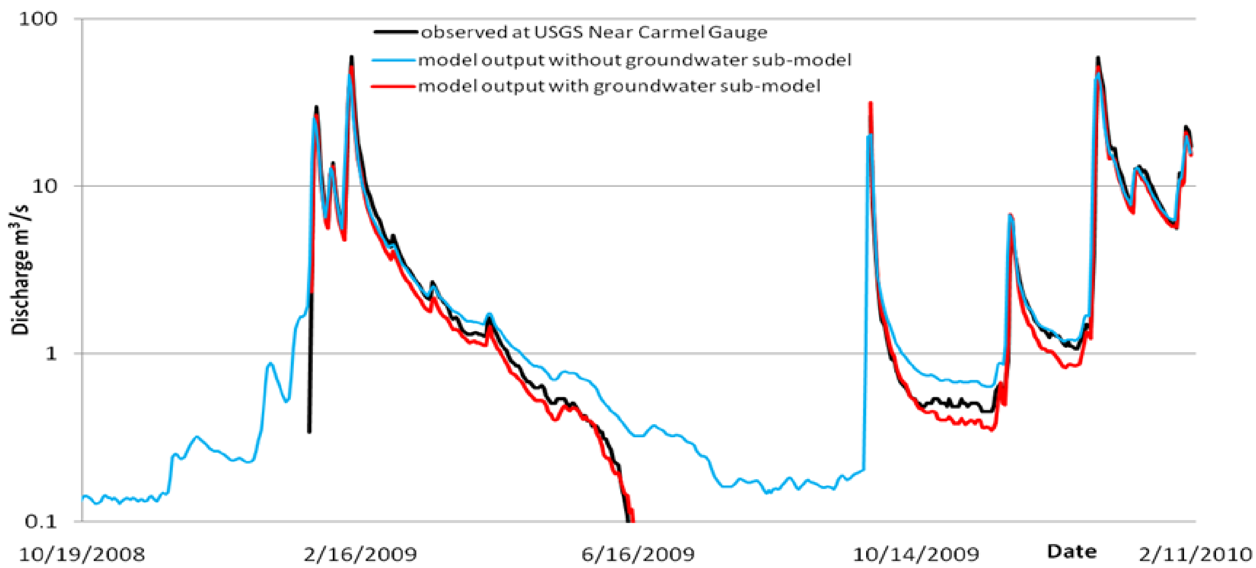

Figure 8. The hydrograph of the modeled data with the inclusion of the groundwater sub-model compared to both observed data and the model output without the groundwater sub-model.

The NSC for this model was 0.97, an improvement over the model run without the groundwater interactions (NSC = 0.88).

Visualizations of the working model provided qualitative results. The interaction between the surface water and groundwater allows the elevation of the water table to control the discharge in the river channel. The water in the channel percolates into the near surface storage, and then into the aquifer, thus, reducing the surface water in the channel. When groundwater filled the aquifer or the near surface storage to capacity, percolation ceased, and the surface water runoff was free to travel down the river channel. A longitudinal profile of the model output, Figure 9, shows the hydrologic control of the surface water by the groundwater.

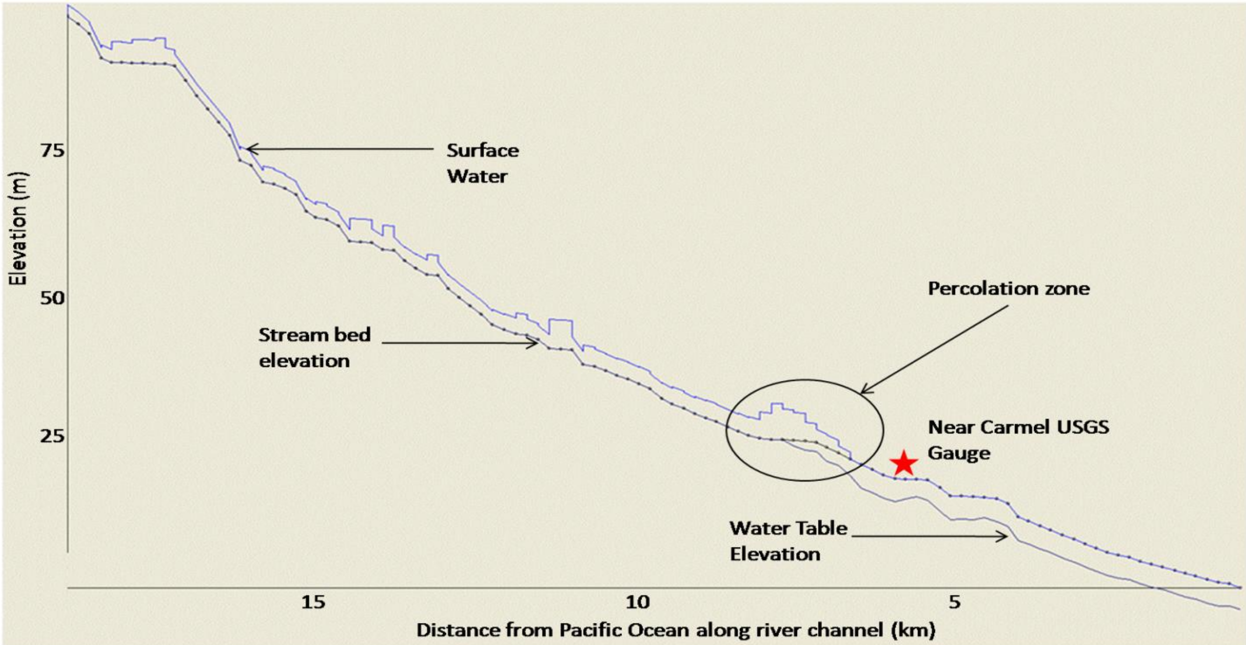

Figure 9. This longitudinal profile of the network data set representing the stream channel shows the groundwater level acting as a control to the surface discharge.

Discussion

The qualitative and quantitative analysis of the model outputs with the inclusion of the added groundwater sub-model supports the postulate of this capstone. Quantitatively, the Nash-Sutcliffe Coefficient was improved. Qualitatively the model outputs as shown in figures 8 and 9 show an increase in model effectiveness and a more accurate simulation of the natural system, respectively.

This model has potential to make predictions of the spatial distribution of surface runoff under hypothetical groundwater pumping scenarios, which could be useful to stakeholders and decision makers. With an input of observed runoff at the Robles Del Rio USGS gauge and a hypothetical set or parameter values and initial conditions, the migration habitat available for steelhead can be estimated. The model, when run with hypothetically averaged pumping rates (scenario 1) predicted that the stream channel would be dry in mid April 2009 past the Cal-Am's Manner #2 Well pumping station (Fig. 10).

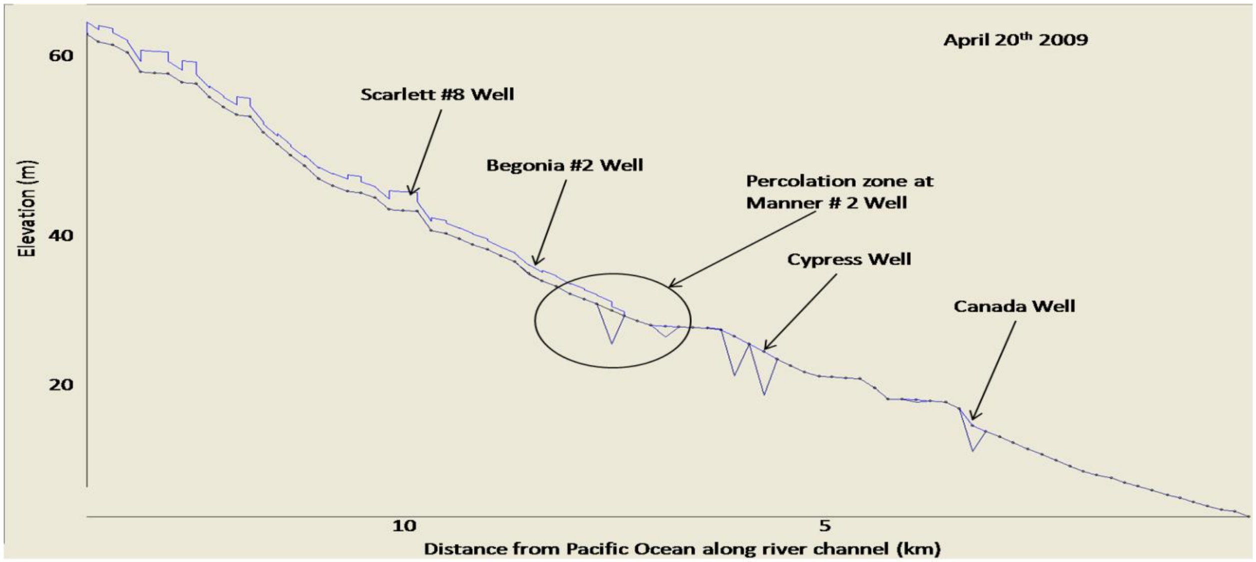

Figure 10. Predicted outcome of a hypothetical pumping Scenario 1. The streambed was predicted as dry below the Manor #2 Well in mid April 2009. The model was run with aquifer diversions at a rate of 10,000 afy distributed evenly throughout the Cal-Am production wells. Simulated cones of depression at production wells are shown in this longitudinal profile of the model output.

When the same model was run with half of the averaged pumping rates (scenario 2) the Manner #2 Well did not create a cone of depression, because the surface water was able to recharge this zone. Ecologically, 2.5 km of additional potential steelhead migration habitat was simulated to become available downstream of the Manner #2 Well as a result of reduced pumping. Under, this hypothetical scenario, the streambed was predicted to be dry past Cal-Am's Cypress Well pumping station in mid April 2009 (Fig. 11).

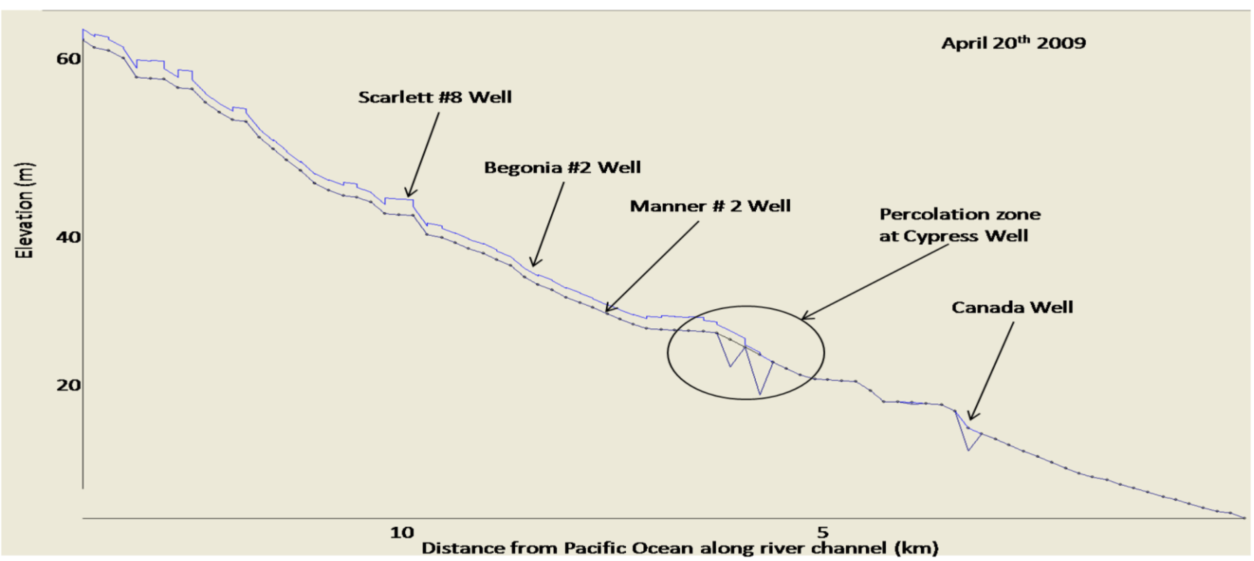

Figure 11. Predicted outcome of a hypothetical pumping Scenario 2. The streambed was predicted as dry below the Cypress Well in mid April 2009. The model was run with aquifer diversions at a rate of 5,000 afy averaged throughout the Cal-Am production wells(i.e. half of the pumping under Scenario 1). This increased the potential Steelhead migration habitat by 2.5 km.

The model output showed a direct connection between the spatial distribution of surface water and rates of diversion from the aquifer. This model can be used to communicate the connection between river management and ecosystem habitat.

The major weaknesses of the model were the lack of parameter optimization, the reliability of model inputs, and the lack of a Los Padres Reservoir sub-model. With the groundwater model dependent of several parameters such as hydraulic conductivity, evapotranspiration and percolation to both the shallow and deep aquifer, optimum parameter values would be tough to identify. The simulated discharge was dependent on the precipitation input. To truly simulate the spatial distribution of surface water runoff, an accurate spatial distribution of precipitation must be used as an input to the model. The precipitation data used as a model input were collected at one location in the lower watershed. It was unrealistic to assume that the precipitation is homogeneous across the entire watershed, and this assumption could have been the cause of poor timing and an inaccurate volume of water running off into the stream channel from precipitation as the input. As the Los Padres reservoir fills to capacity, it acts as a buffer between precipitation and surface discharge in a similar manner to the aquifer, also causing poor timing and accuracy of predicted spatial distribution of surface flow.

With continued improvement of this model, the spatial distribution of surface water runoff and water table levels would be more accurately predicted. Advancements made on this model can ultimately help lead to protection of Steelhead, and can aid with water management decisions. It has been shown quantitatively and qualitatively that including a sub-model that simulates the interactions between the surface and groundwater improves productiveness of the Marmoset model when applied to the Carmel River. This supports the idea that there is a direct connection between surface water and groundwater in the Carmel Watershed. The qualitative result was especially apparent when visualizing the model output as it changed with time. Creating video of model outputs would be an effective way to communicate the results of this project. To most effectively communicate these results using visualization, and help inform management decisions, the accuracy of the model needs to continue to be improved. The ultimate goal of this project is to work towards a complete spatial model of the runoff from precipitation as an input to aid in maximizing the production of water for humans while maintaining a healthy ecological system.

Acknowledgements

A very special thank you to Fred Watson, Alberto Guzman, and Doug Smith. This capstone could not have been completed without your help and guidance.

I would like to thank Bill Head, Claudia Makeyev, Christina Mata and Matt Subia for all of their support at UROC.

Contributions to this capstone have been made by many, including, but not limited to: Sam Adelson, Sharon Anderson, Albert Joseph Cecchettini, Tim Faulk, Dan Fernandez, Lindsey Flores, Dorothy Frame, Robynn Frame, Russell Frame (Sr., Jr. and III), Katherine Frietes, Monica Galligan, Cory Garza, Crystal Gonzalez, Brandon Goyer, Todd Hallenbeck, Hongde Hu, Nancy and Jake Jacobson, Danny Kerfeld, Rebecca Kersnar, Katherine E. Klein, Rikk Kvitek, Marc Los Huertos, Steve Litven, Don Mautner, Tom Miranda, Steve Moore, Kristy Morris, Tanya Mullen, Duncan Ogilvie, Heath Proskin, Victor Ramos, Bradley Shafer, Dan Shapiro, Aparna Sreerivasan, Kyle Stoner, Tom Thein, Sherrie Vignau, Alysia Walther and Myriam Weber

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