Meeting Sustainability Constraints for Berry Farming in the Pajaro Valley, California

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1 Introduction

The edge of the Pajaro Valley lies on the Pacific Ocean. Recent monitoring of underground aquifers in the coastal region shows saltwater intrusion of many previously fresh water resources. One of the causes of the saltwater intrusion is the crop irrigation activity in the agricultural sections of the valley. Berries are one of the primary crops grown in the region and require intense irrigation while maturing. While crop rotation management presents one avenue for efficient water use, a full analysis of the problem and possible solutions requires a study of the underlying aquifer (water-bearing region). This effort to reduce the impact of berry farming is lead by Driscoll's Berries, one the major employer of the berry farmers in the valley. The background for this problem was provided by Seth Edman and Kelley Bell of Driscoll's Berries along with Dan Balbas of Reiter Affiliated Companies.

Urban water use was estimated at 10 000 acre-ft/yr (see [1], page 20). According to the same USGS report, the Pajaro Valley Water Management Association (PVWMA) service area encompasses about 70 000 acres, of which about 40 percent is used for agriculture. The sustainable water yield of the basin is estimated between 24 000 acre-ft/yr and 48 000 acre-ft/yr, the higher yield being possible if pumping at the coast is eliminated and replaced by water from a different source (cf. [2]). Thus, the sustainable amount of water available is between 0.5 acre-ft/yr and 1.36 acre-ft/year per acre of agricultural land (taking into account urban water use).

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One strategy for meeting the sustainability constraint is the use of smart crop rotation. Over the winter, berry farmers lease their land out to other vegetable farmers.. This is to help recuperate the money lost when the land is not in use. It takes two harvests of these crops to recuperate the entire cost to the berry farmers. The rotation crops may not require water to grow or at least use less water. Therefore, smart rotation would require a farmer to not recuperate all of his rent for a winter in order to reduce aquifer draw. Smart crop rotation could be used in the main berry season as well. It would continue when a parcel of land is no longer usable for a particular berry and crop rotation is needed. This is done by taking the land that is being rotated to a different berry; the decision of which type of berry to grow is based on a comparison of the profits of the land use and the amount of water that is required to make that money. As Driscoll's Berries has farms in other areas that may not have an issue with water overdraw, they could use the land in this valley for lower impact berries while using land with no water issues for the more demanding berries.

Another method to reduce the impact of berry farms is through runoff collection and aquifer recharge. This requires digging basins in natural recharge areas, allowing captured water to infiltrate the aquifer. Currently, the majority of the water will run into streams or rivers and flow directly into the ocean, and only a small fraction of it will be used to recharge the aquifer. Often the streams and rivers are at a trickle if they have any water in them but once a rain storm hits the valley their banks swell delivering the rain water to the ocean. It is estimated that thousands of acre feet of water are lost every year due to this "feast to famine" way the rivers and streams work. The basins could be used to regulate this flow by bleeding water into the rivers and streams as their beds are natural recharge points.

In this work, we consider three mathematical modeling approaches for meeting a sustainability constraint for berry farming based on the above ideas. These are (1) the creation of a virtual farm model to study alternative crop management strategies and the impact on water usage and profit, (2) using an optimization framework to maximize a profit model while meeting a water budget constraint, and (3) a surface water analysis to understand feasible ways to capture rainfall for re-infiltration to the aquifer. The subsequent, sections explain the progress made in each of these areas over the course of the week and point the way towards future work.

2 Virtual Farm Model

The virtual farm tool is a dynamic, user driven approach to analyzing different crop management schemes. The virtual farm tool allows users to test different scenarios that depend on an initial crop configuration. We consider strawberries, blackberries, raspberries, cover crops (referred to as lettuce), and fallow land. The user must provide an initial amount of each crop and the total acreage. Then, the model "steps" through time, prompting the user for crop choices when land becomes available. Throughout the simulation, water usage and profit are calculated. Below we describe the necessary information to construct the model and provide some preliminary results.

2.1 Crop Planting Rules

Each crop has guidelines and a specific month for planting and harvesting which we summarize here.

- Strawberries are a 14 month crop, with land being assigned to them in September and occupy their plot until the following November.
- Blackberries are a 60 month crop, and need to have land assigned to them in September.
- Raspberries are a 24 month year crop, with preparation for planting starting in September. They yield twice during this period.
- Lettuce is a four month crop (including preparation), which can be planted at any month.
- The acreage each berry type cannot change more than 20% year to year.
- 5% yield increase in strawberries following raspberries.

2.2 Notation

i : an integer from 1 to N indicating the type of crop. [dimensionless]

N : total number of crops to be considered in the system [dimensionless]

S_i : cost of seeds for crop i. [$/acre]

L_i : cost of labor for crop i. [$/acre]

A_i : Acreage of crop i [acre]

$(C_{RT})_i$: cost of field rotation to crop i. [$/acre]

C_r : cost of installing and maintaining the run-off collection system. [$/acre]

A_R : the amount of acreage where the run-off collection system is installed. [acre]

U_w : total water consumption that comes from aquifer. [acre-feet]

W_i : water consumption for crop i. [acre-feet/acre*year]

R : volume of run-off water collected [acre-feet]

P_w : price of water [$/acre-feet]

Y_i : yield of crop i [acre/acre]

P_i : the price that crop i is sold at [$/acre]

2.3 Relationships

Relationship 1: Planting cost for each crop(C_i) is = the cost of seeds per acre(S_i) plus cost of labor per acre (L_i) multiplied by the total acreage of that crop (A_i):

$$(S_i + L_i) \times A_i \tag{1}$$

Relationship 2: Rotation cost for each crop(C_i), if occurs, = the cost of rotation per acre ($(C_{RT})_i$) multiplied by the total acreage of that crop (A_i):

$$(C_{RT})_i \times A_i \tag{2}$$

Relationship 3: Runoff collection cost for the entire system = the cost of the system per acre(C_R) multiplied by the total acreage where the system is installed (A_R):

$$C_R \times A_R \tag{3}$$

Relationship 4: To obtain the total Aquifer Water Usage (U_w), we first sum up the total water usage by the crops. This is calculated as, for each type of crop, the water usage per acre (W_i) multiplied by the total acreage of that crop (A_i). Then, we subtract from the summation the amount of rain water that will be collected from the runoff system (R):

$$U_w = \sum_{i=1}^{N} (A_i \times W_i) - R \tag{4}$$

Relationship 5: Total Aquifer Water cost (C_{water}) = total aquifer water usage multiplied by the price of water(P_w) that is charged to the farmers :

$$U_w \times P_w \tag{5}$$

Relationship 6: Total Sales income is the amount of total revenue earned by selling the products. It is calculated as the summation of revenues earned by each type of crop, which is equal to the sale price per acre (P_i) multiplied by the total average for that crop (A_i). Here we assume there are (N) types of crops:

$$\sum_{i=1}^{N} (Y_i \times A_i) \times P_i \tag{6}$$

2.4 Profit and Water-usage Models

We describe the profit and sustainable water budget used in the virtual farm and also in the optimization study in the subsequent section. We include the impact of a catchment basin for recharge in this discussion but that component was not included in the working model and will be considered future work. Moreover, the feasibility of recharge options is discussed in detail in the last section of this report.

Ultimately, we are searching for the combination of acreages for each type of crop (A_i) along with the amount of runoff (R) collected that will yield the least amount of aquifer water used by the farm. Meanwhile, we want to guarantee that the profit of the farm stays as high as possible. Here we are searching for the right selection of acreage for each crop (A_i), runoff collected (R), and crop rotation strategies that yield the maximum amount of profit subject to the water budget constraint. Profit is calculated as the total revenue (see relationship 6) less the cost described in relationship 1,2,3 and 5 and is given by

$$profit(\{A_i\}_{i=1}^{N}) = \sum_{i=1}^{N}(Y_i \times A_i) \times P_i - \Big(U_w \times P_w + C_R \times A_R + \sum (C_{RT})_i \times A_i + (\sum S_i + L_i) \times A_i\Big) \tag{7}$$

The water used is obtained with

$$W_a = (\sum_{i=1}^{N}(A_i \times W_i) - R). \tag{8}$$

The information used for calculating the profit and water use was obtained from coversations with Driscoll associates.

2.5 Preliminary Results

Crop rotation will be modeled over a 4 year period. Since the considered crops have even-month life spans, without loss of generality, we can use 2 month long periods. Table 1 shows the profit and water-usage for several runs of the virtual farm model. Here, we consider three levels of profit (high, medium, and low). The initial crop scenarios are specified in terms of the percentage of each crop although throughout the simulation, each acre is tracked over time to ensure the planting rules are followed. Of particular interest are the two scenarios beginning with 30% strawberries, 10% each of cover crops (fallow), blackberries and raspberries, and 40% lettuce. This configuration is approximately the scenario for the whole valley but simulated on a smaller farm-sized scale (100 acres). Although both farms began with the same initial configurations, choices made over the four years resulted in the same amount of water used (96 acre-feet) but significantly different profits. It should also be noted that raspberries can yield the largest profit with the least water, which is expected.

3 Optimization

With a profit and water usage model in place, we can investigate planting choices that will maximize profit while meeting the water budget constraint. Let A denote the total acreage of the farm, and w_a be the sustainable amount of water available per acre per year (in acre-ft), i.e., $0.5 \leq w_a \leq 1.36$. Then, for a period of 4 years, the farm can use up to $4Aw_a$ acre-ft of water. Note that this water restriction will be imposed for the 4-year period, as opposed to every year, i.e., during certain years the water use can exceed Aw_a acre-ft, but for the 4-year period the amount used cannot exceed $4Aw_a$ acre-ft.

Let x_s^i denotes the percentage of land allocated to strawberries during period i. Similarly, x_b^i, x_r^i, x_v^i, x_c^i denote the percentage of land used by blackberries, raspberries, lettuce, and cover crops respectively. We pose the optimization problem in terms of these 120 real variables, x_j^i

Scenario Initial config.	*Profit over 4 years*	*Water use over 4 years*	*Scenario Initial config.*	*Profit over 4 years*	*Water use over 4 years*
100% lettuce	low	125 acre-ft	100% raspberries	high	67.7 acre-ft
50% raspberries 50% lettuce (*scenario 1*)	medium	100.4 acre-ft	50% raspberries 50% lettuce (*scenario 2*)	medium	97.5 acre-ft
30% strawberries 10% blackberries 10% raspberries 40% lettuce 10% cover crop (*scenario 1*)	medium	96 acre-ft	30% strawberries 10% blackberries 10% raspberries 40% lettuce 10% cover crop (*scenario 2*)	medium	96 acre-ft
30% strawberries 70% lettuce	medium	113 acre-ft			

Table 1: Water use and profit for various realistic scenarios, given an initial configuration. The scenarios were run using the virtual farm tool for crop rotation, following the restrictions described above.

(where j indicates the crop type) to avoid the categorical nature of using integers to "assign" crops to specific acres over time. To this end, 208 equality and inequality constraints were needed to ensure the planting rules described above were enforced. Furthermore, we posed the problem as to maximize the linear profit model described above. MATLAB's *linprog* subroutine was used to solve the constrained, linear optimization problem. We proceed by describing the constraints and preliminary results.

3.1 Constraints

Positivity of the variables:

$$x_s^i \geq 0, \quad x_b^i \geq 0, \quad x_r^i \geq 0, \quad x_v^i \geq 0, \quad x_c^i \geq 0. \tag{9}$$

The percentage of all types of land should sum up to 100.

$$x_s^i + x_b^i + x_r^i + x_v^i + x_c^i = 100, \quad \text{for} \quad i = 1, ..., 24. \tag{10}$$

The restriction that land allocated to each type of berry cannot increase or decrease by more than 20%, imposes the following inequality constraints on the variables.

$$\begin{array}{lcll} 0.8x_s^0 & \leq & x_s^1 & \leq 1.2x_s^0 \\ 0.8x_s^1 & \leq & x_s^7 & \leq 1.2x_s^1 \\ 0.8x_s^7 & \leq & x_s^{13} & \leq 1.2x_s^7 \\ 0.8x_r^0 & \leq & x_r^{1or7} & \leq 1.2x_r^0 \\ 0.8x_r^{1or7} & \leq & x_r^{13or19} & \leq 1.2x_r^{1or7} \\ 0.8x_b^0 & \leq & x_b^{1or7or13or19} & \leq 1.2x_b^0 \end{array} \tag{11}$$

The above restriction, together with the fact that strawberries cannot be planted at the same plot they occupied the year before, imposes the following upper bound on the percentage of the farm land occupied by strawberries:

$$0.8x_s^i \leq 100 - x_s^i \quad \Rightarrow \quad x_s^i \leq 56, \quad \text{for} \quad i = 2, 8, 14, 20. \tag{12}$$

Additionally, the water budget imposes the following upper bounds on percentage of land allocated to raspberries and blackberries.

$$x_r^i \frac{A}{100}(2 + 1.5) \leq 4Aw_a \quad \Rightarrow \quad x_r^i \leq 114w_a, \quad i = 1, 7, 13, 19. \tag{13}$$

$$2x_b^i \frac{A}{100} \leq Aw_a \quad \Rightarrow \quad x_b^i \leq 50w_a, \quad i = 1, 7, 13, 19. \tag{14}$$

Thus, if the sustainable water availability is $w_a = 0.5$ acre-ft/yr, (14) implies that no more than 25% of the land can be allocated to blackberries.

No berries can go right after strawberries, as strawberries are taken out of the ground at the end of October, and only cover crops and vegetables can have land allocated to them at this point of the year.

$$\begin{array}{rcl} x_s^5 & \leq & x_v^8 + x_c^8 \\ x_s^{11} & \leq & x_v^{14} + x_c^{14} \\ x_s^{17} & \leq & x_v^{20} + x_c^{20} \end{array} \tag{15}$$

Berries can only have land allocated to them in September. Thus, if we consider a 4 year period, plots can be assigned to strawberries, blackberries and raspberries in periods 1, 7, 13, and 19. This imposes the following additional constraints. For strawberries we have:

$$\begin{array}{rcl} x_s^2 & \leq & x_s^1 \\ x_s^2 & = & x_s^3 = x_s^4 = x_s^5 = x_s^6 \\ x_s^8 & \leq & x_s^7 \\ x_s^8 & = & x_s^9 = x_s^{10} = x_s^{11} = x_s^{12} \\ x_s^{14} & \leq & x_s^{13} \\ x_s^{14} & = & x_s^{15} = x_s^{16} = x_s^{17} = x_s^{18} \\ x_s^{20} & \leq & x_s^{19} \\ x_s^{20} & = & x_s^{21} = x_s^{22} = x_s^{23} = x_s^{24} \end{array} \tag{16}$$

Similarly, accounting for the fact that the plots assigned to blackberries can only change in September, the restrictions on blackberries are:

$$\begin{array}{rcl} x_b^1 & = & x_b^2 = x_b^3 = x_b^4 = x_b^5 = x_b^6 \\ x_b^7 & = & x_b^8 = x_b^9 = x_b^{10} = x_b^{11} = x_b^{12} \\ x_b^{13} & = & x_b^{14} = x_b^{14} = x_b^{16} = x_b^{17} = x_b^{18} \\ x_b^{19} & = & x_b^{20} = x_b^{21} = x_b^{22} = x_b^{23} = x_b^{24} \end{array} \tag{17}$$

Finally, the restrictions on raspberries are:

$$\begin{array}{rcl} x_r^1 & = & x_r^2 = x_r^3 = x_r^4 = x_r^5 = x_r^6 \\ x_r^7 & = & x_r^8 = x_r^9 = x_r^{10} = x_r^{11} = x_r^{12} \\ x_r^{13} & = & x_r^{14} = x_r^{14} = x_r^{16} = x_r^{17} = x_r^{18} \\ x_r^{19} & = & x_r^{20} = x_r^{21} = x_r^{22} = x_r^{23} = x_r^{24} \end{array} \tag{18}$$

3.2 Preliminary Results

Although not good news for strawberry lovers, the preliminary results indicate that a combination of raspberries and cover crops can meet the sustainability constraint. This answer makes sense given that raspberries make the most profit with the least amount of water. The details are given in Table 2.

Water budget	*Crop Distribution*	*Profit*
0.5acre-ft/acre*yr	20-30% raspberries 70-80% cover crop	low
1.36 acre-ft/acre*yr	75-80% raspberries 20-25% cover crop	high

Table 2: Maximizing the profits under a fixed water budget for two cases of sustainable water yield - 24 000 acre-ft/yr and 48 000 acre-ft/yr.

3.3 Discussion

The current optimization approach has provided a framework to use real variables in the context of the planting rules and the preliminary results make sense. However, the model has several weaknesses. For improvement, the initial status of the farm will be included, which will involve change the right-hand side of the linear system. For the above results, the farm started out as a blank slate. Also, the model will be adjusted to account for a demand on specific crops as the abandonment of strawberries (and blackberries for that matter) is not realistic.

4 Surface Water Analysis

The underlying issue with the Pajaro Valley project was an unsustainable rate of water use, primarily by agriculture in the Pajaro River Basin, California. In ballpark numbers, the annual water use is 65,000 acre-ft/year, and the sustainable extraction rate for the aquifer is around 35,000 acre-ft/year. Consequences include salinity intrusion from the west, and, eventually, depletion of the aquifer. The solution mechanisms we studied during the workshop included a reduction in water use by agriculture, through crop rotation, and infiltration enhancement, through the introduction of catchment basins in the region.

The Pajaro Valley Water Management Agency (PVWMA) has a contract in place to perform groundwater modeling for the basin and preferred that we not duplication that work. Thus, our research group focused on two tasks: a unit-farm optimization effort to explore alternative crop mixtures, and a surface water analysis to help evaluate the potential for surface water capture and re-infiltration.

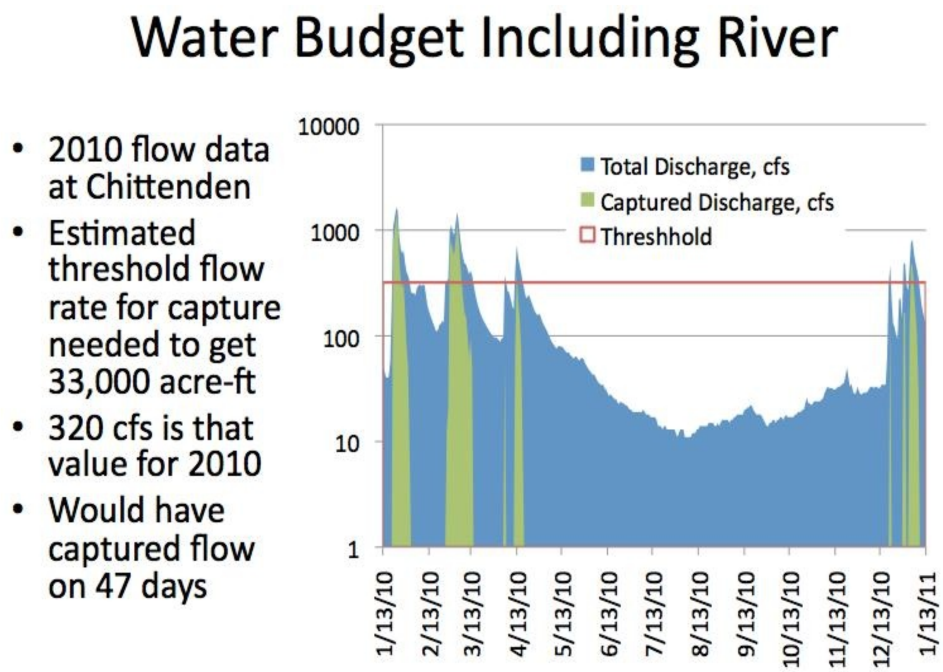

Figure 1: **Water budget analysis to explore a floodwater capture system**

4.1 Alternative A: Floodwater capture system

Extraction of water from the river is currently not an option. There are many claims on the river's water and there are concerns (environmental and other) about maintaining adequate base flow. An obvious question is, "If we could extract the water from the river only under flood conditions, how would it affect flow in the river?"

We wanted to know the flow rate that could be maintained in the river while capturing the needed 30,000 acre-feet. We found measured flow data from the Chittenden gage for 2010. Using these data, we estimated crudely that, if we could capture all of the river flow above 320 cubic feet per second, we would have about 30,000 acre-feet. The system to capture this water would have operated only 47 days in 2010. This simple water budget analysis says nothing about the engineering required to capture the water and deliver it to the deeper sand aquifer. As this is largely a political issue, no further work was done.

4.2 Alternative B: Distributed infiltration system

Another approach might be a distributed infiltration system that could be developed by the farmers themselves on private land. This idea is appealing because it could be used in places where the Aromas sands outcrop, thereby avoiding the potential for mobilizing nutrients in the surface alluvial aquifer. It is also appealing because capturing overland or stream flow may be an easier political task than diverting water already in the Pajaro River. This idea, while already under consideration by the PVWMA, was not considered until halfway through the week. Nonetheless, progress was made in studying this solution. Seth Edman, the industrial contact from Driscoll, chose a location in the northeast part of the valley, near the hills. This region in shown in Figures 2 and 3.

Figure 2: **Map showing the location of the sample watershed**

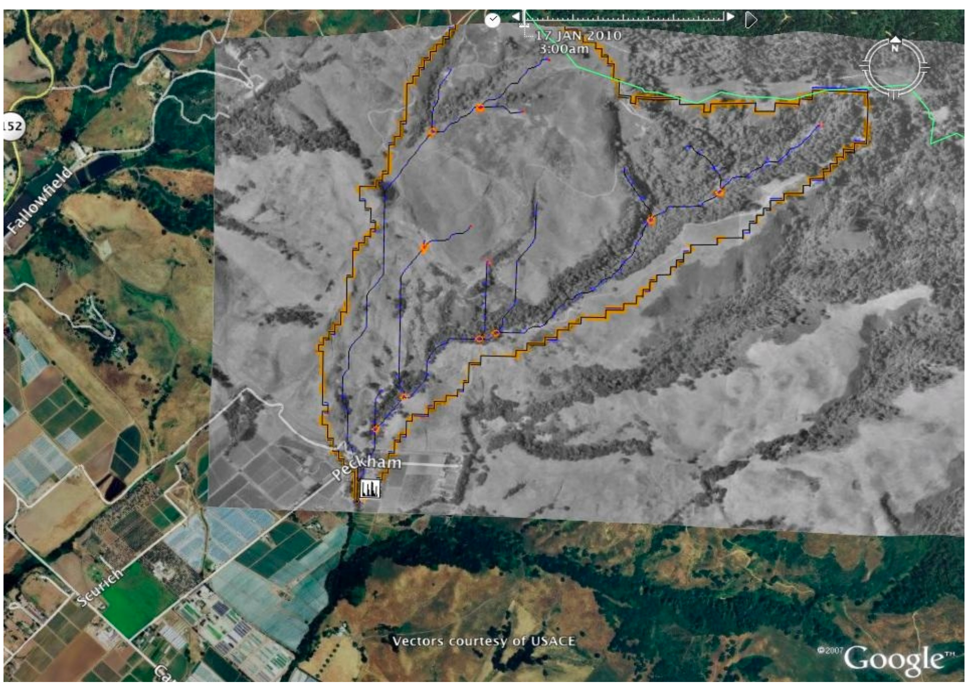

Figure 3: **Closer view of the 500-acre sub-watershed (outlined in yellow) off Peckham Road**

Digital elevation data were downloaded for the area under consideration. Seth chose a location on the property of a landowner who might be open to a local infiltration plan. A watershed delineation program was used to estimate the watershed boundaries. The sub-watershed chosen, shown in Figure 4, was about 500 acres. A coarse grid was applied to the watershed, shown in Figure 5, and overland flow was simulated using two freely available overland flow packages.

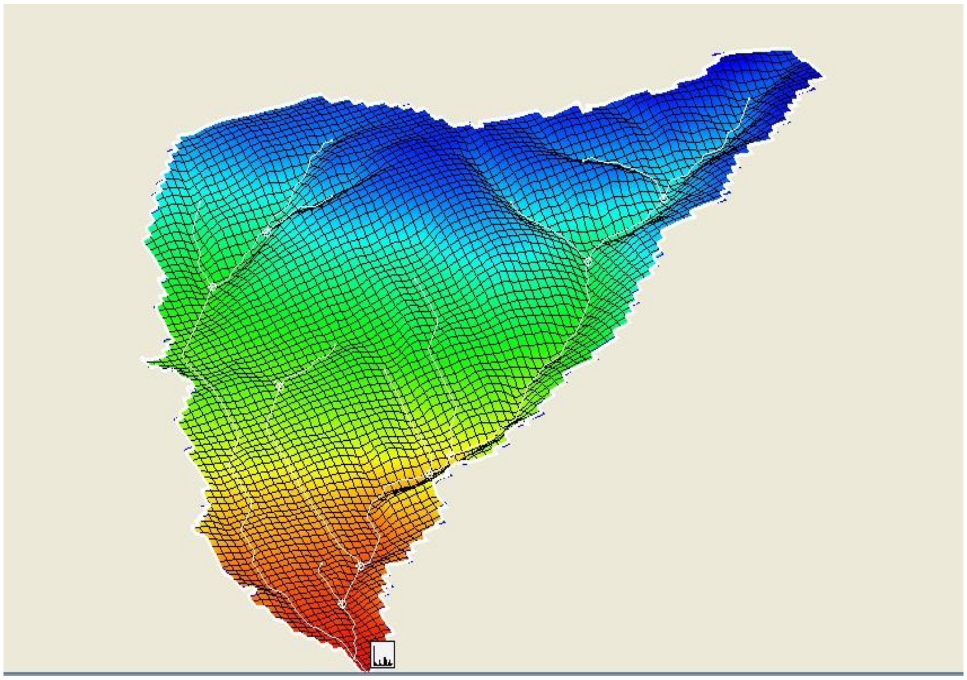

Figure 4: **Watershed boundaries and surrounding topography**

A rain event was chosen from meteorological data gathered from Watsonville, CA. A four-day period in January 2010 was selected for study. The Gridded, Surface-Subsurface Hydrologic Analysis (GSSHA) model was run on the watershed to estimate water depths and flow rates for this storm. For this initial simulation, the surface land cover was not divided among wooded, grass-covered, or agricultural uses. Moreover, only a first attempt was made at simulating infiltration over the watershed. These draft results, shown in Figure 6 and 7 show a peak discharge near 4 cubic meters per second and a total volume for the 3-day event to be about 130 acre-ft. Obviously, it would take many of the distributed capture and infiltration systems to produce the needed water.

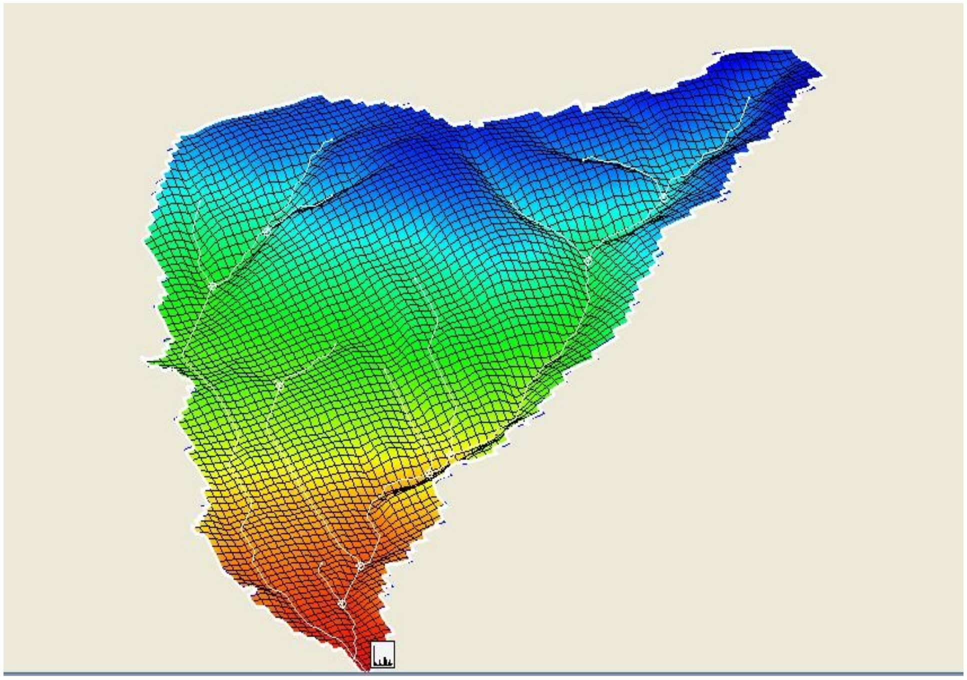

Figure 5: **Grid colored by elevation and draped on the digital elevation model**

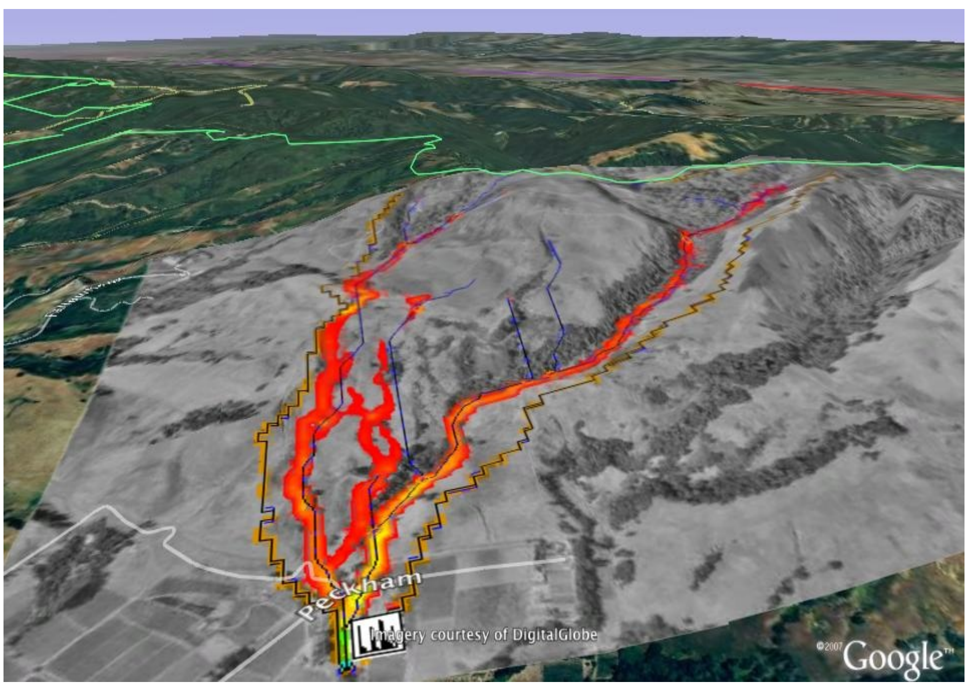

Figure 6: **Contours of simulated water depth during the rainfall event**

A reason for choosing a distributed hydrologic model rather than a sub-watershed, lumped parameter model is the option of exploring changes in land use. A model of this type could be applied to a larger area with the goal of comparing the effects of land use change on runoff and infiltration.

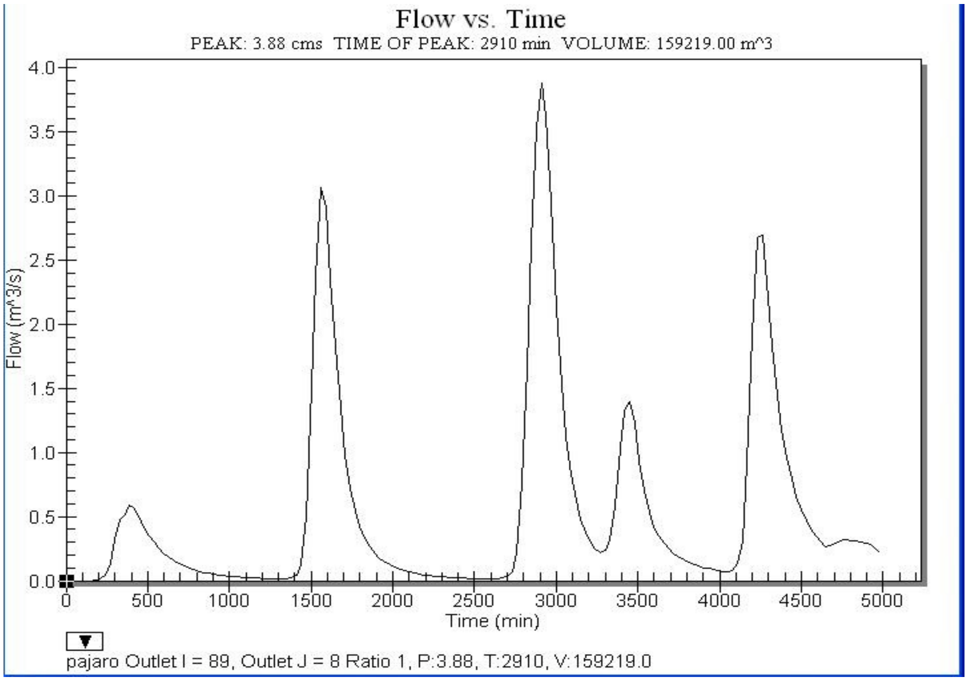

Figure 7: **Preliminary estimated flow rates at the watershed outlet for the simulated rain event**

Because the GSSHA model is distributed with a commercial model interface, a parallel effort was undertaken with a freely available watershed model, CASC2D. Members of the group were able to compile the code, execute simulations, and visualize results with another freeware product, ParaView.

5 Summary

Three analyses were undertaken to help compare alternatives for achieving sustainable water use in the Pajaro Valley. First, a virtual farm tool is in place to understand the impact of planting scenarios and crop management choices on water use and profit. Second, an optimization framework is in place for a four year planting period with 120 decision variables (the percentage of acreage for five different crops for two month periods) with 208 constraints in place to enforce planting guidelines and schedules. Preliminary results make sense but there is much room for making the problem more realistic. The third is a surface water analysis that explored (1) the potential for capturing floodwaters at the river for infiltration and (2) the potential for a distributed infiltration system across the watershed. The floodwater capture analysis provides a very crude estimate of the maximum river flow rate that might be maintained while still capturing enough water to achieve a sustainable system. It lacks specifics and is intended only to encourage further conversation among the parties about the alternatives. The sub-watershed analysis used a distributed hydrologic model to estimate runoff and infiltration from rainfall events. Results of these simulations should not be used without additional work, but do show the potential to estimate local flow rates and water depths needed to design effective engineering solutions for infiltration.

References

[1] Geohydrologic Framework of Rrecharge and Seawater Intrusion in the Pajaro Valley, Santa Cruz and Monterey Counties, California, Pajaro. Valley Water Management Agency.

[2] Pajaro Valley Groundwater Basin. California's Groundwater Bulletin 118.