Meeting a Sustainable Water Yield for Agricultural Practices through Crop Rotation and Catchment Basin Design

J. C. Chrispell[1], K. R. Fowler[2], E. W. Jenkins[3], M. Minik[2], T. Sendova[4], S. E. Howington[5]

AUTHORS: [1]Department of Mathematics, Indiana University of Pennsylvania, Indiana, PA 15705, USA
[2]Department of Mathematics and Computer Science, Clarkson University, Potsdam, NY 13699, USA
[3]Department of Mathematical Sciences, Clemson University, Clemson, SC 29634, USA (corresponding author, lea@clemson.edu)
[4]Department of Mathematics and Computer Science, Bennett College, Greensboro, NC 27401, USA
[5]US Army Engineer Research and Development Center, Vicksburg, MS 39180, USA
REFERENCE: Proceedings of the 2012 South Carolina Water Resources Conference, held October 10-11, 2012 at the Columbia Metropolitan Convention Center

ABSTRACT. Increased demands for water from a variety of sources has placed severe stresses on the groundwater aquifers near the Pajaro Valley region in northern California. Initially developed as an agricultural region in the late 1800s, decades of pumping to serve the needs of the agricultural industry have caused significant saltwater intrusion into the underlying aquifer. The classification of the groundwater basin as one with critical conditions of overdraft has resulted in water use restrictions being placed on the entire Pajaro Valley region.

Representatives of a berry-farming consortium in the region are working to mitigate the saltwater intrusion while studying strategies for profitable farming under water use restrictions. In this paper, we discuss the results of an optimization study designed to uncover optimal crop rotation and planting scenarios while incorporating possible grass roots solutions for aquifer recharge.

INTRODUCTION

The Pajaro Valley region in central California was developed for agriculture in the late 1800s. In the decades since its establishment, continued stresses on the groundwater basin from significant pumping for primarily (84%) agricultural use have resulted in the basin being in a “critical condition of overdraft” (Johnson 1983; Johnson et al. 1988; Hanson 2003). This designation has caused the entire region to operate under water use restrictions, a concern to the many berry farmers that are located in the surrounding area. California grows more berries than any other region in the world (Cook 2012). In 2007, the state provided roughly 87% of the country's strawberries. Other berry crops produced in the region include raspberries, blackberries, and blueberries. Strawberries are typically a high water usage crop, requiring 2.67 acre/ft of water per year, while raspberries and blackberries use only 2 acre/ft (or less) of water per year (see Table 1). The estimated sustainable yield for the region is 1.36 acre/ft of water per year for each acre of agricultural land. Thus, farmers in the region must balance profitability against the restrictions on water usage.

Stakeholders in the Pajaro Valley, including farmers, landowners, environmental agencies, and residents, have been working on a multifaceted solution to the overdraft problem. The community holds quarterly dialogues, along with monthly subgroup meetings, to discuss possible long-term, and short-term, resolutions to the problem. A task force involving the Pajaro Valley Water Management Agency (PVWMA) has also been established, and members of the task force asked for help on resolving the underlying optimization problem, which seeks to balance the competing interests of the different parties.

In this paper, we discuss the strategy we are developing to help the community analyze the problem. We describe of the optimization problem we have proposed and the computational tools we have generated to solve the optimization. We give an initial framework for introducing recharge into the optimization problem. Finally, we provide conclusions on our preliminary work and future directions.

Table 1. Parameter values for objective functions

Parameter	Strawberry	Blackberry	Raspberry Year 1	Raspberry Year 2	Lettuce 4 months	Cover
Operational Costs ($/acre)	22,000	22,522	27,000	12,000	2,200	1,850
Water Use (acre-ft/year)	2.67	2	2	1.5	1	0
Yield (boxes/acre)	7,000	3,500	4,800	5,000	1	0
Sale Price ($/box)	4.30	6.50	6.34	6.34	2,650	0

PROJECT OBJECTIVES

One of the objectives in this study was to develop water saving techniques based on financial and hydrologic criteria. In the context of objective functions, we sought to maximize profit while minimizing water usage.

PROJECT DESCRIPTION

Related works, considering multiobjective linear programming in the context of crop rotation and environmental farm planning include works by (El-Nazer and McCarl 1986; Beneke and Winterboer 1984; Sahoo, Lohani, and Sahu 2006; Annetts, Audsley, and others 2002). In our model, the objective function associated with profit was given by

$$P = \sum_{i=1}^{N} [Y_i \times P_i - (W_i \times P_w + S_i)] \times A_i \qquad (1)$$

where N is the number of crops (including cover crops), A_i is the number of acres allocated to crop i, Y_i is the yield (in boxes per acre) for crop i, P_i is the sale price of crop i (in dollars per box), W_i is the units of water required, per acre, to grow crop i, P_w is price of each unit of water, and S_i is the operational cost per acre for crop i.

Simultaneously, we seek to minimize the water usage, modeled using the objective function

$$W = \sum_{i=1}^{N} A_i * W_i \qquad (2)$$

In our model, we used the values in Table 1 provided by a farming member of the advisory board. Note in Table 1 that lettuce is a 4-month crop. Thus, the water use reported in the table for lettuce, when extrapolated for the year, would be 3 acre feet per year, since three harvests of lettuce over a twelve-month period can be collected from the same plot.

METHODS

We developed a MATLAB-based software tool to simulate crop rotation and planting on a 100-acre farm. Our model obeyed the following constraints on planting crops during a five-year cycle:

1. Strawberries are a 14-month crop, with land being assigned to them in September. Strawberries occupy their plot until the following November. They yield only once during this period.
2. Blackberries are a 60-month crop; land is assigned for blackberries in September. They yield every year.
3. Raspberries are a 24-month crop; land is assigned for raspberries in September. They yield twice during this period, with different operational costs, water usage, and yield during the two years (see Table 1).
4. Lettuce is a four-month crop (including preparation). Land can be designated for lettuce during any month of the year.
5. The acreage allocated for each berry type cannot change more than 20% year to year.

Our initial optimization attempt sought optimal (in terms of profitability) planting strategies over a five year period subject to the planting rules and a specified water budget. Specifying a water budget as a constraint is a variation of the ultimate goal, which is to analyze the dual objective problem. The above planting rules were translated into a mathematical set of inequality and equality constraints so that the problem could be posed as seeking the optimal percentages of each type of crop to maximize profit (Eq.

$$P = \sum_{i=1}^{N} [Y_i \times P_i - (W_i \times P_w + S_i)] \times A_i \qquad (1)$$

while meeting a water budget constraint placed on Eq.

$$W = \sum_{i=1}^{N} A_i * W_i \qquad (2)$$

). The resulting problem is a linearly constrained, linear optimization problem and was solved using MATLAB subroutine `linprog`, an implementation of the simplex method.

We made the assumption that the initial farm state was completely empty to test the problem formulation and optimization approach. We then extended the model to allow an initial (non-empty) farm state that evolved to an optimal state over a five-year time span. The initial state is passed to the farm simulation tool, and availability of acres for planting is evaluated every two months. Crops are chosen for the available acreage based on the restrictions defined above. Water usage and profitability are calculated over the five-year time period. When testing the scenario with an empty initial farm, the optimal solution was all raspberries and fallow land planted over the five-year period. This is a reasonable outcome, in that raspberries use the least amount of water and give the most profit. When the initial farm was non-empty, the solutions obtained phased in raspberries over the time horizon. Future directions for the optimization are moving towards a multi-objective optimization approach to analyze trade-offs between maximizing profit, minimizing water usage, and balancing the current demand on strawberries from the region.

Several regional landowners have indicated their willingness to house catchment basins on their property. Thus, we have begun efforts to incorporate any recharge into the groundwater aquifer through the basins into the optimization. Initial points for basin placement will be selected, and a watershed delineation process will define the area contributing to that location (**Figure 1**). Hydrogeological modeling tools will be used to calculate the recharge based on surface water runoff from rainfall events in the region.

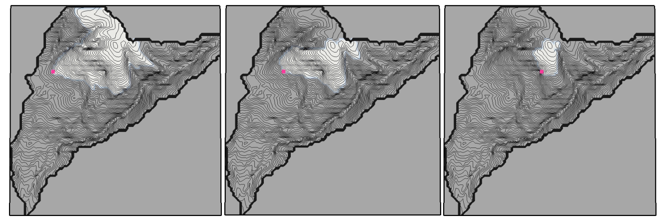

Figure 1. Sample basins delineated using different starting points

CONCLUSIONS

The difficulties encountered in the Pajaro Valley are not unique. Groundwater aquifers in near-coastal regions are increasingly subjected to saltwater intrusion further inland, while water usage for agricultural and industrial purposes is required for the livelihoods of residents. Our goal is to provide analysis of farm management strategies to members of the farming consortium that will allow them to maintain their livelihoods while operating under restrictions imposed by the PVWMA. We also aim to provide strategies for replenishment of natural resources when possible, giving all members of the community the opportunity to positively impact the environment.

This work has been a first attempt at using mathematical modeling, optimization, and simulation together to understand how changes in practice can positively impact the berry farming community and has laid the foundation for future efforts. We are currently coupling our optimization algorithm to the MODFLOW FMP package (Harbaugh 2005; Schmid and Hanson 2009) to generate more realistic simulations of the farm ecosystem. The FMP package will allow us to locate wells on property and generate more detailed information on water usage based on pumping rates and rainfall data. The FMP package also allows for placement of catchment basins on individual farms to better understand surface water flow and infiltration. With the new simulation tool in place, the multi-objective optimization framework will allow a more detailed analysis of trade-offs for crop rotation strategies and catchment basin development.

LITERATURE CITED

Annetts, J E, E Audsley, and others. 2002. “Multiple Objective Linear Programming for Environmental Farm Planning.” *Journal of the Operational Research Society* 53 (9): 933–943.

Beneke, R R, and R Winterboer. 1984. *Linear Programming. Applications to Agriculture*. Aedos.

Cook, Robert L. 2012. “Three Part Series: Fundamental Forces Affecting Growers and Marketers. Part 2: The Dynamic Berry Industry.” *Blueprints*.

El-Nazer, T, and B A McCarl. 1986. “The Choice of Crop Rotation: A Modeling Approach and Case Study.” *American Journal of Agricultural Economics* 68 (1): 127–136.

Hanson, Randall T. 2003. *Geohydrologic Framework of Recharge and Seawater Intrusion in the Pajaro*. Sacramento, CA.

Harbaugh, A W. 2005. “MODFLOW-2005: The U.S. Geological Survey Modular Ground-water Model: The Groundwater Flow Process.”

Johnson, Michael J. 1983. *Groundwater in North Monterey County, California, 1980*. Sacramento, CA.

Johnson, Michael J, Clark J Londquist, Julie Laudon, and Hugh T Mitten. 1988. *Geohydrology and Mathematical Simulation of the Pajaro Valley Aquifer System, Santa Cruz, and Monterey Counties, California*. Sacramento, CA.

Sahoo, B, A K Lohani, and R K Sahu. 2006. “Fuzzy Multiobjective and Linear Programming Based Management Models for Optimal Land-water-crop System Planning.” *Water Resources Management* 20 (6): 931–948.

Schmid, Wolfgang, and R T Hanson. 2009. “The Farm Process Version 2 (FMP2) for MODFLOW-2005: Modifications and Upgrades to FMP1.”