Integrated analysis for agricultural management strategies

organized by
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Workshop Summary

The goal of this workshop was to gather together a variety of researchers to consider problems associated with agricultural resource management. In particular, we focused on issues associated with agricultural water use in California, which is currently experiencing an unprecedented drought. Water conservation measures have been imposted state-wide, and various news articles have highlighted the difficulties associated with balancing the competing interests of the wide range of water consumers.

Eighty percent of the fruits and vegetables consumed in the United States are produced in California. Thus, stresses on the agricultural sector in the state are propagated throughout the country. Our aim is to provide analysis-based studies and tools that can be used to shape different aspects of water use management plans. We hope to aid water management agencies, farmers, and other stakeholders by enhancing the structure of current discussions related to strategies and provide mechanisms for cooperative planning throughout a given region. While our focus has been on California, our work is equally applicable in an abstract sense to any agricultural region in the country.

Much of our focus during the week was on consolidation of existing ideas and techniques. Thus, participants in this workshop included researchers in agriculture economics, hydrology, statistics, uncertainty quantification, mathematical modeling, and software development. The research group selected four main topics to consider during the week: (1) development of efficient frameworks for virtual farming using MODFLOW-OWHM [han141]; (2) analysis of managed aquifer recharge networks; (3) modeling the effects alternative water conservation policies, and (4) integrating hydrological and economic models with agent-based farmer simulations to form a decision support system for policy makers. Each of the problems were studied by a multidisciplinary team. Each team included at least one each of a mathematician, a statistician, a hydrologist, an agricultural economist, and a software developer. This integrated approach to problem-solving allows for a more holistic study of these complex issues.

Efficient Frameworks for Virtual Farming

Agriculture can and does have a significant impact on an underlying aquifer and surrounding hydrological system. In cases of severe drought, this interaction can be extreme. In the Pajaro Valley of California, overdraught from the aquifer, coupled with an historic drought, has resulted in unprecedented sea water intrusion into the primary aquifer used for irrigation and drinking water supplies. Water resources used for agricultural irrigation in this region have been continually depleted over time. Extensive efforts have been made to accurately model this region using sophisticated simulation software [han031, han081]. Part of these efforts has been the creation of a series of packages linked to the United States

Geological Survey software MODFLOW [dog011, sch091, han101, han132]. Over the last few years, optimization algorithms (typically genetic algorithms) have been paired with similar simulation tools to try to understand optimal planting strategies based on particular stakeholders (farmers, business owners, etc...) [dev061, gro121]. One framework was developed to link MODFLOW-OWHM with the DAKOTA software developed at Sandia National Labs [fow151, han132, dakota]. In that work, three crops with competing properties in terms of water use, profitability, and demand were considered. Optimization was used to determine the distribution of crops a farmer should plant by generating trade-off curves so that an analysis could be performed in terms of those competing objectives (water-usage, profit, and meeting the market demand). The framework treats the underlying simulation tool as a black-box and uses the input and the output of the model to evaluate those objectives. Currently, the framework is flexible in the sense that more realistic or different objectives could easily be incorporated if they depend on water usage and yield of a set of crops that is planted once over a two year time horizon. However, now that MODFLOW-OWHM has been shown to work in conjunction with optimization algorithms, there are multiple directions that can be explored in terms of using the framework as a decision-making tool.

The goals of this working group are to (1) extend the capabilities of the framework to be able to handle dynamic planting decisions, (2) consider the effects of uncertainty in key model parameters (such as rainfall, climate, and crop models) on the optimal crop portfolios over both long and short time horizons, and (3) consider other model parameters as decision variables (for example, what if the optimizer instead selected optimal crop features instead of selected from a set of prescribed crops?). We began by addressing (1) since the current state only allows for one specified distribution of crops over the entire time horizon. In reality, when land opens up after a crop's growing cycle is complete, a farmer may decide to plant something different. Although obvious in concept, the implementation requires significant changes to the framework. In addition, a newer version of the hydrological model is available with several changes that result in adjustments to the current framework. One benefit of the new underlying model is that evapotranspiration values, which are used to calculate the yield of a given crop, are now readily available at specified locations on a given farm. During the week, the primary developer of the model, Hanson, worked with us to understand how crops evolve over time within the model and what aspects of the simulation tool's input need to be modified to reflect crop rotations. In turn, python wrappers are required to modify those input data files so that at each optimization iteration, a new planting scheme can be analyzed automatically. Development of the new wrappers was initiated during the week. In addition, with the new ET values available, we considered how to incorporate this new output into a yield model (developed as an external subroutine). Model parameters for a first test case were chosen and significant progress was made towards linking the new problem formulation with DAKOTA. However, the next step is to determine (given the three crops we selected) a planting calendar to identify the correct decision variables and formulate the constraints needed to enforce a planting and harvesting schedule [fow141]. For objectives (2) and (3), primarily future work was outlined and time was spent identifying new directions for uncertainty quantification and sensitivity analysis, and re-phrasing an optimization problem to consider new decision models.

Managed Aquifer Recharge Networks

Water management agencies are considering the use of managed aquifer recharge networks to reduce the stress on an underlying aquifer due to over pumping. Our workshop group considered problems motivated by the design of such a network, including an analysis of the parameter space used to define the network and an extension of existing measures for optimal placement of such a network in an existing watershed region.

In 2008, Travis and Mays [tra081] applied an optimization strategy to minimize the cost of constructing a storm water catchment network. They defined a network of seven basins over a hypothetical watershed region incorporating several iso-drainage lines and sub watersheds. Regulatory requirements impose minimum and maximum times for drainage of surface water produced during a storm event. The minimum time to drainage is used to mitigate effects of standing water (e.g., mosquito infestation), while maximum time to drainage is used to reduce pollutants in water that has infiltrated the subsurface before the water reaches an aquifer. Sizes of the basins were constrained by both the underlying hydrology and physical boundaries imposed by the surrounding topology. In previous workshops, we extended this idea to consider a network constructed on a sub watershed region in the Pajaro Valley. However, uncertainty quantification of the model proposed by Travis and Mays had not been done. We attempted to remedy this deficiency in the overall model analysis during the May 2015 Agricultural Management Workshop.

Our first strategy during the week was to determine uncertainty measures associated with the intensity-duration-frequency (IDF) models used to simulate the the storm event. The parameters in the model are used to vary the physical aspects of the event, and the objective of the empirical models is to define frequencies, or probabilities of occurrence, for storm events of a certain size [idf]. Stormwater runoff networks are often constructed to comply with regulatory requirements associated with construction of new developments (e.g., strip malls, apartment complexes, etc.). As such, they must demonstrate a capacity to contain runoff for events which are intense but occur with low probability, or for more frequent events with longer duration. The objective is to minimize the cost of constructing the basin network under the constraints imposed by drainage times, regulatory requirements, and bounds on areal dimensions. Our objective function is modified to consider "target" recharge amounts, either as a percentage of the runoff produced by a storm or as an absolute runoff value computed as a portion of the annual pumping deficit for the aquifer. Thus, the IDF information plays an important role in quantifying the usability of the solution returned by the optimization procedure. Given a likely storm event, there is a minimal cost solution for constructing the network that incorporates the areal dimensions of each basin. The information on the network needs to be enriched to consider the uncertainty associated with this decision and evaluate the validity of any "nearby" solutions. This evaluation of uncertainty in the storm parameters will give decision makers more confidence that the construction of such a recharge network will actually work as intended.

Another strategy associated with uncertainty quantification for the network motivated by the Travis and Mays work is to evaluate the effect of perturbations on the answer on the objective function. This was a study proposed by a workshop participant whose research interests include evaluation of optimal solutions under uncertainty; this was not achieved during the week but is one of the primary problems to be considered in future work.

The second project associated with managed aquifer recharge network is an extension of previously published work by geohydrologists who have been studying the feasibility of these networks in the Pajaro Valley for some time. Two of the primary researchers associated with this existing work, Tess Russo and Brian Lockwood, were part of the project effort. As part of previous work, their group defined an index to indicate the suitability of a given location as a potential recharge site. This suitability index aggregates a number of quantities including the the local permeability, probability that a target aquifer underlies the location, as well as measures of the infiltration capacity. The relative weighting on the various factors can then be selected according to the purpose of the network. For instance, if the objective is to recharge the Aromas aquifer, the suitability index for the area overlying the outcrop region for the aquifer should be higher than surrounding indices. While the position of a recharge site provides some indication of the likelihood of captured runoff recharging a given aquifer, it is only indirect. As an alternative, our group considered a simulation-based approach in which unit recharge is applied to given surface locations and simulated through MODFLOW-OWHM. For each of these calculations, the net increase in storage for target aquifers can be measured and a resulting 'efficiency' calculated. This approach can incorporate subsurface flow dynamics as well as the impact of surface routing and well pumping rather than relying strictly on spatial proximity. It could also allow a quantitative measure of recharge contribution that could then be incorporated into pricing formulas for paying for the runoff captured by a recharge basin.

Our future plan is to continue the uncertainty quantification analysis for the Travis and Mays model, which we use as a surrogate for the more complicated and realistic water management systems of interest. The analysis of the surrogate will help us determine which parameters must be accurately measured or remodeled when we consider recharge over the entire valley. We also plan to continue the work on extending the suitability indices developed for the region, with an eye towards abstracting these concepts for use in any region in the world.

Modeling Alternative Water Conservation Policies

Members of this working group took a conceptual framework approach to investigate policy issues as they relate to agricultural water use with a particular focus on groundwater usage. The model couples an existing economic model and a simple hydrologic model. To understand the coupling of the socio-economic and hydrologic systems, the model is applied over the Pajaro River watershed in California as a test study.

We began with the following questions that could potentially be answered with such a modeling approach:

- How many years of current water usage will significantly draw down the groundwater aquifer?
- What are the impacts (societal, perhaps jobs) of mandating fixed average long term aquifer groundwater levels?
- What should the price of water be to have steady state hydrology?
- What is opportunity cost of recharge?

Total agricultural groundwater pumping (and hence groundwater levels) are a function of the planted crop acreage, water use by crops, and climate. The planted acreage is a function of prices/cost which in turn is dependent on groundwater levels. This defines a feedback loop between the hydrologic and economic models captured in the initial version of the conceptual model.

The modeling framework consists of two components: a simplistic representation of hydrology as a bucket model [Troy_prep] and an economics model that uses a Constant Elasticity of Substitution (CES) production function and Positive Mathematics Programming (PMP) method for calibrating the model [Howitt:2012]. The information exchange between the models uses the precipitation and available groundwater resources predicted from the hydrologic model to generate crop-based information from the economic model. The input for the economic model includes information on crop parameters, generated revenue and land costs, and maximum allowable water stresses. The output, which is then fed into the hydrologic model, includes the crop portfolio and associated water needs. In the current model formulation, the net planted acres are held constant and tradeoffs occur between planted areas for lettuce, apples, raspberries, strawberries, and unplanted, or fallow, land.

The response of the model is sensitive to the estimates made for various model parameters in addition to the following key assumptions.

- The total water use prescribed by the economic model is currently not a function of varying climate.
- Water use in the hydrologic model is scaled to equal the water output of the economic model.
- The economic model is currently calibrated to one year of data corresponding to a dry year (2013).

Despite the current model limitations, it is computationally very efficient and contains mechanisms for feedbacks between the hydrologic and economic systems. The predictions on crop acreage and water use affect the groundwater levels, which in turn alter the pumping costs for the economic model.

The hydrologic model parses the landscape into surface water and groundwater buckets. The surface water model uses precipitation and potential evapotranspiration (PET) as meteorological forcings. The Food and Agriculture Organization (FAO) crop coefficients for the four crops are then used to calculate crop water requirements with no water limitations. Irrigation is applied whenever soil moisture is unable to meet the crop water requirements; this assumes perfect irrigation efficiency, which could be modified in the future. Groundwater recharge is calculated as a function of precipitation, based on the values of recharge in a USGS report [Hanson:2014], with approximately 10% of total recharge reaching the aquifer from which water is primarily drawn.

We considered a test problem based on long-term simulations. We ran the model using daily meteorological data taken from 1996 to 2014 at Station 129 (Pajaro) available from the California Department of Water Resources (http://www.cimis.water.ca.gov/Stations.aspx). The inputs to the economic model were held constant, including the revenue per crop, yield, input costs, and coefficients of production, total available land for farming, maximum allowable water stress, and the general elasticity of substitution. The exception is the water cost, which was set as a function of groundwater depth, as specified above.

Overall, we found that the economic model was relatively insensitive to falling groundwater levels. This appears to be realistic: the cost of water is low compared to other input costs, and falling groundwater levels do not cause significant water cost increases. On the other hand, the hydrology is sensitive to the economic model, with the different cropping choices having an impact on irrigation water requirements and therefore groundwater levels.

The model predicts a modest increase in fallow lands in response to groundwater levels, with slight decreases in raspberries and strawberries, across time. In this case, time is not what happened historically; instead, the historical meteorological data is used to run the coupled model and allow the system to evolve over time.

We investigated the relationship between precipitation and groundwater use and noted these two time series are (unsurprisingly) anti-correlated: the years with higher precipitation require less groundwater for irrigation. In the uncoupled model, the correlation is stronger; the feedbacks in the fully coupled model weaken the relationship between precipitation and groundwater through changing cropped areas in response to groundwater levels.

In order to explore the sensitivity of the agricultural decisions to the hydrology (specifically the groundwater levels), we applied a scaling factor to the water to adjust it from a 5% increase to a 1600% increase. We noted through an examination of the associated groundwater time series that cropping decisions are not noticeably affected until there is a 100% increase in pumping costs with further reductions with increases in pumping costs. We also found the groundwater use is relatively insensitive to pumping costs until there is a 50% increase. From a 100% price increase and above, the groundwater use decreases approximately linearly with each doubling of water pumping costs.

Our plan for future work includes model improvements, uncertainty analysis, model scenarios to answer our original research questions, as well as additional model testing using other regions. Further development of the model requires calibration of the economic model with more years of data, rather than the one dry year used. Currently, surface water and groundwater for irrigation are specified as fixed percentages based on the prevailing use in the Pajaro Valley. In the future, we would like to incorporate surface water and groundwater substitution based on water prices and availability. The agricultural production decisions are currently insensitive to climate, with fixed amounts of water per crop per acre. In reality, crops will use different amounts of water based on the growing season rainfall. However, this may not affect decisions, because farmers need to make cropping decisions with very little information about the coming season's rainfall. The model currently has one "farmer" that decides to allocate acreage to different crops; in the future, having multiple farmer classes would be more realistic. The model currently does not incorporate values for ecosystem services. Including this in a future version would better inform the surface water/groundwater allocations. As is, the model does not deal with surface water quality at all, but agricultural chemical usage affects surface water quality and groundwater pumping can lead to saltwater intrusion along the cost. Both of these activities have negative repercussions, with potential values that could be placed on avoiding either of these cases.

Other case studies may be pursued, in particular the Yakima and Walla Walla regions in Washington and agriculture-intense regions of Nebraska. These areas likely have the data needed for the economic model, use both surface water and groundwater to meet existing water needs, and have crop portfolios with distinct crop parameters. These case studies will be explored by the group members.

Uncertainty analysis of the model parameters was begun at the workshop, and this will need to be finished. At the close of the workshop, the local sensitivity had been evaluated; the global sensitivity still requires evaluation.

Finally, and perhaps most interestingly, scenarios can be explored to answer the research questions with which we began. How many years of current water usage will significantly draw down the groundwater aquifer? What are the impacts of mandating fixed average long term aquifer GW levels? What should the price of water be to have steady-state hydrology? What is opportunity cost of recharge? One of the strengths of this model is its ability to explore policy scenarios and big picture questions.

Integrated Modeling as a Decision Support System

The overarching goal of this group was to develop a framework by which economic and hydrological models can be linked with agent-based simulations of farmer behavior. This framework can then serve as a tool for decision makers to evaluate policy alternatives in concert with different climate change scenarios. The group initially explored the possibility of developing the single-farmer crop-rotation model developed by Bokhiria, Fowler and Jenkins [fow141] into a three-farmer agent-based concept. The idea was to incorporate different farmer attitudes that would be reflective of (1) family farmers intent on maintaining status quo for foreseeable future; (2) tenant farmers who might readily abandon their operations if faced with anything more than minor reductions in profitability; and (3) large commercial concerns like Driscoll's whose departure from the agricultural economy would be devastating.

Initial discussions and evaluation of the Bokhiria-Fowler-Jenkins model served as a springboard for two related explorations, namely (1) linking state-of-the-art hydrological and economic models; and (2) development of robust time-varying expressions for agent-based farmer behavior. These exploration are described below and were investigated by splitting the group into two sub-groups.

Linking state-of-the-art hydrological and economic models.

The Pajaro Valley aquifer is well characterized with regard to hydrological resources, and workshop participants were given access to a wide variety of data sets for the region (Brian Lockwood, personal communication). Such data sets are not usually available to economists tasked with projecting the demand for shared resources in response to policy strategies that directly or indirectly effect the price of such resources. In particular, extraction rates of wells used by farmers throughout the Pajaro Valley have been recorded for several years. This has yielded an extensive spatiotemporal data set on water usage which can be correlated against the time-varying cost of water resources throughout the region which allows for the estimation and modeling of site specific, weather conditional demand functions. Linking these cost and usage data sets facilitated development of a detailed spatially and temporally distributed economic model of the water demand curve throughout the valley. This demand curve model can be used in a predictive capacity to project water usage and corresponding extraction rates at existing wells under alternative prices that may result from conservation-based water policies. Additionally, the spatiotemporal water demand model can project changes in demand in response to climate drivers such as changing weather patterns and fewer, more extreme, recharge events. However, the water demand model is not capable of describing the "health" of the aquifer. As such, an economic model, by itself, cannot be used to assess the effectiveness of conservation-based policies. Thus, it is necessary to link the economic model with an equally detailed hydrological model that can simulate the natural processes which govern aquifer health and sustainability.

As it happens, outputs from the aforementioned water demand model can be directly linked to the MODFLOW-OWHM hydrological model, a complex process-based spatiotemporal model that is maintained and distributed by the United States Geological Survey (USGS). In particular, water withdrawals projected by the economic model can serve as inputs (i.e. extraction rates) to the well field module of the hydrological model. In this way the water demand model represents the projected response of individual farmers to changes in policy and/or climate. We can then run the hydrological model to determine whether the farmers behavior is good or bad in terms of aquifer longevity. Ensemble realizations of the linked econohydrological model can be run to generate distributions of outcomes of interest. For example, one outcome of interest is the amount of seawater intrusion that is generated in response to different withdrawal rates and weather patterns. Another outcome of interest is the time frame for sustainable usage of the Pajaro Valley aquifer under alternative pricing strategies and climate change scenarios.

We are currently concentrating our efforts on formally linking the economic model of water demand developed at the workshop with the soon-to-be-released MODFLOW-OWHM model of the Pajaro Valley aquifer. Once linked, these models will be run using thousands of alternative climate change scenarios across a spectrum of alternative pricing strategies. The simulations will be performed using the high performance computing facilities at the University at Buffalo Center for Computational Research. Once complete, we will post-process these simulations and prepare a manuscript that summarizes our findings.

Development of robust time-varying expressions for agent-based farmer behavior.

A critical component of a *Decision Support System Toolbox* is the ability to both qualitatively and quantitatively assess the impact of policies that are to be considered. With regard to agriculture and the associated water resources, it is, therefore, desirable to link *policy actions* to *hydrological* impacts. In general, implemented policies do not directly affect the hydrology. Rather, a *policy* will drive a change in behavior of the farmers, which leads to subsequent impacts on not only the hydrology, but also the farmers themselves, with resultant impact upon the broader economy. Aggregated models, can be quite effective in predicting steady state implications of policy, though they may struggle to predict conditions far from the current equilibrium. As such, it may be useful to study an agent based representation of the system, where simulation-based modeling may be used to explore qualitative implications of policy. Additionally, if sufficient data exists to calibrate these agent based models, they may be able to make reasonable quantitative investigations of policy outcomes.

As a simple starting point, we envision that a farmer's goal is to maximize some financial utility, which may be associated to Net Present Value (NPV) of some cash flow over a specified time horizon. This maximization must account for not only the cost of resources, but also (perhaps), limitations on such constraints. With this framework, the farmer solves a resource allocation problem (under dynamic conditions), to maximize utility. Water control policies that might be implemented would (typically) either impact the constraints (amount of water available, for example) or the cost (fee applied to water extraction, perhaps) associated with the resources. A farmer, acting optimally, would adapt his planting plan and operations to adjust to any changes, assuming he has the ability to do so. A policy maker would hope to implement policies that would (in general), (1) allow the water resource to be maintained at sustainable levels, while (2) preserving the livelihood (economic value) of the farmer.

At the aggregated level, it may be sufficient to model the agricultural sector as a single agent — The Farmer. However, where policy is required to drive significant change in behavior, it will be critical to acknowledge that a likely result is the process of moving from one steady state (the current condition) to another (with policy restrictions in place) that not all actors in the economy will survive. Some farmers may go out of business, to be replaced by others who farm in a different way. To capture the impact on *individuals* requires a more refined description. As such, a reasonable approach is to model the agriculture not as a single *Farmer,* but as a collection of *farmers* (agents) each solving their own optimization problem. Within this agent based framework, it seems important to distinguish between at least three different broad categories of *farmer:*

- Family farmers, typically with smaller operations, have a long (perhaps even infinite) economic horizon. However, they may be more limited with regard to the ability to adapt to changing environments.
- Tenant farmers, with only a short term investment in a parcel, will have increased incentive to extract short term gains but are (likely) able to quickly divest from farming a particular crop if profit margins dictate.
- Corporate farmers, have adequate resources to change more quickly (if change is financially viable). However, those brought resources may also allow that they could quickly move operations to another location (even outside the state or country) if better profit margins exist elsewhere. Time horizons for such corporations are dictated by broader corporate policies.

We conjecture that a very important consideration for the policy maker will be the potential negative impacts on family farms and farming, as that impact is not only economic, but social — affecting an entire way of life. From a behavioral standpoint, the key difference between the family farmer and the other agents is that the family farmer will be significantly more entrenched in a particular farming practice (crop choice, methods, etc.). One specific modeling objective was to capture this aspect in the optimization framework that prescribes agent behavior. We denote this characteristic as *sticky resource allocation* and incorporate into the model using two distinct mechanisms: Firstly, "change" has an associated *cost*, which we directly represent in the utility function. Secondly, the limit on rate-of-change results in a natural feasibility constraint that restricts the maximum allowable shift in resource allocation per unit time. This second condition more accurately represents a condition where the farmer is *unable* to change quickly, even if they recognize that change would be desirable (yielding higher utility). This stickiness representation appears to be a unique contribution to the literature.

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