Using simulation-based optimization to guide allocations of surface and ground water resources for agricultural water use

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ABSTRACT. Simulation-based optimization has been used in multiple contexts to evaluate water resource problems, including well field design, evaluation of groundwater supply and hydraulic capture, and irrigation management strategies. In this work, we discuss the use of simulation-based optimization to guide agricultural management decisions in the face of limited availability of water. As surface water is a primary water source in South Carolina, we consider both surface water routing and water stored in groundwater aquifers as water sources in our model. We describe our strategy for obtaining feasible solutions that potentially satisfy the often competing objectives of regional stakeholders. Our algorithm uses the One Water Hydraulic Model extension to the MODFLOW groundwater software package (MF-OWHM) as the simulation tool and several different optimization strategies to evaluate outcomes for a variety of objective functions. We discuss numerical results for a model farm and provide possible extensions of this work to consider new economically and environmentally defined objectives.

INTRODUCTION

Efficient water use is becoming increasingly vital as periods of sustained drought, increased activity in previously undeveloped regions, and overuse of water supplies have placed long-term availability of water in peril. As world populations continue to grow, the availability of natural resources is reduced. Our ability to support existing and future populations is dependent on our ability to sustain, and even supplement, these resources. Solutions to these problems require inter-disciplinary advances in modeling, simulation, and optimization.

Water availability has become especially critical in the agriculture-intensive states of California and Kansas, as farming practices, coupled with extreme drought, have put a critical strain on groundwater resources. Our research has been motivated, in part, by the need to assess the impact of farming practices on water resources using a variety of farm scenarios, including crop management practices and farm irrigation efficiencies.

Our previous work (Chrispell, et al., 2012, Fowler, et al., 2014, Bokhiria, et al., 2014, Fowler, et al., 2016) used only water supplied from groundwater aquifers as the source of agricultural irrigation. However, in South Carolina, farming irrigation needs are met using both groundwater and surface water resources. In this paper, we extend our previous results to consider both types of water resources, and we include in our simulation region a riparian zone where regulatory agencies may impose minimum water requirements, multiple farm instances, and an urban area. In particular, we investigate optimization strategies for balancing the use of water resources from distinct supply routes, including the appropriate mechanisms for defining objectives functions to meet the needs of all stakeholders in a simulation region and incorporating constraints to meet regulatory requirements. Our simulation-based optimization utilizes the capabilities of the U.S. Geological Survey MF-OWHM software tool, which accounts for water units at all discrete locations in the model domain. Based on defined stakeholder objectives, which are often competing, we generate a set of possible solutions to enhance community dialogue in areas where water conservation strategies are being evaluated.

PROJECT DESCRIPTION

Our objective in this work is to aid in the decision-making process of farmers and water management agencies via the coupling of mathematical modeling and simulation software with optimization algorithms. Towards this end, we have been developing a flexible software framework to enable farmers and water management agencies to better evaluate the effectiveness of water management strategies relative to objectives connected with stakeholders in an agricultural region.

Gomaa, et al. provide a brief survey of related work (Gomaa, et al., 2011), where many of the referenced studies occurred outside the U.S. and covered a range of objective considerations. A more extensive review of works related to the development of models supporting crop management decisions is given in the work by Dury, et al. (Dury, et al., 2011). This review paper includes summaries of works where the crop decisions are made based on overall acreage devoted to a single crop versus those works where the crop decisions incorporate spatial considerations, including information on properties such as soil nutrient levels.

Any modeling and optimization strategy intending to aid farmers and water management agencies in decision making must be able to account for multiple, competing objectives. For example, attempting to maximize profit for farmers may require growing more water intensive crops. In regions experiencing drought, simultaneously minimizing water usage is critical but can be in conflict with the profit objective. In addition, the farming process itself is dynamic, with farmers naturally transitioning farm states based on previous crop performances and availability of resources. The performance of the crop portfolio depends, in part, on the availability of water, the nutrients available in the soil (which may depend on previous plot allocations), and the water requirements of the crops. In order to meet irrigation requirements for the crops, farmers often incorporate a variety of irrigation methods, including pumping and surface water delivery systems (Schmid and Hanson, 2009). The mechanism for water delivery determines the efficiency of the farm; the health of supply aquifers determines any extraction limits on the pumping wells. There is no single planting schedule that will simultaneously satisfy all the stakeholders it will impact; in fact, individual farmers in a given region with the same base crop portfolio may make different planting decisions based solely on personal goals. The existence of wetland and urban areas within a water balance region also play a role in defining stakeholder objectives. Wetland areas often have minimal water requirements imposed by regulatory agencies, and urban residents also have minimal daily use requirements.

METHODS

Our approach centers on simulation-based optimization, which uses mathematical models and computational simulation tools for an underlying physical process to evaluate objective functions. The communication between the optimization algorithm and the simulation tool is handled through Python-based wrappers, which translate the design points suggested by the optimizer into input files which can be interpreted by the simulator. These wrappers also parse the output files returned from the simulator to obtain the data required to evaluate the objective functions. We provide details on the simulation environment and the optimization software below.

Our work is the first to incorporate the USGS One-Water Hydrologic Flow Model (MF-OWHM, Hanson, et al. 2014a) as a simulation tool coupled to external optimization algorithms. Our previous analysis utilized the predecessor to MF-OWHM, the MODFLOW Farm Process Model (MF-FMP2, Schmid and Hanson, 2009). MF-FMP2 and MF-OWHM are agriculturally focused water management programs, with the latter offering extended support for the analysis of a wide-range of conjunctive-use issues within a given region. We chose this software as our simulation workhorse for several reasons. First, the USGS MODFLOW water simulation software is widely used and well respected. Water management was the primary concern of our farming partners in California who were responsible for the genesis of our study. Second, both MF-OWHM and MF-FMP2 have been used extensively in a variety of contexts to study water resource management in heavily farmed areas, where conjunctive use analysis is required to represent the interests of all of the stakeholders in the region (Faunt, et al., 2009, Faunt, et al., 2015, Hanson, et al., 2008, Hanson, et al., 2013, Hanson, et al, 2010, Schmid, et al., 2009, Hanson, et al, 2014d, Hanson, et al, 2012). Finally, MF-OWHM supports a range of mechanisms for predicting water usage from a variety of sources based on climate and plant growth characteristics, all of which enables us to easily evaluate increasingly complicated objective functions with physically realistic parameter spaces.

We utilize the suite of optimization tools available within the DAKOTA optimization package (Adams, et al, 2009), developed and maintained by researchers at the U.S. Department of Energy Sandia National Laboratory. We chose DAKOTA because of its capabilities in handling simulation-based optimization problems. Users only need to supply subroutines to evaluate the objective functions and constraints without providing any gradient information. Moreover, DAKOTA has a variety of different optimization algorithms, which allows us to choose the optimization paradigm best suited for the problem under consideration.

The One-Water Hydrologic Flow Model (MF-OWHM, Hanson, et al., 2014a) is a MODFLOW-based (MF-05, Harbaugh, 2005) integrated hydrologic flow model that is the most complete version, to date, of the MODFLOW family of hydrologic simulators needed for the analysis of a broad range of conjunctive-use issues. MF-OWHM fully links the movement and use of groundwater, surface water, and imported water for consumption by agriculture and natural vegetation on the landscape, and for potable and other uses within a supply-and-demand framework. MF-OWHM is based on the Farm Process for MODFLOW (MF-FMP) (Schmid, et al., 2006, Schmid and Hanson, 2009) combined with local grid refinement, streamflow routing, surface-water routing process, seawater intrusion, and riparian evapotranspiration.

MF-OWHM allows not only for head-dependent flows of a traditional groundwater model but also flow-dependent and deformation-flows for a more complete coupling within the hydrosphere. By retaining and tracking the water within the hydrosphere, MF-OWHM accounts for “all of the water everywhere and all of the time.” This approach provides more complete water accounting and provides a platform needed to address wider classes of problems such as evaluation of conjunctive-use alternatives, including sustainability analysis, potential adaptation and mitigation strategies, and development of best management practices (Hanson and Schmid, 2013). MF-OWHM's broader ability to simulate more of the hydrosphere has served as a valuable tool for multiple research and applied modeling projects.

As research tools, both MF-FMP and MF-OWHM have been modified to investigate mathematical techniques, including subsidence feedback on conjunctive use (Schmid, et al., 2014), effects of climate change (Ferguson and Llewellyn, 2015; Hanson, et al., 2012), crop optimization (Fowler et al., 2014, Schmid, et al, 2006, Schoups et al, 2006), water-rights driven surface water allocations (Schmid and Hanson, 2007), and proper orthogonal decomposition model reduction (Boyce, 2015, Boyce and Hanson, 2015, Boyce, et al., 2015). MF-FMP and MF-OWHM have also been used to evaluate many applied projects within the U.S. Geological Survey and the private sector (Boyce and Hanson, 2015, Faunt, 2009, Faunt, et al., 2009, Faunt, et al., 2015, Hanson, et al., 2013, Hanson, et al, 2014d, Hanson, et al., 2014c, Hanson, et al, 2014, Hanson and Sweetkind, 2014, Russo, et al., 2014).

The decision variables for this optimization problem are the percentage of crops planted each time land becomes available after a harvest. There are two objectives used for this study; to maximize yield and to minimize the farm water deficit. The yield is calculated from the evapotranspiration values of the crops as in Fowler et al., 2016. The water deficit is calculated based on the difference between the initial total farm delivery requirement (TFDR) and the final farm delivery requirement. These values depend on the amount of each crop planted, their water needs, and the amount of water available. TFDR is defined as the portion of crop demand that is not met by precipitation and uptake from groundwater, increased by the inefficiency losses from irrigation.

The allocation of crops is input for an MF-OWHM simulation and evapotranspiration and water usage values are extracted at the end of a simulation. As mentioned above, Python wrappers facilitate the connection of the optimizer by handling the I/O and computation of the objective functions. This workflow is illustrated in Figure 1. The details of the crops and the physical description of the farm for this work are described next.

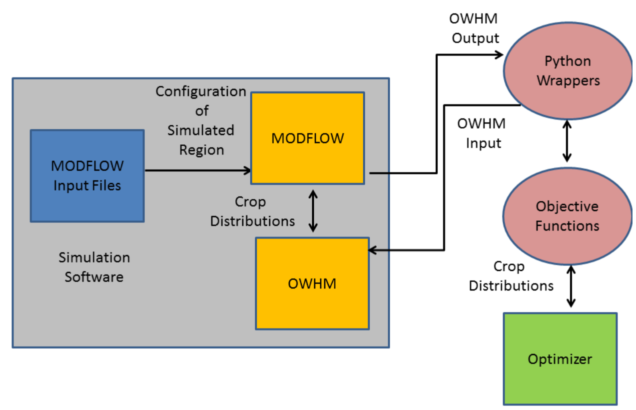

Figure 1: Flow chart of optimization-simulation framework. The MODFLOW filers describing the physical setting are created once, then Python wrappers are used to handle the input/output between MF-OWHM and the optimization algorithm and calculates the objective function values. This requires the creation of some new data files at each optimization iteration.

RESULTS

Our model problem is based on one of the model problems provided in the MF-OWHM software distribution (Hanson, et al., 2014a). A schematic of the model problem is shown in Figure 2. The simulation domain contains eight farm accounting units and three crop-type identifiers. Five of the farm accounting units are associated with crop-planting regions, one is a riparian region, one is an urban region, and one is a natural vegetation region. Both the riparian and natural vegetation regions are non-irrigated regions. The crop type identifiers are associated with potatoes, a stone-fruit crop (orchard), and vegetable row crops.

The topography slopes downward from west to east and converges from the north and south toward a riparian region along the eastern edge. The underlying geology contains seven aquifer layers, three of which are layers of confining material with thicknesses ranging from 5 m to 15 m. The aquifer nearest the surface is unconfined with varying depth. The remaining three (confined) layers are uniformly 60 m thick. The saturated hydraulic conductivity varies from 10 m/day in the aquifer nearest the surface to 0.15 m/day in the aquifer furthest from the surface. More specific details on elements of the model problem can be found in the MF-OWHM User's Guide (Hanson, et al., 2014a).

The optimization algorithm used here provides a suite of possible planting configurations in the form of a trade-off curve (i.e. Pareto front). For this work, the orchards are considered permanent so that only potatoes and vegetable row crops can be swapped out or replanted. We consider a four year time simulation. Based on the growing season of those crops, this leads to 12 total decision variables (i.e. planting possibilities for potatoes and row crops).

The trade-off curves allow stakeholders to make decisions based on their individual preferences. An example trade-off curve is shown in Figure 3. The points on that front represent specific crop portfolios and the axes are the two objective function values. Here yield is given in tons and the water deficit is given in cubic meters. The shape of the curve indicates the competing nature of the objectives and range of objective function values provide stakeholders with a wide range of possibilities to select from.

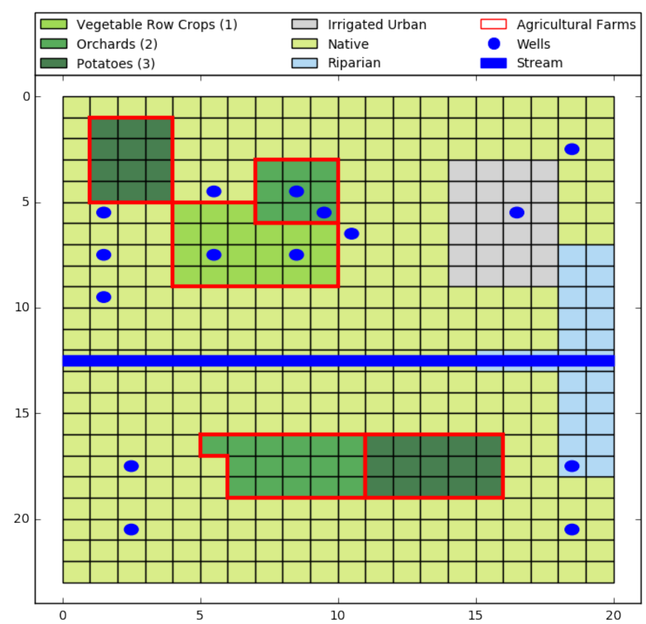

Figure 2: A diagram of the model configuration. Note that the agricultural farms are outlined in red, and the wells are represented as blue circles. The color of each square in the grid refers to the crop type planted on that piece of land. The three colors within the agricultural farms refer to the three agricultural crops used in this study. The gray cells denote an urban area, the light blue cells represent riparian vegetation, and remaining cells are native vegetation.

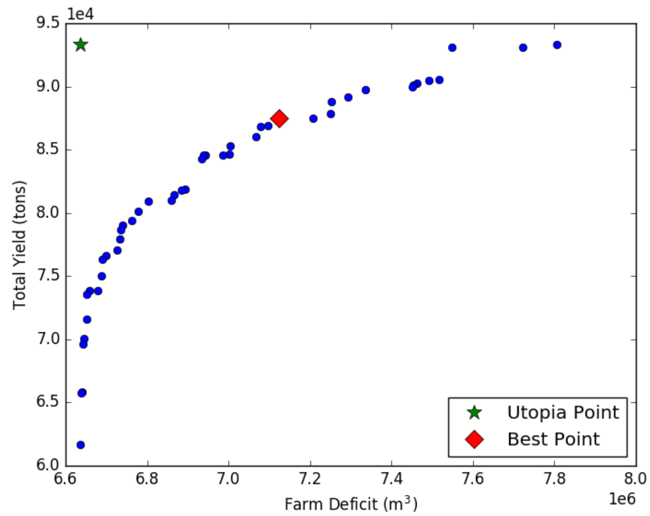

Figure 3: Sample tradeoff curve showing the competing objectives; maximizing yield (tons) vs minimizing deficit (m^3)

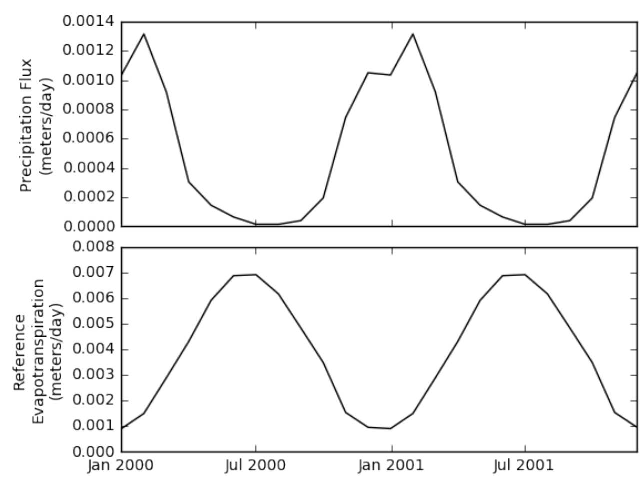

Figure 4: The top figure shows the precipitation data used in simulation which includes a drought scenario where very little precipitation occurs during the summer months. The bottom figure shows the reference evapotranspiration values that are used to calculate the yield in accordance with the evaporation values for each crop over the simulation time.

	Best Point	Mean	Std. Dev.
P_1^1 (Apr. Yr 1)	0.30	0.31	0.22
P_1^1 (Apr. Yr 2)	0.67	0.43	0.23
P_1^1 (Apr. Yr 3)	0.11	0.17	0.22
P_1^1 (Apr. Yr 4)	0.74	0.51	0.19
P_3^4 (Feb. Yr 1)	0.07	0.17	0.17
P_3^4 (Feb. Yr 2)	0.93	0.81	0.15
P_3^4 (Feb. Yr 3)	1.00	0.86	0.21
P_3^4 (Feb. Yr 4)	0.93	0.89	0.07
P_3^5 (Feb. Yr 1)	0.00	0.05	0.14
P_3^5 (Feb. Yr 2)	0.00	0.10	0.19
P_3^5 (Feb. Yr 3)	0.00	0.12	0.23
P_3^5 (Feb. Yr 4)	0.42	0.21	0.13
Total Yield (tons)	87496	81789	7892
Farm Deficit (m^3)	7123360	6992888	329797

Table 1: Fractions of Crops 1, 2, 3 and the resulting yield and deficit. Note that P_c^f denotes the fraction of farm *f* planted with crop *c*.

DISCUSSION

This work demonstrates how MF-OWHM can be used to analyze planting strategies with attention to water availability when surface water, ground water, and precipitation are the primary sources. The sophisticated underlying models can be adapted for specific rain events, crops, or water delivery mechanisms. When paired with an optimization algorithm, objective functions that represent stakeholders can be used in conjunction with the simulation tool to guide agricultural practices. In this work, we considered the yield and water deficit. However, any mathematical realization of a stakeholder's objective can be implemented so that the framework is a flexible decision-making tool. Future work includes the consideration of environmental constraints and a better understanding of the sensitivity of the solutions to the model parameters.

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