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Integrating complex economic and hydrologic planning models: An application for drought under climate change analysis

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ABSTRACT

Climate change can affect a region's environment and economy through changes in water resource flows and allocations. The hydrologic and economic components of these impacts require complex models to reflect both the environment's physical and individuals' behavioral responses to climate change. This paper describes a model that combines the strengths of the State Wide Economic Agricultural Production Model (SWAP), an agricultural economic optimization model, and Water Evaluation and Planning (WEAP), a climate-driven hydrological model. A step function approximation of water demand curves from SWAP is used in an iterative search process to estimate crop land allocation based on annual regional water availability and economic value. SWAP value functions serve as input for an optimal discretization of water demand functions. The methodological integration of the SWAP and WEAP models creates the EconWEAP model. This paper shows the improved analytic ability of this integration by comparing agricultural revenues from WEAP vs. EconWEAP. Results for EconWEAP runs in the California's Central Valley show a significant increase in revenues for the Central Valley, maintaining the same hydrology, through the economically optimal allocation of water. This integration approach can be applied to other types of economic and hydrologic models.

1. Introduction

Water resources systems are often complex in nature, with high levels of uncertainty in describing future conditions, and problems that are hard to define and, therefore, resolve [1]. In irrigated systems, agricultural production uses around 70% of the water supply [2,3]. Understanding farmers' economically driven decisions under changing climatic conditions and management arrangements is important for the analysis of environmentally sustainable and economically feasible policy options [4–7]. This study combines the strengths of a simulation water management model, WEAP (Water Evaluation and Planning), that contains a Plant Growth Model (PGM) to assess crop yields and an economic optimization model, SWAP (State Wide Agricultural Production), exploring how changes in allocation of basin water flows, storage and diversions in times of scarcity actually change the behavior at the farm level, and the associated economic outcome, particularly in dry years.

Problems related to water resources are often difficult to define, and efforts to address the problems often fail to yield resolutions

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[1]. Climate change can alter a region's hydrologic cycle by affecting storm frequency, rainfall intensity and timing, and quantity of snowmelt [8–10]. Climate change exacerbates the challenge water managers face in trying to understand and analyze future hydrologic conditions [11]. Hydrological simulation models represent complex systems of natural hydrology, water management, and infrastructure, all at a finite temporal and spatial scale. Simulation models can represent the interaction of different systems in a basin (environmental, urban, agricultural and industrial); the spatial and temporal dependencies; and the effects of climate change and human-induced activities on environmental systems [12–14]. Agricultural systems in simulation models are often represented by fixed crop proportions, and the water allocations are often ruled by priority allocation between sectors. The Water Evaluation and Planning (WEAP) system simulation model [3] can capture the aforementioned characteristics and long-term impacts of climate change under different representations of subsystems around the world [10,15–18].

Policymakers struggle to assess the effects of potential policies and environmental changes on water resources systems, their ecological status, urban communities, and different economic activities [11]. One of the most evident impacts of climate change on hydrology is on snowpack in California's Sierra Nevada Mountains. This snowpack is the main water supply for the Central Valley, [2] which has a population of 6.5million [19], thriving industrial development and irrigated agricultural output valued at $42 billion [20]. California's complex and highly regulated water supply system includes a high-value irrigated agricultural production system [21]. Adequately representing farmers' decisions on crop allocation, water use and future expectations in climate conditions and policy respond is one of the main challenges for economists. One example of this is in reaction to policies on surface and groundwater availability, water scarcity expectations, drought and changes in climatic conditions [22,23]. Fixed coefficient models cannot adequately represent how agricultural production systems may adapt to changes in water availability. Optimization models are better suited to represent farmers' responses by using agricultural production functions. SWAP applies the Positive Mathematical Programing (PMP) method developed by Howitt [24] to parameterize a non-linear cost and production function using identities in the first-order conditions of a profit maximization program and the opportunity costs of the limited land and water resources. These limits are usually considered to be known in a traditional optimization modeling exercise. The model allocates land and water based on regional marginal economic criteria based on the observed annual distribution of water availability and water prices, and to each region's agricultural production technology.

In irrigated agricultural systems which are vulnerable to drought conditions, water managers face a series of challenges when deciding on an allocation of scarce water supply that produces environmentally sustainable outcomes that are also economically feasible [11,25]. Harou et al. [5] describes the realm of hydro-economic modeling, where the economic value of water varies according to the type of water use. Irrigation, hydropower generation, and industries use water as a production factor, where the valuation of the water depends on the demand and subsequent value of the final good or service produced. The challenge is to account for these behavioral responses, and their impact on water demand, within the water allocation systems so that the dynamics of optimal water use can be captured in the application of allocation rules. Representing various water system components requires models to consider and assess socio-economic activities, water management options, and climatic and hydrological effects at the basin level. Because hydrologic simulation models are mainly driven by a priority system based on water allocation and/or a water rights regime, they often have limited ability to capture the economic value of water. Static water management optimization models usually maximize the economic benefit of a resource to evaluate the trade-offs associated with the allocation of water for agriculture based on a maximization problem subject to a set of system constraints [5,26–30]. However, static optimization models usually are not specified to capture the interdependency of water use within sectors on allocation rules or temporal interdependence, since each time period is conventionally solved as a separate optimization [5].

Integrated comprehensive hydro-economic systems models provide the tools to support decision-makers in the formulation of environmentally sustainable and economically feasible solutions [5,11]. The two prevailing types of water resources modeling tools have been simulation and optimization models, and recently planners have begun to combine them. One of the main challenges in linking these two types of models is the difference in time scale: *simulation* of variations in water requirements on a monthly scale versus economically driven *optimal* land allocation decisions made annually and based on future expectations. Another main challenge is a difference in spatial scale: management-based, climate-driven *simulation* of upstream-downstream spatial schemes for surface water availability with varying microclimates versus *optimization* based on farm-level characteristics that may correspond to water rights or specific production characteristics, rather than physical boundaries.

Hydro-economic models have been used for quite some time and at different fields of research. Harou et al. [5] offers a review of the key aspects to consider in the development of hydro-economic models from 80 modeling efforts. Momblanch et al. [31] contains a review of close to 100 hydro-economic modeling studies focused on environmental concerns alone or coupled with other sectors, such as agriculture, hydropower, urban, industry and navigation. Hydro-economic modeling research that focuses on the agricultural sector was developed to address varying concerns: evaluating allocation policy concerns and impacts of climate change [4,6,32,33]; water licensing regimes and water markets; and optimal allocation surface water and groundwater quality concerns [34–36] and management [32,37–39].

Within the California context, a bundle of key modeling applications has contemplated hydro-economic modeling integration. CALVIN [27], a state-wide economic optimization model for water management in California, incorporates agricultural water scarcity costs estimations from SWAP using perfect foresight of water availability levels from a historic 72-year monthly time period to estimate economically optimal water allocations to urban and agricultural uses [5,27]. Connell et al. [37] approximated climate change hydrology for CALVIN by perturbing historic hydrologic data from 1921 to 1993 in California. The hydrology estimates are deterministic and static; surface and groundwater hydrology are imported from other models. Whereas policy insights can be obtained using pure network optimization models that include economic values of water in various uses [32], this setting often relies on external hydrological inputs under perfect foresight, ignoring the fact that these uses can have a feedback influence on the