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Integrating water supply constraints into irrigated agricultural simulations of California

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ABSTRACT

Simulations of irrigated croplands generally lack key interactions between water demand from plants and water supply from irrigation systems. We coupled the Water Evaluation and Planning system (WEAP) and Decision Support System for Agrotechnology Transfer (DSSAT) to link regional water supplies and management with field-level water demand and crop growth. WEAP-DSSAT was deployed and evaluated over Yolo County in California for corn, rice, and wheat. WEAP-DSSAT is able to reproduce the results of DSSAT under well-watered conditions and reasonably simulate observed mean yields, but has difficulty capturing yield interannual variability. Constraining irrigation supply to surface water alone reduces yields for all three crops during the 1987–1992 drought. Corn yields are reduced proportionally with water allocation, rice yield reductions are more binary based on sufficient water for flooding, and wheat yields are least sensitive to irrigation constraints as winter wheat is grown during the wet season.

Software availability

Name of software: WEAP-DSSAT
Developers: Charles Young, Jonathan Winter, Vishal Mehta, Alex Ruane
Contact address: Dartmouth College, 6017 Fairchild Hall, Hanover, NH 03755
Telephone: +1 603-646-6456
Email: jwinter@dartmouth.edu
Year first available: 2016
Hardware required: PC, Intel with 4 GB RAM recommended
Software required: Microsoft Windows
Availability and cost: Licensed software
Program language: Fortran, Python, and Delphi
Program size: 500 MB

1. Introduction

Irrigated farms account for 80%–90% of consumptive water use in the United States and $118.5 billion of US agricultural production (Solley et al., 1998; Schaible and Aillery, 2012). Despite the high productivity of irrigated croplands, agriculture is typically the lowest value sector in a water resources system, and, subject to water regulations and rights, vulnerable to reductions during drought. A major challenge for the hydrologic and agricultural communities is assessing the effects of climate change on the sustainability of regional water resources and irrigated agricultural land (Walthall et al., 2013). A key component of this challenge is the fact that most agricultural models that have sophisticated representations of crop physiology, management, and yield, and are thoroughly evaluated at the field scale, lack constraints on irrigation supply (Winter et al., 2017). Many crop models are run with

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scheduled irrigation or unlimited automatic irrigation (e.g., Bondeau et al., 2007; Jones et al., 2003; Raes et al., 2009), each of which has important disadvantages. With scheduled irrigation the dates and amounts of irrigation are prescribed in advance. This is problematic in locations and years where this information is not readily available, or in predictive applications (e.g., seasonal forecasts, climate change projections). Automatic irrigation doesn't require prior knowledge of water applications, instead relying on a rule-based approach (often linked to soil moisture) to irrigate from an unlimited water supply. This leads to inconsistent, and occasionally implausible, biases and errors that muddle the picture for stakeholders and policymakers seeking to understand agricultural sustainability issues.

Multiple studies have addressed the impacts of climate on irrigated agriculture at scales ranging from regional to global; however, few have explicitly coupled a crop model to a calibrated hydrologic and water resources allocation model. Elliott et al. (2014a) compared water supply projections from ten global hydrologic models and water demand projections from six global gridded crop models. Results suggested that the effects of reduced irrigation were comparable to the direct impacts of climate change on global production of maize, soybean, wheat, and rice, with some acute regional impacts. However, Deryng et al. (2016) noted discrepancies in projections of agricultural water supply and demand due to varying responses of crop water use to increased CO_2 by global gridded crop models, and the lack of response of crop water use to increased CO_2 by some global hydrologic models. Piontek et al. (2014) explored climate change impacts on multiple sectors, including water availability and agriculture. Several areas were found to have overlapping risk for severe change both in water availability and climate, including the southern Amazon Basin and regions in South Asia. Wada et al. (2013) used a set of seven global hydrologic models to explore the change in irrigation water demand by the end of the century, finding a considerable increase during summer months in the northern hemisphere. Huntington and Niswonger (2012) focused on the seasonal timing of streamflow and surface and groundwater interactions over the Western United States. Specifically, they used an integrated model of surface water and groundwater inclusive of snowpack and snowmelt forced with twelve general circulation model (GCM) projections. Future climate was shown to decrease summertime flows by more than 30% averaged across the ensemble, with reductions found even in GCM simulations that projected increased annual precipitation. Groundwater is a critical source of water for irrigated agriculture, and groundwater management remains a salient issue for sustainable irrigated agriculture (Döll et al., 2012). Taylor et al. (2013) outline the complexity of groundwater response to climate change and human impacts, including annual precipitation and streamflow; timing, intensity, and duration of precipitation and streamflow; land use; snowpack; groundwater pumping; and surface water irrigation. Groundwater pumping has been shown to be unsustainable in the Central Valley of California; however, to date the use of groundwater has been largely unrestricted in California (Famiglietti, 2014).

The water-agriculture nexus has been identified as a high priority area within the Agricultural Model Intercomparison and Improvement Project (AgMIP; Rosenzweig et al., 2015, 2013). The importance of irrigated agriculture to global food production, as well as the response of crop water supply and demand to climate, necessitate explicitly simulating effects of water availability on irrigated yields. In the following sections, we describe the development, application, and evaluation of a coupled hydrologic, water resources allocation, and crop model. The objective of creating this coupled model is to more realistically simulate irrigated agricultural yields, and specifically to develop a modeling system in which water shortages (e.g., decreased precipitation, enhanced evapotranspiration, changes in allocation) directly impact irrigated crop yields, with applications for identifying and testing policy and management approaches.

2. Model description and development

To simulate water demand and supply for irrigated agriculture, a model must link information about regional water supplies and management with field-level water demand and crop response as it develops throughout the season. To accomplish this, we coupled the Decision Support System for Agrotechnology Transfer (DSSAT; Hoogenboom et al., 2012; Jones et al., 2003) to the Water Evaluation and Planning system (WEAP; Yates et al., 2005a, 2005b). Below we describe the development of the coupled model, WEAP-DSSAT, as well as our iterative simulation approach, which together add water supply constraints to automatic irrigation in DSSAT and detailed crop water use and yields to WEAP.

2.1. Water Evaluation and Planning system

The Water Evaluation and Planning system (WEAP) is used to model water supply and management within WEAP-DSSAT. WEAP is an object-orientated model that solves a time evolving mass balance based on a water allocation objective function. At each time step, hydrologic fluxes from the surface and near surface are passed to appropriate river and groundwater objects, where they are balanced with an objective function that maximizes satisfaction of demand and instream flow requirements, subject to supply priorities based on water rights and regulations, demand site preferences, mass balances, and other constraints (Yates et al., 2005a, 2005b). WEAP has a flexible time step that can range from daily to annual, which also determines the time scale over which water allocation is calculated.

WEAP divides study regions into user-defined sub-catchments; groundwater basins; irrigated areas; urban/export uses; environmental requirements; and water system elements such as canals, diversions, and reservoirs. Water supply in WEAP is provided by an embedded hydrologic model forced by an external climate dataset that simulates runoff, groundwater-surface water interactions, and snow processes. Before the addition of DSSAT, agricultural water demand in WEAP could be simulated using a variety of approaches that range in complexity from a simple crop coefficient method to more complex hydrology-based algorithms that incorporate runoff, infiltration, soil moisture storage, deep percolation, and evapotranspiration as a function of soil moisture status.

The WEAP framework readily accommodates user specified models, or modules, that can be plugged into and controlled by WEAP's water budget and allocation logic. WEAP has been used for range of applications, including large river basins with substantial irrigation such as California's Central Valley (Mulligan et al., 2011; Sandoval-Solis et al., 2010), village scale modeling of community livelihoods (Varela-Ortega et al., 2011), and the exploration of climate change impacts on hydropower generation (Mehta et al., 2011). WEAP deployed over the Central Valley has been shown to adequately represent both local and regional water balances, and the allocation of groundwater and surface water supplies (Purkey et al., 2008; Yates et al., 2009, 2008).

A feature critical to assessing the impacts of climate change on agriculture, and which is notably lacking in the California implementation of WEAP, is a representation of plant physiology in plant water use and yields. WEAP simulates crop water use by assigning a seasonal cycle of agricultural vegetation to every user-defined subcatchment. For each time step, potential evapotranspiration is scaled by a crop coefficient. This approach, while reasonable for