Forecasting tools in water resources to ground public policy and management debates in sound scientific methods

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Abstract Society faces challenges in management and use of water resources that are global in nature and yet impact communities and individuals locally. While this presentation focuses on issues common to irrigated agriculture in semi-arid grasslands with applications from the central plains of the USA, the computational framework is extensible to other challenges. Individually, computational models are overviewed that enable studies of groundwater hydrogeology, agricultural economics, and agro-ecology. Each model is capable of reproducing historical data (groundwater declines, economic decisions, crop yields), and provides a tool to forecast disciplinary perspectives into the future. Collectively, models are integrated using the Open Modelling Interface (OpenMI), which enables output from one model to be used as input to others and provides a tool to integrate perspectives. This novel framework is being applied to study the impacts of policy change on water resources, land-use choices, and agricultural productivity.

Key words groundwater; Analytic Element Method; modelling; OpenMI; economics; agriculture; Ogallala Aquifer; High Plains, USA

INTRODUCTION

Temperate grasslands such as the central plains and prairies in the USA and the downs in Australia have the potential to cover over 1/3 of the world's land surface. This terrestrial biome has been cultivated extensively worldwide to provide food for modern society. While grasslands provide ideal soils for agriculture, their climate is often predominated by episodic precipitation events where additional water supplies are required for successful crop production during dry periods. In the High Plains region, the Ogallala Aquifer provides groundwater for 30% of the irrigated agriculture of the USA. Subsequently, many regions are experiencing sustained regional declines in the groundwater table of the order of 0.5–1 m/year. While a variety of policy and management tools exist to address this challenge, it is important to provide information to these debates that is grounded in sound scientific methods.

The interdisciplinary nature of this problem is illustrated in Fig. 1. Land-use choices (the types of crops to be grown) are largely controlled by the economic decisions of individual land owners. Agricultural practices (irrigation frequency and technology) require groundwater irrigation that varies by the type of crop and characteristics of the parcel of land. Groundwater processes (recharge, saturated thickness, geologic properties, etc.) impact the movement of groundwater and the quantity available for pumping. Clearly, decision support requires methods and tools to integrate these disciplinary perspectives.

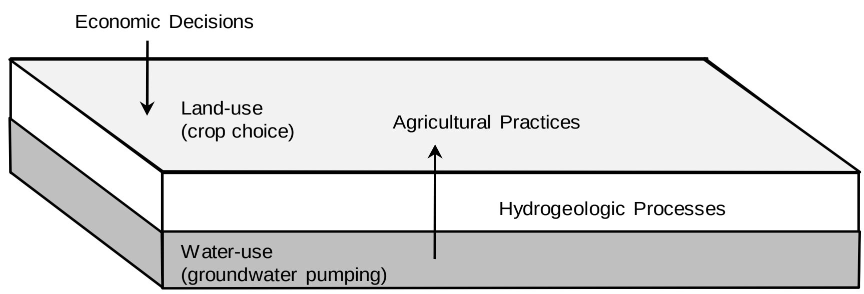

Fig. 1 Irrigated agriculture using groundwater in semi-arid grasslands: Processes and their interactions with water- and land-use. Economic decisions control land-use and the crops chosen to be grown. Agricultural practices impact the quantity of groundwater irrigation. Hydrogeologic processes control the movement and availability of groundwater.

METHODS

A team of researchers at Kansas State University has been working towards development of interdisciplinary tools to study and forecast the impacts of change in a water resources system. This presentation explains these methods to the perspective of international hydrologic science.

Disciplinary models

The disciplinary models for groundwater, economics, and ecology related to agriculture are illustrated in Fig. 2. Individual modelling paradigms, and the important input and output parameters for this study are described next.

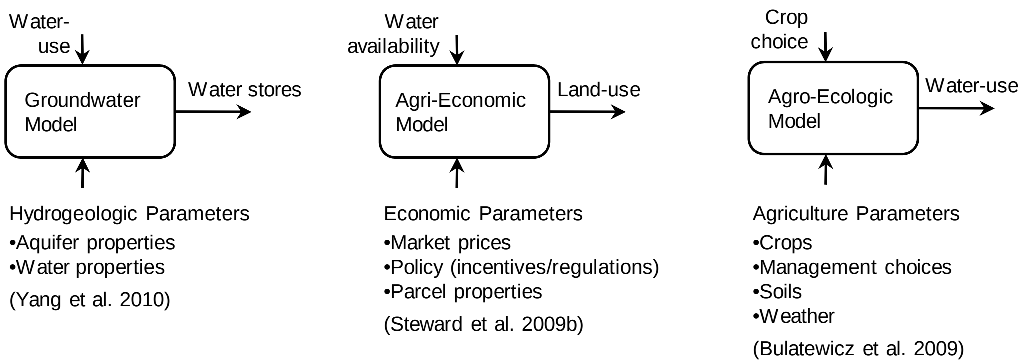

Fig. 2 Inputs and outputs for groundwater, economic and agricultural models.

Groundwater methods Groundwater studies the hydrologic properties of mass (how much groundwater exists), flux (how quickly is it moving), pathways (what are the interactions with surficial processes and pumping), and residence time (Reckhow, 2004). The data used to study groundwater are related to the aquifer (geological properties such as base elevation, hydraulic conductivity and specific yield) and related to water (river elevation, recharge rates, etc.) For the models used here, the pumping rates for wells required for irrigated agriculture are given as inputs and the groundwater model provides predictions of the temporal and spatial availability of groundwater (saturated thickness and depth to water).

The groundwater model is founded in conservation laws (continuity of flow and conservation of energy) and constitutive relations between groundwater elevation and the rate of flow (Darcy's Law). For this study, these equations were implemented using the Analytic Element Method (Strack, 1989). Since the Ogallala Aquifer has a sloping base, the impact of the base was modelled using a stepping base approximation (Steward 2007; Steward *et al.*, 2009c) with the implementation of line elements in Steward *et al.* (2008).

Agricultural-economic methods Agricultural economics studies the development, management, and production of material wealth related to the agriculture sector. Locally, economics is impacted by the properties associated with the parcel of land (type of soil, irrigation technology, local weather, etc.). Regionally and globally, economics is impacted by markets and policies. For the models here, the availability of water is given as inputs since the saturated thickness impacts the quantity of available water and the pumping rate and the depth to water impact the energy cost associated with pumping water. The economic model provides annual predictions of the crop choice for each parcel.

The agricultural economic model is founded in the polychotomous choice selectivity model introduced by Lee (1983). This was implemented in Steward *et al.* (2009b) by developing functional relations to predict crop choice given a wide range of economic parameters associated with each parcel. Regression was used to calibrate coefficients in these equations and these statistics are summarized in Steward *et al.* (2009b).

Agro-ecological methods Agro-ecology studies the relationships between organisms and their environment in agricultural settings. The data used in this study are related to the type of crop, the soil characteristics, weather (min/max daily temperature, humidity, wind speeds, etc.) and management practices (such as planting dates, fertilizer applications, and irrigation scheduling). The crop choice for a given parcel for a given year is given as an input to this model, and the model predicts crop yields, deep percolation to groundwater, and irrigation water demands.

The agro-ecology model employs a tipping bucket scheme, whereby precipitation is partitioned into runoff, evaporation, and infiltration and the infiltration moves downward through layered soil horizons which either remove water due to root water uptake or allow water to seep to lower layers, until eventually the water seeps downward past the root zone. The specific computer model used here is EPIC, which is described by Sharpley & Williams (1990). The unknown parameters associated with management practices were estimated using clustering and maximum entropy techniques described in Bulatewicz *et al.* (2009).

Integration using OpenMI

The three models are linked naturally through the information they individually require as input and produce as outputs, as illustrated in Fig. 3. The economic model predicts annual crop type to be grown on a parcel of land, which is used by the ecology model to predict groundwater irrigation requirements, which is used by the groundwater mode to predict changes in groundwater stores, needed by the economic model to know how much groundwater is available for the next growing season. The data required for the individual models in Fig. 2 has been organized in GIS repositories associated with the groundwater model (Yang *et al*., 2010), the agri-economic model (Steward *et al*., 2009b), and the agro-ecologic model (Bulatewicz *et al*., 2009).

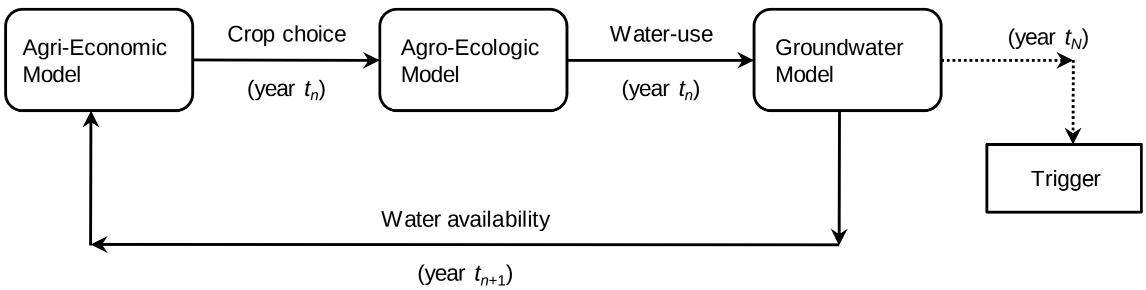

Fig. 3 Integration of model components using OpenMI.

The Open Modelling Interface (OpenMI) provides a standardized methodology to define, describe and transfer data between software components that run simultaneously on a time basis (Gregerson *et al.*, 2007). The OpenMI was developed to support the EU Water Frameworks Directive and enable a plethora of computational tools to be brought to bear in decision support, without pre-ordaining the methodology used within each model. In the OpenMI, a GetValues function is developed for each component that enables one model component to request values from another component at a specific time. Thus, for one year of computer execution, the groundwater model calls the GetValues function for the ecology model to get the water-use for a parcel; the ecology model calls the GetValues function for the economic model to get the crop choice for a parcel; and the economic model calls the GetValues function for the groundwater model to get the groundwater availability given the water-use from the previous year. A trigger is called to begin execution of the model by requesting the values for a model at the end of simulation in year t_N and the OpenMI automatically sequences model execution to begin at a set of initial conditions and pass information between models until all steps have been completed. The implementation details of this model are available from Bulatewicz *et al*. (2010).

APPLICATION

The integrated computational framework has been applied in the semi-arid grasslands in Sheridan County, northwest Kansas, USA. The native biome of this High Plains region is short-grass prairie with an annual precipitation of 0.5 m/year. Irrigated agriculture began in the late 1950s with the advent of modern hydraulic well technology and the region was fully developed by the early 1980s. Groundwater is supplied by the Ogallala Aquifer, which had an average predevelopment saturated thickness in the region of approximately 30 m. The primary irrigated crop is corn (maize), which has been used locally as feedstock for cattle and more recently for ethanol (biofuel) production. The majority of irrigated agriculture was developed using flood and central pivot with overhead sprinklers, but have largely been converted to more efficient central pivot with low pressure sprinkler heads in drop lines.

Each of the three models (groundwater, agricultural economics and agro-ecology) was first individually applied to the study region. Model coefficients (groundwater parameters, economic regressors, agricultural coefficients) were calibrated for each model such that they successfully reproduced the important disciplinary outputs (groundwater elevation, economic crop choices, agricultural crop yields). Additionally, the groundwater and agro-ecology models were calibrated when running as coupled models (Bulatewicz *et al*., 2009).

The results of a coupled model run using the OpenMI methodology is shown in Fig. 4. Models were run beginning at a set of baseline conditions in 1990 until the end of the model run in 2005. The groundwater results illustrate the distribution of water-use in wells and the formation of a regional cone of depression formed by wells in the high water use region towards the middle of the study region. The agro-ecology results illustrate the total revenues obtained by multiplying the crop yields by their market values. The agri-economic results illustrate the most frequently selected crops for each parcel. After running the integrated computer models using baseline conditions, the models were then executed over other possible policy scenarios that could have been implemented in 1990, such as regulation using the prior appropriation doctrine and incentives using a water buyback programme. The results of those studies may be found in Steward *et al*. (2009c) and Bulatewicz *et al*. (2010).

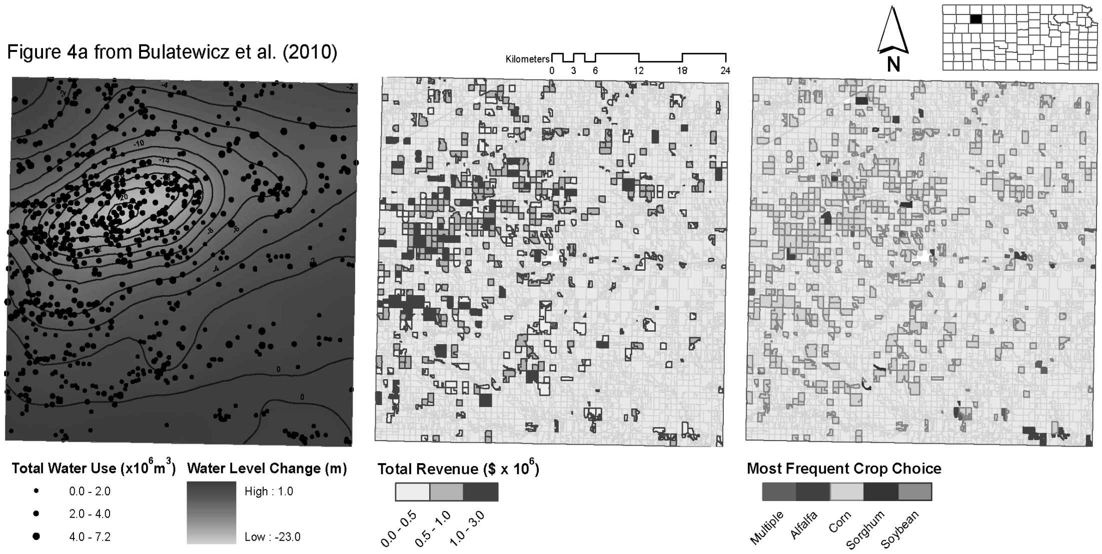

Fig. 4 Model results from the integrated modelling platform in Sheridan County, Kansas USA.

CONCLUSIONS

A strong need exists to support public policy and management debate using methods grounded in solid scientific methods. A set of models are presented in Fig. 2 that each individually represent current modelling approaches that are used in isolation to study groundwater, agricultural economics and agro-ecology. Each model contains a set of disciplinary specific input parameters as well as input and output data that are useful for the other models. The OpenMI framework was adopted using Fig. 3 to automate the process of extracting the output from one model and using it as input for the next. Collectively, this enables a modelling framework that represents disciplinary perspective while integrating perspective and results across model components.

Results in Fig. 4 illustrate the types of outputs that are provided by this new decision support framework. While each of these outputs could have been obtained individually by one of the model components, the interactions between components are only available through coupled model execution. This integrated framework enables changed in the water resources system to be evaluated, for example, model runs have been performed to illustrate the impacts of changes in policy (enforcement and incentives) on the groundwater availability, the crop revenue, and the economic decision for which crops to grow.

This framework has the potential to be adapted to study other challenges in water resources. For example, the impacts of phreatophytes (Steward & Ahring, 2009) could be incorporated to study a broader scope of land-use including trees and hedgerows which are important in Australia. The spatial and temporal variability of recharge from irrigation using surface water could also be incorporated to study issues such as rising water levels of saline groundwater in Australia.

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REFERENCES

Bulatewicz, T., Jin, W., Staggenborg, S., Lauwo, S. Y., Miller, M., Das, S., Andresen, D., Peterson, J., Steward, D. R. & Welch, S. M. (2009) Calibration of a crop model to irrigated water use using a genetic algorithm. *Hydrol. Earth System Sci.* **13**, 1467–1483.

Bulatewicz, T., Yang, X., Peterson, J. M., Staggenborg, S., Welch, S. M., & Steward D. R. (2010) Accessible integration of agriculture, groundwater, and economic models using the Open Modeling Interface (OpenMI): Methodology and initial results. *Hydrol. Earth System Sci.* **14**, 521–534.

Gregersen, J. B., Gijsbers, P. J. A. & Westen, S. J. P. (2007) OpenMI: Open modeling interface, *J. Hydroinf.* **9**(3), 175–191.

Lee, L.-F. (1983) Generalized econometric models with selectivity. *Econometrica* **51**, 507–512.

Reckhow, K., Band, L., Duffy, C., Famiglietti, J., Genereux, D., Helly, J., Hooper, R., Krajewski, W., McKnight, D., Ogden, F., Scanlon, B., & Shabman, L. (2004) *Designing Hydrologic Observatories: A paper prototype of the Neuse Watershed*, Technical Report 6, Consortium of Universities for the Advancement of Hydrologic Sciences, Inc., Washington, DC, USA.

Sharpley, A. N. & Williams, J. R. (1990) *EPIC Erosion/Productivity Impact Calculator*. US Department of Agriculture Technical Bulletin no. 1768, 235 pp. US Department of Agriculture, Agricultural Research Service, Washington, DC, USA.

Steward, D. R. (2007) Groundwater response to changing water-use practices in sloping aquifers. *Water Resour. Res.* **43**, W05408: 1–11.

Steward, D. R. & Ahring, T. (2009a) An analytic solution for groundwater uptake by phreatophytes spanning spatial scales from plant to field to regional. *J. Engng Mathematics* **64**(2), 85–103.

Steward, D. R., Le Grand, P., Jankovic, I. & Strack, O. D. L. (2008) Cauchy integrals for boundary segments with curvilinear geometry. *Proceedings of The Royal Society of London, Series A* **464**, 223–248.

Steward, D. R., Peterson, J. M., Yang, X., Bulatewicz, T., Herrera, M., Mao, D. & Hendricks, N. (2009b) Groundwater economics: An object oriented foundation for integrated studies of irrigated agricultural systems. *Water Resour. Res.* **45**, W05430: 1–15.

Steward, D. R., Yang, X., & Chacon, S. (2009c) Groundwater response to changing water-use practices in sloping aquifers using convolution of transient response functions. *Water Resour. Res.* **45**, W02412:1–13.

Strack, O. D. L. (1989) *Groundwater Mechanics*. Prentice Hall, Englewood Cliffs, New Jersey, USA.

Yang, X., Steward, D. R., de Lange, W. J., Lauwo, S. Y., Chubb, R. M. & Bernard, E. A. (2010) Data model for system conceptualization in groundwater studies. *Int. J. GIS* **24**(5), 677–694.