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Integrated Eco-hydrological Modelling by a Combination of Coupled-model and Algorithm Using OMS3

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Abstract: Modelling integration using the component-based and modular approach has become an effective method to understand the critical component interactions and processes in complicated natural systems. This study developed an integrated eco-hydrological model using Object Modelling System 3 (OMS3) to improve water resources utilization and predict crop production in local agricultural management. In the integrated eco-hydrological model, the crop growth model, WOFOST, and the hydrological model, HYDRUS-1D were coupled into the OMS3 framework. The parameters optimization, uncertainty analysis/sensitivity analysis (UA/SA), data assimilation were conducted through creating and configuring model simulation by the simulating Domain Specific Language (DSL) in the OMS3. The integrated model was validated by real irrigated-wheat experimental studies in the middle reaches of the Heihe River, which located in semi-arid and arid region of northwest China. Good agreements were achieved between the simulated and observed values of the evapotranspiration, soil moisture and crop production under wheat crop. The shuffled complex evolution optimization method (SCE) was tested to identify the soil hydraulic parameters and improve simulating soil moisture profile.

***Keywords**:* Eco-hydrological modelling; OMS3; WOFOST; HYDRUS; Integration

1 INTRODUCTION

The modular integrating scheme of natural systems usually requires taking account of various processes modelling (e.g., crop growth, hydrology, ecology, and solute transport), data sources, management alternatives, and analysis algorithms. This is particularly highlighted in the case of agro-ecological systems, where awareness of the general public requires careful understand on interaction between ecological and hydrological processes in order to save water resources and to protect soil, water quality.

In the last decades, research has been conducted to enhance the knowledge on the complex interactions between agro-ecological systems and the hydrological cycle, contribute to the development of eco-hydrologic models and soil-plant-atmosphere models [van Ittersum, 2003; Smettem, 2008]. Although a many of eco-hydrologic models are available, such as Expert-N [Engel and Priesack 1993] and CropSyst [Stockle et al. 1994], they are typically constrained to the specific data, specific scales and specific purposes. Furthermore, many models are not modular in design and lacking the flexibility to meet current needs for more synthesized natural resource management considering the multidisciplinary scene [Ahuja et al., 2005; Kralisch and Krause, 2006; Ewert et al., 2009].

The current challenges has demand for modular modelling method and flexible modelling framework, with which researchers can conveniently integrate existing and future modular models. As the earliest modular model, the European Hydrologic System Mode (SHE) was developed by the Danish Hydraulic Institute, the British Institute of Hydrology and SOGREAH (France) with the financial support of the Commission of the European Communities [Abbot et al., 1986]. Leavesley et al. [2002] firstly developed a software framework named Modular Modelling System (MMS) which offered the support for modular hydrologic models integrating. In the last 20 years, Many modelling integrating frameworks have been springing up, such as the Invisible Modelling Environment (TIME) [Rahmana et al., 2003], European Open Modelling Interface (OpenMI) [Gregersen, 2007], Common Component Architecture (CCA) [Bernholdt et al., 2004], Earth System Modelling Framework (ESMF) [Collins, 2005], Catchment Modelling Toolkit (CMT) [Moore, 2007] and Object Modelling System (OMS) [David et al., 2002]. With these frameworks, modellers can easily assemble different modular models into a new integrated model which could be driven by problem objectives, scale of application, and data [Ahuja et al., 2005; Kralisch and Krause, 2006].

In this study, the crop growth model, WOFOST [Boogaard et al., 1998] and hydrological model, HYDRUS-1D [Šimůnek et al., 2008] were rewritten from original Fortran codes into modular components to integrate two modules in the OMS3 framework. The parameters optimization, uncertainty analysis/sensitivity analysis (UA/SA), data assimilation were conducted through creating and configuring model simulation by the simulating Domain Specific Language (DSL) into the OMS3. The irrigated-wheat management in the middle reaches of the Heihe River, which located in semi-arid and arid region of northwest China, was chosen as a real example. The integrated model was used to simulate the processes of crop growth and water cycle under local irrigation scheme. The inverse modelling method, SCE algorithm, was used to identify the soil hydraulic parameters for accurately simulating soil moisture profile. The UA/SA method was used to reveal the risk of crop production loss as irrigation decrease. The data assimilation method was used to improve crop production accuracy for real-time prediction. But because of the reason of pages limitation, the latter two methods were not described in detail.

2 METHODS

2.1 OMS3

OMS, currently being developed by the USDA-ARS Agricultural Systems Research Unit and Colorado State University, provides a component-based environmental modelling framework [David et al., 2002]. Although based on the Java platform, it is interoperable with C/C++ and FORTRAN through Java Native Access (JNA) technique on all major operating systems and architectures.

In order to make development easier, the model component of OMS3 is implemented as a Plain Old Java Objects (POJO) (www.martinfowler. com/bliki/POJO.html) which doesn't need to extend or implement any specialized classes and interfaces. When components are combined to create an integrated model, the annotation technique is used to identify the logic and data flows among the components and create an executable model. Meanwhile, OMS3 utilizes the simulating DSL to provide a concise, robust, and flexible representation for model simulations. With simulating DSL, it is easy to adjust simulating types (e.g., parameter estimation, UA/SA, data assimilation) and provide the users with a high degree of freedom in setting up complicated simulations (e.g., batch processing of ensemble prediction) [David et al., 2010]. Furthermore, in OMS3, like most modelling framework, the unified input/output mechanisms between data and models and communication mechanisms among different sub-models are provided, which reduces the much effort of coding for I/O and function calling such that makes modellers can absorb in science modelling.

2.2 Crop Growth Model and Hydrologic Model

WOFOST (WOrld FOod STudies) was developed by the Center for World Food Studies (CWFS) in cooperation with the Wageningen Agricultural University, the DLO-Center for Agrobiological Research and Soil Fertility (AB-DLO). It is a very useful code for determining the potential production, optimizing crop management and quantifying yield gaps of various crops (e.g., wheat, rice, potatoes).
HYDRUS-1D, developed at the U.S. Soil Salinity Laboratory, is a hydrological model for analysis of water flow and solute transport in variably saturated subsurface media [Šimůnek et al., 2008]. The program numerically solves the Richards equation [Gerke and van Genuchten, 1996] for saturated-unsaturated water flow. The water flow equation incorporates a sink term to account for water uptake by plant roots. The root water uptake and actual transpiration are calculated according to Feddes et al. [1978]. The evaporation is calculated with Penman-Monteith equation [Monteith, 1990]. The soil hydraulic properties are modeled using the van Genuchten-Mualem constitutive relationships [van Genuchten, 1980].

2.3 Model Integration

In the integrated eco-hydrological model, HYDRUS module simulates water flow in unsaturated zone, root water uptake, and the water stress factor (the ratio of actual root uptake and potential transpiration). WOFOST module simulates crop growth under water stress (including CO_2 assimilation, crop respiration, carbohydrate change into dry matter accumulation and partition among the various crop organs, and morphological development).
The water stress factor, which was calculated by HYDRUS, input to WOFOST. WOFOST feeds back the values of vegetation characteristic parameters, such as leaves area index (LAI), root depth, and crop height to HYDRUS. The flow of coupled HYDRUS and WOFOST models is shown in Figure 1.

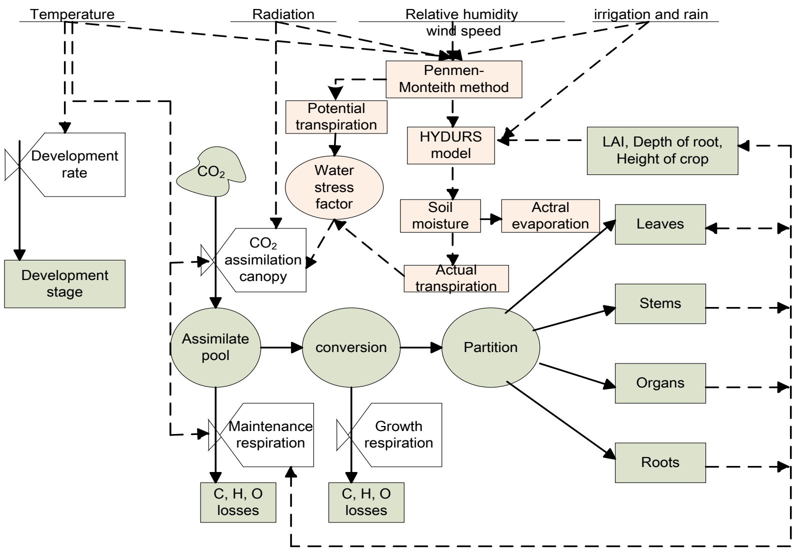

Figure 1. Flow chart of the coupled HYDRUS and WOFOST model.

2.4 Coupled Model Implementation

Both WOFOST and HYDRUS were originally monolithic models. To make them as off-the-shelf components in OMS module library, some adaptations were done to let components easily update, replace, and integrate with different analysis algorithms. WOFOST and HYDRUS were separately wrapped into self-contained components respectively. HYDRUS component wrapped dynamic link library which compiled from HYDRUS' FORTRAN source codes (Listing 1). WOFOST component is rewrite with JAVA because its main functions, crop growth, is title coupled with time control and I/O module and difficulty to use directly. Then, both components were conducted as plain objects.

Information exchange between two components is bidirectional. The execution and data flow of the coupled model are defined in a class, which is shown in Listing 2. The inputs, outputs and parameters information of models and coupled model is specified with the metadata by means of annotations to describe "points of interest" for the framework. For instance, "*In*" and "*Out*" are used to data fields to identify inputs and outputs of the component respectively; "*Execute*" identifies the implementation logic of the component. The external dynamic link library (HydrusLib.dll) is referred by "*DLL*" annotation.

Listing 1. Implementation of Hydrus component.

```
/ *
  *Hydrus component, adapted from Hydrys 6 for
  *DOS, Wrapped with JNA from dll file compiled
  *from *FORTRAN
  */
package oms3.prj.hydrus;

import com.sun.jna.*;          //Import JNA package
  ……
public class Hydrus {          //POJO
   //Input variable
   @In public double Lai;      //LAI
   @In public double Rd;       //Root Depth
                ……
   //Output variable
   @Out public double rRoot;    //Potential Evap
   @Out public double vRoot;    //Actual Evap
    ……

//Wrapping HydrusLib.dll with JNA
   @DLL("HydrusLib")
   interface Et extends com.sun.jna.Library {
       Et lib = NativeLibraries.bind(Et.class);
       void HYDRUS (double Lai,double Rd,
            DoubleByReference ref_rRoot,
            DoubleByReference ref_vRoot);
   }
   // Invocation point of sub-model
   @Execute  public void compute( ){
       ……
       //Calling HydrusLib.dll
       Et.lib.Hydrus (Lai, Rd, ref_rRoot,
                      ref_vRoot);
       vRoot = ref_vRoot.getValue( );
        rRoot = ref_rRoot.getValue( );
       ……
   }
}
```

Listing 2. Definition of the coupled model.

```
package oms3.prj.wofostHydrus;

import oms3.prj.wofost.*;
import oms3.prj.hydrus.*;
……
public class Wofost_and_Hydrus extends Iteration
{
   // Input parameters list
   //Weather file name as input parameter
   @Role(PARAMETER + INPUT)
   @Description("Weather file.")
   @In public File weatherFile;

   //Output file name as input parameter
   @Role(PARAMETER + OUTPUT)
   @In public File outputFile;
   ……
   // Instantiation of all sub-model
   private Meteo meteo = new Meteo( );
   //Read weather file and drive the model running
   private Cropsim cropsim = new Cropsim( );
   //Calc. the crop growth
   private Hydrus hydrus = new Hydrus( );
   //Calc. the evaporation, evapotranspiration
   private Output output = new Output ( );
   //Output
    ……
   @Initialize public void init( ) {
    //Conditions for model executing
   conditional(meteo, "moreData");

    // Define dataflow with out2in/feedback
    out2in(hydrus, "vRoot",cropsim);
    out2in(hydrus, "rRoot",cropsim);
       ……
     // feedback, *_fbs is a String object to
     // facilate feedback the value of *
     feedback(cropsim, "Lai_fbs", hydrus);
     feedback(cropsim, "Rd_fbs", hydrus);
       ……
     //Parameters mappingt, defined with mapIn
     mapIn("weatherFile",meteo,"weatherFile");
     // param "weatherFile" is passed to Metero
     mapIn("Lat",meteo,"Lat");
    // param "Lat" is transferred to Metero
       ……
     initializeComponents( );
   }
}
```

2.5 Integrating Model and Analysis Algorithms with Simulating DSL

The simulating DSL technique is used to conduct various model simulations with a unified way [David et al., 2010]. These applications include model calibration, optimization, UA/SA, data assimilation, etc.

Take for example, the SCE algorithm in the Luca (Let us calibrate) simulation library of OMS3, was used to identify the soil hydraulic parameters for simulating soil moisture profile. The Nash-Sutcliffe coefficient (NSE) was chosen as the objective function. The simulation for parameters optimization was conducted using a hierarchy of elements to specify the value of the parameters. Other types of simulations, such as UA/SA and data assimilation, are analogous with the parameters optimization.

3 RESULTS AND DISCUSSION

3.1 Study Region and Experimental Station

The experimental station (latitude 39°20.9'N, longitude 100°7.8'E, altitude 1382 m) was established in the middle reaches of the Heihe river, Northwest of China, which is shown in Figure 2. The region has a typical temperate continental climate, with the mean annual precipitation and evaporation ranging from 60 to 280 mm and 1000 to 2000 mm, respectively [Wang, et al., 2008]. The effective management of agricultural water resource and optimized irrigation are keys to solve water scarcity and ecological problems of this region.

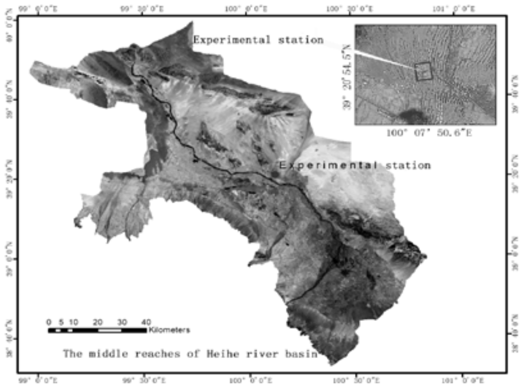

Figure 2. Location of the experimental station.

The experimental field was cultivated with spring wheat and quantitatively irrigated. The field was irrigated 11 times throughout the period of crop growth, summed up to 483.6 mm. The field was intensively monitored throughout the study period, which lasted from 21th March through 24th July, 2007. The sowing date, emergence date and harvest date of spring wheat were 21th March, first Apr, and 24th July, respectively.

3.2 Test Coupled Model

Running the coupled model requires atmospheric and irrigation conditions at daily scale, the parameters of crop characteristics, and the soil hydraulic parameters. The meteorological data are acquired from the meteorological station. The amounts and times of irrigation are recorded manually. Many characteristics of the wheat cultivar in our study were similar to those of the wheat 102 cultivar in the WOFOST crop database, with respect to drought resistance, cold resistance, plant height, leaf width, grain size, and so on. So, the wheat data set (wheat 102), which was provided by European Community [Boons-Prins et al., 1993], is chosen for the parameters of crop characteristics.

The soil profile was divided into three layers in vertical direction according to the soil physical properties. The first layer was from the surface to a depth of 30 cm. The second layer and the third layer were from the depth of 30 cm to 60 cm and from 60 cm to 150 cm, respectively. The optimized soil hydraulic parameters of the different layers have been estimated using SCE algorithm. The final optimized parameters are shown in Table 1. The comparison between fitting soil moisture processes using SCE algorithm and observed soil moisture is shown in Figure 3.

Table 1. The estimated parameters of soil hydraulic properties of three soil layers and the NSE values of the fit to observed data.

	θ_r	θ_s	α	n	*NSE*
	$cm^3\ cm^{-3}$				
The 1st layer	0.018	0.36	0.06	0.60	0.750535
The 2nd layer	0.025	0.38	0.06	0.57	0.746587
The 3rd layer	0.021	0.40	0.05	0.42	0.875384

where, θ_r: residual soil water content [$cm^3\ cm^{-3}$]; θ_s: saturated soil water content [$cm^3\ cm^{-3}$]; α: air entry value; n: pore-size distribution index.

The simulating time period is between the cultivation of wheat from sowing to harvest. The time step is one day. The simulated total above-ground dry matter (TADRW), dry weight of storage organs (WSO) and LAI are compared with the observations, which are shown in Figure 4 and Figure 5. The RMSE values for TADRW, WSO and LAI are 49.79 g m^{-2}, 24.36 g m^{-2} and 0.26 m^{2} m^{-2} respectively. The NSE values for TADRW, WSO and LAI are 0.978, 0.98 and 0.948, respectively. The results show that the simulated dry matter accumulation and partition between the various crop organs match the observations well.

The comparison between simulated and observed actual evapotranspiration are shown in Figure 6. The RMSE and NSE values for actual evapotranspiration are 0.705 mm and 0.798, respectively. The results show the simulated evapotranspiration also matches well the evapotranspiration observed by eddy covariance systems (EC). From the Figure 6, it also can be achieve that the coupled model can reflect the reality more accurately than HYDRUS only.

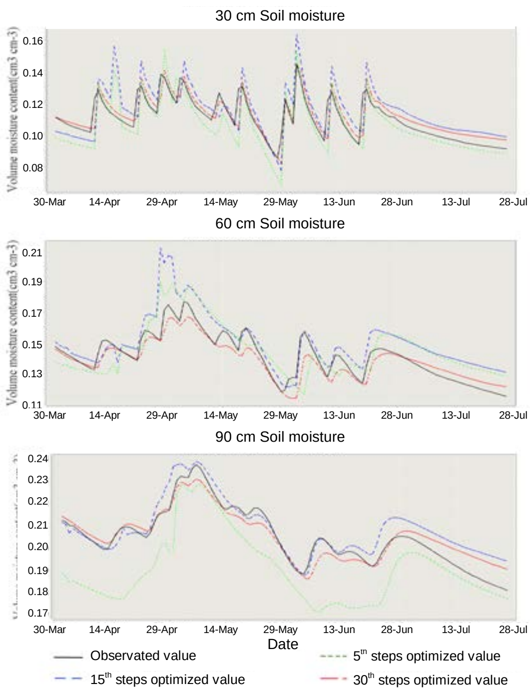

Figure 3. Comparison between observed and fitted soil moisture by SCE algorithm.

The comparison between simulated and observed actual evapotranspiration are shown in Figure 5. The RMSE and NSE values for actual evapotranspiration are 0.705 mm and 0.798, respectively. The results show the simulated evapotranspiration also matches well the evapotranspiration observed by eddy covariance systems (EC).

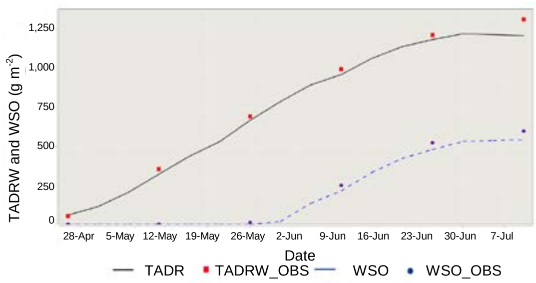

Figure 4. Comparison between simulated and observed TADRW and WSO.

The above results of the model indicate that the related parameter values are reasonable for local wheat characteristics and soil properties in the study field. The coupled model in OMS can be used to quantitatively predict agricultural production under water-limited conditions.

4 SUMMARY AND CONCLUSIONS

An integrated eco-hydrological system was conducted by coupling hydrological and crop growth model using the OMS3. The coupled model in the OMS has shown that the structure for components have a more intuitive design and save development time using fully embracing language annotations for modelling metadata. For the integration of the eco-

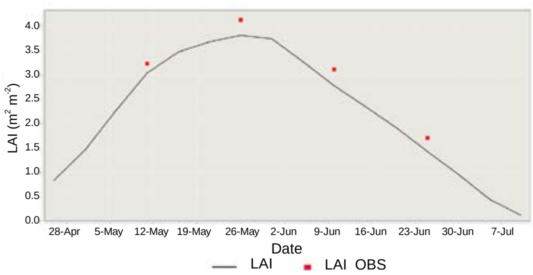

Figure 5. Comparison between simulated and observed LAI.

hydrological modules, great care was taken to design the OMS components as flexible and open as possible to guarantee their reusability for other models. During the implementation of coupled WOFOST and HYDRUS modules, only minor parts of original programme had to be adapted to expose interface based on metadata mechanism and ensure proper information exchange between modules. This structure for components supports rapid adaptation for the existing models and easier implementation of new models. The integration of model and algorithm in OMS has shown an extensible and lightweight layer for simulation description that is expressed as a simulating DSL based on the Groovy language. DSL technology is convenient to define basic model simulations, or for more complex setups for calibration, sensitivity analysis, etc. This type of “programmable” configuration displays as an extremely useful tool to support simulating aspects such as automated parameters, batch models runs, UA/SA, etc.

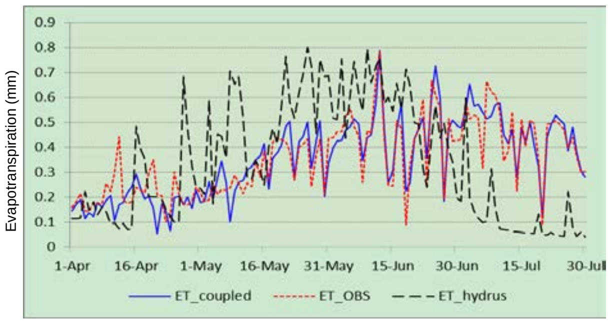

Figure 6. Comparison between simulated (HYDRUS only and coupled model) and observed actual evapotranspiration.

The component-based approach of the OMS and the modules/models implemented in the OMS will provide the basis for more efficient and collaborative modelling development in the future [David et al., 2010]. This type of modules and open-source approach is desperately needed in order to solve challenges to complicated natural resource systems, such as sustainable management of natural resource systems and the impact of climate change and human activity on natural resource systems.

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