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Implementation of hydrological processes and agricultural management options into the ATB-Modeling Database to improve the water productivity at farm scale

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Abstract. To meet the food demands of a growing world population, the productivity of agricultural water use for food production at farm scale, must be increased. A modeling database has been developed to quantify water use, i.e. the use of precipitation, soil water and irrigation water at the farm scale, and to calculate water-use indicators based on farm operating data. These indicators can be used to assess agronomic measures for their merit in improving the productive use of water in different agricultural operation systems. The benefit of the ATB Modeling Database lies within its speed and inherent flexibility which allows further water-related indicators, management options and water-related processes in different regions and farm systems to be easily implemented. The description of the ATB Modeling Database demonstrates the development of a new solution to handle comprehensive farm and regional data, providing a tool to explore possibilities to enhance the productivity of water use in different farming systems.

Key words: agricultural management options, ATB Modeling Database, data at farm scale, farm-scale, indicators, water productivity.

ABBREVIATIONS
ET_0 [mm]: potential evapotranspiration of a grass reference surface;
ET_c [mm]: potential crop evapotranspiration;
$ET_{c,act}$ [mm]: actual crop evapotranspiration;
T_c [mm]: potential crop transpiration;
$T_{c,act}$ [mm]: actual crop transpiration.

INTRODUCTION

To meet the future food demands of a growing world population, increases in agricultural productivity over the current level will be necessary. A more productive water management for securing high water productivity and minimising water losses is one strategy to reduce negative impacts on water quantity in many places (e.g. Gordon et al., 2010). Currently much work is underway to assess the amount and types of water resources used in worldwide food production and trade with models at the global level. Based on an analysis of global model results, Hoff et al. (2010) see a need for a more realistic quantitative modeling of crop water productivity as well as a strong demand for the integration of technological development in further global model development. However, a prerequisite for the use of such information by scientists, policy-makers, consultants and farmers to improve on-farm water management, is the ability to quantify the current resource utilization in farming systems at the local level and predict the effects of proposed measures. Several whole farm modeling tools have already been developed, which incorporate water on different levels of complexity. Some models incorporate the calculation of a daily water balance (IFSM, FASSET, APSIM, GPFARM), while other models reduce the yield of a crop in dependence on the available precipitation and the potential evapotranspiration (Hurley Pasture Model, SEPATOU). Since the focus of such tools is on farm production and profitability, the quantification of the water flows as explicit outputs and the consideration of the indirect water use has been neglected. Parallels exist in the development of the tool life cycle assessment (LCA). Water use has rarely been quantified, partially because of the lack of focus on water resources, but also because of the plethora of forms and routes in which water enters and exits production systems (Mila I Canals et al., 2009). However, in order to improve agricultural productivity, system analysis and optimisation of the whole farm system has to be carried out, including not only the farm economic and biomass outputs, but also the water-related processes and flows. The quantification and assessment of the water flows for the assessment of the effects of technical innovations and different management options has to be moved into the focus of attention. The assessment step requires the development of water-related indicators and the generation of ranges of values for those indicators. Moore et al. (2011) have proposed a conceptual framework containing a collection of water-related indicators that can be used to aggregate data and assess the productivity and sustainability of alternative farming practices. They point out that there is currently a lack of data at the farm scale that could be used to validate and calibrate the various models available. The main goal for developing the software is to provide a tool for evaluating options to increase the productive use of precipitation and soil water in different farm systems in various regions. This requires the manipulation of large datasets on local climate, soils, farm practices and outputs coupled with models for management options and hydrological processes.

The purpose of this paper is to describe the database, beginning with an overview of the system and its boundaries, followed by a description of the modeling processes, the indicator water productivity and further water related indicators. After the discussion of the input data requirements, a technical description of the database is presented.

METHODS

The Modeling Concept

The purpose of the ATB database tool is to model the water demand at the farm scale and to calculate water related indicators. A standardized method for modeling the water flows at the farm scale is being developed based on studies of several farming systems in Germany for producing plant-derived food and animal products. Different management options in plant production and in livestock farming to enhance water productivity are being incorporated into the system. The newly developed software is designed to benefit from the capabilities of the underlying Database MongoDB, which allows it to be flexible and adaptable to different regions and farm systems.

The farm system and system boundaries in the ATB Modeling Database

The model takes into account all the direct and indirect water flows crossing the spatial boundaries of the farm system, which are set from an institutional perspective, in the sense that any physical feature that belongs to the farm also belongs to the system. The farm system may incorporate plant production, which includes crops and fields, as well as livestock production, which includes the livestock and the livestock facilities. The linkages between the two subsystems are taken into consideration, in addition to other appropriate configurations as needed to assess water related indicators at other scales. The modeling database allows the calculation of the direct water flows, e.g. precipitation, tap water, irrigation water, transpiration, interception losses from plant leaves and mulch, deep percolation and evaporation from soil. However, animal perspiration and respiration are not considered, nor is any evaporation due to leakage in the animal cleaning and drinking systems. The system boundaries of the operating data are defined from ‘cradle to farm gate’. Indirect water flows are considered in the calculations. These are water flows associated with materials used on the farm from previous stages in their life cycle, i.e. water used for the construction of farm buildings and machines, as well as for imported feed. Fig. 1 illustrates the water flows and processes taken into account at the farm scale. From these flows and values for the farm output generated, water related indicators are calculated for the farm system.

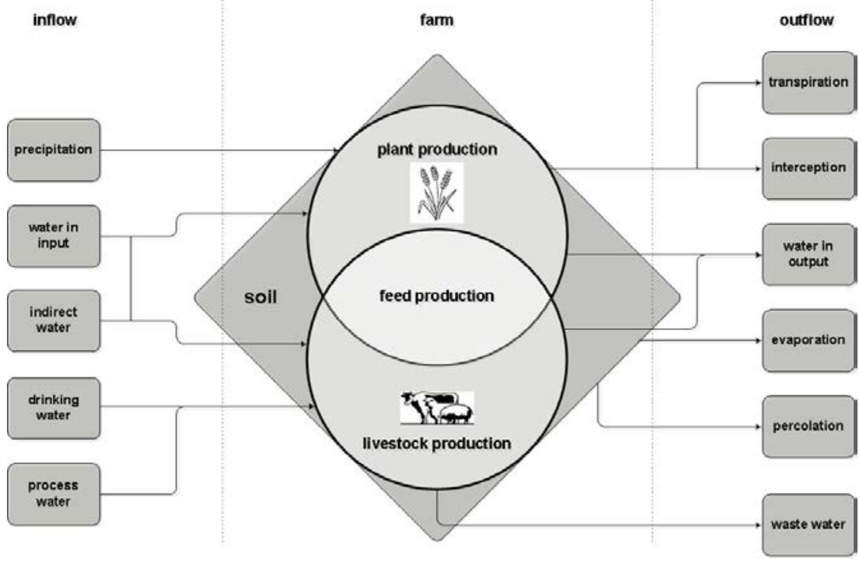

Figure 1. Water inflows and outflows and boundaries of the farm system for the calculation of the water demand at the farm scale. The modeling and investigation is done within the three analysed sections soil, crops and livestock and within the two production branches plant production and livestock production.

Evaluation of the water productivity of farm systems

Various agricultural management strategies have been proposed to increase the productivity of water use in food production. An overview of the strategies is presented in Tab. 1, differentiated for plant production and livestock production. A selection of these are being simulated, quantified and assessed in the ATB Modeling Database. Not only the individual measures, but also the interlinkages between the two production systems are considered. For example, the water used in producing livestock feed is accounted for in dairy farming, whether it is grown on farm or imported. This water accounts for the main share of water used in dairy farming (Drastig et al., 2010[a]). Based on the simulation results, the impacts of individual strategies are quantified and interactions analyzed to derive strategies for an effective, site-specific management.

In order to assess how effectively the water is being used, the Farm Water Productivity (Prochnow et al., 2012) is used as an indicator for yield improvement ('more crop per drop'), as it shows the relation between water use and the production of on-farm produced products. Farm Water Productivity is an integrative indicator for the assessment of the whole water value chain of the farm system. The concept of the indicator Farm Water Productivity is used to analyze and quantify management options and measures serving to raise water productivity in plant production and livestock farming.

Table 1. Management strategies investigated to increase the productivity of water use and to reduce the amount of process water within the branches plant production and livestock production (Drastig et al. 2010[b])

Plant production	Livestock production
Soil tillage and humus conservation application of organic matter, mulching, turning under of crop residues	Feeding strategies with varied diet ingredients
Cultivation under different regionalcharacteristics 'usual' varieties, drought-tolerant varieties, varieties with low transpiration coefficient	Increase the water productivity in meat production intensity of production, breed farming intensities (cow and pig), site specific characteristics
Seeding high crop density, consideration of the current vegetative period	Increase the water productivity in the barn milking systems, cleaning processes, cooling processes
Fertilizing sufficient potassium supply , support of root formation	
Optimizing of crop rotation and use of intermediate crop	

Abstracting the farm system for the model

In order to calculate the water demand in different farm systems, an extensive set of physical models and input data are needed to take the variety of agricultural management options into consideration. The input data range from large datasets on local climate and soils, to specific operating data on farm practices on the farm systems investigated. The operating data is generated through interviews with farmers, while the other data stems from local, federal, and international services.

Since the use of MongoDB allows this information to be stored individually in documents, rather than into a rigid schema of tables with rows and columns, a new logical structure has been developed (Fig. 2): the farm system has been abstracted and divided into two types of elements. One type of element is an *object*, which represents a physical or real world object such as the analysed sections – soil, crops and livestock (Fig. 1). The other kind of element is a *model*, which is used to describe a process that takes place on the real world objects.

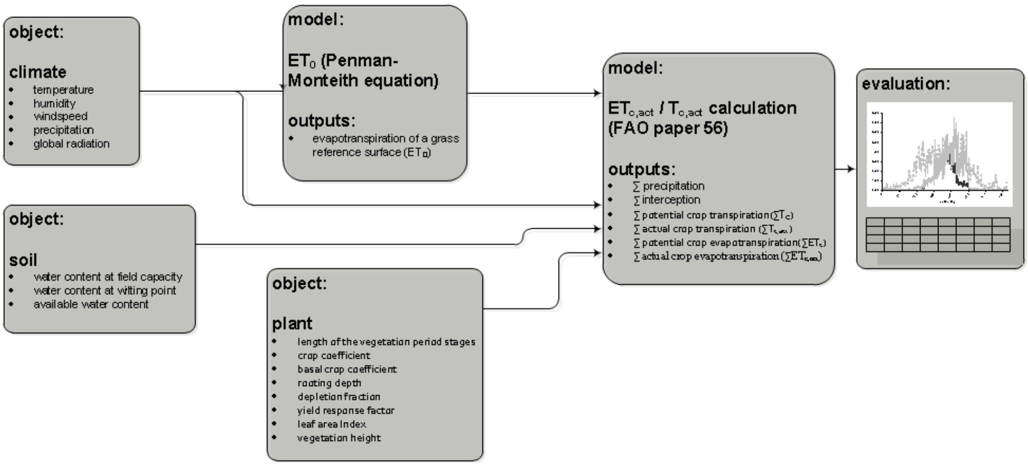

Figure 2. Logical structure of an example model set-up for the two classes of farm abstraction elements: objects and models. Objects represent data/measurement values or functions involved in the modeling process. Models contain computing instructions. Function interfaces are the connection points for the modeling network.

Objects

The required input data sets in the modeling process are abstracted as *objects*. The *objects* currently defined in the ATB Modeling Database are *climate*, *soil*, *plant*, *crop, imported feed, machines, farmland and farm buildings* (Table 2). *Objects* possess characteristics (or parameters) with temporal and spatial dimensions. A parameter can be data (e.g. a local minimum or maximum temperature) or it can also be an embedded formula to make a calculation that is relevant only to the specific object. These can range from a simple calculation of the mean temperature to the more complex calculation of the global radiation based on the results of Oesterle (2001) in the *object climate* or the calculation of the soil cover fraction following Baroni & Gandolfi (2009) in the *object crop*. These parameters are grouped together in *parameter sets,* one parameter set per dimension (i.e. date, day, coordinates (geographical grid) or depth (z-axis)). Each object in the database contains base data to identify it (name, description, coordinates, sources etc.). The set of parameters linked to that object is stored in a separate database collection for each time step or depth or location. The index (or argument) for accessing the correct *parameter set* to retrieve the desired values is the dimension of the object, implicitly defined by the object type. An overview of the required input data and embedded formulas, how they are grouped to objects, their respective sources and the required spatial and temporal resolution is given in Table 2. At any time in the modeling process, new object definitions, parameters and parameter sets can be easily added.

Table 2. Data set for the modeling of the water demand in different agricultural operation systems and water related indicators

Object	**Parameter sets (data and embedded formulas)**	**Source**	**Resolution** time	spatial
Climate	Temperature, daily relative humidity, sunshine hours, wind speed, precipitation global radiation	DWD[a], global radiation Oesterle, (2001)	Daily	at one point
Soil	Water content at field capacity, water content at wilting point, available water content	Allen et al. (1998), BGR[b], LBGR[c]	Permanent value, at respective date	at one point, on field scale
Crop	Crop coefficient, basal crop coefficient, vegetation period, rooting depth, leaf area index, depletion fraction, yield response factor, length of the vegetation period stages, vegetation height	Allen et al. (1998) Scurlock et al. (2001)		
Management options: crop	Pre-crop, sowing dates, harvest dates, crop rotation, irrigation per field, yield, pesticides, fertilization, machinery	Operating data	In respective periods, at respective date	on field scale
Management options: livestock	Head of animals, milk yield, replacement, feed, ration diet, milking, drinking water demand, cleaning and disinfection (e.g. milking parlour), water demand for cooling, stables, technique	Operating data	Within period under consideration; 3 years	farm scale, including feed produc-tion
Farmland	Size, location	Operating data		farm scale
Farm building	Water from wells public water	Operating data	Within period under conside-ration	farm scale

[a]German Weather Service, [b]Federal Institute for Geosciences and Natural Resources, [c]Brandenburg State Office for Mining, Geology and Raw Materials

Models

All elements called *models* contain computing instructions. The computing instructions are contained in program code written in Java script in the model. In addition, each model contains all information needed for the calculations to be carried out. It contains base data (name, description, sources etc.), inputs (function calls to *objects* or other *models*) and outputs (functions). Examples of current *models* in the modeling system are the rainfall interception, the potential evapotranspiration of a grass reference surface, and the actual crop evapotranspiration.

Matching fingerprints (of outputs and inputs) can be tied together during the modeling task. Once created, a model can be used easily in further modeling tasks.

The software is able to operate using any time step and is capable of performing long term simulations over any time period. This resolution strikes a balance between the need for detail and speed in modeling the relevant processes at farm scale. For example, the water use over the vegetation period of a crop can be calculated by aggregating the daily values over the appropriate period.

INNOVATIVE SOFTWARE APPROACH

Database

The new software implementation 'ATB Modeling Database' has been created to exploit the features of MongoDB, a high-performance, document-oriented database. The new open source project MongoDB was introduced in 2009 to meet the new requirements of growing internet platforms. MongoDB is being actively developed and continuously undergoing rapid improvements. In comparison to usual database applications, faster calculation is possible due to the embedding of calculation algorithms into the database server. Database queries from the client application are no longer necessary. The immense datasets of local climate and soils linked to a wide variety of management options and hydrological processes for the farm systems in the various regions investigated can be quickly implemented. Besides the speed, the strength of the ATB Modeling Database is its inherent flexibility. It allows the extension of the database for actually unknown requirements without changing the structure of the software or the already stored objects. So a fast response to future demands is guaranteed in the software development.

The non-relational database MongoDB uses *documents* as database objects. No predefinition of database structures is necessary; all structures are implicitly created on insertion. Technically the database is a *key-value store*, which is optimised for the handling of large data sets on distributed servers. Database-integrated functions like map/reduce, parallelization or geospatial procedures allow the fast processing of huge datasets of climate, soils and other data. The current 'ATB Modeling Database' is replicated over three distributed servers, which are ready for operation after a few hours of installation time.

CONCLUSIONS AND OUTLOOK

With the ATB Modeling Database, the influence of various agronomic measures on how efficiently precipitation, soil water and irrigation water are used can be quantified. The detailed modeling of the water flows within the various sections of farm systems allow indicators to be calculated for each section, aggregated over different time periods of interest.

The modular design principle of the ATB Modeling Database allows the individual farm systems to be constructed easily. In addition, the implementation of the software with the data processing on the server allows the modeling of complex systems with large data sets even through slow internet connections. A further strength of the ATB Modeling Database is the ease with which the model can be expanded to evaluate further water related processes and indicators, as well as management options for different regions and farm systems.

Currently, the impacts of individual management options and combinations of these on the overall farm system, as well as impacts of changes in the farm system (e.g. higher milk yield or longer lifespan of dairy cows) in various regions in Germany are being investigated. Based on these results, water demand and water use productivity for different food production techniques will be identified, and the best management options to increase water use productivity of total representative systems will be determined for the various regions and farm systems. This information base will assist decision makers on the local and regional level in finding appropriate, affordable solutions to increase the productive use of local water resources.

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