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VIRTUAL WATER VALUES - A PROJECT FOR GLOBAL AND REGIONAL ASSESSMENT OF AGRICULTURAL YIELDS AND WATER USE EFFICIENCY

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Abstract

Virtual Water Values (ViWA) is an interdisciplinary research project of geographers, remote sensing scientists, agro-economists, computer scientists and landscape planners. It aims at supporting the implementation of water and food related SDGs by first developing a global, high resolution monitoring system for agricultural yields, water use efficiency and actual virtual water contents of agricultural products based on COPERNICUS Sentinel-2 time series. This data is used as input to GCE simulations of global agricultural trade and to identify global hot-spots of unsustainable (inefficient) water use and trade (both green and blue) by agriculture. Scenarios of trade incentives and regulations will be analyzed for their potentials and effectiveness to improve the sustainability of global agricultural water use. The Danube river basin is one regional case study of ViWA.
Here the role of irrigation water use as well as upstream-downstream water conflicts is studied. First results of the continental and regional monitoring and simulations of actual yields, water use efficiencies and virtual water contents are shown and discussed.

Key words*: SDGs, COPERNICUS, Danube, water-use-efficiency, sustainable water use.*

INTRODUCTION

The United Nations through their Sustainable Development Goals (SDGs, UN 2015) have set out the ambitious goal to achieve sustainable global development by 2030. Food and water security are systemic for cultural development and among the most critical issues addressed by the SDGs. Agriculture constitutes approx. 92-99% of global green and blue water use (Mekkonen et al., 2014; Hoekstra et al., 2012). It differs from domestic and industrial water use, which both extract blue water from rivers or aquifers, change its property and largely release it back to rivers and aquifers for further downstream re-uses.

Agricultural water use is largely evapotranspiration of green (rainfall) or blue (irrigation) water into the atmosphere in the course of plant production and its removal from the place of use through atmospheric mixture and circulation. Re-use is thus impossible. A holistic view of the water use by agriculture and its sustainability therefore has to take into account both green and blue (and in some places even the small grey) water flows that enable crop growth. This is obvious e.g. for blue water use in irrigation but it also holds for rain-fed green water use.

Especially high intensity rain-fed agriculture harvests soil water to maximize evapotranspition and plant production at the expense of soil-moisture, which may not be available to recharge rivers or aquifers thereby allowing further downstream water uses. This has large consequences for water availability to different users and makes agricultural water use a conflicting issue related to land use and land use intensity.

The efficiency with which water is used around the Globe to produce an agricultural commodity (expressed in kg harvest / m^3 evapotranspiration) varies by roughly by a factor of 5. There is a clear and general tendency towards increasing water use efficiency with increasing farming intensity (Zwart and Bastiannsen, 2004). Since water is a renewable resource low WUE and the related waste of water to agriculture is not an issue of sustainability as long as sufficient water is available to all users (including natural habitats and biodiversity).WUE nevertheless indirectly determines the amount of land that is required to satisfy growing food demands and thereby low WUE fosters expansion of cropland, which puts pressure on natural ecosystems. Low WUE becomes an issue of sustainable water use whenever water is a scarce resource and e.g. aquifers are overdrawn, conflicts arise between different water uses and natural ecosystems are eliminated in favor of cropland.

The global agricultural commodities market does not reflect agricultural WUE. It also does not consider whether and to what degree the water was used sustainably at the place of production. The global agricultural commodities market in its current form therefore inefficient and unsustainable water use in agriculture.

Central aims on the way to achieving the SDGs therefore are to develop ways to identify in a transparent way inefficient and unsustainable agricultural water use on the local, regional and global level, to identify hot spots, where coordinated action to increase WUE should start and to develop alternatives how global trade can foster efficient and sustainable water use in agriculture.

The research project Virtual Water Values (ViWA, viwa.geographie-muenchen.de) was established within the research initiative Global Resource Water (GROW) of the German Ministry for Education and Research to follow these aims. Researchers from hydrology, agro-economics, remote sensing and landscape planning team up to for the first time carry out a detailed and spatially explicit analysis of the relation of global agricultural yields and water use efficiencies based on crop modeling and the now available Sentinel satellite Earth observation capabilities. This information is used in ViWA to simulate global agricultural trade and related virtual water flows. For the first time the selected trade model (CGE) considers the shortage and inefficiency of the water that is used locally for agricultural production. Scenarios are developed and analyzed on how global trade, water competition and prioritization of local hot spots of agricultural development can help increase agricultural water use efficiency in a sustainable way. ViWA thereby aims at supplying valuable information to decision makers in public administration, industry and society and at contributing to achieving the UN Sustainable Development Goals (SDGs). The paper gives and outline of the research framework and goals of ViWa, introduces to its global approach and its two regional pilot regions with special emphasis on the Danube basin and shows first results on the continental scale.

MATERIALS AND METHODS

The high-resolution monitoring system for water-related SDGs

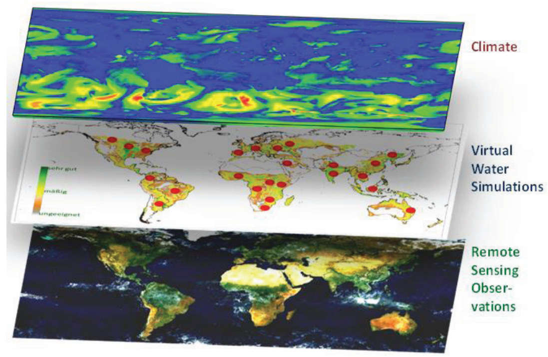

Figure 1. The ViWA-concept of a global monitoring approach for water use efficiency and actual yield. Global climate data drives ensemble of high resolution global crop growth simulations representing existing farming practices. At randomly selected global sites (exemplary red dots) for each pixel of the Sentinel time series (see bottom layer) the best-fitting ensemble member is selected is taken to determine from the model runs actual green and blue water flows, water use efficiency and actual agricultural yield are determined from the model runs. The results from the test sites are then scaled up to the global cropland

So far missing are timely, spatially explicit, high-resolution combined data on quantity, efficiency, scarcity and sustainability of the water resources used for agriculture in order to determine and assess the local and regional

water use, especially in crop production and for virtual water trade.
The availability of unprecedented data streams from the European COPERNICUS satellite observation system (Zitat) opens up new possibilities to observe growth of individual crops down to the plot scale by looking e.g. at the change in leave area, which can be accurately derived from the Sentinel-2 images. Weather and a-priori unknown farming-practices (cultivar selection, fertilization, irrigation, pest control) lead to different leaf-area development, that is associated with different yields, water consumption and water use efficiencies (Figure 2). The observation time series of Sentinel-2 images therefore contains information about the actual plot management and the resulting yields and water use efficiencies for green and blue water. To be able to extract these information satellite observation alone are not conclusive. It is first vital to separate the impact of climate and weather on crop development from the impact of the farming practices and second mandatory to indirectly infer yield and water use efficiency, which cannot directly be measured from satellite. Plant growth models that make crops grow under given weather conditions with a wide range of different farming practices allow this separation. They can be used for cultivation ensemble simulations, which cover the agricultural management space but they are, without external information not able to reproduce the actual crop development in each specific field. The actual crop development though can be determined by selecting from the cultivation ensemble that member that fits best leave development measured by the satellite observation time series.
This framework has already successfully been applied by Hank et al. (2015), it allows obtaining large coverage and high-resolution information on actual yields, water use efficiency and water scarcity in a timely manner. The schematic representation of the approach is shown in figure 1. The monitoring system in ViWA uses the complex, numerically expensive land surface processes model PRO-MET (Mauser et al., 2015). It is driven globally by downscaled weather data (ERA-Reanalysis Uppala, 2005, CORDEX-10 km data) at high temporal (1 h) and spatial (1 km) resolution. Large amounts of satellite data also have to be processed to automatically derive the leave development for each 10 x 10 m pixel in the selected.

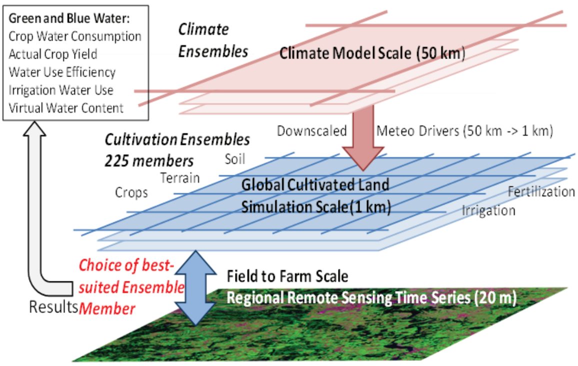

Figure 2. The scaling and simulation concept of ViWA. Meteorological inputs dynamically down-scaled from climate models drive a 225 member ensemble of hourly simulations representing the major crops and cultivation practices (fertilization, irrigation, cropping intensity) for each 1km pixel on the global cropland plus 1 member for each non cropland class. The resulting growth curves are compared with high resolution time-series of Sentinel remote sensing data to identify local water use efficiency, actual yield and virtual water content.

The ensemble data on crop growth resulting from the simulations, which contains local, detailed information on the potentials of different farming practices and related water-use efficiency forms the basis for extended scenario analyses in which e.g. water use efficiency is improved and different irrigation techniques are installed.
Figure 3 shows an example of a cultivation ensemble member. The leaf area for maize in

Europe for August 14, 2016 is shown at a spatial resolution of 0.008333 degree (in Europe app. 900x500 m) for the following management parameters: seeding: standard date for regions, fertilizer: 200 kg/ha, no irrigation.

Regional high-resolution case studies for validation

The monitoring data is also used to simulate and analyze in detail the ecological, agricultural and societal water flows in selected watersheds in order to study the competition for water among the different sectors (domestic and industrial use, ecosystems, agriculture and irrigation) and the sustainability of water use in terms of groundwater and surface water extraction e.g. for irrigation. Evapotranspiration, lateral flows and groundwater recharge rates for managed and natural ecosystems, near-surface groundwater flow and base flow as well as water use efficiency and yields are simulated using a PROMET to generate river flows.

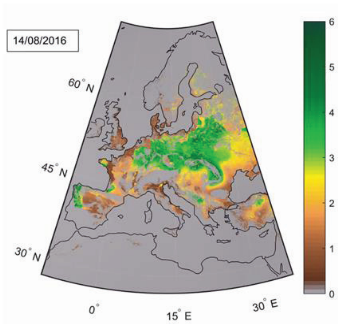

Figure 3. Sample of the distribution of the simulated leaf area [m²/m²] from a cultivar ensemble member of Europe for maize on August 14, 2016. Standard seeding date, 200 kg/ha N-fertilization and no irrigation is shown

The Danube and Zambezi were selected as regional case studies. They form the basis for a detailed upstream-downstream and local-to-global economic analysis of the virtual water flows, which includes the available information on quantity, efficiency, scarcity and sustainability of the managed water resources.

The Danube River Basin as a pilot region of ViWA

The Danube Basin is an ideal regional case study for ViWA in the sense that it 1) covers a palette of climate and hydrological condition from high-Alpine to dry Mediterranean. 20 countries with very different cultural and economic backgrounds, of which 11 are members of EU, share the Danube waters. Farming practices and farming intensities differ largely in the Danube basin and range from high intensity mostly in the upstream countries to often small-scale low-intensity further downstream. Rainfall shows a gradient from the NW to the SE leaving the Romanian plain and large parts of Bulgaria with a structural water deficit for agriculture. There large potentials exist for yield increase through deficit irrigation. In the Danube basin special emphasis is put on the evaluation of the potentials for increasing water use efficiency through different irrigation options, their water demand their yield potentials and on ways to sustainably supply the necessary irrigation water by the upstream countries and regions. ViWA intends, for the first time, to model in detail the related water and commodity production and flows and the related economic aspects.

The economic evaluation of virtual water flows in ViWA

In the past the economic analyses of the use of scarce water resources have concentrated on the efficiency or inefficiency of local rules of water allocation. In parallel, the importance of international trade for the exchange of virtual water and the resulting possible reduction of local water scarcity was analyzed. Both the analytical and the action level nevertheless were not previously linked. First attempts explicitly examine the economic importance of water with the help of CGE-models (Beritella, et al., 2007; Calzadilla et al., 2010; Taheripur et al., 2013), however, limited to the agricultural sector. In these, the scarcity of water is represented, at a high level of regional aggregation (GTAP AEZ, 2008), by shadow prices arising from the difference between the yields of irrigated to non-irrigated agriculture. In a study of the implications of water scarcity and economic growth, the relevance of other sectors (households, energy production, industry, and environment) is emphasized (OECD, 2014).

ViWA combines the high resolution water-food monitoring concept described above with detailed CGE-simulations of the world market with special emphasis on agricultural commodities and the role of water, its scarcity, its efficiency in the use for agriculture and the competition for water between different economic sectors. Thereby the project identifies and quantifies in unprecedented detail the international trade in virtual water. The coupling of monitoring data with CGE-simulations also makes it possible to model and derive scarcity measures for regional water resources. Scarcity of water resources can be defined in various dimensions, as competing uses between crops and between regions within a watershed, between sectors and between countries. These aspects are examined in the model compound by deriving shadow prices for water use from the econometric analyzes for water productivity. Using the shadow price of water in different uses regional inefficiencies of water use within a country as well as in the distortions in international trade will be identified.

These activities provide the conceptual framework for the analysis of scenarios for an efficient and sustainable water use.

Sustainability assessment and Governance of water resources and SDGs in ViWA

The real and virtual water flows and their governance are examined in light of the water-related SDGs. For this purpose a sustainability assessment is carried out based on the monitoring approach and the economic evaluations. The project addresses numerous proposed UN-SDG-indicators (UN 2015). It will specifically contribute to quantify the proposed global indicators No. 13,15,16,48, the national indicator 2.11 and it will contribute to quantify global indicators 83 and 85. It specifically identifies and evaluates with the involvement of stakeholders trade-offs in achieving the SDGs food security (SDG 2), water (SDG 6), bioenergy (SDG 7), climate (SDG 13) and protection of ecosystems (SDG 15). This contributes to the refinement and application of existing indicator systems to monitor progress of SDGs. From these results water shortage areas with unsustainable water use (hot spots) and areas with abundance of water (cold spots) are delineated globally based on the trade-offs between potentially affected area units and available water / energy / land use. Trade-offs between ecosystem services and agricultural production (food security, bioenergy) are analyzed for different ecosystem types using the simulated changes in water flows and yields in the representative watersheds with the aim to classify sensitivities (e.g. organic matter, water-dependency) and assignments (e.g. case studies on the Red List of Ecosystems, IUCN) by means of a GIS-based "environmental risk assessment". The water supply situation is analyzed in high resolution with indicators of Vörosmarty (2010), data from 3.1 and global population data (LandScan (2015), 1km^2) and validated using FAO and Aquastat NEESPI data. The result represents areas and residents affected by different degrees of a lack of water.

For the hot-spots of unsustainable water use "spatial problems of fit" are determined (asymmetry between the spatial extent of ecological processes and political decision spaces). They are the starting points for case studies (literature based) on potential institutional obstacles to a sustainable and efficient water use (target 5).

Analysis of scenarios for sustainable water use

The outcome of the high-resolution monitoring system for water-related SDGs, the integrated economic evaluation of virtual water flows and the sustainability assessment and governance of water resources and SDGs will be discussed with stakeholders using the approach outlined in Mauser et al. (2013).

Together scenarios are formulated and implemented to identifying effective and efficient control instruments for a more sustainable and efficient water management that go beyond the ones that are already identified, which are: 1) investigate the vulnerability of water use by looking at the natural climate variability represented by the El Nino event 2015/16 as well as the years 2017 and 2018. They are compared and analyzed specifically with regard to hot-spots of water shortage and the impact on water use and economic feedback effects on the global agricultural markets; 2) scenarios to simulate options for a globally efficient and sustainable water management. For this purpose local water use efficiency are changed by improving farming practices. They are introduced into the model compound similar to the approach in Mauser et al. (2015); 3) similar methods are used to simulate the effectiveness and efficiency of control instruments, such as usage restrictions of fossil groundwater or water pricing. The scenarios analyses allows to identify and highlight the potential benefits and trade-offs of different regulatory instruments for water use.

All project partners, including the stakeholders, participate in the review and evaluation of the results of the scenarios. Here, e.g. the potential yield increases that go along with increased water use efficiency and the welfare effects of a more efficient water use and appropriate management options are demonstrated and the economic distribution effects of sustainable water use in intra-regional and inter-regional level are assessed. In addition trade-offs between different SDGs related to water are discussed and evaluated based on results.

CONCLUSIONS

ViWA consequently uses the new opportunities that the globally available data streams from the European COPERNICUS satellite observing systems offer. The combination of detailed high performance computing simulations of environmental processes, like crop growth, with the satellite observation lead to new data driven monitoring approaches, which allow to realistically quantifying important sustainability indicators like yield, water use efficiency both in rain-fed and irrigated agriculture and the degree of sustainability with which water is used locally to produce agricultural commodities. This allows identifying priorities for action and their respective trade-offs on the way towards reaching the water related SDGs.

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