Tools for analyzing the water-food-energy-ecosystems nexus

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This document describes some notable recent approaches to analysing multiple resource dynamics. They are discussed in terms of i. geographical scope; ii. data intensity; iii. modeling/technical capacity required and iv. Inter linkages. Reference is also made to whether or not, there is explicit hydrological modelling. This is important in cases where local water constraints and interactions become important. Further, effort is placed on analysis that can be applied on the basin level, rather than at global level. Several important efforts at a global level exist, but are not designed to explicitly tackle constraints at basin level.

Recent tools and efforts – integrated accounting frameworks

Several tools and efforts focus on accounting for the inputs and outputs of resources when delivering services. Two efforts focus on input-output approaches, with limited hydrological accounting. They include MuSIASEM[1] (Giampietro et al., 2014), WEF Nexus tool[2] (Mohtar and Daher, 2014), and Integrated IO Nexus Approach (Sharma, 2014). These indicate where and how resources are linked, as well as how those linkages will compound direct and indirect demands. Each have an explicit focus on water, energy and land-use activities and how those are linked. In the case of Foreseer efforts there is explicit linkage with climate change. In the case of MuSIASEM there is accounting for human capital – as well as the potential to incorporate any other flows of inputs or outputs. It emphasizes ecosystem inclusion. And, in the case of the Integrated IO Nexus Approach economic impacts are accounted for and advances focus on dynamically changing input output coefficients. Individual resources models are integrated. Data requirements involve a mix of globally available data sets, national accounts and extended national accounts. Depending on the locations where the study would be applied, ease of data collection would be limited.

The Foreseer (Allwood, n.d.) tool builds useful Sankey diagrams indicating the use of resource to service for land, water and energy systems from resource to services. This allows a user to investigate a set of scenarios that have been run using a model developed on top of a series of spreadsheets. The WBCSD WEF[3] (Water, Energy, Food/Fiber/Fuel) Tool is also a detailed spreadsheet based model that simultaneously considers water and energy demands for cropping as a function of a changing climate. Embodied GHG emissions associated with fertilizer use, together with energy requirements are used to calculate GHG balances. An analogous approach is taken by (Hermann et al., 2012) ($CLEW_3$). That focused on (Climate, Land-, Energy-Water-use in) Burkina Faso.

Limited at present to Qatar, the WEF Nexus Tool (Mohtar and Daher, 2014) incorporates similar dynamics. However, the user is can calibrate the inputs used to produce with parameters indicating water method of production, energy use in water production as well as levels of trade. The tool is noteworthy due to its ease of use. However, as with Foreseer, analysis by a non-expert user is limited to pre-calibrated cases.

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[1] The Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) is an approach to integrate quantitative information generated by distinct types of conventional models based on different dimensions and scales of analysis. It allows to effectively analyze the nexus between energy, food, and water, considering heterogeneous factors such as population dynamics, greenhouse gas (GHG) emissions and land-use changes at the national or sub-national level using several innovative concepts derived from Bio economics and Complex Systems Theory. M. Giampietro and others. Resource Accounting for Sustainability Assessment: The Nexus Between Energy, Food, Water and Land Use. (Routledge, 2014).

[2] The Water, Energy, Food Nexus Tool 2.0 (Texas A&M) builds scenarios in order to quantify interlinkages between water, energy and food considering also the effects of population growth, changing economies and policies, climate change and other stresses. The required inputs are: Food portfolio (identifying local food production levels versus imports, and technologies in agricultural production); Water portfolio (identifying different sources of water and amounts needed of each); Energy portfolio (identifying sources of energy for water, and energy for agricultural production). The outputs provided for each scenario are: Water requirements (m^3); Local energy requirements (kJ); Local carbon emissions (ton CO_2); Land requirements (ha); Financial requirements ($); Energy consumption through import (kJ); and Carbon emissions through import (ton CO_2)

More complex system dynamics

Next we describe tools – or sets of tools – that capture special features of the Food, Energy, Ecosystem and Water nexus. In some cases, fully integrated tools that exist as single pieces of software are used. Some are used in an ensemble and linkages are softer, with data passed with various levels of automation between tools. In the case of the latter, some common components are described.
The WEAP-LEAP tool is a recent toolkit combining an energy system (LEAP) together with an hydrology (WEAP) model. Further, WEAP integrates CropWat. CropWat allows for the concurrent analysis of agricultural production. The tool has been applied in the context of the Tana River Basin in Ethiopia (Karlberg et al., 2015) and California (Yates and Miller, 2013). It is a flexible toolkit that can be shaped around data availability. Its explicit GIS based hydrological and temporal modeling allows for water and energy related constraints to be captured. As a simulation (rather than an optimization tool) it is limited to exploring explicitly user defined scenarios. Thus optimal resource allocations are found by the analyst exploring a technically consistent solution space.

$CLEW_1$ GAEZ-WEAP-LEAP (Howells et al., 2013) was the first integrated modeling approach of this type. It softlinked an ensemble of customizable tools. By so doing it analyzed concurrent scenarios of GHG mitigation, adaptation, energy, water and agricultural development. The effort is being replicated in several countries[3]. This was an interagency effort and included the IAEA, UNDESA, FAO and others.

$CLEW_2$ GAEZ-WEAP-OSeMOSYS-MAMS CLEW approach. Based on $CLEW_1$, $CLEW_2$ includes optimization in the energy sector using the open source energy modeling system (OSeMOSYS). OSeMOSYS allows for the optimization of energy investments and their operation. The link with this work is being carried out by UNDESA for a series of member states.

World Bank's Evaluating Climate Resilience (WBecr) approach, is the most comprehensive work to date (Cervingni, 2015). It simultaneously evaluated Africa's 8 most important river basins, agricultural plans, over 40 countries as well as four power pools. It used an ensemble of models including: WEAP, OSeMOSYS, CLITools and RDM uncertainty analysis. Models were softlinked and hundreds of thousands of scenarios evaluated. Approaches are open source and allow for dynamic optimization and trade-off's for water use in each basin. Allowing for an accessible starting point, hydrology was programmed in WEAP and then sent to a more powerful optimization software suite (CLIBASIN and CLIOPT).

UNECE WE2F Nexus (UNECE) LISFlood-OSeMOSYS was employed for the Sava River Basin. It is currently being extended to Europe. It's special characteristic is the employment of the LISFlood (Van der Knijff et al., 2010; de Roo et al., 2014) model to develop potential hydro production limitations in an OSeMOSYS (Howells et al., 2011) model. This tool not only considers average hydrology, but also potential flood impacts. Further, both tools are open source. In this instance they were applied to the Sava river basin and the riparian countries sharing this basin in the Western Balkans.

ASBmm (ICWC) The Aral Sea Basin Management Model (ASBmm) and BEAM (Riegels et al., 2013) the Basin Economic Allocation Model are software products consisting of a number of information modules and computer programs. They are useful for assessing projects and use of water, land and other natural resources. That allows for the evaluation of social, ecological, and economic conditions of particular zones and countries. For transboundary water projects the models make it possible to assess an impact of actions undertaken in one country on water availability and environment in neighbouring countries and further may serve as a tool for coordination of mutually acceptable decisions. However, while BEAM includes aspects of economic allocation of water, this is not yet extended to the energy system. Plans are afoot to make it so.

Some underlying tools that are either adapted or used as components of Nexi assessments are summarized below. These include: For crop production: CROPWAT, AquaCrop and GAEZ. For hydrological modelling: WEAP, BEAM, CliTools.

CROPWAT is a program for the calculation of crop water and irrigation requirements based on soil, climate and crop data. In addition, the program allows the development of irrigation schedules for different management

[3] See "Joint ICTP-IAEA Workshop on Uncovering Sustainable Development CLEWS; Modelling Climate, Land-use, Energy and Water (CLEW) Interactions | (smr 2242) (30 May 2011 - 3 June 2011)," n.d.

conditions and the calculation of scheme water supply for varying crop patterns. CROPWAT can also be used to evaluate farmers' irrigation practices and to estimate crop performance under both rain fed and irrigated conditions. AquaCrop is a crop water productivity model developed by the Land and Water Division of FAO. It simulates yield response to water of herbaceous crops, and is particularly suited to address conditions where water is a key limiting factor in crop production. Foreseer tool (Cambridge)
GAEZ Global Agro-Ecological Zones (FAO, n.d.) is a global tool that helps calculated potential yields and water for up to 280 crops/land utilization types under alternative input and management levels for historical, current and future climate conditions. It takes into account Land and water resources, including soil resources, terrain resources, land cover, protected areas and selected socio economic and demographic data; Agro-climatic resources, including a variety of climatic indicators; Downscaled actual yields and production of main crop commodities, and Yield and production gaps, in terms of ratios and differences between actual yield and production and potentials for main crops.

CLITools. Developed by MIT and Indecon (Cervingni, 2015). These are open source tools that allow dynamic optimization of water allocation, including optimization across crops. It consists of: CLIRUN: Rainfall runoff model. CLIFLOOD: Gridded flood model. CLICROP: Crop model CLIBASIN: Water systems model and CLIOPT: Optimization shell for CLIBASIN that enables basin-level simulation optimization.

BEAM is short for the Basin Allocation Model (Riegels et al., 2013). The BEAM model estimates welfare changes associated with changes to how water is allocated between the five countries in the Syr and Amu Darya basin. The model representation includes water resources, including 14 river sections, 6 terminal lakes, 28 reservoirs and 19 catchment runoff nodes, as well as land resources (i.e. irrigated croplands). The model covers 5 sectors: agriculture (crops: wheat, cotton, alfalfa, rice, fruit, vegetables and others), hydropower, nature, households and industry. The focus of the model is on welfare impacts associated with changes to water use in the agriculture and hydropower sectors

OSeMOSYS is the Open Source energy Systems Model. It as been routinely extended to include water, land and account for GHG emissions (Howells et al., 2011). Such extensions amongst energy modeling tools are not uncommon. The MESSAGE tool has been extended to include concurrent water and energy demand and production for the Gulf Cooperation Council (Almulla, 2015).

WEAP (Yates et al., 2005) is short for the Water Allocation Planning model. WEAP integrates water supplies generated through watershed-scale hydrologic processes with a water management model driven by water demands and environmental requirements and is governed by the natural watershed and physical network of reservoirs, canals, and diversions. It includes demand priorities and supply preferences, which are used in a linear programming heuristic to solve the water allocation problem as an alternative to multi-criteria weighting or rule-based logic approaches.

LISFLOOD (Van der Knijff et al., 2010) is a GIS-based spatially-distributed hydrological rainfall-runoff-routing model developed at the JRC. It includes a one-dimensional hydrodynamic channel routing model It is currently used for simulating water resources in Europe, Africa and at the global scale. Driven by meteorological forcing data (precipitation, temperature, potential evapotranspiration, and evaporation rates for open water and bare soil surfaces), LISFLOOD calculates a complete water balance at a daily time step and every grid-cell. Processes simulated for each grid cell include snowmelt, soil freezing, surface runoff, infiltration into the soil, preferential flow, re-distribution of soil moisture within the soil profile, drainage of water to the groundwater system, groundwater storage, and groundwater base flow. Runoff produced for every grid cell is routed through the river network using a kinematic wave approach. Although this model has been developed with the aim of carrying out operational flood forecasting at the pan-European scale, recent applications demonstrate that it is well suited for assessing the effects of land-use change and climate change on hydrology.

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