International Conference on Efficient & Sustainable Water Systems Management toward Worth Living Development, 2nd EWaS 2016

Designing water efficiency measures in a catchment in Greece using WEAP and SWAT models

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Abstract

The Ali Efenti catchment is a rural upstream subcatchment of the Pinios river basin that suffers from seasonal water shortages due to the rapid increase of the total water abstraction in the summer months, which is mainly attributed to local crop irrigation. Catchment modelling is being implemented using two different modelling approaches: a conceptual model based on water balances, the Water Evaluation And Planning system (WEAP), and a physically-based model coupled with routines for irrigation and crop growth, the Soil and Water Assessment Tool (SWAT). Both models were set up, calibrated and validated using observed streamflows. The strengths of the two models were combined in order to design effective, efficient and comprehensive demand-side measures for the urban, tourism, industrial and agricultural sectors to achieve sustainable water management in the Ali Efenti catchment. The comparison of the two models and the results of modelling are being discussed.

Keywords: hydrological modelling; WEAP; SWAT; water efficiency; Pinios;

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1. Introduction

Water scarcity and drought are a serious concern for Mediterranean countries, as well as many central and northern European regions [1]. Since climate change is expected to exacerbate the already existing water stresses, the improvement of water efficiency lies in the core of EU action against water scarcity & drought [2]. Actually, the enhancement of resource efficiency is a key target of the EU 2020 Strategy [3] for smart, sustainable and inclusive growth. The flagship initiative on Resource-efficient Europe [4], which is a part of the Europe 2020 Strategy, supports the transition to a low-carbon, innovative and sustainable economy through the promotion of efficient resource use, including water use. One of the cornerstones of the flagship initiative is the Roadmap to a Resource Efficient Europe [5], which sets out a vision for the structural and technological changes needed up to 2050 and frames future action on the topic. The action towards resource efficiency is further promoted by the recent Communication on Circular Economy [6], which aims at shifting the EU economic and environmental paradigm from a linear to a closed-loop economy. The vision of circular economy focuses on efficiency, reuse, recycling and recovery of resources to minimise total waste production across Europe. The target of increased resource efficiency has been integrated in the policy agenda of the European countries and, depending on the national context, water efficiency has been identified as a priority issue for many of them [7]. There is still a great potential for water saving in all the main water using sectors, such as the agricultural, domestic (i.e. distribution networks, buildings), industrial and energy sectors [8,9]. Water saving measures need to be incorporated in the Programmes of Measures (PoMs) of the River Basin Management Plans (RBMPs), which are developed by the European countries on a regular basis in line with the Water Framework Directive (WFD) [10] with the ultimate goal of achieving good status for surface and groundwater bodies. Designing water efficiency targets and measures to be included in the RBMPs requires deep understanding of the hydrological regime, the sectorial structure of total water use and the relevant socio-economic impacts at local level [2].

The quantitative estimations of water availability, water demand and water consumption both on a temporal and a spatial scale can be supported by modelling tools, capable of simulating the hydrological processes and the water management practices at catchment level for the current status, as well as for various scenario alternatives. Two main types of hydrological models are the conceptual and the physically-based models, which can be (semi-)lumped or (semi-)distributed [11, 12, 13]. The Water Evaluation And Planning System (WEAP) is a conceptual model based on water balances [14], whereas the Soil and Water Assessment Tool (SWAT) is a physically-based model coupled with routines for land use and agricultural management [15]. Both models were used for modelling a small rural catchment in Greece, the Ali Efenti catchment in upper Pinios river basin. The capabilities of the two models were combined in order to address the seasonal water deficit in the region. Effective, efficient and comprehensive demand-side measures were designed for the urban, tourism, industrial and agricultural sectors, focusing on the improvement of water use efficiency.

2. Methodology

2.1. WEAP model description

WEAP is developed by the Stockholm Environment Institute's US Center (SEI-US). Due to major advances, the current version is officially labelled as WEAP21 to distinguish from previous versions. WEAP21 attempts to combine an integrated modelling tool for water resources planning and management with a selection of conceptually simple models for watershed hydrology. It operates on the basic principle of a water balance and can be applied to a single watershed or a complex transboundary river basin system [14]. WEAP21 is considered a conceptual model taking into account the schematization approach for the physical system and the nature of the models used for describing the hydrological processes [16]. The components of the natural system (e.g. catchments, aquifers, rivers and lakes) and the components of the technical system (e.g. reservoirs, boreholes, diversions, pipes, canals, cities, wastewater treatment plants, hydropower facilities and irrigated farms) are schematized using a network of inter-connected model elements without geographical reference. Model elements can fall into two main categories: nodes, where water is demanded or made available for supply, and links, which transfer water between the nodes. The water management model is driven by user-defined demand priorities, supply preferences and environmental requirements for the various

nodes. The water allocation problem is solved using linear programming on a daily or monthly basis. The catchment nodes offer a selection of simplified hydrological models, such as a runoff-coefficient method or a two-bucket groundwater model. Evapotranspiration, runoff, interflow, baseflow and percolation are estimated using empirical equations. Crop growth and yields can also be estimated at catchment level. WEAP21 allows for the introduction of user-defined variables and scripts, dynamic links to spreadsheets, coupling with water quality, groundwater and energy models, flexible scenario building and analysis and visualization of model variables or output results [17].

2.2. SWAT model description

SWAT is developed by the USDA Agricultural Research Service. It is a physically-based, basin-scale, continuous-time model that operates on a daily time step. In the GIS-based SWAT environment a watershed is divided into multiple sub-watersheds, which are subsequently further divided into hydrologic response units (HRUs). The HRUs represent areas with homogeneous land use, management, and soil characteristics [15]. The processes associated with water and sediment transport, crop growth and nutrient cycling, including the agricultural management practices, are modelled at HRU level. Hydrological processes include surface runoff/infiltration, evapotranspiration, lateral flow, percolation, and return flow. The model considers a shallow unconfined aquifer, which contributes to the return flow, and a deep confined aquifer acting as a source or sink. Agricultural management practices, such as planting, harvesting, tillage, irrigation, grazing and nutrient applications can be simulated applying a user-defined schedule. Additionally, irrigation and fertilization can be triggered automatically for pre-defined thresholds of soil water deficit and plant N stress respectively. Irrigation needs are met with water abstractions from model elements acting as water sources: rivers, reservoirs, aquifers or outside sources. Irrigation inefficiencies, such as conveyance losses from the source to the field or additional water application losses on-site, can also be simulated with SWAT. In the crop growth module temperature, water and nutrient stress may act as limiting factors, hence lowering the actual compared to the potential yields [18].

2.3. Study area

The Ali Efenti catchment (~2900 km^2) is a rural upstream subcatchment of the Pinios river basin. The northern and western parts of the catchment are more mountainous, whereas the central and southeastern parts are covered by fertile plains. Forests, pasture, agricultural and urban land account for 33%, 31%, 23% and 2.5% of the total area respectively. The main cultivated crop is cotton, followed by winter wheat, maize and alfalfa. The average annual rainfall is higher than in the rest parts of the Pinios river basin (857 mm), while reference evapotranspiration is also very high (1413 mm). The observed average annual streamflow at the catchment outlet is approximately 40 m^3/s. Irrigated agriculture takes up 90-95% of total water use. The major cities of the region are Trikala and Karditsa. Several industries, mainly from the food sector, are based close to the cities. No major dams exist, but parts of the broader Karditsa area are supplied with water from the Plastiras reservoir, which is considered an outside source. Irrigation infrastructure includes collective systems with open canals, which are responsible for high conveyance losses (30-50%), and an unknown number of illegal boreholes for self-supply. Conveyance losses are also very high in the urban distribution network (~40%) [19, 20].

2.4. Set-up, calibration and validation of models

Relevant datasets for the Ali Efenti catchment were collected and organised in a database. The geospatial information was processed using GIS tools. Data included information on topography, geology/hydrogeology, land use, climate/hydrometeorology, water supply/demand/consumption, water efficiency, wastewater treatment, management practices, administration and socio-economic affairs. The data originate from various sources, such as the Greek Ministry of Environment & Energy, the Public Power Corporation, the National Institute of Geology and Mineral Exploration, the National Institute of Soil Mapping and Classification, CORINE Land Cover, Eurostat and previous studies conducted in the Pinios river basin.

A GIS map of the area was used as reference background to schematize the river network, the subcatchments, the main groundwater bodies and other physical elements of the Ali Efenti catchment in WEAP21. The schematization led to 23 subcatchment nodes, 8 groundwater nodes, 3 spring nodes and 1 outside source node (Plastiras reservoir). Demand-site nodes were added in each municipality dealing with domestic, tourism, livestock and industrial water use. Special nodes were added for the wastewater treatment plants. All nodes were linked with transmission and return elements to account for water transfers between the water sectors and the environment or between the water sectors. Catchment rainfall-runoff modelling followed an approach based on runoff-coefficients. Irrigation needs were estimated using the approach of FAO [21]. The model calibration was executed via a WEAP21-Matlab conjunction [19, 22] using simulated annealing as optimization algorithm.

The GIS maps for land use, soil and topography were used as input to ArcSWAT to divide the Ali Efenti catchment into subcatchments and HRUs. The schematization led to 17 subcatchments and 117 HRUs. Each HRU was linked to a shallow aquifer by default. The Plastiras reservoir was added as an outside source. Agricultural water use was modelled using a GIS crop map with the dominant crops per HRU and the user-defined irrigation schedule. Water abstractions and return flows from big cities or industries were modelled using a manipulation. Point sources were added in the respective subcatchments releasing water equal to the amount of the city or industry effluent. Then, the same amount of water was subtracted from the respective shallow aquifer. The model calibration was executed using the SWAT-CUP tool and Parasol as an optimisation algorithm.

The calibration and the validation were implemented using the observed streamflows at the outlet of Ali Efenti catchment. The calibration period (1981-1984) and the validation period (1984-1988) were the same for both models. The calibrated parameters included model variables which represent attributes of the hydrological processes or hydrological properties of soils. The values of these variables cannot be easily specified by literature, due to their high uncertainty and sensitivity. Three fitness criteria were used for model comparison: Efficiency (Nash-Sutcliffe coefficient), Correlation factor and Mean value bias. The calibration and validation results (Table 1) show that both WEAP21 and SWAT have very good fitting, given the complexity of the study area, but SWAT tends to perform better in simulating the observed streamflows.

Table 1. Calibration and validation results of WEAP21 and SWAT.

Fitness criterion	Process	Ali Efenti gauge	
		WEAP21	SWAT
Efficiency – Nash Sutcliffe coefficient (EFF)	Calibration	0.626	0.777
	Validation	0.571	0.761
Correlation factor (R)	Calibration	0.800	0.882
	Validation	0.765	0.875
Mean value bias (%) (BIAS)	Calibration	-11.6	-1.2
	Validation	+8.4	+7.4

2.5. Baseline and Scenarios for water efficiency improvement

The Baseline scenario (1995-2010) assumes no change and no action in the region, except for the climate, which varies according to the historical data. Land use and management practices were kept constant. Very high initial depths were used for the aquifer model elements to allow for unsustainable water abstractions from non-renewable groundwater resources.

Three scenarios (SC1, SC2 and SC3) were examined with the aim of improving water use efficiency in the catchment (Table 2). The simulation period was the same as for the Baseline to make it possible to estimate the potential improvements which could have occurred. Since the key economic activities are concentrated in the lowland region, water use follows the same pattern. Therefore, it makes sense to prioritize the subcatchments of Ali Efenti and focus on the big consumers and the most problematic areas. For SC1 it is assumed that various measures could be incentivized and promoted in the urban & tourism and industry sectors. The target water efficiency gains are estimated

at 25% and 40% respectively, which can be considered as conservative targets for these sectors [8, 23, 24, 25]. For SC2 and SC3 the target water efficiency gains were set equal to 30% and 25% respectively to account for the water saving potential of deficit irrigation and conveyance efficiency improvement in irrigation networks [8, 20, 26]. SC1 will be simulated using WEAP21, because it is capable of simulating all water sectors explicitly, it provides advanced options for structuring the water use components in each water sector and it includes separate modules for designing water efficiency. SC2 and SC3 will be simulated using SWAT, because this is a tool oriented at agricultural management and it includes a more sophisticated approach for catchment hydrology and crop growth.

Table 2. Customization of water efficiency scenarios.

Scenario	Measures	Target water sector	Target area	Target penetration of measures	Target water efficiency gains	Simulation model
SC1	Leakage reduction program, Installation of new pipes, Water saving devices, Rainwater harvesting	Urban & Tourism	most deficient lowland areas	10% of urban & tourism consumers	25%	
	New heating & cooling systems, Water reuse & recycling, New processing methods, Water saving devices, Rainwater harvesting	Industry		100% of industrial consumers	40%	
						WEAP 21
SC2	Deficit irrigation	Agriculture	lowlands	100% of cotton, maize and alfalfa fields	30%	SWAT
SC3	Upgrade of irrigation network	Agriculture	lowlands	100% of cotton, maize and alfalfa fields	25%	SWAT

3. Results

The two modelling approaches differ significantly conceptually, structurally and methodologically, thus affecting simulation results. This is evident already from the calibration and validation period, where SWAT performed better than WEAP21. In addition, model parameters and output variables are different for the two models. Taking into account all these differences, it was decided that common indicators were needed for the presentation of the models' results. Two key indicators were chosen: Annual Unmet Demand for the baseline and Potential annual water saving for the water efficiency scenarios. These two indicators were chosen because they are simple in logic, comprehensive and policy-relevant.

Table 3. Results of Baseline and water efficiency scenario using WEAP.

Water sector	Annual Unmet demand in Baseline (hm^3)	
Urban & Tourism	0.06	
Agriculture (Irrigation & Livestock breeding)	71.89	
Industry	0.19	72.14 (total)

SC1 impacts	Potential annual water saving (hm^3)	Potential annual water saving (% of Baseline Unmet Demand)
Improved efficiency in Urban & Tourism	0.45	0.6
Improved efficiency in Industry	0.55	0.8

3.1. Baseline and water efficiency measures using WEAP

The simulation of the Baseline with WEAP21 (Table 3) showed that the major water user in the region is agriculture, as expected. The budget deficit in the area appears only in the summer months (Jun-Sep) and is directly linked with the high water abstractions in irrigated agricultural. Unmet demand in the urban & tourism and industry sectors is significantly lower than in the agricultural sector, but taking into account the socio-economic context behind these uses, it should be highlighted that even the smallest cuts could cause serious damages. The reliability of demand coverage was estimated at 99%, 83% and 95% for the urban & tourism, industry and agricultural sectors respectively. The implementation of SC1 suggests that the selected measures could save up to 1 hm^3 in the urban & tourism and industry sector. This amount exceeds the unmet demand of the two sectors in the baseline.

3.2. Baseline and water efficiency measures using SWAT

The simulation of the Baseline with SWAT (Table 4) indicates that there is a high budget deficit in the catchment plains between Trikala and Karditsa, because of unmet demand in irrigated agriculture. The deficit is estimated at 44.3 hm^3, which is 38% less than in the baseline simulation with WEAP21 (Table 3). The implementation of SC2 suggests that if deficit irrigation (-30%) is applied for cotton, maize and alfalfa, then total water use in the region will decrease by 23%. The implementation of SC3 suggests that if the irrigation network for cotton, maize and alfalfa is upgraded (-25%), then total water use in the region will decrease by 7%. It should be highlighted, that the actual water efficiency gains at catchment scale are less than the targets of 30% (SC2) or 25% (SC3). This is because the measures are not applied for all crops and water availability is already too low in some areas, despite the cuts in crop water use or in conveyance losses.

Table 4. Results of Baseline and water efficiency scenarios using SWAT.

Water sector	Annual Unmet demand in Baseline (hm^3)	
Agriculture	44.3	
	Potential annual water saving (hm^3)	Potential annual water saving (% of Baseline Water Use)
SC2 impact: Improved efficiency in Agriculture (Deficit irrigation)	59.5	22.7
SC3 impact: Improved efficiency in Agriculture (Upgrade of irrigation network)	18.8	7.1

4. Conclusions

WEAP and SWAT follow two different modelling approaches. They differ greatly in concept, structure, methodology and operational orientation. WEAP follows a balanced approach between being an integrated water resources planning and management tool and a hydrological model. WEAP's GUI, its flexible and customizable structure and its scenario analysis capabilities constitute its strong features. SWAT follows a more sophisticated approach in modelling hydrology and crop growth. Its scope is focused on agricultural catchments, processes and practices. The GIS-based interface for the insertion of data is considered as one of its advantages. Both of them were set up, calibrated, validated and used to design water efficiency measures in the Ali Efenti catchment, in upper Pinios river basin. This agricultural catchment suffers from summer peaks in water demand due to irrigated agriculture. Measures to improve water efficiency in the urban & tourism and industry sectors could save up to 1 hm^3, which

exceeds the baseline unmet demand in these sectors. Deficit irrigation and upgrade of the irrigation network in the area could save up to 23% and 7% respectively of the baseline water use.

Acknowledgements

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