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Development of SEEA Water Accounts with a Hydrological Model

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Abstract
Worldwide, water resources are increasingly under pressure. The Water accounting approach of the System of Environmental-Economic Accounting (SEEA) has been developed to inform decision-makers on water supply, use, and quality. However, a critical issue in water accounting is finding data and models to populate SEEA water accounts. In particular, there are challenges in aligning hydrological models with accounting principles. Also, there is a need to test further how the SEEA water accounts can be connected to policy uses. The objective of this study is to develop water accounts with the use of a hydrological model. Specifically, we apply the SWAT hydrological model in the Buyuk Menderes Basin in Turkey to estimate the key hydrological parameters required for water accounting. To adapt and link SWAT to SEEA water accounts, we develop supply and use tables and asset accounts following the SEEA water for the year 2014 and explore how water accounts can inform policymaking. This article provides new insights into the added value of using a hydrological model in constructing water accounts for better water resources management.

Keywords
Natural capital accounting;

System of Environmental Economic Accounting (SEEA);

Hydrological assessment;

Water;

Spatial analysis

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1. Introduction

As in many parts of the world (UN WWAP, 2012), water resources are increasingly under pressure in Turkey (Selek and Aksu, 2020). Depletion and pollution of surface and groundwater resources are widespread, and climate change may further exacerbate water shortages in the future (SYGM, 2016). Various methodologies can be used to assess water scarcity and inform about options for sustainable water use (Bazilian et al., 2011; Haddeland et al., 2014; Hanjra and Qureshi, 2010; Hoekstra and Chapagain, 2008; Jackson et al., 2001; Mekonnen and Hoekstra, 2011; Mekonnen and Hoekstra, 2016; Pekel et al., 2016; Vitousek et al., 1997; Vorosmarty et al., 2010). Among these, the System of Environmental Economic Accounting (SEEA) water accounting approach (in short SEEA water) is a statistical approach to inform policymakers on stocks, use, and quantity of water, comprising a set of connected physical and monetary indicators. The SEEA water has been developed under the auspices of the United Nations Statistical Committee and is an internationally agreed statistical framework (UNSD, 2012). It is of particular relevance for assessing water resources and their use in a geographic area, e.g., a country or watershed.

The SEEA water is part of the SEEA Central Framework (UNSD, 2014), an international statistical standard, and the new SEEA Experimental Ecosystem Accounting approach that focuses on measuring ecosystem use and ecosystem assets (Costanza et al., 1997; UNSD, 2013; UNSD, 2014). The SEEA has been developed by the statistical community in collaboration with ecologists, economists, and other scientists to offer countries a framework to compile statistics on the environment and natural resources. The SEEA water focuses on water and allows recording water supply and use of the economic sectors, returns of water from the economy to the environment, emissions, and water quality (UNSD, 2012). The SEEA water is consistent with the economic statistics produced with the System of National Accounts, which provides indicators such as GDP. SEEA water facilitates connecting

economic statistics and indicators on water use, eliciting productivity of water use, employment dependent on water resources, etc. (Bartelmus, 2014; Lange et al., 2007). Furthermore, water data, which is organized within the SEEA framework, is useful for models such as input-output analysis, computable general equilibrium models (CGE), cost-benefit analysis, and risk assessment frameworks (Obst and Vardon, 2014).

A range of water accounts has been developed based on SEEA water in different parts of the world (Charpleix, 2017; Edens, 2013). For example, the Netherlands' water accounts provide information on the use and the monetary value of water resources in the country (Edens and Graveland, 2014). In Australia, SEEA water has been used to support integrating water into economic modeling, among others (van Dijk et al., 2014). Basic water accounts have been developed in Botswana, Colombia, and Costa Rica (Vardon et al., 2018), and more detailed accounts are available for Germany, Norway, and Sweden (Smith, 2014).

SEEA water requires detailed information on water resources, preferably at the level of the lowest administrative unit. In situ collection of some of the required data such as soil moisture, evaporation, transpiration can be costly; therefore, such measurements may have limited spatial and temporal coverage. Furthermore, there are insufficient water monitoring stations to provide these data in many countries. Hydrological models can be used to obtain the data with the required spatial and temporal resolution. However, a challenge is to connect the principles and outcomes of hydrological models to the data requirements of SEEA water (Duku et al., 2015). For instance, water accounts distinguish between stocks and flows of water, whereas hydrological models usually focus on water flows. Hence, even though hydrological models provide a pathway to supply data for water accounts, it is not straightforward to connect hydrological models and water accounts.

The objective of this study is to examine how hydrological modeling can be used to develop water accounts to provide the information and knowledge needed for sustainable water

resource management. We develop water accounts of the Buyuk Menderes basin in Turkey, which covers the provinces of Aydin, Denizli, and Mugla. The Buyuk Menderes basin is subject to both seasonal water shortages, pollution, and floods. We test, in particular, how the SWAT hydrological model can be used in support of water accounting. We compile physical supply and use accounts and complement it with physical water resource asset accounts following the SEEA water. The water accounts are compiled for the year 2014.

This article provides new insights into the added value of using a hydrological model in constructing water accounts for better water resources management. We compile the accounts and examine how hydrological models and the SEEA water can be linked. In particular, the article explores how the temporal resolution of the SWAT model, which can be daily, monthly, or yearly, can enrich SEEA water, which is usually constructed for an accounting period of one year. The article describes the research area, our modeling framework, and the structure of SEEA Water. After presenting the model output and water accounts of 2014, the paper discusses the differences in spatial units: SEEA Accounts follow administrative boundaries, whereas hydrological models follow water basin boundaries. Finally, the paper explores how water accounts provide information relevant for policymaking in the Buyuk Menderes basin.

2. Methods and Study Area

2.1 Study Area

The Buyuk Menderes basin covers an area of about 24,976 km^2 and is located between northern latitudes of 38.067–39.217 and eastern longitudes of 26.700–29.7500 (Figure 1). The Buyuk Menderes river has an annual average flow of 225.47 m^3/s, and it discharges to

the Aegean Sea. There are two major lakes: Isikli Lake in the upstream and Bafa Lake in the downstream of the basin (MOFWA, 2017). The basin has a population of about 2.7 million people. Important economic sectors are agriculture, industry, and – especially along the coast – tourism. The main land cover in the basin is forest and semi-natural vegetation, covering 66% of the basin, followed by agricultural land, covering 31% of the basin. Land use details are provided in Annex 1. The valleys of the basin generally have fertile soils of sedimentary origin and varying texture. However, soil acidification and salinization and pollution of underground water occur in the irrigated areas (Grontmij, 2004).

Figure 1 around here

2.2 Hydrological Model Selection

Hydrological models that capture socio-economic issues have been extensively used in support of water policy formulation and implementation (Blanco-Gutiérrez et al., 2013; Brouwer and Hofkes, 2008; Esteve et al., 2015; Hein et al., 2016; Solera et al., 2018). Hydrological modeling has been used, among others, for integrated assessment of hydrologic–economic issues, integrated river basin optimization, efficient water allocation, management of demand, rivers' response to climate change and supply of water resources (Guiamel and Lee, 2020; Harou et al., 2009; Oo et al., 2020; Schewe et al., 2014). Hydrological and water resource models such as SWAT, PATRICAL, SIMGES, AQUATOOL, RIBASIM, and WEAP have been tested to compile the SEEA water (Dimova et al., 2014; Pedro-Monzonís et al., 2016a; Pedro-Monzonís et al., 2016b).

From these different model options, SWAT has been chosen as the modeling tool for this study because it is particularly suitable for interpreting the relation between land use and

water flows (Krysanova and White, 2015). Moreover, it is one of the most widely used hydrological models, and it has an open access policy with detailed documentation. SWAT allows for continuous simulation, as opposed to single event models. It produces outputs at different spatial scales, including watershed, sub-basin, and hydrologic response units (HRU) and different temporal scales, including annually, monthly, daily, and hourly. SWAT has various process-based biogeochemical sub-models. This strengthens the model's capacity to simulate not only water flows but also to estimate several variables related to water quality, which are useful for compiling SEEA water (Arnold et al., 2012a; Glavan and Pintar, 2012).

2.3 Data

Inputs of SWAT include spatially distributed parameters of elevation, land use, soil types to define sub-basin boundaries, and hydrologic response units (HRU), which have a single land use, and soil characteristics (Winchell et al., 2009). For the Buyuk Menderes basin, these data are from the following sources.

The Digital Elevation Model (DEM) is retrieved from the online Earth Explorer[3]. The map obtained from EarthExplorer is in lat-long projection, and this was clipped and re-projected into UTM. Land use data are obtained from the Corine Land Cover Inventory (CORINE). CORINE consists of an inventory of land cover in 44 classes and is produced for years 1990, 2000, 2006 and 2012 The CORINE land use classes are transformed into SWAT land use types, as detailed in Annex 1. The soil types are extracted from the FAO-UNESCO Soil Map of the World database (UN Food & Agriculture Organization and UNESCO, 2003). The soil types affect the hydraulic properties and the growth patterns of plants. Seven types of soil are

[3] Courtesy of the NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, from the United States Geological Survey (USGS).

observed in the basin. However, four soil types form over 95% of the land in the basin (calcic cambisols, eutric cambisols, lithosols, and calcaric fluvisols). The critical soil water parameters of these soils (moist bulk density, water capacity, soil erodibility factor) are provided in Annex 1. After the delineation process, the clipped land use and soil raster data are overlaid to identify the hydrologic response units.

Climate information (precipitation, temperature, solar radiation, wind speed, and relative humidity) are obtained from the meteorological stations of the State Meteorological Service. The locations of the stations are defined in the SWAT model. The model assigns the data of the closest meteorological station to each subbasin. The river discharge data of the six observation stations for the period 2000-2015 are obtained from the State Hydraulic Institute of Turkey (DSI: Turkish acronym of the State Hydraulic Institute). Data coverage of meteorological stations and the hydrological stations are summarized in Annex 1.

The water abstracted for agriculture is about 82% of the total water use in the basin (TRAGSATEC, 2018). Crops get water from rainfall or irrigation systems. In addition to the irrigation data obtained from DSI, additional data on agricultural water use have been derived from peer-reviewed articles. Water use statistics are available from DSI for the irrigation schemes operated by DSI[4], which form about 65% of the irrigation schemes in the basin. The water extracted for the remaining large schemes has been estimated based on the research results of (Köse, 2009; Şeker, 2015; ÜLÜŞ, 2018; Yilmaz et al., 2009). There are also private irrigation schemes in the basin, whose water use is not measured and recorded. The

[4] DSI is the main organization for the country's overall water resources planning, execution and operation. DSI usually operates the irrigation schemes, which it designs and constructs. Before its closure in 2005, the General Directorate of Rural Services was responsible for developing small-scale irrigation schemes with flows of less than 500 liters per second. The private irrigation schemes are small in size and they have on average 50 ha net irrigation area.

abstraction amount of the private irrigation schemes is estimated with the help of the 'auto irrigation' output of the SWAT model. Water abstracted for irrigation in the basin varies between 800-1,600 million m^3 per year, depending upon the rainfall pattern (DSI, 2017).

The statistics of water supply, wastewater collection, and wastewater treatment are available at the provincial level for the years 2001-2004, 2006, 2008, 2010, 2012, and 2014 (TurkStat, 2014a). In order to convert the provincial scale data to a basin scale data, the percentage of the area within the Buyuk Menderes Basin of each province is used as the correction factor in estimating the municipal water use and wastewater discharge. The provinces' total area and their area within the Buyuk Menderes Basin are provided in Annex 1.

The abstraction of water and discharge of wastewater data of the manufacturing industry for the years 2000, 2004, 2008, 2010, 2012, and 2014 are obtained from the State Statistics Institute (TurkStat, 2014c). The water used for cooling the thermal power plants is recorded under the manufacturing industry. Water use and abstraction data of the mining sector are available on a national scale only. The data on the export of mining goods are available at the provincial level (TurkStat, 2014b). This data is used as the proxy multiplier to disaggregate the national scale mining water use and discharge statistics to the provincial level.

Hydropower plants' (HPPs) water use data are not publicly available. Electricity generated depends upon the height difference between the water in the dam and the turbine, the volume of water and the efficiency of the turbine (Gulliver and Arndt, 1991). Information on electricity generated, height difference and efficiency for every dam in the basin was obtained from public sources (Enerji Atlasi, 2018). These numbers were used to estimate the water volume passing through each dam. Therefore, their water use is estimated based on the

waterfall height and the electricity generated by the plants. The number of HPPs under operation in the basin is 17, and the total installed power has reached 300 MW.

Isikli Lake, which is in the upstream part of the Basin, is used as a natural reservoir for irrigation purposes; therefore, the discharge from the lake is monitored, and data are available. We have included this lake in the SWAT model. There are no water records available for the Bafa Lake, which is in the downstream part of the Basin. We have not modeled this lake in SWAT and we have not included this lake in the water accounts. Water from this lake is drained almost directly to the sea, so we don t expect this to have a significant impact on the results.

Table 1 around here

2.4 Model Calibration and Validation

By following the SWAT model calibration protocols reported by Douglas-Mankin et al. (2010) and Tuppad et al. (2011), the following nine parameters have been adjusted to calibrate the model. Surface runoff is calibrated with curve number (CN2), and soil available water content (SOL_AWC) parameters. The baseflow process is calibrated with 'water-depth in the shallow aquifer required for return flow to occur to the stream' (GWQMN), 'groundwater delay time' (GW_DELAY), 'baseflow recession constant' (ALPHA_BF), 'groundwater revap' (GW_REVAP), 'deep aquifer percolation fraction' (RCHRG_DP), 'threshold depth of water in the shallow aquifer for percolation to the deep aquifer to occur' (REVAPMN) and 'depth from the soil surface to bottom of layer' (SOL_Z) parameters (Arnold et al., 2012b). SWAT-Cup software is used for the calibration of the model. The whole period of 2000-2015 is divided into three periods. The year 2000 is used as the warm-up period. The period

of 2001-2012 is used for the calibration, and the period of 2013-2015 is used for the validation. For more information about the use of SWAT-CUP, see (Abbaspour et al., 2004) and (Abbaspour et al., 2007). The fit between model results and the observations is quantified and expressed as 95 % prediction uncertainty (95PPU). R- factor is the thickness of the 95PPU envelop (Abbaspour, 2015). The objective function of the calibration function is to maximize Nash-Sutcliffe (NS), where Q is a variable (e.g., discharge), and m and s stand for measured and simulated data points, respectively. The bar stands for average (Abbaspour, 2015).:

$$NS \quad = 1 - \frac{\sum_i (Q_m - Q_s)_i^2}{\sum_i \left(Q_{m,i} - \bar{Q}_m\right)^2}$$

m *:* measured

s *:* simulated

i *: i*th measured or simulated data (Abbaspour, 2015)

2.5 SEEA Water

SEEA water covers the stocks and flows of water between environment and economy, the environmental pressures of the economy in terms of water abstraction and discharge, the supply of water and its use as input in different economic activities, the reuse of water within the economy (UNSD, 2012). Physical flows comprise surface water, groundwater, soil water, and precipitation, which are provided by the environment and withdrawn by different economic agents classified by standard ISIC industry classifications including agriculture, mining, manufacturing, electricity supply, water services, and households. There is a difference in how water is used by the economic sectors. For instance, water abstracted for drinking water is

not returned to the environment. However, a significant percentage (80%) of the irrigation water goes back to the environment, and all cooling water and water used to operate hydroelectric power plants returns back to the environment. In addition to these direct physical abstractions and use of the water, some economic activities benefit from the 'physical presence of water' (e.g., navigation, fishing, recreational purposes, etc.). These benefits from the presence of water are not considered in SEEA-water accounts since they don't involve any significant displacement of water. However, these activities may have an impact on the quality of water (UNSD, 2012).

The water accounts can be prepared at any spatial scale, including a river basin, an administrative region, or a city. Since economic activity statistics are usually compiled at the level of administrative areas, a methodology is needed to reconcile the spatial unit of economic activity data with the spatial unit of the hydrological model. In this study, the irrigation statistics are assigned to the relevant subbasin by using georeferencing methods. The drinking water use, which is available at municipal and village scale, is converted to point data based on the settlements' locations. Then, it is recorded into relevant subbasin by overlaying the points on the subbasin map.

3. Results

3.1 SWAT Model Calibration, Output and Validation

The model was calibrated for the 2001-2012 period based on the availability of climatic and hydrological data. Six gauge stations on a continuous stream network were parameterized and calibrated simultaneously. To match the model outputs with the observation data of the six gauge stations, the groundwater, land, and soil parameters of the SWAT model were altered. After observing the baseline run, it was noticed that the baseflow was systematically

overestimated in the model. Therefore, parameters that affect groundwater flow have been chosen for calibration. Overall, nine parameters were selected for SWAT-CUP. The Sequential Uncertainty Fitting (SUFI2) technique was used to fit the model performance with the observed data, and several model simulations were executed with a minimum of 500 simulations in each run (Abbaspour, 2015). When the best fit on monthly runoff data for all observation stations was reached, a sequential single station calibration method is utilized to fine-tune the parameters for a better match between the gauge observations and the model results. The parameters of the subbasins draining to the most upstream gauge station were calibrated and fixed. Sequentially, the next station and its subbasins' parameters were calibrated and fixed. The model parameters were considered optimum after completing the calibration of all stations moving down the basin. These calibration parameters are provided in Annex 1. An analysis of the correlation between the simulated and observed discharge revealed a Nash Sutcliffe value of 0.56, which indicates an acceptable agreement between the datasets. When the model is run with the optimum parameters, the following results in Figure 2 have been obtained. Although generally, the observed and simulated peak flows were calibrated, some peak observations were higher than the simulation results in February in 2005, 2006, 2010, and 2012. However, based on the goodness of the fit between the simulated and observed flow, it can be concluded that the calibration results illustrate that SWAT sufficiently represents the hydrological process that occurred in the watershed.

SWAT generated several output data sets. The basin-wide output data include precipitation, surface runoff, lateral flow, groundwater flow to streams, percolation to groundwater, soil water, and evapotranspiration. The data is available at the basin, subbasin, and HRU scales for years 2001-2015. Lateral flows contributed to 65% of the streamflow, followed by the groundwater flow with 26% and the surface flow with a 9 % contribution. SWAT streamflow dataset includes average daily streamflow into reach, streamflow out of reach, water loss

from reach by evaporation, and the area drained by the stream. The reservoir output data includes monthly and the annual volume of water in reservoirs, average flow into reservoirs, flow out of reservoirs, precipitation falling on the reservoirs, evaporation from the reservoirs, and seepage. The model also provides the yield (kg/ha) and biomass (kg/ha) for each crop in each subbasin. The year 2008 was the driest with precipitation of 407 mm, whereas the following year 2009 had the highest rainfall (897 mm), on average across the basin.

Figure 2 around here

Validation for the period between 2013 and 2015 was conducted to ensure the validity of the calibration process. The Nash Sutcliffe value for the validation was 0.53. Validation results have been shown in Figure 2. The results of 2013-2015 indicate that there is a good agreement between the observed and simulated discharge. However, a comparison of the statistics of the calibration and validation periods reveals that the motel performs better during the calibration period as compared to the validation period. Overall, it can be concluded that the model captures the monthly time series of streamflow well in both calibration and validation periods.

A basic schematic diagram of the main flows and stocks of water, as modeled in SWAT, is shown in Figure 3.

Figure 3 around here

3.2 Water Accounts for the Buyuk Menderes Basin

3.2.1 Physical Supply and Use Accounts

As shown in Table 2 and 3, the combination of SWAT modeling and accessing water statistics allowed compiling the physical supply and use accounts. The physical supply and use accounts show the use of water by economic users, specified by the International Standard Industrial Classification of All Economic Activities (ISIC), which is the international reference classification of productive activities.

The total abstracted water by the economic users was 18,595 million m^3 in the Basin in 2014. Most of the water supply was from precipitation (81 %), followed by surface water (18 %). Groundwater was around 1% of the total amount, which was mainly for urban and rural drinking water use.

Agriculture used 16,095 million m^3, of which rain-fed agricultural practices consumed 15,062 million m^3. It is noteworthy that precipitation is the primary water resource for agriculture, not the irrigation system. The second-largest water user in the economy is the electricity supply sector. Hydropower plants used 2,294 million m^3 water, but most of the water abstracted by hydropower plants return to the environment and are used multiple times. The water supply sector abstracted 177 million m^3 water, 83% of which was from the groundwater sources. The water use in the mining and manufacturing sectors is considerably lower. Mining used 14.3 million $m^{3,}$ and manufacturing used 15.6 million m^3.

The 'flow from the environment' in the SEEA water supply table, see table 2, captures only the abstraction of water by economic units. Therefore, '(I) Sources of abstracted water from the environment' is equal to the grand total of the sectoral water abstractions provided in the Use table, which is 18,595 million m^3 in total. SWAT provides evapotranspiration without separating soils' evaporation and plant's transpiration. This figure was used as the value of the 'Agricultural evaporation.' The grand total of agricultural water supply and use are balanced by adjusting the amount of 'water incorporated into products.' The surplus/deficit in between

the grand total of the Supply and Use accounts were balanced by adjusting the amount of the evaporation from the other sectors. The total return of water was mainly 'to inland water resources.'

Table 2 around here

Table 3 around here

3.2.3 Asset Accounts

The asset accounts show the flows of water (expressed as 'transactions') between different water bodies (rivers, reservoirs, groundwater, soil water) as well as flows from the environment to the economy and vice versa. The SWAT simulation output results were used to calculate the flows of water between different water bodies, and these are shown in green in the stock accounts provided in Table 3.

Physical stock accounts show that additions to the water stock of artificial reservoirs and soil water were higher than the reductions in stock in 2014. In contrast, reductions in the stock of the groundwater were higher than the additions to the stock. According to the SWAT model results, the opening stock of the reservoirs was 3,678 million m^3 at the beginning of 2014. Total additions of 8,422 million m^3 to the stock of water in reservoirs is slightly more than the reduction of 8,225 million m^3. These additions were from other inland water resources, in particular rivers discharging in the reservoirs.

The accounts point to an essential concern for water management, i.e., the depletion of groundwater reservoirs in the Buyuk Menderes basin. The reduction in water held in these reservoirs across the basin was about 392 million m^3 in 2014. Inflows from soil and rivers as percolation, recharge of the deep aquifer, seepage from rivers and reservoirs accounted for in total 1,809 million m^3. However, the overall reductions in the form of abstraction (171 million m^3), and inflows to other water bodies (2,033 million m^3) accounted for 2,204 million m^3 in total. Hence, only 82% of the outflows of water is replenished. The water level graphs of the basin's groundwater observation wells show that there is a downward trend in the level of the groundwater table (see Annex 1) (Tarim ve Orman Bakanligi, 2019).

In the water system, the soil plays an important role. Lateral flows were considered in the SWAT model and in the accounts. Half of the transactions of water among water bodies happens through soil water. Total additions to the stock of soil water were 20,373 million m^3, which was 52 % of the total of the additions to the stock of all water bodies. Soil transferred 14,035 million m^3 of water, of which 11,550 million m^3 back to the atmosphere through evapotranspiration and 2,485 million m^3 to other inland water bodies.

The total of the additions to the stock of rivers was 6,301 million m^3, which was inflows from reservoirs, surface flow, lateral flow and ground flow, and returns from economic water use (2,428 million m^3). Of this total flow, 8,458 million m^3 was transferred to the other water bodies in the basin (reservoirs, groundwater, and soil water). Evaporation accounted for 268 million m^3 of the reductions in stock. Finally, only 2 million m^3 discharged to the sea, which was insignificant. This low amount indicates that there is minimal scope to increase the use of river water in the future; more water is not available. Consequently, further economic growth in the basin needs to be decoupled from an increase in water use.

The SEEA water requires specifying opening and closing stocks of water in rivers and streams, groundwater, and soil water. However, defining these stocks is, in practice, very

difficult. Since stocks vary in time, a stock may be calculated for a given second in time or expressed as an average stock over, say, a week or a month. Instead of the volume of water in rivers and groundwater, their yield (the cumulative of additions and reductions in stock) can be measured and used for the stock accounts (McLennan, 2000). In 2014, total additions to stock were 39,335 million m^3, which was 18% more than the total reductions in stock (33,193 million m^3).

Table 4 around here

3.3. Linking Hydrological Models to the SEEA Water

The SEEA water requires environmental data that are not regularly collected by the water management authorities. As shown in Table 4, SWAT provides most of the data needed for the stock accounts. SWAT model results are especially helpful in calculating the transfers between different water bodies of reservoirs, rivers, groundwater, and soil water. Moreover, the information provided by SWAT is more detailed than what is required by SEEA water.

We subdivided inflows from and outflows to other inland water resources into two subsections: surface water and subsurface water. This provides more precise information on the transaction of water among different water bodies. Similarly, the nature of water use by economic activities is very different. Hence the returned water has different characteristics as a function of the sector using the water. For instance, water abstracted for hydropower is used multiple times and returned to the environment without any significant biological or chemical changes. To identify such differences, we provided subcategories for returns and abstractions.

SWAT is limited in providing information on opening and closing stocks of water bodies, except in the case of reservoirs. The water stock is defined as the quantity of water in a territory measured at a specific point in time (usually the beginning of the end of the accounting period), which is the requirement of SEEA water to analyze closing and opening stocks of river water (and similarly groundwater as well). The common principle of SEEA is that one unit of measurement should be used across the accounting tables so that aggregation is possible (UNSD, 2014). The stock of natural or human-made reservoirs is essential information since the water in reservoirs is still, and the temporal change of the amount of water can be measured. The opening and closing stock of reservoirs can be obtained from SWAT. However, the volume of rivers and groundwater cannot be calculated with the same unit used for reservoirs because it is not clear what temporal unit should be used in this calculation.

Another important point is that rivers' net stock (total additions – total reduction) should always be zero because the stock account includes 'outflows to the sea', which is the outer boundary for the freshwater system. There is a need to revise SEEA water's requirement for stock values for the river, groundwater, and soil water resources. It could be considered to allow for the net stock of rivers to be zero. Instead of using opening and closing stocks, the cumulative of additions to and reductions in stock can be used to monitor the stock balance of groundwater and soil water.

SWAT fills some of the data gaps and provides spatial precision on precipitation, melted snow, irrigation, evapotranspiration, river discharge, groundwater flow, and soil water. The spatial precision cannot be shown with SEEA water that is typically compiled for a specific administrative unit or watershed. Lastly, SWAT provides more information than the information that the SEEA water system can capture, such as crop water yield, surface runoff, daily streamflow, groundwater recharges at different spatial and temporal scales. These data

sets don't contribute to SEEA water. However, they can be used to measure different provisioning, regulatory, and cultural ecosystem services, which can be used in ecosystem accounting. For instance, SWAT can be used to model the impact of forests on the timing and volume of water flows, a regulating service (UNSD, 2018).

4. Discussion

4.1 Using SWAT for Accounting

There is a wide range of hydrological models that, in principle, can all be used to fill the missing data required for developing water accounts. Dimova et al. mention that the WEAP model facilitates analyzing hydrological cycles, and they consider the WEAP a reliable model to support the production of water accounts under the SEEA water methodology (Dimova et al., 2014). Pedro-Monzonis et al. use the PATRICAL model, a large-scale, conceptual, monthly, and spatially distributed water balance model integrated with AQUATOOL, a generalized decision-support system for water-resources planning and operational management (Pedro-Monzonís et al., 2016c). (Pedro-Monzonís et al., 2016a) use the physically-based distributed model (TOPKAPI), and a water balance model at basin scale (RIBASIM) to compile water accounts for the Po River.

Compared to other hydrological models, a specific advantage of SWAT is that it allows modeling how land use change modifies streamflow parameters (Paul et al., 2017), something which is of high interest in natural capital accounting (UNSD, 2012). Other advantages of SWAT are that it is widely used and that there is a large group of expert SWAT users worldwide and that it is open access (Arnold et al., 2012b). Compared to some other models, parameterization and modeling of lakes are challenging and in SWAT. Usually, these important water bodies are omitted from models, which results in a misrepresentation of

hydrological dynamics in the basin (Jalowska and Yuan, 2019). Therefore, it needs to be considered on a case-by-case basis if SWAT is the preferred hydrological model to underpin water accounts. Criteria for the selection of a model include local capacities in applying the model, data availability, need to consider impacts of land use change on water flows or not, presence of reservoirs and lakes, among others.

In connecting the outputs of SWAT to SEEA water, the six principles of data quality identified by Vardon et al. (2018) are relevant. These are data relevance, accuracy, timeliness, accessibility, interpretability, and coherence (Vardon et al., 2018). *SWAT output data are highly relevant to the SEEA water.* Many of these data are not collected by the Statistics departments compiling water accounts such as flows from the environment, evaporation, transpiration, soil water, and precipitation. It is noteworthy that *SWAT provides data at higher temporal and spatial resolution compared to the entries of the SEEA water.* Spatial factors influence hydrological processes (Creed et al., 2011), and SWAT demonstrates the spatial dynamics in a watershed. However, SEEA water doesn't recognize spatial heterogeneity. For instance, some locations may be small in areas, but they may have an important role in the water cycle because of their location or land cover type. SWAT can identify such areas. SWAT is also capable of describing vegetation growth, water, sediment, and nutrients circulation (Devia et al., 2015), which influence the water cycle. Besides, temporal variability is essential in the water cycle. SWAT provides daily, monthly and annual data. This temporal resolution may provide additional information on flood or drought-related issues.

SWAT's main strength lies in modeling and calibrating a series of hydrological processes that determine streamflow in a watershed, e.g., surface runoff, evapotranspiration, soil, and groundwater (Francesconi et al., 2016). Information about the accuracy of model-generated data is automatically provided through the calibration and validation process.

Uncertainties in model design, its parameters, and the measured data used in calibration affect the accuracy, appropriateness, and validity of the model (Arnold et al., 2012b). SWAT has detailed documentation, which provides disclosure of standards in the generation of simulation-based data. Its open access policy enhances the interpretability of simulation results.

SWAT outputs can be derived from various meteorological and hydrological variables that are often measured continuously, such as precipitation and streamflow. Therefore, it is possible to have regular and rapid updates of SWAT outputs as soon as these underlying data are made available.

SWAT offers access to data in multiple forms, which enables easy-to-use for exploring data and discovery. SWAT input and output data are in text and tabular formats (Arnold et al., 2012a). Consequently, SWAT output data can be easily integrated into the SEEA water template.

Statistical data, as currently collected in statistical offices, may not include all data required for the compilation of SEEA accounts. For instance, statistical offices do not routinely collect data on sub-soil water flows, even though such data would be needed for compiling water accounts and SEEA experimental ecosystem accounts. SWAT provides some of these data grouped in different spatial scales (basin, sub-basin, HRU), temporal scales (daily, monthly, annually), and hydrological elements (main reach, ponds, artificial reservoirs) (Abbaspour et al., 2015).

The interpretation of SWAT data is facilitated by detailed model documentation. SWAT documentation includes full descriptions of the underlying theories the model is based on, and detailed explanations of input and output parameters (Neitsch et al., 2011). Similar to metadata files of statistical data, SWAT provides a detailed description of terminology, limitations, unit of each output data.

The SWAT outputs have spatial and temporal coherence (Gassman et al., 2007). SWAT operates at the smallest spatial unit called hydrologic response unit, which has a unique land cover, soil type, and slope, which affect the movement of water, soil, nutrients, and chemicals. The subbasin scale information is derived from HRU calculations, and watershed scale information is derived from subbasin level data. In addition to spatial coherence, SWAT operates dynamically. Inputs and outputs of the model at a specific time affect the inputs and results of the consecutive years. Therefore, the coherence across time is naturally established through the model's dynamic nature.

At the same time, it is essential to note that compiling a SWAT model is a data-intensive and challenging undertaking. Especially when SWAT models need to be collected for all basins in a country, using SWAT to underpin water accounts would be a significant task. Also, in the case of countries are part of transboundary watersheds, a challenge arises: SWAT requires data for the whole basin or sub-basin that would, therefore, need to be shared between countries.

4.2 Implications for Water Accounting

SWAT provides more information than can be shown in SEEA water. As part of its standard presentation, SEEA water provides information on stocks and flows of water resources; and the supply and use of water within the economy (UNSD, 2012). SWAT calculates the amount of water, sediments, nutrients, and pesticide loadings from each land cover, slope, and soil type. Furthermore, SWAT provides information on the routing phase, including the discharge of water and chemical concentration in the stream and streambed. This information may be essential to identify the pressures on the water in terms of added emissions.

4.3 Policy Implications on the Buyuk Menderes Basin

Water accounts have been used as a decision support tool for different policy challenges such as mitigating the impacts of droughts (Borrego-Marín et al., 2016a), cost recovery of water services (Borrego-Marín et al., 2016b), and integrated water resource management (Momblanch et al., 2018). The Netherlands' water accounts have been used in support of the implementation of the Water Framework Directive, for monitoring of 'green growth' in the Netherlands, and selection of cost-effective water management measures (Ruijs et al., 2017). The value-added of the accounts is in establishing objective, comprehensive, and trusted baseline data in support of policy and decision making. These data can also be used as a basis for (policy) scenario analysis, where obtaining baseline data is often a key constraint (UNSD, 2014).

In the Buyuk Menderes basin, planning and research on integrated water resource management have a history of over 15 years. A river basin management plan for the Buyuk Menderes basin to implement the EU Water Framework Directive was developed in 2004 (Grontmij, 2004). The first plan included measures on better planning for water resource management. A monitoring system was designed to track the status of the water bodies in the basin. Further measures were defined for removal of waste, sectoral water use, water pricing, and institutional arrangements that were proposed to facilitate the implementation of these measures. In 2010, the Ministry of Environment prepared a basin protection plan for the Buyuk Menderes (TÜBİTAK, 2010). The plan provided a qualitative assessment of pressures on water use and suggested a set of recommendations on the reduction of point and diffused sources of pollution. The protection plan was updated in 2016 (Ministry of Environment and Urbanization, 2016). The protection plan proposed measures to control point and diffused sources of pollution.

The Ministry subsequently issued an action plan for the protection of lakes and wetlands (MOFWA, 2017; TRAGSATEC, 2018). The action plan prioritizes the preparation of the inventory of natural lakes, preparation of bathymetry maps, and water budgets of the lakes. However, the plan doesn't provide any quantitative assessment of water resources. The water accounts developed for the Buyuk Menderes basin in this paper give, therefore, complementary insights into the use of water resources in the basin. In particular, the accounts elicit the availability and use of water resources. The water accounts show, for instance, that agriculture uses 85% of the overall water resources in the basin, with water mostly from rainfall. Given that in much of the basin, water availability is a primary limiting factor in crop production (Tarim ve Orman Bakanligi, 2019), this shows the vulnerability of the basin to potential changes in rainfall patterns resulting from climate change (Tarim ve Orman Bakanligi, 2016).

The accounts also show that the amount of water that reaches the sea is negligible, indicating that all surface water in the watershed is diverted for economic use. There is also an increasing use of groundwater in the basin. Without having detailed information on the total accessible reserve of groundwater, it is difficult to assess the impact of the use of groundwater depletion. However, the water level data of the basin's groundwater observation wells show that there is depletion in the basin (Tarim ve Orman Bakanligi, 2019) (See Annex 1-Figure 5 for the trend of the level of the groundwater table). The SEEA Asset accounts also show that the current groundwater use is not sustainable: groundwater depletion was around 392 million m^3 in 2014.

The accounts detail the use of water resources by sector. Notably, drinking water abstraction per capita has decreased from 62.8 m^3 to 60.6 m^3 between 2004 and 2014. This per-capita decrease can be due to several reasons, which need to be investigated further. For instance, the end-use might have changed, or the water loss in the distribution network might have

decreased. On the other hand, the abstraction of water for drinking water in absolute terms increased by 12% from 158 million m^3 to 177 million m^3 in the period from 2004 to 2014. In the future, it will be challenging to sustain drinking water abstraction at this level, given the depletion of groundwater. The accounts also show the efficiency of water use. Between 2004 and 2014, agricultural production per cubic meter of irrigation water has decreased from 1.96 TL (in 2019 prices) to 1.92 TL (in 2019 prices). Farmers downstream usually receive less water than they demand. Therefore they invest more in efficient irrigation methods compared to the upstream farmers. If soundly implemented, accounts can enhance transparency and facilitate an earlier and fuller understanding of the interaction between environment and economy. From this perspective, aggregated accounts provide limited information. When the water accounts are spatially disaggregated, more details on dynamics between the environment and economy can be provided.

5. Conclusion

This paper examines how a hydrological model (SWAT) can be used to create a set of simulated hydrological data that can be used to develop water accounts. This approach was tested in the Buyuk Menderes basin in Turkey, where efficient management of water resources is an urgent need for the sustainable development of the region. To adapt and link SWAT to SEEA water, physical supply-use tables, and physical asset accounts were developed for the case study area. The case study shows that the SWAT model provides comprehensive spatio-temporal output data, such as precipitation, inflows, and outflows among different inland water bodies, and evapotranspiration, which is needed for developing SEEA water. This paper demonstrates how SWAT can be adapted and used in the development of water accounts, as in the case study area, at the basin, regional or national scales in other contexts.

The research shows how the SWAT output data can be used to fill data gaps, which are critical for developing comprehensive, accurate, and reliable water accounts, which in turn enables making informed judgments for the efficient use of water. Specifically, SWAT provides estimates on crop yield calculated from the total biomass, surface runoff, evapotranspiration, ground flow to inland surface water bodies, aquifer recharge, infiltration, precipitation on agricultural fields, phosphorus load, nitrate load, and sediment yield across the basin, specified by hydrological response unit. Given that much of these data are difficult to obtain through sampling, hydrological models such as SWAT are essential for preparing comprehensive water accounts.

At the same time, the SWAT model is more detailed than the SEEA water in terms of the number of hydrological variables covered and the spatial and temporal resolution. For example, SWAT can supply hydrological data on a daily basis, whereas the SEEA water usually aggregates data over months, seasons, or years. Also, SWAT allows modeling the impacts of land use change on water flows, which is highly relevant for SEEA Experimental ecosystem accounting (since it can reveal hydrological ecosystem services, see, e.g., Duku et al., 2015 and Francesconi et al., 2016) but is less relevant for SEEA water. Using SWAT in filling data gaps in SEEA water brings its limitations. Compared to some other models, compiling a SWAT model is a data-intensive undertaking, and modeling of lakes is challenging, even though some of the required meteorological and spatial data (DEM, land cover, and soil type) are available from global datasets. Hence, SWAT should be considered on a case-by-case basis.

Further integration of SEEA Central Framework, SEEA water, and SEEA Experimental ecosystem accounting by the statistical community could consider better aligning hydrological models and the SEEA framework. In particular, it is important to ensure that the most relevant hydrological parameters are captured in SEEA, that information

not relevant from a hydrological or policy perspective (such as stocks of river water) is excluded, and that a minimum amount of modeling effort is required to populate the various SEEA accounts.

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Figure 1

Figure 2

Figure 3

Table 1

Sector	**Use**	**Years**	**Data Source**
Agriculture, forestry and fishing	Irrigation	2000-2015	Peer-reviewed articles
Mining and quarrying	Final Water Consumption Wastewater	2010, 2012, 2014	Derived from the SSI's Water, Wastewater and Waste Statistics of the Mining Sector (State Statistics Institute, 2014b)
Manufacturing and construction	Process water Boiler water Cooling water Domestic water Wastewater	2004, 2008, 2010, 2012, 2014	Derived from the SSI's Water, Wastewater and Waste Statistics of the Manufacturing Industry (State Statistics Institute, 2014c)
Electricity, gas, steam and air conditioning supply	Turbine water	2000-2015	Own calculation
Water collection, treatment and supply Wastewater	Municipal Drinking Water Municipal Wastewater	2001-2004, 2006, 2008, 2010, 2012, 2014	(State Statistics Institute, 2014a)

Table 2

SUPPLY YEAR: 2004

Abstraction of water; production of water; generation of return flows 000 m3

Physical supply table for water	**Agriculture, forestry and fishing**	**Mining and quarrying**	**Manufacturing and construction**	**Electricity, gas, steam and air conditioning supply**	**Water collection, treatment and supply**	**Sewerage**	**Households**	**Flows from the environment**	**Total supply**
(I) Sources of abstracted water									
Inland water resources									
Surface water								2,198,022	**2,198,022**
Groundwater								156,759	**156,759**
Soil water								0	**0**
Total								**2,354,780**	**2,354,780**
Other water sources									
Precipitation								*16,006,329*	**16,006,329**
Sea water								6	**6**
Total								**16,006,335**	**16,006,335**
Total supply abstracted water								**18,361,116**	**18,361,116**
(II) Abstracted water									
For distribution					**56,704**				**56,704**
For own-use	17,448,685	2,949	12,882	738,768	101,128	0			**18,304,412**
(III) Wastewater and reused water									
Wastewater									
Wastewater to treatment	0	131	2,323				30,786		**33,240**
Own treatment	0	546	11,208			0			**11,754**
Reused water produced									
For distribution	0	0	0			0			**0**
For own use	0	0	0	0	0	0	0		**0**
Total	**0**	**677**	**13,532**	**0**	**0**	**0**	**30,786**		**44,994**
(IV) Return flows of water									
To inland water resources									
Surface water		6,269	11,985	738,768	0	53,651	0		**810,674**
Groundwater		290	1,467		0	3,071			**4,829**
Soil water	4,130,393	0	0			0			**4,130,393**
Total	**4,130,393**	**6,560**	**13,452**	**738,768**	**0**	**56,723**	**0**		**4,945,896**

To other sources		306	515			9,689			**10,511**
Total return flows	**4,130,393**	**6,866**	**13,967**	**738,768**	**0**	**66,412**	**0**		**4,956,407**
of which: Losses in distribu-tion					101,128		453		**101,582**
(V) Evaporation of abstracted water, transpiration and water incorporated into products									
Evaporation of abstracted water	*11,949,298*	6,846	7,473			0			**11,963,618**
Transpiration						0			**0**
Water incorporated into products	17,449	0	0			0			**17,449**
Total supply	**33,545,825**	**17,338**	**47,854**	**1,477,537**	**258,960**	**66,412**	**31,239**	**18,361,116**	**53,806,281**

Table 3

YEAR: 2004

USE	Abstraction of water; intermediate consumption; return flows						Final consumption			000 m3
	Agriculture, forestry and fishing	Mining and quarrying	Manufacturing and construction	Electricity, gas, steam and air conditioning supply	Water collection, treatment and supply	Sewerage	Households	Accumulation	Flows to the environment	Total supply
	A	M	M2	E	W	S	H		V	T
(I) Sources of abstracted water										
Inland water resources										
Surface water	1,442,368	1,256	2,100	738,768	13,530	0				**2,198,022**
Groundwater	0	1,681	10,776	0	144,302					**156,759**
Soil water	0									**0**
Total	**1,442,368**	**2,937**	**12,876**	**738,768**	**157,832**	**0**				**2,354,780**
Other water sources										
Precipitation	*16,006,317*	12	0			0				**16,006,329**
Sea water	0	0	6	0	0					**6**
Total	**16,006,317**	**12**	**6**	**0**	**0**	**0**				**16,006,335**
Total supply abstracted water	**17,448,685**	**2,949**	**12,882**	**738,768**	**157,832**	**0**				**18,361,116**
(II) Abstracted water										
Distributed water	0	72	9,390	0		0	47,242			**56,704**
Own-use	**17,448,685**	**2,949**	**12,882**	**738,768**	**101,128**	**0**				**18,304,412**
(III) Wastewater and reused water										
Wastewater										
Wastewater received from other units						33,240				**33,240**
Own treatment	0	546	11,208	0	0	0	0			**11,754**
Reused water received										
From distribution	0									**0**
From own wastewater	0	0	0	0	0					**0**
Total	**0**	**546**	**11,208**	**0**	**0**	**33,240**	**0**			**44,994**
(IV) Return flows of water										
To inland water resources									*4,945,896*	**4,945,896**

To other sources									10,511	**10,511**
Total return flows									**4,956,407**	**4,956,407**
(V) Evaporation of abstracted water, transpiration and water incorporated into products										
Evaporation of abstracted water									11,963,618	**11,963,618**
Transpiration									0	**0**
Water incorporated into products								17,449		**17,449**
Total Use	34,897,369	6,515	46,362	1,477,537	258,960	33,240	47,242	17,449	16,920,025	**53,704,699**

Table 4

Stock Accounts 2014 (*) (**)

000 m3

	Surface water				
	Artificial reservoirs	**Rivers and streams**	**Groundwater**	**Soil water**	**Total**
Opening stock of water resources	***3,678,320***				
Additions to stock					
Returns	1,482	809,192	4,829	4,130,393	4,945,896
from hydro power plants		*738,768*			738,768
from other economic activities	*1,482*	*70,424*	4,829	4,130,393	4,207,128
Precipitation	*82,405*			14,979,171	15,061,576
Inflows from other territories					
Inflows from other inland water resources	8,338,165	6,300,581	1,808,827	*-355,106*	16,092,467
from surface water	*5,211,526*	*5,034,865*	*0*	*965,667*	11,212,058
from subsurface water	*3,126,639*	*1,265,717*	*1,808,827*	*-1,320,774*	4,880,410
Discoveries of water in aquifers					
Total additions to stock	8,422,051	7,109,773	1,813,657	18,754,458	36,099,940
Reductions in stock					
Abstraction	2,198,022		156,759	0	2,354,780
for irrgigation	1,442,368				1,442,368
for hydropower generation	738,768				738,768
for process water (including mining)	3,356		12,457		15,812
for drinking water	13,530		144,302		157,832
Evaporation and actual evapotranspiration	*131,141*	268,297		11,549,861	11,949,298
Outflows to other territores			0		0
Outflows to the sea		2,128	0		2,128
Outflows to other inland water resources	4,734,815	6,839,348	*2,032,894*	2,485,410	16,092,467
to surface water	*4,734,815*	5,211,526	*589,135*	676,582	11,212,058
to subsurface water		1,627,822	*1,443,760*	1,808,827	4,880,410
Total reductions in stock	7,063,977	7,109,773	2,189,653	14,035,270	30,398,674
Closing stock of water resources	***3,875,410***				

* Green color in the table shows the data obtained from SWAT, light blue color shows the subtotals and dark blue shows the grand totals.

** Ground water withdrawal value (170,971) only includes the withdrawals from 'Mining and quarrying', 'Manufacturing and construction', and 'Water collection, treatment and supply, Sewerage'. The data on withdrawal of groundwater for irrigation are not publicly available, therefore not included in the accounts.

Credit Author Statement

Sitki Ersin Esen: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization.

Lars Hein: Supervision, Conceptualization, Methodology, Formal analysis, Writing - Review & Editing, Project administration, Funding acquisition.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- SEEA water records, water availability, use, and quality.
- SWAT hydrological modeling is instrumental in compiling water accounts.
- Detailed physical supply-use tables and asset accounts show how water is used in the Buyuk Menderes Basin, Turkey.
- Water accounts facilitate managing scarce water resources in the Buyuk Menderes Basin.

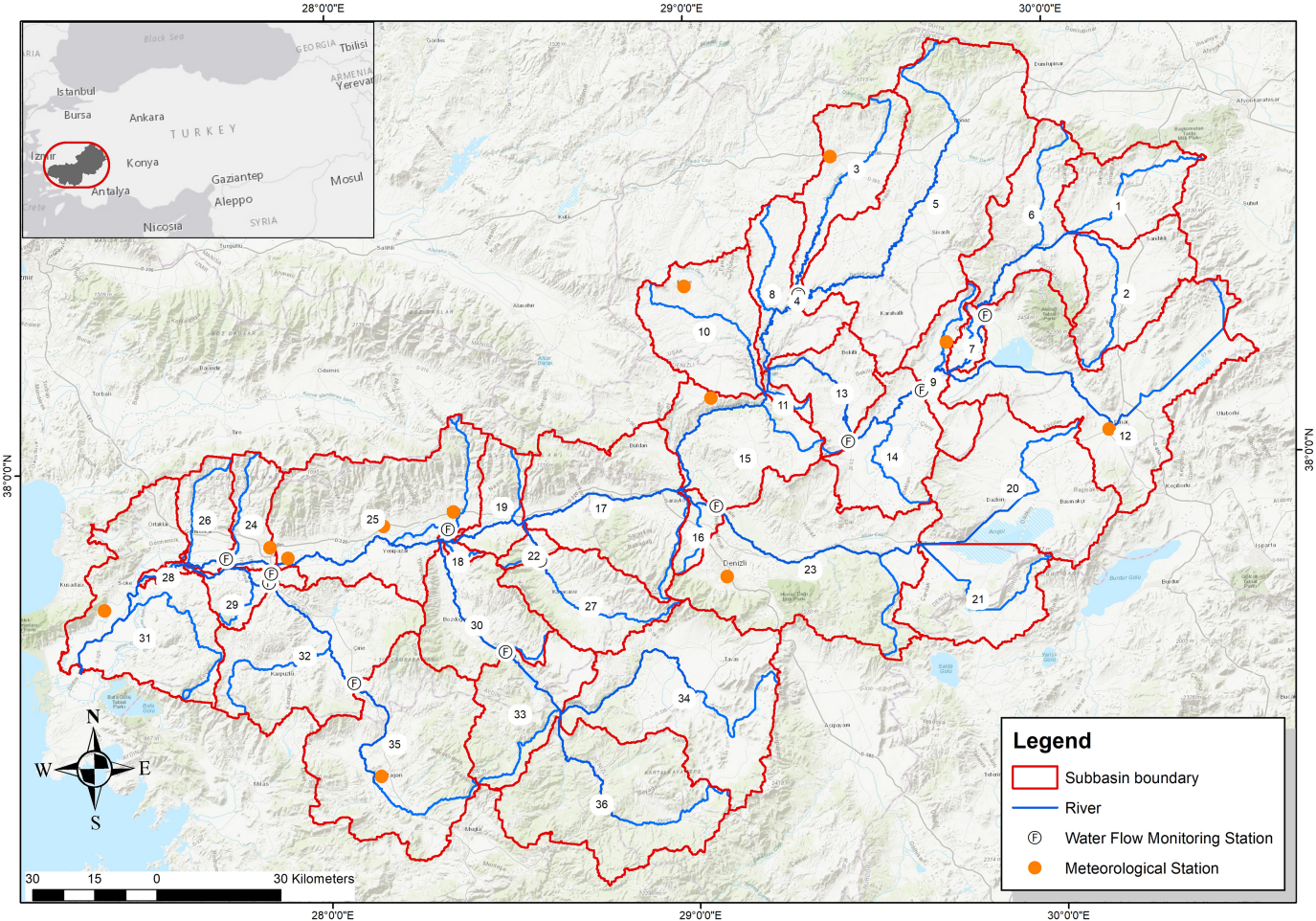
28°0'0"E
29°0'0"E
30°0'0"E
38°0'0"N
Black Sea
GEORGIA
Tbilisi
ARMENIA
Yerevan
Istanbul
Bursa
Ankara
TURKEY
İzmir
Konya
Gaziantep
Mosul
Antalya
Aleppo
Nicosia
SYRIA
Legend
Subbasin boundary
River
Water Flow Monitoring Station
Meteorological Station
N
W
E
S
30
15
0
30 Kilometers

Figure 1

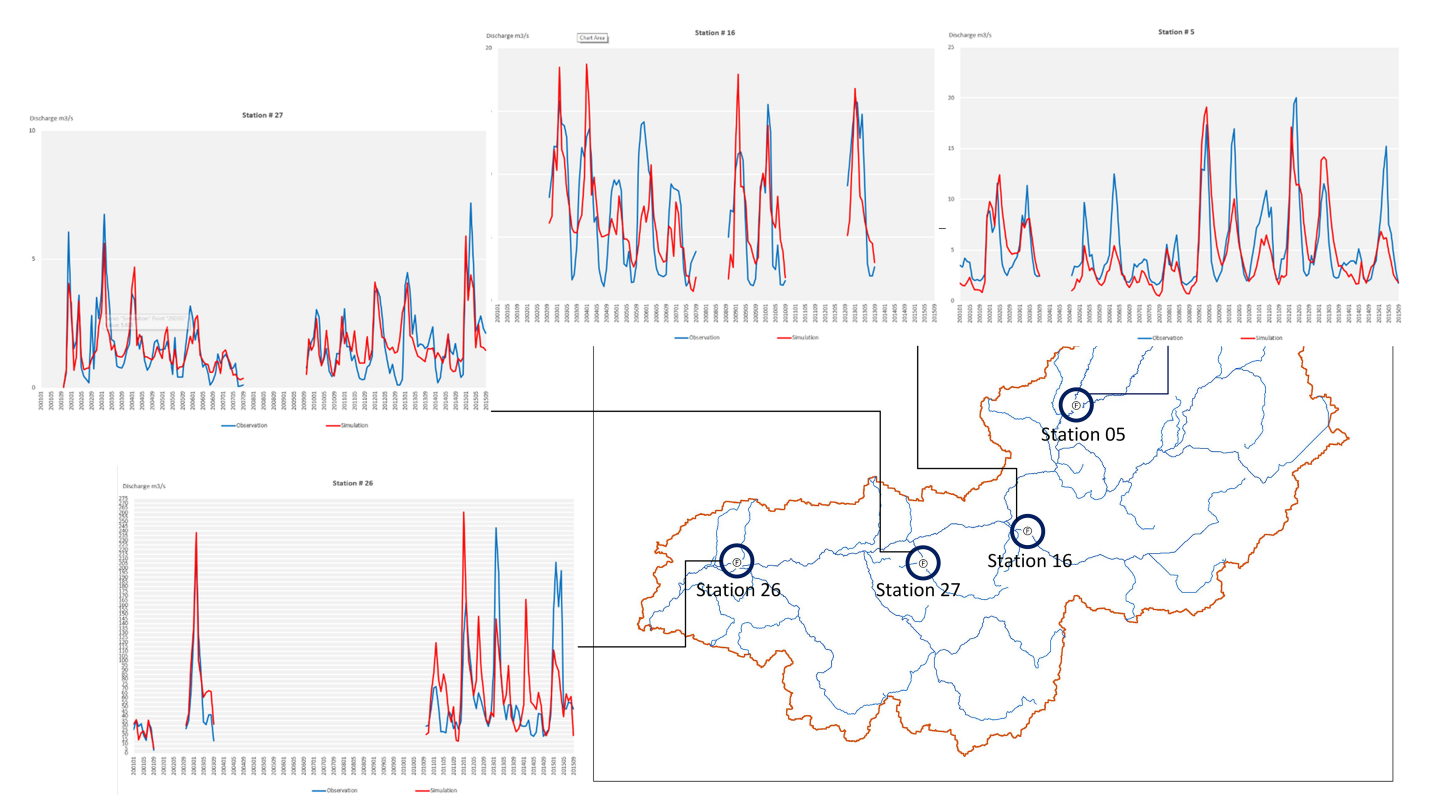
Station # 27
Discharge m3/s
Observation
Simulation
Station # 16
Discharge m3/s
Chart Area
Observation
Simulation
Station # 5
Discharge m3/s
Observation
Simulation
Station # 26
Discharge m3/s
Observation
Simulation
Station 05
Station 16
Station 26
Station 27

Figure 2

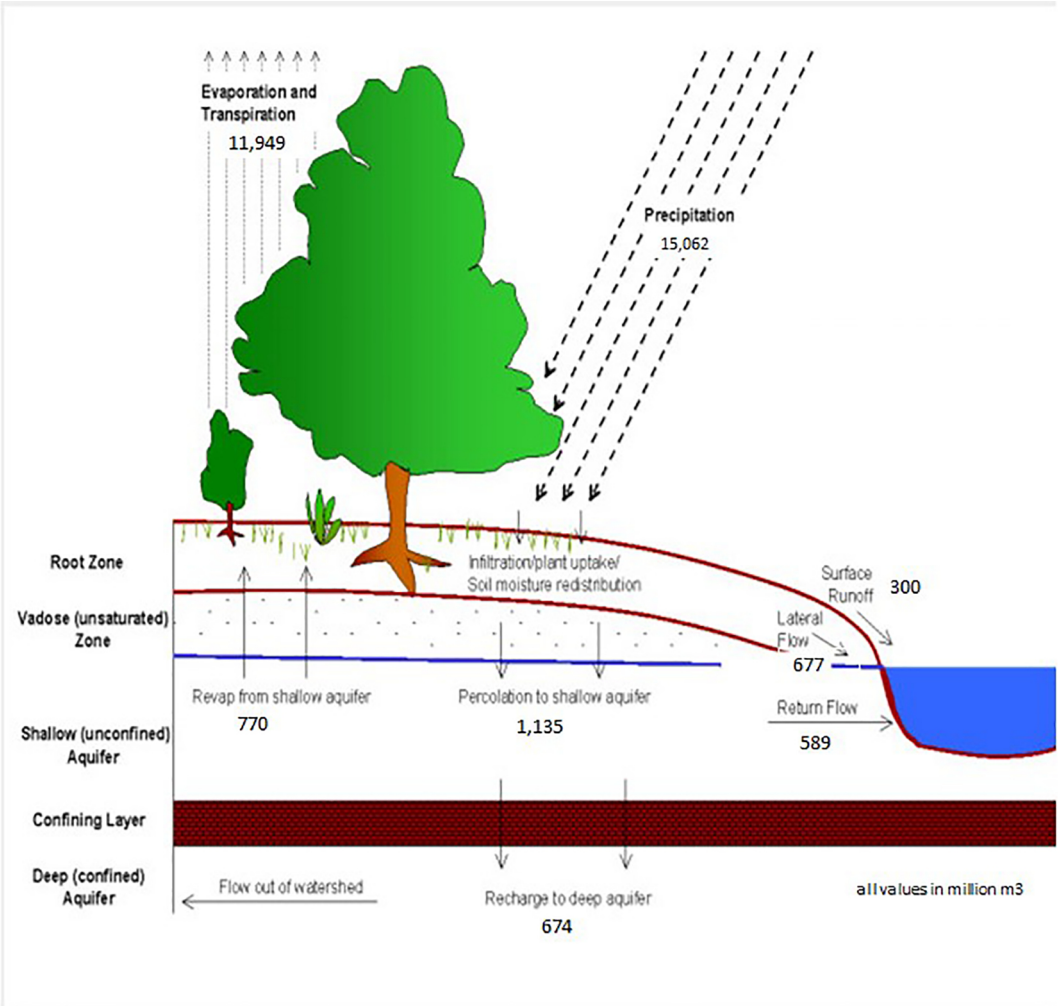
Evaporation and Transpiration
11,949
Precipitation
15,062
Root Zone
Vadose (unsaturated) Zone
Infiltration/plant uptake/ Soil moisture redistribution
Surface Runoff
300
Lateral Flow
677
Revap from shallow aquifer
770
Percolation to shallow aquifer
1,135
Return Flow
589
Shallow (unconfined) Aquifer
Confining Layer
Deep (confined) Aquifer
Flow out of watershed
Recharge to deep aquifer
674
all values in million m3

Figure 3