**Appendix 1**

This appendix has the purpose of extending the methodological description including detailed calculation of variables and modeling validation.

**Scales**

Even though watersheds are the object of study of hydrology par excellence, they are not in societal metabolism of water. One of the main reasons is the scale mismatch on available data. Economic variables are crucial to study the self-organization of social systems. These are not usually available at the exact boundaries of a catchment and have either to be aggregated from lower administrative divisions (municipalities or similar), or disaggregated from upper ones. Focusing on the watershed level we gain connection with eco-hydrological processes and water governance but we lose the capacity to delve in the economic relations within the social system. To this purpose, administrative units are more appropriate as analytical extent (see for instance Madrid et al. 2014).

Agriculture is commonly the main water consumer in a river basin and the societal metabolism approach to agro-ecosystems is the rural systems analysis (Ravera et al. 2014, Serrano and Giampietro 2014). It focuses on the allocation of land and human activity in terms of time use of rural households and the associated production and consumption of biophysical and monetary flows (Scheidel 2013). These studies are usually carried out at local scales, gathering data and building metabolic typologies on a bottom up basis through surveys to farmers and households. The size of a river basin and the necessary consideration of urban water require coarser modeling resolutions.

River basins are always middle scales, between the social and hydrological, between the local and the regional, between the rural and the urban. Allen and Hoekstra, 1992:64 shed light on the problematic with middle scales: “these have too many parts to model each one separately, but not enough to allow averages that fully subsume the individuality of the part. Questions that cannot be answered imply a middle number system specification. They are unpredictable because the constraint structure is unreliable. […] At middle scales, each part of the landscape has its own individual explanation”. The multi-axes holarchic representation (Figure 2b of the paper) is an attempt to escape this middle scales dialectic. Any holon results from the composition between the observed system and the observer interests. We set the organizational levels for our system, and with them the relevant parts of the system that we want to observe. There is a tendency to augment the size of the system and thus its spatial extent with the level, but holons can be analyzed at any temporal and spatial scale (we can study a rock holding it with our hand or looking through a microscope). Main constraints are data availability and modelling capacity.

Figure 1 shows the temporal and spatial levels used for the Upper Andarax grammar according to these constraints. We run the BalanceMED model on temporal monthly and spatial Hydrological Units (HU) resolutions. Results were aggregated to the extents of one year and land uses and covers types. Socioeconomic data are available for a variety of grains (see Table 1). Human activity is mapped for whole urban areas (municipal level) and agricultural land uses for irrigation communities and rain-fed agriculture polygons. Note that we could do a municipal level analysis (comparing each municipality Land-Human activity budgets) but this would enlarge the amount of results and loose the purpose of the study: the operationalization of the SESWM framework for the analysis of water management at river basin scale. As Schneiel 2013 explains "every kind of data collection is always a 'heroic simplification' of a complex rural system and the issue is rather to find the adequate simplification, which allows answering some relevant research question". A more detailed hydrological resolution and, especially, temporal series of water use would clearly improve the method analytical potential.

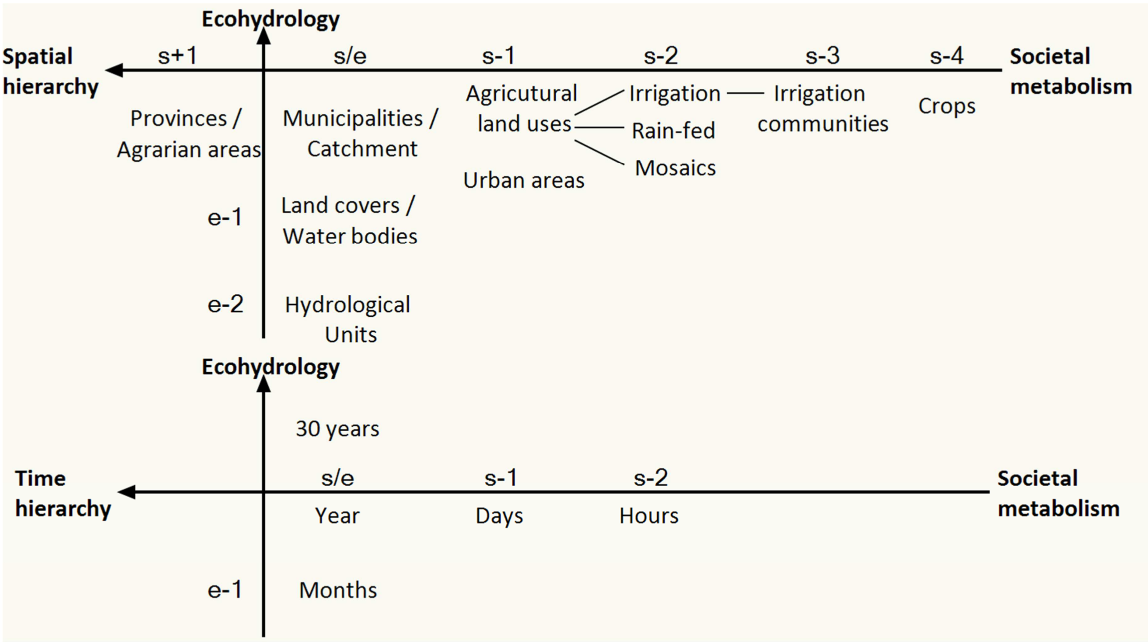


**Figure 1-** Temporal and spatial hierarchies in the Upper Andarax water grammar

**Conceptual model and formal categories**

The conceptual model for variables calculation is presented in Figure 2 and the formal categories of the grammar in Table 1. Codes and databases can be downloaded here:

https://www.dropbox.com/sh/45za6hqmnjelqoi/AAD-ObuilYtGzFwVKyJ_WzQ5a?dl=0

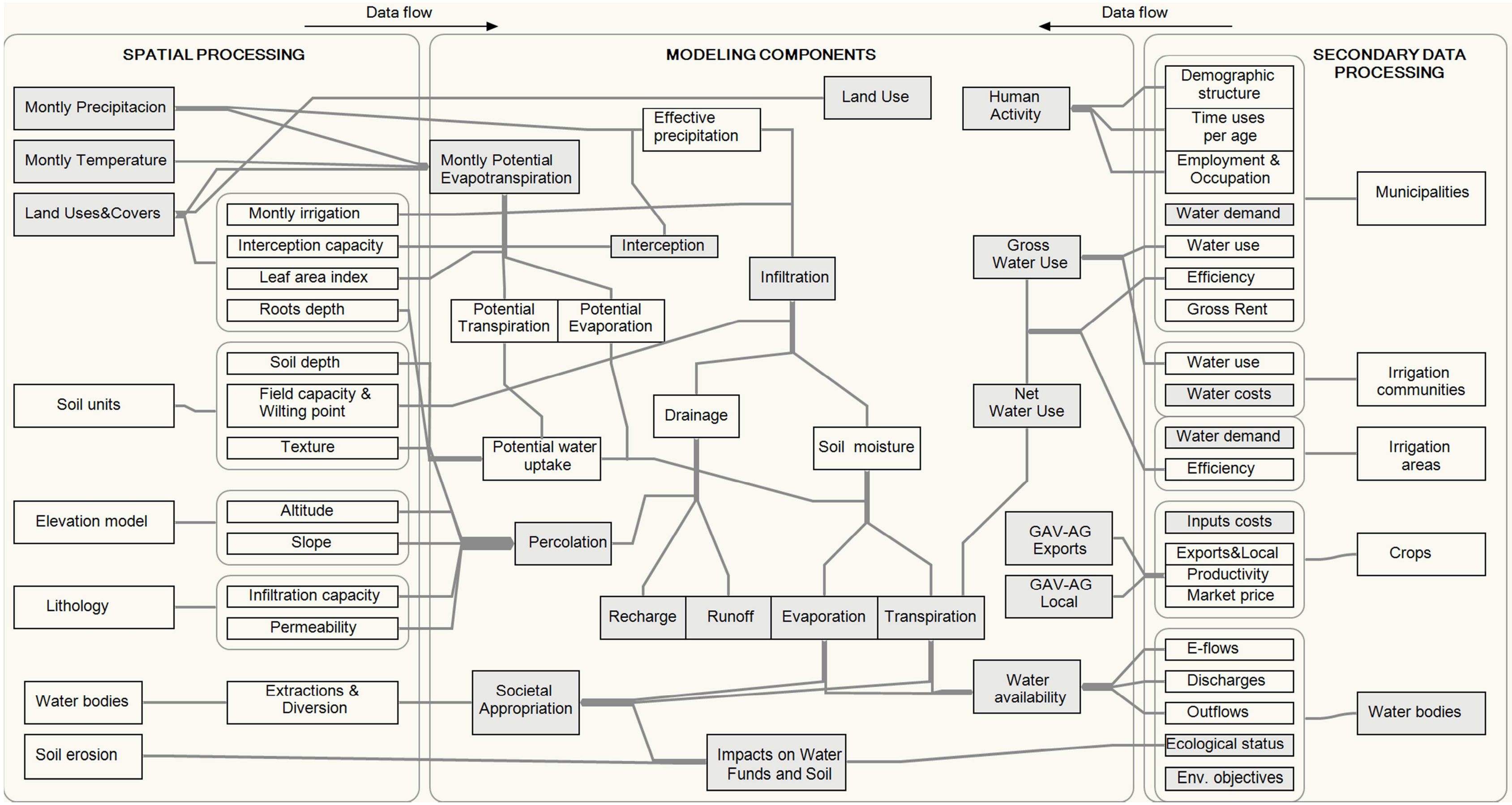


**Figure 2 -** Conceptual scheme for water grammar formalization

**Table 1**- Formal categories of the water grammar

| *Semantic categories* | *Types* | *Description* | *Units* | *Temporal resolution* | *Spatial resolution* | *Data sources* |
|---|---|---|---|---|---|---|
| **Water exchange** | | | | | | |
| Climate | Precipitation | Average precipitation from the series 1970-71/2000-01 | mm/$Hm^3$ | Months | Raster 10 m | Secondary Climatic Stations National Network (8) |
| Water funds turnover | Runoff | Total runoff to surface water bodies | mm/ $Hm^3$ | | HU | BalanceMED |
| | Recharge | Infiltrated rain water that percolates to aquifers | | | | BalanceMED, APPLIS recharge model |
| | Soil Infiltration | Infiltrated rain water that is evapotranspired or contributes to soil reserve | | | | BalanceMED |
| Societal appropriation & Availability | Surface | Direct diversion from the river for human uses | $Hm^3$ | Year | Municipalities &Irrigation communities | (1), (2), (3) |
| | Groundwater | Extractions from aquifer | $Hm^3$ | | | |
| | Soil water | Soil moisture in land used by humans | mm/ $Hm^3$ | Months | HU | BalanceMED |
| Gross water use | Withdrawn | Ground and surface water consumption | $Hm^3$ | Months | Municipalities &Irrigation communities | (1), (2), (3) |
| | Soil | Evapotranspiration from land uses | | Months | HU | BalanceMED |
| Net water use | Urban supply | Water supply*Efficiency in supply chain | $Hm^3$ | Year | Municipalities | (1), (2) |
| | Food production | Water withdrawal for agriculture*Efficiency in supply chain*Efficiency of irrigation system + Transpiration from rain water | | Months | Agricultural areas & Irrigation communities | (1), (4), (5) |
| | Forestry &*Esparto* gathering | Transpiration from rain water | | Year | Land cover polygons | BalanceMED |
| | Cattle | Surface water requirements + transpiration from rain water | | Year | Watershed, land cover | (1), BalanceMED |
| | Loses | Gross Water Use minus Net Water Use | | Year | Municipalities& irrigation areas | (1), (2), (3) |
| Water demand | | Deficit for irrigation purposes in the RBMP | | Year | Irrigation areas | (1) |
| Water rights | | Authorized withdrawals from each water | | Year | Water bodies | (1) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | body | | | | |
| **Organization** | | | | | | |
| Climate | Temperature | Average precipitation from the series 1970-2001 | ºC | Months | Raster 10 m | Secondary Climatic Stations Network (8) |
| Water bodies | Rivers | Descriptive category: water bodies types considered in the RBMP | - | 6 years | 6 years | (1) |
| | Aquifers | | | | | |
| Land covers | | Surface occupied by land cover types | Hectares | 4 years | Land cover polygons | Map of Land Uses and Covers of Andalusia 2003 (9) |
| Managed land uses | | Surface occupied by land uses types under managed land | Hectares | 4 years | Land use polygons | |
| Human activity | Physiological overhead | Hours devoted to personal care, eating, sleeping and dependent people time | Hours | Hours | Municipalities | Time Use Survey of Almeria province 2002/03 (10)<br>Spanish Population and Households Census 2001 (11)<br>Local population census 2005 and 2011 (10) |
| | Social, Leisure &Education | Hours devoted to traveling, leisure activities, education and volunteering | | | | |
| | Unpaid work | Hours devoted to households work | | | | |
| | Paid Work | Hours devoted to each type of paid work sector by the working population | | | | |
| Technical capital | Hydraulic infrastructures | % of surface of irrigation communities supplied by acequias | % | Year | Crop types | (3) |
| | Irrigation technology | % of surface of irrigation communities with drip irrigation | | | | (3) |
| Monetary exchange | Agricultural inputs& Water costs | Total expenditures of irrigated agriculture on water and other inputs | € | | Crops types & Irrigation communities | (3), (7) |
| | Gross Added Value | Total income from local and external markets | | | Crops types | (3), (6) |

(1) CMAT 2012. Andalusia Mediterranean River Basins Management Plan 2009-2015. [online] URL: http://www.juntadeandalucia.es/medioambiente/site/portalweb/menuitem.7e1cf46ddf59bb227a9ebe205510e1ca/?vgnextoid=6d3173f2c746a310VgnVCM2000000624e50aRCRD&vgnextchannel=0bb66af68bb96310VgnVCM1000001325e50aRCRD

(2) Martinez, J. 2011. Energy Footprint of the urban water supply in Almeria province.

(3) CA 2008. Inventory and characterization of irrigation in Andalusia. [online] URL:

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(4) Fundación Cajamar. 2004. Irrigation doses for intensive horticulture in Almeria.[online] URL: http://www.publicacionescajamar.es/series-tematicas/centros-experimentales-las-palmerillas/
(5) CA 2011. System of technical assistance to farmers of the Andalusian government. [online] URL: http://www.juntadeandalucia.es/agriculturaypesca/ifapa/sar
(6) CMAT 2006. Andalusia Multiterritorial Information System. [online] URL: http://www.juntadeandalucia.es/institutodeestadisticaycartografia/sima/index2.htm
(7) CA 2005. Annual statistics on agriculture and fishing of Andalusia. [online] URL: http://www.juntadeandalucia.es/agriculturaypesca/portal/servicios/estadisticas/estadisticas/agrarias/resumen-anual.html
(8) AEMET. Spanish State Agency of Meteorology. [online under payment] URL: http://www.aemet.es/es/serviciosclimaticos/datosclimatologicos
(9) REDIAM. Andalusian Network for Environmental Information. [online] URL: http://www.juntadeandalucia.es/medioambiente/site/rediam
(10) IECA. Andalusian Statistical and Cartography Office. [online] URL: http://www.juntadeandalucia.es/institutodeestadisticaycartografia
(11) INE. Spanish Statistical Office. [online] URL: http://www.ine.es/jaxi/menu.do?type=pcaxis&path=%2Ft20%2Fe242&file=inebase&L=0

**BalanceMED**

*Precipitation and potential evapotranspiration*

GIS raster layers of average monthly precipitation and potential evapotranspiration (PE) variables were obtained from the Andalusian Network for Environmental Information (REDIAM) for the period 1971-2000. Monthly scale reflects better the normal Mediterranean environmental conditions due to the usual lack of rainfall in finer time scales generated by long periods of water deficit. This source of information was chosen because it is the same used by the River Basin Authority for hydrological modeling. We found hydrological variables (runoff and recharge) were greatly overestimated using this data source. Mean values are usually not representative when dealing with very irregular regimes with skewed precipitation density functions such as the ones in the Andarax. In arid and semiarid climates, the median as central statistic measure is more robust. For this reason, median monthly values of were obtained at the closer 24 meteorological stations with available data for the 1971-2000 period (within a buffer of 10 km). These stations belong to the Spanish State Agency of Meteorology and only provide temperature and rainfall data. PE was estimated using an excel macro based on Thornthwaite method (HydroBio3, Camara and Martinez 2002). All data series where then spatialized using the Inverse Weighted Distance interpolation in ArcGIS 10.2 to obtain continuous information to be entered in the model. Results significantly improved making estimates closer to real conditions.

*Hydrological units processing*

Hydrological units are obtained from the intersection of soil and land cover GIS layers. Previously, several parameters were calculated for each of them. Roots depth, Leaf Area Index and interception capacity were gathered for vegetation species through literature review. Weighted means per number of species were obtained for each land cover unit. Soil parameters are wilting point, field capacity and soil depth. These are calculated from data on lime, clay and organic matter fractions extracted from the soil cartography of the Desertification Prevention in the Mediterranean Project (LUCDEME) of the Spanish Ministry of Agriculture.

*Percolation*

The APLIS equation was proposed by Andreo et al. 2004 for determining the average rate of recharge in carbonate aquifers. This rate is expressed in BalanceMED as a percentage of drainage for each hydrological unit and calculated as:

$$R(\%) = (A + S + 3L + 2I + S)/90$$

Where A is the Altitude, S is the Slope, L is the Lithology, I the preferential Infiltration layers and S the Soil. Punctuation categories are established for each variable between one (minimal influence in recharge) and ten (maximum influence). In our study, slope was corrected to zero for agricultural land uses in order to introduce the leveling effect of terraces. These parameters are averaged for HU grain.

*Model calibration, validation and limitations*

A detail description of BalanceMED can be found in Willaarts et al. 2012. For this study, the model was translated from a Microsoft Excel macro to an R script to gain flexibility for future implementations. Model calibration was done through standard hydrograph plot (Figure 3). Monthly volumetric runoff rates are recorded at the only one available gauging station in the basin for the time series 1971-2000. Mean-monthly values of observed runoff were contrasted against model runoff. The peak of runoff in April responds to the monthly precipitation pattern but is not observed in the gauging station likely because it is the month were irrigation starts and pools are filled with diversions from river.

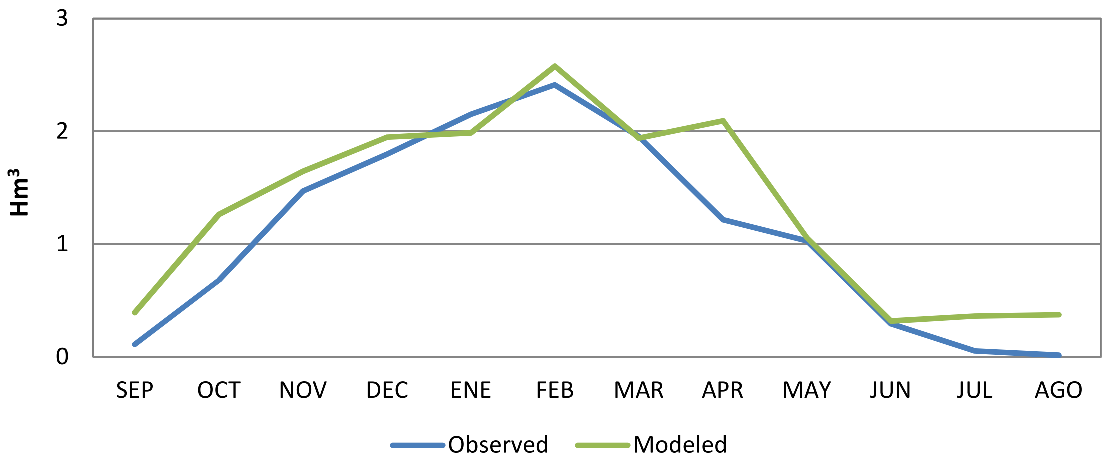


**Figure 3 -** Plot of observed vs modeled runoff volumetric rates

In order to validate results, the evaluation statistics recommended by Moriari et al. 2007 were used: (i) the Nash-Sutcliffe efficiency (NSE) which indicates how well the plot of observed versus simulated data fits the 1:1 line, (ii) the Percent bias (PBIAS) which measures underestimation tendency of the model and (iii) the RMSE-observations standard deviation ratio (RSR), which is a standardized version of the root mean square error. The model performance can be judged as satisfactory according to these criteria (NSE > 0.50 and RSR < 0.70, and if PBIAS ≤25% for streamflow) (Table 2). The model efficiency shows a good plot fit between observed and simulated data. The PBIAS indicate a slight overestimation of runoff.

**Table 2 -** Model evaluation of BalanceMED. Three metrics were calculated to validate modelresults: Nash-Sutcliffe efficiency (NSE) (range =−∞/1, optimum 1); Percent bias (PBIAS) (range =−∞/+∞, optimum 0); and RMSE-observations standard deviation ratio (RSR)(range =0/+∞, optimum 0).

| Statistics | Value |
|---|---|
| NSE | 0.80 |
| PBIAS | 12.00 |
| RSR | 0.44 |

*Post processing water grammar variables*

Main results from BalanceMED are the volumetric variables of recharge, runoff, soil infiltration, transpiration and evaporation on a monthly and HU resolution. Intensive variables (mm or $m^3$/ha) used for spatial analysis of ecosystems-water funds relation are obtained by weighted means per area for each type of LULC considered. Extensive volumetric variables (total $Hm^3$) were obtained by aggregation per HU area.

**Societal metabolism**

*Human activity*

A thorough description of human activity accounting can be found in Kovacic and Ramos-Martin 2014. The Total Human Activity in a given society is calculated in hours as:

$$THA_{year\ i} = 365 * 24 * Population_{year\ i}$$

This total is disaggregated in subsequent hierarchical levels according to case-study objectives. In our case, the categories considered are explained in Table 1 and the equation to valid is:

$$THA_{2005} = HA_{PO} + HA_{SLE} + HA_{UW} + HA_{PW}$$

Where *PO* is physiological overhead; *SLE* is social, leisure and education; *UW* is unpaid work; *PW* is paid work. These variables were calculated for each municipality with data on employment, occupation, education and demographic structure from Spanish Census of Population and Households 2001 and the Time Use Survey 2002-03 for Almeria province. This latter establishes shares of hours devoted to the different activities in a day per age ranges. Since that information is only available every ten years in Spain, the obtained human activity shares were then extrapolated to the population evolution until 2005. Considering there was not mayor societal changes those years (pre economic crisis 2008 scenario), it is a reasonable assumption. The new census 2011 collected data from 2011 to 2013 and did not reach the same detailed level of municipality for required data inputs. For this reason it is not possible to update the human activity budget.

*Land uses*

Two geographical layers were used for the land budget analysis: the Map of Land Uses and Covers of Andalusia 2003 (MLUCV03) and the Inventory and characterization of irrigation in Andalusia 2008 (ICIA08). This latter collected data through surveys to Irrigation Communities from 2002 to 2008 and is the baseline used for the RBMP. It contains crops surface per irrigation community. Categories of irrigated agriculture in the MLUCV03 were coerced to match those of the ICIA08. For the rest of land uses and covers, we broke the hierarchical structure of the MLUCV03 in order to group them in types and levels relevant our analysis. MLUCV03 was intersected with the parks boundaries to obtained categories of land management. For each type of LULC and protection category (High protection in the National Park, Medium protection in the Natural Park, no protection in the rest of the watershed) a land use ratio was assigned as shown in Table 3.

**Table 3 –** Land and soil water use coefficients.

| | High protection | Medium protection | Not protected | Water uses |
|---|---|---|---|---|
| Irrigated agriculture | 1 | 1 | 1 | Irrigated agriculture |
| Rainfed agriculture | 1 | 1 | 1 | Rainfed agriculture |
| Abandoned | 0 | 0 | 0.2 | Grazing |
| Quercus forest | 0 | 0.1 | 0.2 | Forestry |
| Pine plantations | 0 | 0.1 | 0.2 | Forestry |
| Riparian forest | 0 | 0 | 0 | |
| Shurbs | 0 | 0.2 | 0.3 | Grazing (2/3) and |

| | | | | |
|---|---|---|---|---|
| | | | | gathering (1/3) |
| Pastures | 0 | 0.3 | 0.5 | Grazing |
| Urban | 0 | 1 | 1 | Urban supply |

*Monetary flows and technical capital*

Crops economic data and irrigation infrastructures were also double-sourced:

- Irrigated crops: Gross Added Value/ha, Working Days/ha, agriculture Inputs Costs/ha and Water Costs (cent €/$m^3$) were obtained from ICIA08. The type of trade (exports, local or self-consumption) and water supply and irrigation systems are also included in this database. Total extensive variables were obtained for each type of crop and trade.

- Rain-fed crops: production in Tons/ha per type of crops and prices received by farmers in €/100 kg were obtained from the annual statistics on agriculture and fishing of Andalusia 2005. Total Gross Added Value per crop was estimated based on the surface of rain-fed agriculture land uses.

There is no available data of added value for other economic activities than agriculture at municipal level. The total Gross Rent in the basin is calculated aggregating for each municipality rent per capita.

*Water use*

Water withdrawals and use were obtained from three sources:

- The Andalusia Mediterranean River Basins Management Plan 2009-2015, which includes extraction from different sources, water allocation to different uses and average irrigation efficiencies.
- The Inventory and characterization of irrigation in Andalusia 2008– ICIA08 contains data on gross water use for each irrigation community from different sources. Net water use was estimated by multiplying for the average efficiency in their area.
- The report from Martinez 2011 is the only data source with actual urban gross and net water use measured data for all municipalities in the Almeria province as well as water sources.

These variables are provided for one year. For seasonal analysis, monthly irrigation was estimated based on schedules from the technical assistance to farmers system of the Andalusian government and personal communication from farmers in the area. Multi-crops areas were averaged. Urban water was broken into equal monthly shares for residents and commercial uses and non-residential use was added to summer months. Water withdrawals were spatialized by splitting the river length in segments according to water withdrawal points by each municipality and irrigation community. Soil water use is calculated applying the same coefficients of land covers use and relating them to activities presented in Table 3. Gross water use is the total evapotranspiration and net water use is transpiration in those covers. The separation of transpiration from irrigation and from rain water was obtained by the difference between running the model with and without irrigation.

**Ecosystem health**

The assessment of the ecological status of water bodies is the baseline of the RBMP. Aquifers are evaluated on their quantitative (exploitation index) and qualitative (pollution) status. Rivers are evaluated on their biological (biodiversity), hydro-morphological and physic-chemical status. The information provided in the plan is rather dated (only one sampling campaign) and the final evaluation based on expert evaluation. We provide additional analysis of available secondary data to complement and discuss this assessment: erosion rates, water table levels and surface and groundwater quality.

The cartography of average erosion rates for the period 1992-2006 is available at the natural hazards section of the Andalusian Network of Environmental Information [Online] URL: http://www.juntadeandalucia.es/medioambiente/site/rediam/portada/. The calculation method used by the Andalusian Environment Agency is the Universal Soil Loss Equation (USLE) and the scale set by this institution by normalizing the range of average soil loses values in the region from low (<12 ton/ha yr) to high (>50 ton/ha yr). Water table levels change was also averaged for the available series from 1992-2006 from the network of piezometers of the Spanish Institute of Geology and Mining Water Database [Online] URL: http://info.igme.es/BDAguas/. There are more control piezometers but only 32 have data and 22 data for the selected period. Most series stop in 2004 and there is no data afterwards in this database. The Spanish Ministry of Environment has been monitoring only 9 of them from 2006 on. The decrease in water table monitoring points is therefore considerable. Groundwater and surface water quality variables have been download from the Andalusian River Basins Network for physic-chemical and biological control of water quality, which contains all the sampling campaigns from 2002 to 2013 [Online] URL: http://laboratoriorediam.cica.es/Visor_DMA/?urlFile=http://laboratoriorediam.cica.es/Visor_DMA/service_xml/capas_dma.xml]. Available series for this period for each control point were averaged.

Regarding ecosystems water requirements, land ecosystems transpiration is a result from BalanceMED, environmental flows for the river are proposed in the RBMP on a monthly volumetric rate and aquifer discharges to springs and other connected aquifers were estimated in the Hydrogeological Atlas of Andalusia 1980-1990 [Online] URL: http://aguas.igme.es/igme/publica/libros1_HR/libro110/Pdf/lib110/in_32.pdf.

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